Stored Product Protection

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1 Introduction

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Management of Grain, Bulk Commodities, and Bagged Products, Oklahoma State University Publication E-912, was published in 1991. The first edition was sponsored by the USDA Federal Grain Inspection Service (FGIS), partially to help protect grain in the FGIS loan program. The loan program often went for multiple years, and generally the grain was in poor condition due to pests and moisture migration. The second edition, titled *Stored Product Management*, was published by OSU in 1995. It has been widely used by extension educators, researchers, and stored product managers as a practical, easy-to-read reference and "how-to" guide for protecting stored grain and grain products from insects, molds, and vertebrate pests. Demand for the publication still exists, but paper copies are no longer available for distribution.

Many changes in government regulations that influence stored product protection and advances in pest management techniques have occurred in the 16 years since *Stored Product Management* was published. To bring readers up to date, we have developed this companion book, *Stored Product Protection*, which is available online as well as in print. The 1995 edition of *Stored Product Management* is available at http://www.ksre.ksu.edu/library/p.aspx?tabid=70 and contains information not covered here in *Stored Product Protection*.

This new book expands on the 1995 OSU publication. Besides grain, this book includes information on pest management in other raw commodities, food processing facilities, and value-added, finished food products. It begins with biology and ecology of insects, molds, and vertebrates in storage systems. There are separate chapters on insect pests of grain and legumes, dried fruit and nuts, and processed and durable commodities of both plant and animal origins. The next four sections address various aspects of pest management — prevention methods, monitoring-based methods, decision making, economics, regulations, and marketing.

Stored Product Protection is intended as a training manual that will give readers an understanding of pest biology, behavior, and ecology in the marketing system; pest management methods; and pertinent economic and regulatory considerations for various products. Understanding pests is important because pest management is applied ecology (chapters 2–7). Many methods are available for managing pests, and each can be used in a variety of ways (chapters 8–12, 14–17, 26). Because insects readily develop resistance to pest management methods (particularly chemical methods), resistance management programs should be part of all pest management programs (chapter 13). Choosing the best method, and the best time and way of using that method, is complex (chapter 18–20). Properly timed pest management may require a number of monitoring programs (chapters 18, 21–24). Because of the complexity, extension agents and private consultants often play a role in developing integrated pest management programs for field and orchard crops and in developing optimal pest management programs for stored products (chapter 25). Such decisions require cost-benefit analysis, so an understanding of economics is important (chapters 27–29). Several government agencies oversee regulations concerning food quality, pesticide residues, and worker safety. Pest management programs must meet a variety of regulatory standards (chapters 30-31).

Three new regulations have influenced stored product protection in the United States since publication of the 1995 OSU book. The Food Quality Protection Act (FQPA) of 1996 called for a review of all pesticides registered by the Environmental Protection Agency (EPA) and mandated that exposure limits and use patterns be revised so that the most vulnerable members of human society, such as children and the elderly, would be protected from exposure. Changes in pesticide labels under FQPA and loss of registrations for certain compounds led to alternative methods of pest control for stored products.

The Clean Air Act, as influenced by the international agreement known as the Montreal Protocol, mandated the phase-out and eventual ban of the fumigant pesticide methyl bromide. As a result, much research and development after 1995 dealt with alternatives to methyl bromide (see chapter 14) for stored product protection. The National Organic Program of USDA established regulations as to how foods approved as being "organic" should be produced, stored, and distributed, with widespread impact on the use of synthetic additives and pesticides. Chapter 20 addresses organic considerations that were not even mentioned in the previous book, and low-input or chemical-free control measures are specified in several chapters of this volume.

Stored Product Protection is written for individuals involved with grain storage, commodity storage and management, food processing, and pest management. The target audience also includes academic, government, and private sector researchers in these fields, and regulatory personnel. The book focuses on North America, though examples are drawn from stored product experiences in many parts of the world.

The following list of 76 books and book chapters allow the reader to find additional information on subjects covered in this book. The chronological bibliography allows readers to follow the history of stored-product protection by starting at the top of the list or to find a recent discussion of a subject by starting at the bottom.

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2 Biology, Behavior, and Ecology of Stored Grain and Legume Insects

Linda J. Mason
Marissa McDonough

Stored grains and legumes are subject to insect infestation and deterioration from molds and bacteria. In 1990, postharvest losses in the United States were estimated to be $500 million per year (Harein and Meronuck 1991). The United States estimates that in developed countries the average minimum overall losses from biological degradation is 10% (National Research Council 1978), while in developing countries that estimate may be up to 20%. In sub-Saharan Africa losses are estimated to be around $4 billion a year (World Bank and FAO 2011). High environmental temperatures and moisture, along with dockage and broken kernels, provide conditions that accelerate mold and insect development within the grain mass, increasing grain losses. Storage infestations may originate in the field by highly mobile insects leaving the storage site and flying to grain standing in the field. They may also move to newly stored grain from fields and infested grain bins nearby. Insect populations can reach high levels when left unchecked in grain bins, subfloors, or aeration ducts, and in grain-moving equipment or discarded grain. These areas must be kept free of insects to reduce migration to newly harvested grain.

Insect movement within the grain mass is determined by seasonal conditions and grain temperature. During summer and fall, insect infestations will be found on the grain surface and distributed in clumps throughout the grain mass. In cold weather, especially in bins where the fines have not been redistributed or removed from the core, insects congregate at the center and lower portions of the grain and may escape detection until numbers increase. This is compounded by the fact that in cold grain (typically grain below 50 to 55°F), insects are not mobile and are easier to miss in random sampling.

A major concern with the presence of insects is potential to vector disease organisms. Many stored-grain insects possess hairs and indentations on their exoskeletons that can act as mechanical vectors of pathogens. Maize weevils have been shown to carry numerous fungi species, including *A. niger, A. glaucus, A. candidus, Penicillium islandicum, P. citrinum, Paecilomyces, Acremonium, Epicoccum, F. semitectum*, and yeasts (Smalley 1989, Dix 1984). Smalley (1989) noted that they were particularly loaded with *A. flavus* and *F. moniliforme*. Dix (1984) found that adults did not suffer from aflatoxicoses despite carrying a high density of spores. Hairy fungus beetle has been reported to carry *Salmonella enterica* serovar Infantis and is capable of transmitting it over long distances (Hold et al. 1988). They are also known to feed on aflatoxin, a contaminant in peanuts and grain, with no apparent deleterious effects (Tsai et al. 2007).

Association with other fungi or fungal toxins has been found in other stored product insects including lesser mealworm and confused flour beetle with zearelenone (Eugenio et al. 1970) and confused flour beetle with *F. graminearum* and *F. tricinctum* (Wright 1973). Dunkel (1988) examined the effects of other toxins on black carpet beetle (*Attagenus unicolor*) and confused flour beetle and found that ochratoxin A, citrinin, rubratoxin B and patulin had little or no effect on growth of confused flour beetles and slightly affected larval growth of black flour beetles.

The most favorable grain moisture range for stored-grain insects is from 12 to 18%. In many cases, insect infestation amplifies mold problems in grain by exposing otherwise hidden endosperm surfaces to molds, transporting mold spores to new areas, and encouraging mold germination in microhabitats made moist by insect metabolic activity (Sinha and Wallace 1966). Insect and mold metabolic activity can raise grain temperatures to 43°C (110°F). Tsai et al. (2007) observed feeding behavior of hairy fungus beetles in laboratory experiments and noted that the bodies of the mold-feeding larvae were "always coated with fungal spores, especially when fed cultures of *A. flavus* and *P. purpurogenum*. Newly molted larvae and pupae were whitish and free of fungal spores on the surface of their bodies, but quickly covered once feeding resumed." This insect has been shown to feed on aflatoxin, with no toxic effect to the insect (Tsai et al. 2007).

Insect populations should be controlled before grain is damaged by insect boring, feeding, and mold germination. Grain should be inspected every 21 days when grain temperature exceeds 15°C (60°F). Plastic pitfall traps should be used to monitor insects and record the species and number. Grain temperatures should also be monitored. The number of insects in each trap should be recorded and charts constructed to track changes in population size. Increasing numbers of insects indicate that management tactics need to be changed to prevent grain-damaging infestation levels. Grain can be inspected by screening or sieving and searching screens for insects and by examining kernels for damage, checking grain for webbing, and investigating off-odors.

Some insects damage grain by developing inside kernels, feeding on the inner endosperm, and producing holes in the kernel through which adults exit. The entire life cycle (egg, larva, and pupa) takes place inside the kernel, and the insect can survive only when whole kernels are present. These insects are known as internal feeders or primary pests. Examples of internal feeders include maize weevil, rice weevil, granary weevil, lesser grain borer, bean weevil, cowpea weevil, and larvae of Angoumois grain moth.

Other insect species develop on the cracked or broken kernels and grain dust, which can be produced by harvesting or binning procedures. They can also enter the kernel through feeding damage created by internal pests. These insects are known as external feeders, bran bugs, or secondary pests. They include Indianmeal moth, psocids, grain mites, flour beetles, saw-toothed grain beetles, flat grain beetle, rusty grain beetles, and cadelle beetle.

The next category of storage insects is mold feeders, and although they are external feeders, they do not directly damage the grain through feeding. Instead, these insects contaminate the grain mass through their presence and metabolic activity. Metabolic activity generates heat and produces water through the process of condensation, which encourages mold growth and grain spoilage (Magan et al. 2003). The growth of insect populations in the vicinity of these hot spots can significantly reduce grain quality through metabolic wastes and contamination from body parts or fragments. Mold feeders usually indicate that grain is going out of condition and that some mold growth has occurred. Common mold feeders include foreign grain beetle, rusty grain beetle, hairy fungus beetle, and psocids.

Insects such as grasshoppers, wasps, stinkbugs, butterflies, ground beetles, and lady beetles have been observed in stored grain but do not feed on the grain. They are usually trapped in the grain during harvesting and binning or become trapped after flying into the bins. They do not damage grain and can be removed in the cleaning process. No insect control action is needed.

Insects damage grain by boring holes into the kernels and reducing grain quality through weight, nutritional, or quality loss; spreading and encouraging mold germination; adding to the fatty acid content of the grain; and leaving quantities of uric acid that cause grain rancidity. While feeding, insects also create fines and broken kernels that reduce airflow through the grain when aeration fans are used. This reduction in air flow can cause an increase in temperature, compounding the problem. In addition to the direct damage, the presence of insects in a grain sample can result in cash discounts for the grain.

Two live insects in 1,000 grams of wheat, rye, or triticale cause the grain to be graded as "infested," resulting in significant cash discounts to the seller. The presence of live insects does not affect the numerical grade of the grain. In corn, barley, oats, soybeans, and sorghum, the conditions required for grain to be graded as infested are different. Grain may be designated as infested if a 1,000-gram sample contains more than one live weevil, one live weevil plus any five or more other live insects, or no live weevils but 10 other live insects injurious to stored grain.

Insect tolerances are stricter in finished commodities such as flour or cornmeal. For example, the defect action level (or the maximum number of insects permitted before the item is considered contaminated) set by the Food and Drug Administration for insect and insect fragments in cornmeal is one or more whole insects (or equivalent) per 50 grams or an average of 25 or more insect fragments per 25 grams (Food and Drug Administration 2009).

Identifying the specific pest found within a sample is important because insects have different damage potentials, biologies, behaviors, growing temperatures, moisture requirements, and reproductive potentials. Insect species create different types of damage and have different activity periods. Identification of the insect is the first step in understanding and controlling insect problems. Knowledge of insect biology is necessary for integrated pest management programs. The following is a summary of the major insects that can be found in stored grains and legumes and a description of the biology, behavior, and ecology of each.

Stored Grain Insect Pests

Granary weevil, *Sitophilus granarius* (L.)

Average minimum life cycle

38 days at 30°C and 70% relative humidity (RH).

Distribution

Worldwide, but primarily temperate zone, northern distribution.

Biology

Eggs – Up to 250 per female, average 200; internal feeder – eggs laid inside the grain.

Larvae – Within grains; can survive at least 10 weeks at 5°C.

Adults – 2 to 3 mm long, flightless; easily overwinter in unheated buildings and bulk grain.

Granary weevils feed on unbroken and broken grain kernels, including barley, buckwheat, corn, millet, oats, rice, rye, and wheat. They have been reported from birdseed, sunflower seeds, and chestnuts (Lyon 2011). They do not do well in finely ground material such as flour but can survive on many manufactured cereal materials such as kibbled pet food, macaroni, spaghetti, cereal, and noodles. If the grain is milled into a particle size smaller than needed for larval development, oviposition will not occur. Generally one to two eggs are oviposited into the endosperm or germ of a single kernel. When more than one egg is oviposited, only one adult will emerge from a single grain due to larval cannibalism. Eighty percent of eggs hatch when conditions are good; eggs laid by older females have lower hatchability rates (Arbogast 1991). Oviposition rate increases as food availability increases, indicating that in a grain bin with unlimited food supply, oviposition will be at the maximum rate (Fava and Burlando 1995).

Larvae are creamy white with a tan head and legless. They spend their entire lifetime within the kernel, hollowing out the kernel as they burrow. Development from egg to adult at 21°C (69.8°F) ranges from 57 to 71 days, depending on grain moisture (Khan 1948, Richards 1947). At warmer temperatures, development times are shorter. For instance, at 25°C (77°F), development is complete in 45 days. There are four larval instars, the last one forming a pupal cell out of frass, flour, and larval secretions at the end of the burrow. Newly emerged adults do not immediately leave the kernel. They often remain inside the kernel while their adult cuticle hardens and may feed there for up to a week. Adults live seven to eight months, moving around the grain mass throughout the day. There can be four generations per year. Adults will feign death when disturbed.

Granary weevils are unable to fly and generally do not infest standing grain. Their primary mode of locomotion is walking, but they are easily distributed when infested grain is transported from one site to another through infested harvesting equipment, auger systems, legs, bins, trucks, or barges.

Granary weevils are shiny reddish-brown and similar in appearance to maize and rice weevils. All weevils have a prolonged head or snout, which is distinctive and separates them from other beetles. The adults can be identified by the presence of elongated pits on the thorax, and also by the absence of flight wings and four light-colored markings on the wing covers. They are tolerant of low temperatures and cold climates and are seldom found in semitropical areas. They are 3.1 to 4.8 mm in size, depending on the size of the grain fed in as larvae.

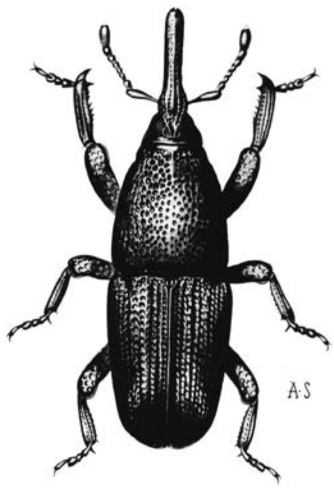

Figure 1. *Rice weevil (from Linsley and Michelbacher 1943) (3 to 4.6 mm long).*

Rice weevil, *Sitophilus oryzae* (L.)

Average minimum life cycle

25 days at 29.1˚C (84.4˚F) and 70% RH.

Distribution

Tropical and temperate areas; least cold tolerant of all the grain weevils.

Biology

Eggs – Laid in grains in the field and storage.

Larvae – Feed internally within a grain kernel.

Pupae – Found within the kernel.

Adults – Fly, 3 to 4.6 mm long; normally do not overwinter in temperate areas unless in warm grain.

Rice weevils (Figure 1), like granary weevils, are pests of whole grains such as wheat, corn, barley, sorghum, rye, oats, buckwheat, cottonseed, and rice. Like granary weevils, they prefer whole grains but have been reported to feed on beans, nuts, processed cereals, spaghetti, macaroni, pasta, cassava, birdseed, nuts, pet food, and decorative Indian corn. They are internal feeders, and the entire development cycle occurs within the kernel. Eggs are laid when the environmental temperature is between 13.0 and 35.0˚C, with maximum oviposition occurring between 25.5 and 29.1˚C (77.9˚F-84.4˚F) (Birch 1945a). Usually, one small white egg is deposited into a cavity created by the female. The cavity is about as deep as the length of the snout of the weevil. After laying the egg, she slowly withdraws the ovipositor, filling the cavity with a gelatinous material that hardens as a plug to protect the newly laid egg. Egg hatch generally takes five days, and hatchability is about 75% (Arbogast, 1991). Maximum oviposition occurs one to two weeks post-adult emergence.

Developmental times from egg to adult range from 25 days at 29.1˚C to an average time of 35 days at 27˚C (80.6˚F)(Arbogast 1991; Sharifi and Mills 1971a) with maximum developmental times at 18.2˚C taking 94 days if one larvae is in the kernel. If three eggs are oviposited into a kernel, the developmental period increases to 110 days at 18.2˚C (64.8˚F) or 36 days at 29.1˚C (84.4˚F) (Birch 1945b), probably as a result of competition for food. Lower grain moisture content (about 11%) will add four to five days to the normal developmental period (Arbogast 1991). There are four larval instars, each about five days, and a pupal period of five days. Adults emerge and may remain in the kernels up to five days and live on average about three months, although some have been known to live over a year.

Rice weevils can fly and easily distribute themselves throughout a storage facility. Because of their flight ability, they may also infest grain while it is still standing in the field, especially if the harvest is delayed and the temperatures are mild. Because of this fact, it is important to inspect incoming loads for this pest, even if the loads are coming directly from the field. Although very similar in appearance to the other grain weevils, rice weevils are 2 mm in length (generally slightly smaller than maize weevils), have small longitudinally elliptical punctures on the thorax except for a smooth narrow strip extending down the middle, and possess red/yellow oval-shaped markings on the forewings. They are less tolerant of cold temperatures than the granary or maize weevil. Freezing is an easy method to control this pest. Rice weevils have a wide distribution, including both temperate and tropical areas.

Maize weevil, *Sitophilus zeamais* Motschulsky

Average minimum life cycle

26 days at 30°C (86°F) and 75 to 76% RH.

Distribution

Tropical and temperate areas, warm humid areas where corn is grown are favored but can be found in colder climates like Canada.

Biology

Eggs – 300 to 400 per female; laid in cereals grains in the field and storage.

Larvae – Feed in grain.

Pupae – Found within kernel.

Adults – 3 to 3.5 mm long.

The maize weevil has a host range similar to the rice and granary weevil, and although it is commonly found on maize, it can feed on most cereal grains, including wheat, barley, sorghum, rye, and rice. Maize weevils prefer whole grains but have been reported to feed on many processed grain products including pet food and pastas. They have a wider tolerance for host moisture content, even feeding on stored apples. Typically one egg is laid per kernel (Lathrop 1914; Gomez et al. 1982), but on occasion more than one adult may emerge. If multiple eggs are laid, larvae compete with active aggression among the seed occupants (Guedes et al. 2010). Immature survivorship is only 18% (Throne 1994). Eggs are not laid if relative humidity is below 60% (Arbogast 1991). Infestations of immatures can be determined by staining the kernels to readily see the oviposition plug placed in the egg cavity to protect the immature weevil. The life cycle of the maize weevil averages 35 days at 27°C (80.6°F) (Sharifi and Mills 1971b) with a maximum development time of 110 days at 18°C (64.4°F). Survivorship of all immature life stages is highest at 25°C (77°F) (Throne 1994). Minimum temperature for development is 13°C (55.4°F). The egg, larva, and pupa stages are rarely seen because they are confined to the inside of the grain kernel. Eggs are creamy white and barely visible to the naked eye. Hatchability is about 90%, and first instar larval mortality can be as high as 30% at 50% RH (Arbogast 1991). Larvae are creamy white with a brown head and legless. They go through four instars before pupating within the kernel. During the four to five months of cold winter weather, the larva remains within the kernels. There are generally four to five generations per year in most grain storage facilities. Heated storage buildings may house twice that many generations. Adults live about four to eight months.

Adult maize weevils are slightly larger — 2.5 to 4 mm — than rice weevils. They have circular punctures on the thorax compared to oval punctures on the rice weevil and more distinct colored spots on the forewings. Maize weevils are stronger fliers than rice weevils.

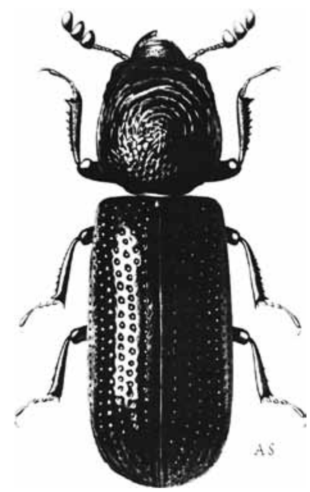

Figure 2. *Lesser grain borer (from Linsley and Michelbacher 1943) (2 to 3 mm long).*

Lesser grain borer, *Rhyzopertha dominica* F.

Average minimum life cycle

25 days at 34°C (93.2°F).

Distribution

Worldwide; both adults and larvae are voracious feeders.

Biology

Eggs – 300 to 500 per female, laid on grain surface, often in groups.

Larvae – Eat into grain and feed on grain dust.

Pupae – Usually form cell inside grain, but may leave grain to pupate in grain dust; stage lasts five to eight days.

Adults – Voracious feeder, reddish brown, bullet shaped cylindrical body, clubbed shaped antennae (Figure 2).

The lesser grain borer is a small — 2 to 3 mm — black-brown, highly destructive insect related to some wood boring beetles. It is easily identified by its shape. The body is slim and cylindrical, similar in shape to a bullet. The head is tucked up under the thorax and the hood shaped rounded neck shield. The hood is covered with pits that get gradually smaller toward the posterior. The 10-segmented antenna is clubbed with the last three segments forming a loose club.

The eggs, up to 500 per female, are laid outside the whole kernels and young larvae bore inside. Moisture content of the grain is critical to oviposition and development. Wheat with moisture content below 8% is not suitable to oviposition. Egg development takes 32 days at 18.1°C (64.6°F) but only five days at 36°C (96.8°F). The effect of this temperature range is even more subtle for larval development. A 3-degree increase in temperature (25 to 28°C) (77 to 82.4°F) results in a 17-day increase in larval development. Larvae are white and c-shaped. They have four to five larval instars if on whole grain, or two to seven (usually three to four) if feeding on whole meal. The limiting temperatures for larval development are 18.2°C (64.8°F) and 38.6°C (101.5°F) (Arbogast 1991). Both the larvae and adults are voracious feeders and leave fragmented kernels and powdery residues. The larvae may complete their development in the grain residue. Adults usually remain within the kernel for a few days prior to emergence. Mated females start ovipositing about two weeks later and continue for about four months.

Lesser grain borers infest all types of cereal grains, but prefer wheat, corn, or rough and brown rice. Tropical in origin, possibly from the Indian subcontinent, they also feed on peanuts, nuts, birdseed, cocoa beans, and beans as well as processed products such as macaroni, tobacco, and dried spices. They do well in the flour created by the initial infestation of beetles. Grain infested with lesser grain borer has a characteristic sweet and slightly pungent odor. This odor contains the male-produced aggregation pheromone that has been demonstrated to be an effective lure for use in insect traps. The lesser grain borer flies, but because of its size it is easily caught by air currents. Flight times are influenced by season and light conditions (Potter 1935). For example, peak flight activity occurs during May and again in September through October (Toews et al. 2006). They don't appear to infest standing grain (Hagstrum 2001) but may survive outside the grain environment on seeds and acorns of other plants (Jia et al. 2008).

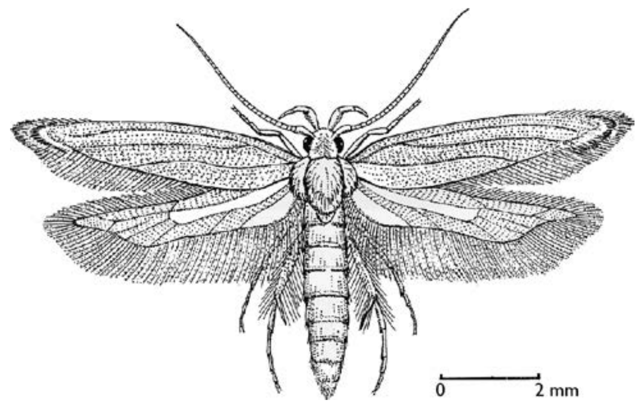

Figure 3. *Angoumois grain moth (from Hill 2002) (6 to 9 mm long).*

Angoumois grain moth, *Sitotroga cerealella* (Olivier)

Average minimum life cycle

35 days at 30°C (86°F) and 75 to 76% RH.

Distribution

Tropical grains (maize, paddy, sorghum); attacks before harvest.

Biology

Eggs – 40 to 150 eggs laid on grain surface.

Larvae – Bore into grain, stay until pupation.

Pupae – Form in grain.

Adults – Non-feeding, short-lived, wingspan 6 to 9 mm, dark spot on wings, long fringe on fore and hind wing, hind wing margin taper to a fingertip projection on tip (Figure 3).

The Angoumois grain moth was a major pest of crib-stored corn, but modern harvesting and storage procedures have significantly reduced losses due to this insect. It usually does not cause major damage to shelled corn, although in southern areas of the

United States, it can occasionally be a major problem, even in shelled corn. It requires whole grain for development, and is commonly found in corn, wheat, sorghum, peanuts, rice, and pearl millet, although it has been found as a museum pest feeding on dried plant material in a herbarium (Grabe 1942). The moth is more sensitive to low temperatures than other stored product moths and, as a result, is not common in unheated structures in the northern United States. They may be found coexisting with sawtoothed grain beetles, but if grain is infested with other internal feeders, such as maize weevil and lesser grain borer, Angoumois grain moth populations will be suppressed.

Adults are short-lived, do not feed, and are attracted to light. Oviposition occurs on the exterior of the seed, usually during the overnight hours (Cox and Bell 1991). As the larvae within the eggs mature, the eggs darken. Egg development can last five to six, six to seven, or 10 days at 30°C (86°F), 25°C (77°F), or 20°C (68°F), respectively (Boldt 1974; Cox and Bell 1991). Eggs can hatch at temperatures as low as 12°C and as high as 36°C. Larvae are 5 mm (¼-inch long) and are yellow-white with brown heads. Larvae spend their entire lifetime within the kernel. In cold climates, larvae become dormant for four to five months. Pupation occurs within the kernel, lasting eight, 10 to 12, or 20 days at 30°C, 24°C to 27°C, and 20°C, respectively. Adults are short-lived, generally less than one week. Minimum temperature for population development is 16°C, optimum development occurs at 30°C, and maximum temperature for population development is 35°C to 37°C (Cox and Bell 1991).

Cowpea weevil, *Callosobruchus maculatus* (F)

Average minimum life cycle

21 days at 30°C (86°F) and 70% RH.

Distribution

Worldwide, on legumes (pulses) both in store and in the field before harvest.

Biology

Eggs – Laid in pods before harvest or among seeds in storage.

Larvae – Enter and feed within one seed.

Pupae – Form in seed, which then shows characteristic "window" at seed exterior.

Adults – Non-feeding, short-lived (10 to 14 days), basal segments of antennae are reddish yellow, remainder of segments darker.

Cowpea weevils are not true weevils (they lack a snout) although they are weevil-like. Adults are reddish brown elongate beetles, about 3 mm in length (Texas AgriLIFE Extension 1999). They have two blackish red spots on the wing covers, which are short, not completely covering the abdomen. The exposed portion of the abdomen also has two blackish spots visible.

They infest stored legumes, including cowpeas (black-eyed peas), dried peas, chickpeas, lentils. These crops bring in more than 90 million dollars into the U.S. economy for the 1 million metric tons harvested each year. Tropical and subtropical in origin, they are commonly associated with legumes both in the field and in stored and packaged beans worldwide. They do not infest other cereal grains. Six to seven generations per year may occur under ideal storage conditions. They will feign death if disturbed, sometimes not resuming movement for 5 minutes. Males and females can be easily distinguished in the adult form. Females possess dark stripes on the sides of the enlarged plate covering the tip of the abdomen and are dark brown or almost black in coloration compared to the light-brown males.

Unlike other stored product insects, adults of this beetle can be found in two morphological body forms: one with wings and capable of flight, and the other without wings and flightless. The flying form is produced when larval rearing conditions are crowded, or in continuous light or dark (such as in storage), high environmental temperature, or low moisture content (Utida 1972; Beck and Blumer 2011), conditions often found in storage. In storage, the flightless form is common. The weevils breed on stored seeds while conditions are optimum. As the population grows and conditions become unsuitable, the winged form appears and disperses to breed on growing seeds in the field. Adults often are found in the field on flowers in the spring. Winged females oviposit on beans in the field and the resulting larvae are transported into storages at harvest. Adults that emerge from these larvae are flightless (Arbogast 1991).

In addition to morphological differences between the two flight forms, there are physiological and behavioral differences. Females of the flightless form lay more eggs, and those eggs have a different hatchability than females that fly. For example, at 15°C (59°F) flightless females lay 56.2 eggs compared to 20.0 eggs for flying females, whereas at 35°C (95°F), flightless females laid 77.1 eggs compared to 36.6 eggs for flying females (Utida 1972). Egg hatchability increases from 45.9 to 64.1% for flying versus flightless females at 15°C (59°F) but decreases from 22.5% (flying) to 1.8% (flightless) at warm temperatures at 35°C (95°F). Flying form females emerge with immature ovaries and oviposition is delayed three to four days. They withstand cooler temperatures and require higher humidity. Flying form adult longevity is twice as long as the flightless form.

Fecundity depends on the host, with poor oviposition on lentils (23 eggs per female) to optimal oviposition on broad beans (110 eggs per female) (Utida 1972). Females lay eggs on the outside of the seed and newly emerged larvae bore inside, multiple larvae inhabiting a single seed. Larvae are white and c-shaped. Damage occurs due to larval feeding. Larvae burrow into the seed and feed on the embryo and endosperm until pupation. Characteristic feeding includes larvae feeding very close to the surface of the bean, leaving a thin covering, often called a window, that is about 1 to 2 mm across. Average developmental periods at 28°C (84.4°F) and 75% RH range from 26 days on black-eyed cowpeas to 66 days on lentils.

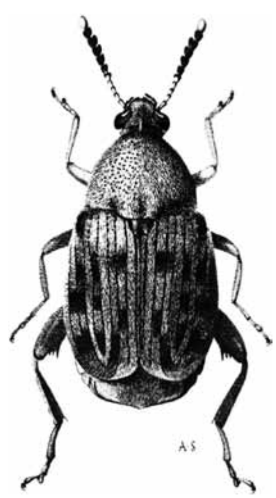

Figure 4. *Bean weevil (from Linsley and Michelbacher 1943) (2 to 3.7 mm long).*

Bean weevil (dried bean weevil, common bean weevil), *Acanthoscelides obtectus* (Say)

Average minimum life cycle

28 days at 30°C (86°F) and 70% RH.

Distribution

Worldwide, primarily on common bean (*Phaseolus vulgaris*) but probably could be found on other species of *Phaseolus*. Found both in storage and in the field before harvest.

Biology

Eggs – Laid in pods before harvest or among seeds, maximum 70 to 75 eggs per female.

Larvae – Enter and feed within one seed.

Pupae – Form in seed, which then shows characteristic "window."

Adults – Non-feeding, short-lived, 2 to 3.7 mm long, grey beetle with short hairs on thorax, antennae have sawtooth like segments (Figure 4).

Bean weevils are not true weevils because they do not have a snout like rice or maize weevils. These beetles are small (3 to 5 mm (⅛ inch)), grayish-brown in color, oval in shape, and may be identified by brown or grayish spots on wing covers and fine yellow-orange hairs on the thorax. Bean weevils develop on the mature bean pods in the field but will also infest beans in storage facilities. They can be found worldwide, but are most common in subtropical areas. They develop primarily on common bean but have been found on other beans. This insect is also capable of feeding and reproducing on fungi (Sinha, 1971).

During her lifetime, a female may lay up to 70 eggs. Multiple whitish eggs are laid loosely on a single bean pod or in pod cracks (Godrey and Long 2008) and multiple larvae may emerge from a single bean, unlike many storage insects where just one insect emerges per seed. The first instar grub-like larva bores into the bean and causes the damage. Immature bean weevils suffer high mortality. At 25°C (77°F), 58% mortality has been reported (Arbogast 1991). Development can occur between 15 and 35°C (59 to 95°F) as long as the humidity is not too high or too low (Howe and Currie 1964; Arbogast 1991). Development is fastest (32 days) at 29°C (84°F), but may take as long as 92 days at 18°C (64.4°F).

Adults do not feed. When the product becomes heavily infested, adults will leave the beans and crawl up the walls of the storage facility or fly around, searching for fresh product to infest. Like many related species, bean weevils will feign death when disturbed. The insect produces a sweet "fruity" pheromone that gives cultures of newly emerged adults a pleasant smell. This insect can be controlled in packaged items in smaller quantities by heating the beans to 54°C (130°F) for 30 minutes to kill developing larvae within the kernels.

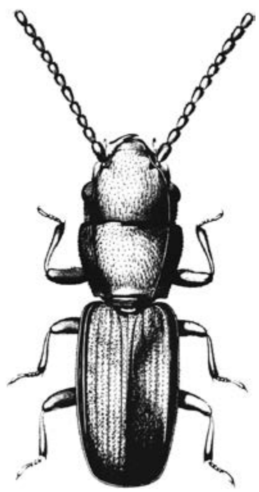

Figure 5. *Rusty grain beetle (from Linsley and Michelbacher 1943) (1.6 to 2.2 mm long).*

Rusty grain beetle, *Cryptolestes ferrugineus* (Stephens)

Average minimum life cycle

21 days at 35°C (95°F).

Distribution

Worldwide; normally a secondary pest, but may attack damaged whole grains.

Biology

Eggs – 200 to 500 eggs may be laid, often in splits or cracks in grain.

Larvae – Prefer to feed on or near endosperm, particularly if grain is attacked by fungi.

Pupae – Create cocoon in the food material with silk.

Adults – Feed, fly, and can live six to nine months.

The rusty grain beetle (Figure 5) has a worldwide distribution and is often found in stored grain in the northern United States and Canada. Adults are cold-hardy and fly well in warm temperatures. This insect prefers high moisture grain or moist, decaying food. It has been recorded from wheat (bran, germ, and flour), rye, corn, rice, oats, barley, oilseeds, cassava root, dried fruits, and chilies, although the preferred host is wheat and development is optimum on this grain. Larvae feed preferentially on the germ of the whole kernels, but they also feed on the endosperm and sometimes hollow out the entire kernel. They cannot attack undamaged grains, although imperfections resulting from handling may permit feeding. Developmental period is shortest and oviposition is higher as cracked grain particle size increases (Sheppard, 1936; Throne and Culik, 1989). Mold growth promotes larval development with development shortest (22 days) on *Trichothecium roseum* (Persoon) Link *ex* S. F. Grey and *Fusarium moniliforme* Sheldon resulting in the longest developmental period (34 days) (Sinha 1965; Arbogast 1991).

Adult rusty grain beetles are reddish brown and about 1.6 to 2.2 mm in length. They have very distinct long, beaded antennae that project forward from the head in a characteristic v-shaped pattern. Adults are strong flyers, and especially prone to flight in warm weather. Females deposit eggs (200 to 500) loosely in the grain mass or in cracks or furrows in the grain kernel. They are white, oval, and 0.5 to 0.8 mm (0.02 to 0.03 inch). Unlike many stored product insects that have a distinct peak in oviposition, rusty grain beetles have a slight decline toward the end of their lifecycle (Arbogast 1991). Oviposition continues for up to 34 weeks, with average reported fecundity of 242 eggs per female (Davies 1949). Eggs hatch in three to five days at 30°C (86°F). Larvae — 3 mm (⅛ inch) — are creamy white and somewhat flattened. The head and a forked process on the posterior end of the larvae are slightly darkened. Larvae, as well as adults, are cannibalistic, consuming eggs, pre-pupae, and pupae (Sheppard 1936). There are four larval instars. The last one constructs a silk cocoon, often located within damaged kernels. The larval period lasts 32 to 37 days at 28.3°C (82.9°F) and the pupal stage lasts five days on corn meal. Development will not occur in very dry grain (moisture content less than 12%; RH less than 40%) (Canadian Grain Commission 2009). Adults emerge from seed five to seven days after pupation. Temperature range for development is 17.5°C to 20°C (63.5°F to 68°F) to 40.0°C to 42.5°C (104°F to 108.5°F) with minimal development time at 35°C (95°F) at 21 days.

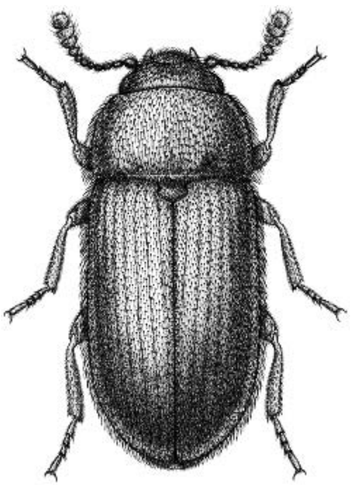

***Figure 6.** Hairy fungus beetle (from Bousquet 1990) (2 to 4.3 mm long).*

Hairy fungus beetle, *Typhaea stercorea* (L.)

Average minimum life cycle

15 days at 30°C (86°F) and 80 to 90% RH.

Distribution

Worldwide; commonly associated with moldy grain.

Biology

Eggs – Up to an average of 128 per day; laid singly in food.

Larvae – Mature larvae are white/pale brown, 4 to 4.5 mm.

Pupae – No pupal chamber built, pupate in food.

Adults – Broadly oval in shape; brown; 2 to 4.3 mm long with hairs on wing covers arranged in rows (Figure 6). Can fly and crawl into storage areas (as well as between storage areas).

The hairy fungus beetle is brown with a distinct three-segmented clubbed antenna. It has short stout hairs on the wing covers that are arranged in lengthwise rows down the back. It prefers to feed on mold and is a good indicator of moldy food. Larvae are whitish to pale brown, 4 to 4.5 mm (⅙ inch) long (Mason 2008). Dark projections at the tip of the abdomen are similar to those found on flour beetle larvae. Adults are strong fliers and often move into grain storages, railcars and food facilities by flight. The presence of this insect is a good indicator of grain going out of condition and probably indicates that mold is present in food. They are attracted to hot spots within the grain mass, and their metabolic heat and fecal material can contribute to the heating of a grain mass (Sinha and Wallace 1966; Tsai et al. 2007).

Tsai et al. (2007) determined that within a 24-hour period, females lay 128 eggs on *Aspergillus flavus*, 89 eggs on *Eurotium rubrum,* and 42 eggs on *Penicillium purpurogenum*. Eggs were laid singly on the fungal colony surface or embedded in the fungal mycelium. Larval development time at 30°C is shortest on *A. flavus* (181 hours) and longest on *E. rubrum* (333 hours) and *P. purpurogenum* (344 hours). The pre-pupal period is about 1 day and the pupal period is about two to three days (Tsai et al. 2007). The total developmental period may range from 15 to 107 days at 30°C to 15°C (86°F to 59°F) and 70 to 90% RH (Jacob 1988), and nine to 25 days at 30°C (86°F) and 72% RH (Tsai et al. 2007). When larvae and adults feed in fungal masses, they quickly become covered with spores. Of greatest concern is that hairy fungus beetles can consume high levels of aflatoxin produced by *A. flavus* and show no detectable deleterious effects. It is possible that they are excreting the aflatoxin, which could indicate the ability to translocate aflatoxin.

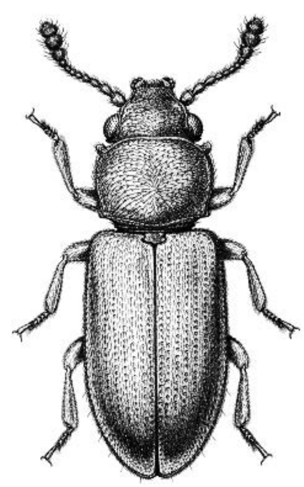

***Figure 7.** Foreign grain beetle (from Bousquet 1990) (2 to 2.3 mm long).*

Foreign grain beetle, *Ahasverus advana* (Waltl)

Average minimum life cycle

22 days at 27°C (80°F).

Distribution

Worldwide; primarily a secondary feeder, an excellent indicator of grain going out of condition due to the presence of mold.

Biology

Eggs – Deposited singly or in clusters.

Larvae – Feed on mold on grain, require high humidity for growth.

Pupae – Enclosed in chamber constructed of cemented food particles.

Adults – Feed on mold on grain, identified by bumps just behind the eyes and three-segmented antennal club (Figure 7).

The foreign grain beetle is easily identified by two bumps on the elytra just behind the eyes. It is light brown with antennae that terminate in a three-segmented club. It has a worldwide distribution and has been found in many commodities including raw grains and cereal products, peanuts, oilseeds, dried fruit, and spices. It prefers commodities that are moldy and is able to survive on mold cultures alone. It can consume several different fungal organisms, many common in stored grains (Shayesteh et al. 1989; David et al. 1974). Population development, specifically larval growth, requires high RH (92 to 75%), and none survive at 58% RH (David and Mills 1975).

Females do not oviposit continuously throughout life; rather, they start laying three to four days post-emergence and alternate 20- to 30-day oviposition bouts with five- to 23-day non-ovipositional bouts. There are generally two to four rounds of ovipositional and non-ovipositional bouts. During an ovipositional bout, females usually lay one to four eggs singly or in clusters of two to three eggs per day but may lay up to eight to 12 eggs per day on occasion (Arbogast 1991; David and Mills 1975). There are two peaks in oviposition during a female's lifetime; during the first two weeks and during the fourth month. At 27°C (80°F) eggs hatch in four to five days. Larvae feed within the food mass, progressing through four to five larval instars for about two weeks (11 to 19 days), after which they construct a pupal chamber by cementing food particles together and attaching themselves to the chamber with anal secretions (David and Mills 1975). Pupation lasts three to five days. Adult longevity varies depending on mating status; unmated males and females live 275 and 301 days respectively, while mated males and females live only 159 and 208 days, respectively.

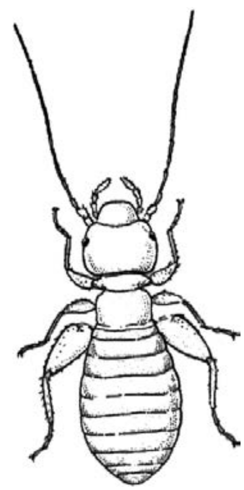

Figure 8. *Psocid (from Michelbacher 1953) (0.9 to 1.2 mm long).*

Psocid (also called booklice), *Liposcelis spp.*

Common Species in the United States

Lepinotus reticulatus*, *Liposcelis bostrychophila*, *Liposcelis brunnea*, *Liposcelis corrodens*, *Liposcelis decolor*, *Liposcelis entomophila*,** and ***Liposcelis paeta (Throne et al. 2006).

Average minimum life cycle

16.1 days at 35°C (95°F) and 75 to 80% RH for *Liposcelis decolor* to 24.6 days at 32.5°C (90.5°F) and 75% RH for *Liposcelis brunnea.*

Distribution

North America and Europe. Not injurious to stored grain. Common when moisture content or humidity is high.

Biology

Eggs – Oval translucent eggs are laid singly (up to 75 eggs in a lifetime for *L. bostrychophila*) 100 to 200 per female for other species.

Nymphs – No larval stage; young resemble adults.

Adults – *L. bostrychophila* adults live an average of three months at 30°C (86°F); however, some species live up to six months. Some species are winged, but most are wingless (Robinson 1991).

Typical of many stored product insects, these soft-bodied insects have no larval stage. Rather, the young resemble the adults, but are smaller and paler in color. Psocids feed on a variety of animal and plant matter, including fungi, but do not actually damage grain. This insect reproduces by obligatory thelytokous parthenogenesis (only females are produced and no mating is required to produce offspring), which allows their populations to grow rapidly under certain environmental conditions. Although numerous species are associated with grain, L. *bostrychophila* has the most detailed biological information reported (Wang et al. 2000), and it will be the species referred to hereafter. *L. bostrychophila* oviposit 52 to 75 eggs in the temperature range of 20°C to 35°C (68°F to 95°F) with maximum oviposition occurring at 27.5°C (81.5°F) (Wang et al. 2000). The lower range for reproduction was calculated as 17.6°C (63.7°F), whereas the upper temperature range was estimated to be 36.5°C (97.7°F). Peak reproduction occurs 2 to three weeks after the pre-oviposition period (generally four days) terminates. Eggs, often adhered to a substrate, are laid on bags and commodities, and take six to 14 days at 20°C (68°F) to 32.5°C (90.5°F) to hatch (Turner, 1994; Wang et al. 2000). Nymphs go through four molts in 12 days at 32.5°C (90.5°F) to 28 days at 20°C (68°F). Adults are small — 0.9 to 1.2 mm — light brown, soft-bodied insects. They have swollen hind femurs (part of leg closest to body) and flattened bodies (Figure 8).

Under humid conditions, populations can expand quickly, causing up to 10% weight loss (Opit et al. 2011), although they are generally thought to be a secondary pest. In some situations, they may be considered a pest of medical importance because some people exhibit allergic reactions after contact with an infested commodity. When populations are high, the insects may coat the grain surface and look like a "dust" or "carpet" moving or coating the grain surface. Psocids feed on a variety of animal and plant matter, preferring processed grain products, but are just as common in most whole grains. They are also found in museums displays and preserved insect collections. They prefer grain that is going out of condition that contains active fungal populations and may contribute to the growth of fungal populations because of moisture and organic matter produced as populations grow. Control is easy if the RH can be dropped to below 50%, but this may not always be possible or feasible.

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S156 – 2 September 2012

3 Biology, Behavior, and Ecology of Stored Fruit and Nut Insects

Charles S. Burks
Judy A. Johnson

Tree nuts and dried fruits vary widely in their quality as hosts for insect pests, but stored product pests can cause economic loss even in commodities that are generally poor hosts. Economic damage can be due to commodity consumed, but the very presence of insect body parts, frass, or webbing can cause expensive rejections and loss of market at the wholesale level due to quality concerns or phytosanitary regulation. Most USDA quality standards for dried fruits and nuts do not allow for any live insects (USDA-AMS 2011).

Stored product pests of dried fruits and nuts can be divided (with some qualifications) into two categories: orchard pests that primarily infest the orchard and do not reproduce in storage, yet affect marketability; and pests that infest and reproduce in storage. In this chapter, the biology of selected pests of dried fruits and nuts in storage are presented. Species descriptions are presented in three groups (Table 1). The first group includes three moths — the codling moth, navel orangeworm, and the carob moth — which are predominantly field pests that infest the marketable fruit or nut. The second group includes non-lepidopteran pests, the driedfruit beetle and vinegar flies, which infest predominantly in the field. Unlike the moth pests, the driedfruit beetle and the vinegar flies feed as adults. The third group includes the Indianmeal moth, almond moth, tobacco moth, and the raisin moth. These last four moths are predominantly storage pests. They (and the Mediterranean flour moth, Chapter 4) respond to the same principal pheromone component, and might be found in the same pheromone trap. Except for the codling moth, each of the moths in this chapter is of the subfamily Phycitinae (Heinrich 1956, Solis 2011).

In addition to these species, the red flour beetle, *Tribolium castaneum*, and the sawtoothed grain beetle, *Oryzaephilus surinamensis*, as well as a variety of other beetle species (Simmons and Nelson 1975), also infest and reproduce in dried fruits and nuts during processing and storage. Their biology is described in Chapter 4. Common names are used here are in accordance with the Entomological Society of America (ESA 2011), but these vary widely internationally, even within the English language.

Life Histories

Figure 1. *Codling moth adult and larva (Jack Kelley Clark, courtesy University of California Statewide IPM Program).*

Codling moth, *Cydia pomonella* (L.)

Adults are mottled gray with brown wing tips, slightly under 0.5 inch long, with wings covering the top and side of the body (Figure 1). Adults do not

Table 1. *Hosts and geographical distribution of selected insect pests of dried fruits and nuts.*

Species	Reproduces in storage?	Hosts	Geographical range	References
Codling moth *Cydia pomonella*	No	Pome fruits, walnuts	Cosmopolitan	(2)
Navel orangeworm *Amyelois transitella*	No	Walnuts, almonds, pistachios, figs	Tropical and subtropical Western Hemisphere	(7; 10; 15; 17)
Carob moth *Ectomyelois ceratoniae*	Yes	Dates, figs, almonds, pomegranates, and citrus	Nearly cosmopolitan	(4; 7; 12-14; 17)
Driedfruit beetle *Carpophilus hemipterus*	No	Figs, raisins, dates	Cosmopolitan	(4; 7; 8)
Vinegar fly *Drosophila* spp.	Maybe	Figs, raisins	Cosmopolitan	(16)
Indianmeal moth *Plodia interpunctella*	Yes	Wide range of stored products	Cosmopolitan	(7; 11; 17)
Almond moth *Cadra cautella*	Yes	Wide range of stored products	Cosmopolitan	(5; 7; 17)
Tobacco moth *Ephestia elutella*	Yes	Dried fruits, nuts, grain and cereal, chocolate, cocoa, and tobacco	Nearly cosmopolitan	(1; 3; 6; 7; 17)
Raisin moth *Ephestia figulilella*	No	Dried fruits, nuts, seeds, beans	Nearly cosmopolitan	(5-7; 9; 17)

References cited: 1) Ashworth 1993. 2) Barnes 1991. 3) Bell 1975. 4) Blumberg 2008. 5) Cox 1975b. 6) Donohoe et al. 1949. 7) Heinrich 1956. 8) James and Vogele 2000. 9) Kehat et al. 1992. 10) Legner and Silveira-Guido 1983. 11) Mohandass et al. 2007. 12) Mozaffarian et al. 2007. 13) Navarro et al. 1986. 14) Nay and Perring 2006. 15) Plant Health Australia 2009. 16) Simmons and Nelson 1975. 17) Solis 2011.

feed. The codling moth is oligophagous (i.e., limited to a few hosts); larvae (Figure 1) develop principally on fruit from the family Rosaceae, and on walnuts (Barnes 1991). Flat, oval eggs are laid singly on nuts or on leaves near nuts. Larvae enter soft, immature nuts quickly, but may require a week to enter hardened walnuts (Barnes 1991). Codling moth larvae are white to tan with a dark head capsule and prothoracic shield, and they lack the sickle-shaped prothoracic spiracle characteristic of navel orangeworm and carob moth larvae. Codling moth larvae exit fruit or nuts to pupate.

Codling moth survives the winter in a genetically determined, photoperiodically induced diapause at the end of the last larval instar (Barnes 1991). Diapausing larvae overwinter in cocoons in protected sites under bark or in debris, but a good number will remain in harvested nuts (Vail et al. 1993). The codling moth has a cosmopolitan distribution at latitudes above 25° in the northern and southern hemispheres (Barnes 1991). In California the generation time (egg to egg) averages 620 degree days (DD)°C, which results in three to four flights a year. Adults emerging in spring from overwintered larvae give rise to a first flight in spring, and their progeny emerge in two subsequent generations, in June and August, respectively. Feeding from the progeny of the first flight can cause nuts to be aborted, whereas progeny of later flights are more likely to cause internal damage to harvested nuts (Barnes 1991). Codling moth larvae are often not present in walnuts damaged by their feeding. But, in addition to direct damage, they can also provide an entry for navel orangeworm, and have been a cause for phytosanitary fumigation treatments of walnuts (Mitcham et al. 2004).

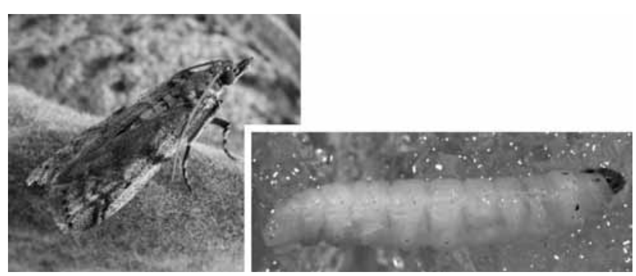

Figure 2. *Navel orangeworm adult (Peggy Greb, USDA-ARS) and larva (Charles Burks, USDA-ARS).*

Navel orangeworm, *Amyelois transitella* (Walker)

Navel orangeworm adults have gray-brown wings with black transverse markings (Figure 2). Slightly over 0.5 inch long, they are superficially similar to Mediterranean flour moth (Chapter 4). Adults do not feed. Essentially a scavenger, the navel orangeworm has a wider and more taxonomically diverse host range than the codling moth, and typically feeds on fruit, nuts, and legume pods, generally in later stages of maturity or decay (Curtis and Barnes 1977). Flat, oval eggs are laid individually or in clumps on fruit or leaves near fruit, where they are glued securely. Eggs are initially cream-colored, and then turn reddish-orange before larval emergence.

Navel orangeworm larvae (Figure 2) are poor penetrators and depend on naturally occurring fissures or entry holes from other insects for access to larval hosts (Curtis and Barnes 1977). They range in color from white to orange. The sickle-shaped prothoracic spiracles distinguish navel orangeworm larvae from codling moth, but navel orangeworm and carob moth larvae share this characteristic and are difficult to distinguish (Solis 2011). Unlike codling moth, navel orangeworm larvae pupate inside host fruit or nuts rather than exiting to pupate elsewhere (Kuenen and Siegel 2010). Evidence for diapause in the last larval instar exists (Gal 1978, Legner 1983), as in other Phycitinae (Cox 1979, Bell 1994), but all larval stages are observed in overwintering populations.

Discrete flights have been described for the navel orangeworm, comprising adults emerging from overwintering larvae followed by two or more successive generations (Sanderson et al. 1989). Larval development time varies greatly for this species (Kuenen and Siegel 2010, Siegel et al. 2010). In areas of higher abundance there is overlap of flights, particularly later in the season. In addition to direct damage to products, the navel orangeworm is a target of some phytosanitary restrictions (Plant Health Australia 2009).

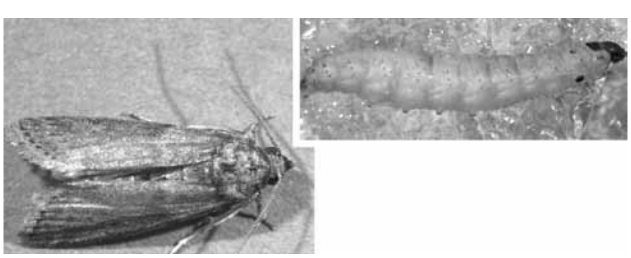

Figure 3. *Carob moth adult (Joel Siegel, USDA-ARS) and larva (Charles Burks, USDA-ARS).*

Carob moth, *Ectomyelois ceratoniae* (Zeller)

The carob moth adult is a gray moth with a light-brown banded pattern (Figure 3). The adult does not feed. It is similar in size to the navel orangeworm, and larger than the Indianmeal moth, raisin moth, almond moth, and tobacco moth. The range and nature of hosts is similar to that described previously for the navel orangeworm (Cox 1979, Gothilf 1984). In particular, it is a worldwide pest of dates (Blumberg 2008) and can become a serious storage pest in almonds (Calderon et al. 1969). Like the navel orangeworm, carob moth eggs are glued directly to the host and are initially white; older eggs turn pink before hatching. Carob moth larvae (Figure 3), like those of the navel orangeworm, are poor penetrators and depend on openings occurring naturally or created by other pests (Gothilf 1984). They usually pupate in the fruit in which they developed, although some individuals pupate under tree bark or ground litter (Botha and Hardy 2004). In Australia this species generally overwinters in diapause (Botha and Hardy 2004), which occurs after the last larval instar (Cox 1979).

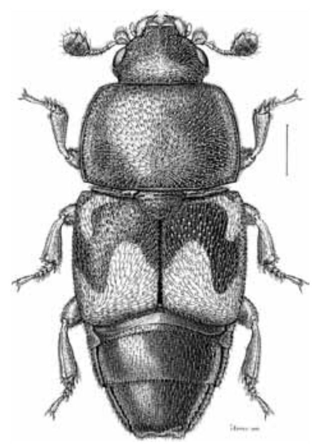

Figure 4. *Driedfruit beetle adult (from Bousquet 1990).*

Driedfruit beetle, *Carpophilus hemipterus* (L.)

The driedfruit beetle adult (Figure 4) is small (0.1 to 0.2 inch) and black with yellow markings on the elytra (forewings). The elytra do not completely cover the abdomen. Adults feed, and live long relative to larval development time. Rotting, fermenting, or overripe fruit are the preferred oviposition site. The driedfruit beetle is an important field pest of dried figs and dates and can infest raisins during the drying process (Simmons and Nelson 1975, Carpenter and Elmer 1978). It also feeds on a variety of other rotting fruits (e.g., peaches and grapes), where it is usually considered of minor importance since sound fruit is not attacked.

Eggs are white, cylindrical, and 2 to 3 mm long. Larvae develop in the host, and are up to 0.25 inch, white to yellow, with two spine-like projections at the tail end. Larvae leave the host to pupate, typically in surrounding soil (Simmons and Nelson, 1975), and emerge as adults. The larval developmental period is potentially as short as 12 days. Adults live for more than 100 days at 25°C, and up to 60 days at 35°C (El-Kady et al., 1962). Unlike the previous moth species, the driedfruit beetle flies during the day and only when the temperature is above 18°C (Simmons and Nelson 1975).

Figure 5. *Vinegar fly adult (Jack Kelley Clark, courtesy University of California Statewide IPM Program).*

Vinegar flies, *Drosophila* species

Vinegar flies (*Drosophila*) adults are small flies (0.1 inch) distinguished by bright red eyes (Figure 5). The species *Drosophila melangoster*, *D. simulans*, and *D. pseudoobscura* have long been associated with dried fruit production around the world (Simmons and Nelson, 1975). Adults feed, and live long relative to larvae. Vinegar flies are occasional pests of dried figs (Burks and Brandl, 2005) and raisins (Buchanan et al. 1984), but they do not infest as often as the dried-fruit beetle or navel orangeworm.

Vinegar flies often are associated with fungus or bacterial infection of figs (Simmons and Nelson 1975). Microscopic eggs are inserted into these hosts. Larvae are white to tan. Unlike the driedfruit beetle, there is no head capsule, but there are paired mouth hooks. Larvae grow up to 0.25 inch long, then pupate in drier parts of the larval host. The pupa has a yellow-brown case. Development from egg to adult can occur in as little as 7 days. Adults live 40 or more days at 20 to 25°C, with an average production of 1,000 eggs per female (Simmons and Nelson 1975).

Vinegar flies are strong daytime fliers and can move over 8 km in a day. They are less likely to fly under very strong light or with even light wind (Simmons and Nelson 1975). In California's San Joaquin Valley, abundance of these species is suppressed during the hotter part of summer, and then increases with cooling temperatures at the end of summer (Simmons and Nelson 1975).

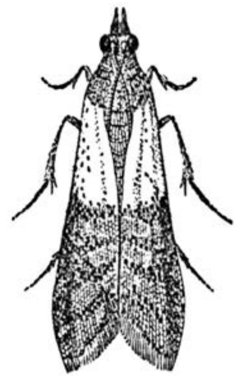

Figure 6. *Indianmeal moth adult (from Linsley and Michelbacher 1943).*

Indianmeal moth, *Plodia interpunctella* (Hübner)

Indianmeal moth adults are slightly under 0.5 inch; smaller than navel orangeworm and carob moth, and similar in size to almond moth, tobacco moth, and raisin moth. The Indianmeal moth is the most common and widely distributed of stored product Phycitinae, and probably causes harm in the widest variety of commodities (Simmons and Nelson 1975). It attacks a wide range of stored grains and pulses, dried fruits and nuts, dried vegetables, and processed foods (Perez-Mendoza and Aguilera-Peña 2004).

The Indianmeal moth adult is distinguished from adults of these other species by a distinct two-tone pattern of the wings (Figure 6), with the upper (proximal) part of the wings tan and the lower (distal) part copper. This pattern may be less evident in older specimens or those from a very dusty environment. Adults do not feed. Both mating and oviposition are less strictly controlled by day-night cycles compared to other stored product moths (Mohandass et al. 2007).

Eggs are white, round to ellipsoid, and more than 0.5 mm in diameter. Eggs are slightly sticky and are preferentially laid on or between host products, but frequently fall between host material rather than adhering to it (Sambaraju and Phillips 2008). When direct access to host material is lacking, oviposition can take place nearby, and newly hatched larvae can find food up to 38 cm away (Mohandass et al. 2007). Larvae do not penetrate unbroken packaging well, but efficiently locate small openings to infest packages (Mohandass et al. 2007). Mature larvae are up to 0.5 inch long with a white integument. They are distinguished from navel orangeworm and carob moth by a more pale integument, and from almond moth, tobacco moth, and raisin moth by a lack of dark sclerotized spots (pinacula) on the abdomen (Solis 2011). Larvae typically leave host material, seeking enclosed sites, with contact on all sides to form a cocoon and pupate. Adults emerge most frequently during the latter half of the day.

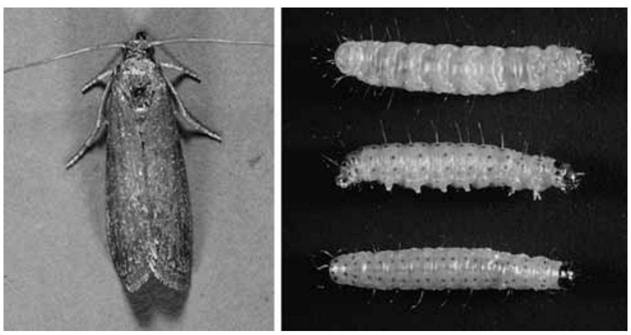

Figure 7. *Almond moth adult and larvae (USDA-ARS).*

Almond moth, *Cadra cautella* (Walker)

Almond moth adults have light gray wings with straight dark lines, most notably near the distal edge of the forewing. The life history of the almond moth (Burges and Haskins 1965) is similar to that of the Indianmeal moth, but is favored by warmer and more humid climates. In the United States, the almond moth is less abundant in California's warm, dry climate and more abundant in the warm, humid climate of the southeastern states (Soderstrom et al. 1987).

In northern Europe this species is associated with food ingredients imported from warmer climates, such as carobs, dates, and cocoa (Cox 1975b). Adults oviposit directly in the infested commodity. Eggs are similar in shape, size, and nature to those of the Indianmeal moth, but slightly gray instead of white. Almond moth larvae can be distinguished from those of Indianmeal moth and raisin moth by the presence of round, black pinacula (Figure 7) (Solis 2011).

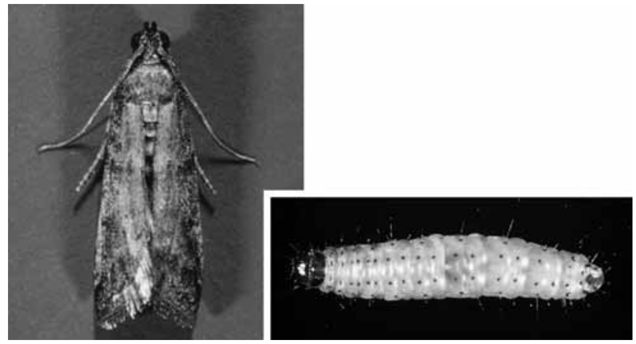

Figure 8. *Tobacco moth (USDA-ARS).*

Tobacco moth, *Ephestia eulutella* (Hübner)

The adult tobacco moth has gray wings with more distinct black markings than the Indianmeal moth, almond moth, or raisin moth (Figure 8). The life history is generally similar to that of the Indianmeal moth and almond moth, but it is a more temperate species that does not develop as quickly as the Indianmeal moth or almond moth under warmer conditions, and it is rarely found in the tropics (Ashworth 1993). In particular, tobacco moth populations increase at 15°C, while those of Indianmeal moth and almond moth do not (Bell 1975).

Eggs are spherical, slightly sticky, and deposited in or near host material, as with the other moths in this group. Eggs are white initially and darken before larvae emerge. Tobacco moth larvae can be distinguished from those of Indian meal moth and raisin moth by the color and form of pinacula and surrounding cuticle, but to definitively distinguish this larva from that of the almond moth requires setal examination (Solis 2011).

While all of the species in this group (i.e., Indianmeal moth, almond moth, tobacco moth, and raisin moth) can exhibit diapause the end of the last larval instar, diapause is more intense in the tobacco moth than the Indianmeal moth or the raisin moth. Adults oviposit on cocoa in preference to grain (Ashworth 1993).

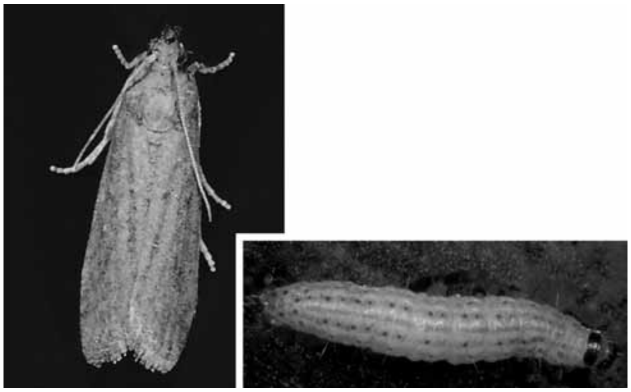

Figure 9. *Raisin moth adult (USDA-ARS) and larva (Joel Siegel, USDA-ARS).*

Raisin moth, *Cadra figulilella* (Gregson)

The raisin moth adult can be often be distinguished from related stored product moths by light pink scales on the forewing (Figure 9). Adults do not feed. The raisin moth is primarily a field pest that attacks mature or overripe fruit (Donohoe et al. 1949, Cox 1974). It is occasionally found in dried fruits and nuts, but there is no evidence that it is able to maintain or increase its population in storage (Cox 1974). The raisin moth is found primarily in the Mediterranean and similar climates in the Americas and Australia. In the United States, it is endemic in California but associated with commerce elsewhere (Donohoe et al. 1949, Cox 1975b).

Eggs are small, round, and slightly yellow-orange. Like the previous three species, eggs are sticky but generally not glued to host material. In central California, raisin moth larvae are found in a wide variety of fallen fruit (Donohoe et al. 1949). More recently they have also been found in mature almonds, but usually are not of concern because they feed on the hull rather than the nut. Raisin moth larvae can be distinguished from those of related species by the tan lines running horizontally along the back (Figure 9). Larvae leave the host before pupation and seek a suitable harborage in which to cocoon and pupate. In the orchard this is typically under the bark near the base of a tree or vine, or in adjacent soil near the surface (Donohoe et al. 1949).

This species overwinters in the last larval instar (Donohoe et al. 1949), presumably in diapause (Cox 1975a). Younger larvae usually do not successfully overwinter (Donohoe et al. 1949). Adults do not fly at less than 13°C and have limited flight at 13°C to 15°C. Field studies in central California in the 1930s found adult activity from April to November, with peak abundance in September and October. There was evidence of three flights and a partial fourth but, because host material was varied and plentiful, the species was abundant throughout the period of adult activity (Donohoe et al. 1949).

Behavior

Insect infestation of dried fruit and nuts, and detection of this infestation, is determined in part by adult behavior, including mating and aggregation, dispersal, and ovipositional preferences. In moths the female releases sex pheromone, and males find females using this scent trail. The codling moth, navel orangeworm, and carob moth each have distinct pheromone blends, whereas the remaining moths are attracted by the same principle component (El-Sayed 2011).

Each of these moth species has a relatively short adult life (Table 2) and feeds only as larvae. In the codling moth, most individuals disperse short distances, but a few may travel farther than 5 km (Schumacher et al. 1997). On average, mated females fly farthest 2 days after adult emergence but 4-day-old unmated females fly farther, suggesting that inability to find a mate is one factor that causes long-distance dispersal in this species (Schumacher et al., 1997). In addition to pheromones for locating mates over large distances, the Indianmeal moth and almond moth use ultrasound in courtship at closer range (Trematerra and Paven 1995, Nakano 2009).

Food volatiles often play a role in the attraction of pests to a product. Mated Indianmeal moth and almond moth females are more responsive to chocolate odors in a wind tunnel compared to unmated females of these species (Olsson et al. 2005) and in the field, the vast majority of navel orangeworm females captured in traps baited with almond meal are mated (Burks et al. 2009). These observations suggest that females of the phycitid moths discussed in this chapter generally mate first, and then disperse for oviposition.

In the oligophagous codling moth, eight volatiles have been identified as host cues, and there seems to be some plasticity in female response to these volatiles in the field (Witzgall et al. 2005). One of these compounds, pear ester, captures both male and female codling moths in the field, and the proportion of sexes captured varies with factors such as cultivated variety and trap type (Knight et al. 2011).

The other moth pests discussed in this chapter generally have a wider host range. Carob moth females are attracted by a compound associated with fungal infection of dates (Cossé et al. 1994), and phenyl propionate, a compound sometimes associated with plant breakdown products, is attractive to the navel orangeworm (Burks et al. 2009). The navel orangeworm is also attracted by host-associated oils (Phelan et al. 1991), as is the Indianmeal moth (Sambaraju and Phillips 2008). In the Indianmeal moth, tactile cues are also important in stimulating oviposition (Sambaraju and Phillips 2008).

Driedfruit beetle and vinegar fly, males and females locate each other and food resources via a synergistic attraction to food odors and aggregation pheromones produced by males. In the driedfruit beetle the aggregation pheromone is a blend of 13- to 15-carbon molecules, released by males and attractive to both males and females (Bartelt et al. 1992). Similar pheromones are produced by the related and often coexisting species, *Carpophilus freemani* and *C. mutilatis* (Bartelt et al. 1995). These aggregation pheromones have little effect by themselves, but when combined with volatile alcohols, esters, and acids produced by food sources, the pheromone is far more attractive than either by itself (Dowd and Bartelt 1991, Blumberg et al. 1993).

Vinegar flies also use a combination of host volatiles and aggregation pheromone. Long-range host-associated cues are primarily acetic acid and similar compounds associated with vinegar (Becher et al. 2010). At closer range mating and oviposition in *Drosophila* is influenced by aggregation pheromone and other pheromones associate with the cuticle. Generally these are produced by males, but in some cases passed to females during mating (Wertheim et al. 2002, Dahanukar and Ray 2011).

Ecology

The number and abundance of species associated with dried fruits and nuts is determined principally by abiotic and host-associated factors and control measures, in part because there is usually a very low tolerance for insects associated with these high-value food items. Factors such as host nutrition and condition, processing methods, field and storage temperatures, day-length, and other storage organisms influence the development and survival of pest populations, as well as their economic impact.

Host suitability and moisture requirements

Various factors determine whether an insect pest can establish or increase population in postharvest conditions. Nutritional requirements are an obvious factor. Survival and development time can also be affected profoundly by the state or maturity of the host, and by the type of host, as demonstrated in studies of the Indianmeal moth (Johnson et al. 1995), the carob moth (Nay and Perring 2008), and the navel orangeworm (Siegel et al. 2010). Moisture requirements are another important variable. The almond moth has greater moisture requirements than the Indianmeal moth at similar temperatures (Burges and Haskins, 1965, Arbogast 2007a), and also benefits more from access to water as adults (Hagstrum and Tomblin 1975).

Storage of large amounts of a commodity can provide a heterogeneous environment (e.g., more fines, broken product, or pockets of fungal infection) that may allow the presence of a pest that cannot develop on small samples of the same commodity under laboratory conditions. This observation has been dubbed the host paradox (Arbogast et al. 2005). Indianmeal moth, for example, does poorly in the laboratory on dried fruits such as raisins or prunes when compared to almonds, walnuts or pistachios (Johnson et al. 1995, 2002), and yet it is still of greatest concern for dried fruit processors. Another situation occurs when certain processing activities—such as partial rehydration of dried fruit during packing—attracts oviposition by field pests such as the driedfruit beetle or raisin moth, resulting in returns of shipments for these pests even though they normally cannot maintain a population on these commodities at that point in the marketing chain.

Temperature and diapause

The effect of temperature on development has been examined using various approaches. For field pests, degree-day models tend to be used. These models assume daily fluctuation in temperature. The upper and lower developmental threshold determined in these models are ultimately parameters in a model

Table 2. *Life history characteristics of selected insect pests of dried fruits and nuts species.*

	Lower and Upper Developmental Limits (°C)	Developmental Time (Egg to Adult, Days)	Lifetime Fecundity (Eggs/Female)	Adult Longevity (Days)	References
Codling moth *Cydia pomonella*	18 to 34	38 at 26°C	160	10	(14; 18)
Navel orangeworm *Amyelois transitella*	13 to 34	32 at 26°C	200	11	(6; 12; 15)
Carob moth *Ectomyelois ceratoniae*	13 to 38	32 at 25°C	200	7	(7; 13)
Driedfruit beetle *Carpophilus hemipterus*	20 to 42	12 at 35°C	>1,000	103	(9; 16)
Vinegar fly *Drosophila* spp.	9 to 30	7 at 26°C	750	25	(16)
Indianmeal moth *Plodia interpunctella*	>15 to >30	26 at 30°C	200-365	11	(1; 8; 10; 11)
Almond moth *Cadra cautella*	>15 to >30	28 at 30°C	400-500	10	(2; 3)
Tobacco moth *Ephestia elutella*	<15 to <30	33 at 30°C	≈200	12	(2; 19)
Raisin moth *Cadra figulilella*	15 to 36	43 at 28°C	351	16	(4; 5; 17)

References cited: 1) Arbogast 2007b. 2) Bell 1975. 3) Burges and Haskins 1965. 4) Cox 1974. 5) Donohoe et al. 1949. 6) Engle and Barnes 1983. 7) Gothilf 1969. 8) Huang and Subramanyam 2003. 9) James and Vogle 2000. 10) Johnson et al. 1995. 11) Johnson et al. 1992. 12) Kellen and Hoffmann 1983. 13) Nay and Perring 2008. 14) Pitcairn et al. 1992. 15) Seaman and Barnes 1984. 16) Simmons and Nelson 1975. 17) Subramanyam and Hagstrum 1993. 18) Vickers 1997. 19) Waloff et al. 1948.

that are of interest primarily for their ability to predict development at intermediate temperatures.

Another approach that has been used in stored product pests is to determine empirically the ability of populations to grow at various constant temperatures of interest. This latter approach implies that populations of interest experience something close to constant temperature, an assumption that is more likely to be met in stored products than in field situations. As a result, a model for the population development for the almond moth includes an implied developmental threshold of 12°C, although empirical studies find that this species does not develop from egg to adult at 15°C under favorable conditions of diet and moisture content (Bell 1975) (Table 2). Temperature ranges for development are one reason that the almond moth is considered a predominantly tropical species (Cox 1975b), and the tobacco moth a predominantly temperate species (Ashworth 1993). The driedfruit beetle develops at higher temperatures than the other *Carpophilus* spp., *C. freemani* and *C. mutilatis* (James and Vogele 2000). This higher temperature tolerence, along with the high temperatures encountered in production of sun-dried figs, may explain why *C. freemani* and *C. mutilatis* comprise 40% of the nitidulids trapped with tri-species traps in fig orchards (C. S. Burks, unpublished data), but were rarely trapped in the substandard fig warehouse (Johnson et al. 2000).

Diapause is another factor that can influence geographical range. There is evidence that all of the moth species discussed in this chapter can be induced by environmental conditions into diapause at the end of the last larval instar (Bell 1994). Diapause is a genetically plastic characteristic; it may assist the codling moth in adapting to local host availability (Barnes 1991), and can vary in presence, prevalence, and intensity in the Indianmeal moth (Mohandass et al. 2007). Despite genetic plasticity, diapause is a factor in limiting the range of the raisin moth (Cox 1975a and b) and the codling moth (Willett et al. 2009). Because diapausing larvae are often the stage most tolerant to disinfestation treatments, particularly fumigation (Bell and Glanville 1973, Tebbets et al. 1986), their occurrence in product may affect control efficacy.

Generations and seasonal abundance

Discrete cohorts are a logical result of a short adult life relative to larval development time, as occurs with the moth pests described in this chapter. This tendency toward a discrete cohort structure can be reduced in the presence of prolonged development on a poor host. For example, both the development time and variation in development time were greater for the Indianmeal moth on dried fruit compared to tree nuts (Johnson et al. 1995). In a substandard dried fig pool, where no attempt was made to control pest populations, the two peaks of activity occurred after diapause termination in spring and in late summer when higher-quality host material was first added with new-season dried figs (Johnson et al. 2000). In the carob moth, discrete cohorts were seen in almonds (Gothilf 1984, Botha and Hardy 2004), but less so in dates (Nay and Perring 2008), where stages and host quality was more variable.

Natural enemies

Dried fruit and nut pests have a number of parasites, predators, and pathogens that may reduce pest populations. Insecticide applications timed to conserve parasite populations and release of *Trichogramma* egg parasites are important parts of integrated pest management for field pests such as codling moth and navel orangeworm (Strand 2003). Research into use of these organisms in the storage environment focuses on the use of microbial pesticides or inundative release of parasites (Brower et al. 1995), generally targeting postharvest pyralids. The most commonly studied parasites are *Habrobracon hebetor* (Say), *Venturia canescens* (Gravenhorst), and *Trichogramma pretiosum* Riley (Brower et al. 1988, 1990, Press et al. 1982). Predatory bugs such as *Xylocoris flavipes* (Reuter) are also common (Bower 1990).

Because of the low tolerance for live insects in dried fruits and nuts, it is unlikely that parasite or predators would ever be sufficient to control pest populations. It was noted that naturally occurring *H. hebetor* populations were capable of dramatically reducing Indianmeal moth populations in stored raisins (Johnson et al. 2002). Johnson et al (2000) demonstrated that *H. hebetor* was active throughout the winter in a substandard fig warehouse in central California, and suggested that winter parasite releases could reduce spring emergence of Indianmeal moth adults.

Within the United States, actual release of natural enemies into bulk stored dried fruits and nuts is considered food adulteration and not allowed, although exemptions for bulk stored grain and packaged products have been obtained (Anonymous 1992). Commercially available microbial insecticides containing *Bacillus thuringiensis* Berliner were used for control of moth species both in storage and in the orchard, but resistance to the bacterium has developed in Indianmeal moth populations, decreasing its effectiveness for this pest (McGaughey 1985, Brower et al. 1990). A microbial insecticide containing the Indianmeal moth granulosis virus was shown to be effective in protecting walnuts (Johnson et al. 1998), almonds, and raisins (Johnson et al. 2002) against damage, even under heavy population pressure.

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S156 – 3 September 2012

4 Biology, Behavior, and Ecology of Insects in Processed Commodities

Rizana M. Mahroof
David W. Hagstrum

Most insects found in storage facilities consume commodities, but some feed on mold growing on stored products. Others may be predators and parasitoids. Insects that attack relatively dry processed commodities (those with about 10% or more moisture content at 15 to 42°C) can cause significant weight losses during storage. Insects occur in flour mills, rice mills, feed mills, food processing facilities, breakfast and cereal processing facilities, farm storages, grain bins, grain elevators, bakeries, warehouses, grocery stores, pet-food stores, herbariums, museums, and tobacco curing barns. Economic losses attributed to insects include not only weight loss of the commodity, but also monitoring and pest management costs and effects of contamination on product trade name reputation.

Life Histories

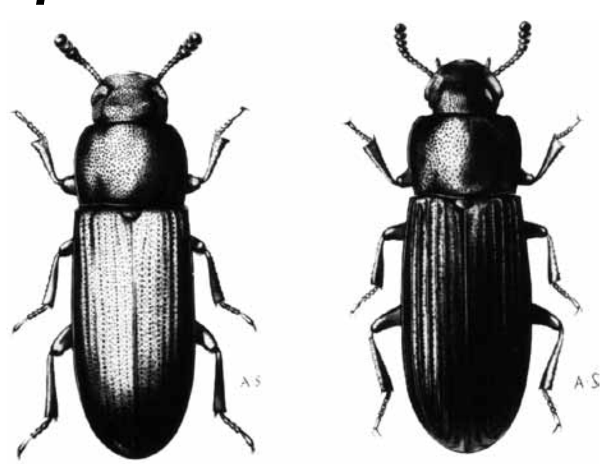

Figure 1. *Red flour beetle, left, and confused flour beetle, right, each 2.3 to 4.4 mm long (from Rees 1996).*

Red flour beetle, *Tribolium castaneum* (Herbst)

Red flour beetle adults (Figure 1) are reddish brown. Eggs are oblong and white. Adults show little preference for cracks or crevices as oviposition sites. Eggshells are coated with a sticky substance that aids in attaching the eggs to surfaces and causes small particles to adhere to them (Arbogast 1991). Larvae are yellowish white with three pair of thoracic legs.

Typically, there are six to seven larval instars, depending on temperature and nutrition. Larvae move away from light, living concealed in the food. Full-grown larvae move to the food surface or seek shelter for pupation. Pupae are white and exarate, which means that appendages are not fused to the body. External genitalic characters on pupae can be used to differentiate males and females (Good 1936).

Average development from egg to adult ranges from 41.8 days at 25°C to 21.7 days at 35.5°C (Hagstrum and Subramanyam 2006). Howe (1956a) found that between 35°C and 37.5°C at a relative humidity (RH) more than 70%, development is completed in 19 to 20 days (eggs in three days; larva in 12 to 13 days; pupa in four days). Males have a setiferous patch on the posterior side of the fore femur, but females do not (Bousquet 1990). Adults of red flour beetles live several months to several years. At 18°C to 29°C, the average life span of males and females ranges from 130 to 198 days. Adults are capable of lifelong reproduction. The preoviposition period is eight to 10 days. At 25°C and 70% RH, a mated female lays three to five eggs per day for the first few days and two to three eggs per day for the rest of her life. A female, on average, can lay a total of 360 eggs during a lifetime, but egg laying decreases in females more than 100 days old (Sokoloff 1972).

Confused flour beetle, *Tribolium confusum* (Jacquelin du Val)

The confused flour beetle (Figure 1) is reddish brown and biologically similar to the red flour beetle. The two species can be distinguished by the number of segments in the club of the antenna (confused flour beetle has four or five and the red flour beetle has three) and the greater distance between the eyes of the confused flour beetle from below (Hagstrum and Subramanyam 2006). Adults of both species have well-developed wings, but only red flour beetles have been observed to fly (Arbogast 1991). The optimum, maximum, and minimum temperatures for confused flour beetle development are all about 2.5°C lower than for red flour beetle. At 32.5°C optimum temperature and 70% RH, confused flour beetle completed development in about 25 days (eggs in four days; larva in 16 days; pupa in six days) (Howe 1960). Developmental time was 20 days at 35°C and 56.2 days at 22.5°C (Hagstrum and Subramanyam 2006). Male confused flour beetles have a setiferous fovea on the posterior side of all femora; females do not (Bousquet 1990).

Natural enemies – Several predators, parasitoids, and pathogens attack red and confused flour beetles. An anthocorid predatory bug, *Xylocoris falvipes*, parasitic wasps *Holepyris sylvanidis,* and number of pathogens, including bacteria, fungi, and protozoa, are known to damage flour beetles (Arbogast 1991; Hagstrum and Subramanyam 2009).

Commodities infested and nature of the damage – In nature, red flour beetles have been found in bee nests, longitudinally split acorns, and bark habitats. They feed on organic material and fungi under tree bark (Linsley 1944). Red flour beetles feed on a wide variety of plant and animal products, and large populations are associated with stored food and feed grains, oilseeds, nuts, dried fruits, spices, pulses, beans, cacao, cottonseed, and forest products. Both larvae and adults feed on seed embryos, grain dust, and broken kernels and tend to prefer floury materials (Arbogast 1991). Red flour beetles do not develop on sound kernels (Anonymous 1986).

Larval and adult tunnels are common in infested flour, appearing as trails on dusty surfaces in food-processing facilities and grain elevators. In heavy infestations of red or confused flour beetles, food may be discolored, have a disagreeable odor and often may contain life stages of the insect, exuviae, and fecal matter. The odor is attributed to chemicals secreted from insects' thoracic or abdominal glands (benzoquinones). The chemicals are heat stable and impart a disagreeable odor to food, which is not removed by cooking (Hodges et al. 1996).

Facilities infested – Both red and confused flour beetles are found in many parts of the world. Red flour beetles inhabit warmer climates, and confused flour beetles are found in cooler climates. These beetles primarily occur in flour mills, feed mills, warehouses, retail grocery stores, boxcars, semolina mills, and bakeries (Cogburn 1973b; Bousquet 1990; Tremeterra et al. 2007). Beetles also occur in empty cargo containers, farm grain bins, farm storages, grain elevators, peanut shelling plants, residences, and pet stores (Hagstrum and Subramanyam 2009).

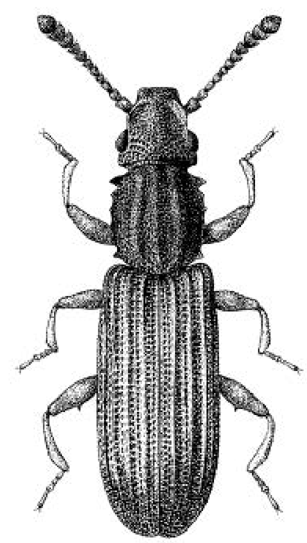

Figure 2. *Sawtoothed grain beetle, 1.7 to 3.2 mm long (from Rees 1996).*

Sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.), and Merchant grain beetle, *Oryzaephilus mercator* (Fauvel)

Sawtoothed (Figure 2) and merchant grain beetles share similar life histories. Eggs usually are deposited singly in crevices of coarse grain but are also laid in finely ground material. Oviposition often begins during the first week of adult life and peaks the second or third week. Average fecundity is about 280 eggs per female. An average of two to four larval instars occurs, depending on nutrition and temperature, but there are typically three larval instars. When the larva reaches maturity, it constructs a crude pupal cell by cementing together food particles. Before pupating the larva fastens its caudal extremity to a solid object. Adults are reddish brown, slender, flat, and about one-tenth of an inch long. Adults have six sawtooth-like projections on each side of the thorax. Adults live six to 10 months. The population growth rate of sawtoothed and merchant grain beetles depends on temperature, humidity, and food type. Adults and larvae are somewhat resistant to cold and capable of withstanding three weeks of exposure to cold temperatures of between -1°C to 1°C (Arbogast 1991).

Sawtoothed grain beetle and the merchant grain beetle can be distinguished by the relative lengths of eye and temple and by male genitalia. Distinguishing features in the male genitalia are that sawtoothed grain beetle has several setae along the posterior edge of sternite VIII, while merchant grain beetle has only three setae on each side near the lateral margin of the posterior edge. In the median genitalia orifice, sawtoothed grain beetle has eight strengthening chitinous rods, merchant grain beetle has 16 rods (Howe 1956b).

Natural enemies – The anthocorid bugs, *X. flavipes* and *X. cursitans,* regulate sawtoothed and merchant beetle populations by predation (Arbogast 1991, Hagstrum and Subramanyam 2009). Some ectoparasitoids such as *Cephalonomia tarsalis* and the entomopahtogenic fungus, *Beauveria bassiana*, are effective in controlling these beetles (Lord 2001). The Bethylidae wasp, *Holepyris sylvanidis,* also is effective in controlling sawtoothed and merchant grain beetles (Arbogast 1991).

Commodities infested and nature of the damage – Sawtoothed grain beetle and the merchant grain beetle feed on stored grain, cereal products, dried fruits, nuts, animal feed, and oilseeds. Sawtoothed grain beetle is more often associated with cereal grains and cereal products while merchant grain beetle is more common in oilseed and high-oil processed foods. Sawtoothed grain beetle cannot develop on food that contains few or no carbohydrates and is unable to attack perfectly sound grain. This beetle attacks grain with small lesions in the bran layer over the germ, then feeds on the germ. Sawtoothed grain beetles occasionally supplement vegetarian diets by feeding on eggs and dead adults of stored-product moths. On the other hand, merchant grain beetles primarily feed on oilseeds and derivatives and processed cereals with a high oil content (Arbogast 1991; Hagstrum and Subramanyam 2009).

Facilities infested – In nature, sawtoothed grain beetles are reported to occur beneath tree bark. This is essentially a crevice-dwelling species that commonly occurs in cracks and crevices of food storage facilities (Linsley 1944). Sawtoothed grain beetles are found in farm storage, grain elevators, flour mills, warehouses, railroad cars, and pet stores. The merchant grain beetle occurs in similar facilities as the sawtoothed grain beetle, but also prevails in feed stores, grocery stores, grocery warehouses, and kitchens.

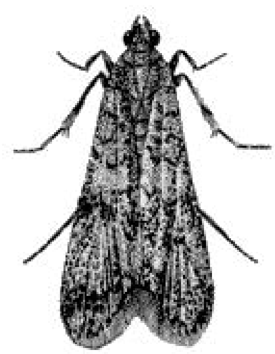

Figure 3. *Mediterranean flour moth, 9 to 11 mm long (from Michelbacher 1953).*

Mediterranean flour moth, *Ephestia kuehniella* Zeller

The Mediterranean flour moth (Figure 3) has a wingspan of slightly less than an inch. Forewings are a pale leaden gray with transverse wavy black markings. Hindwings are dirty white. Adults are nocturnal, emerging late afternoon and evening, apparently in response to changes in light intensity and temperature. Female moths produce a sex pheromone. Within 24 hours of emergence, the female becomes stationary on a suitable surface and assumes the calling posture in which the abdomen is lifted between the wings and scent glands are extruded. Adults mate and lay small white eggs at dusk the next day. Larvae move away from light before pupation. The larva spins a silken thread and mats together food particles it is eating. When fully grown, larvae are whitish or pinkish and about one-half inch long. Inside the silken cocoon, the full-grown larva transforms to a reddish-brown pupa. Larval diapause is important in overwintering. Egg to adult development ranges from 69.1 days at 20°C and 38.2 days at 30°C (Cox and Bell 1991; Anonymous 1986). Under 12 hours of light and 12 hours of dark conditions, adult moths can live for about 9.2 days and lay an average of 241 eggs (Cymborowski and Giebultowicz 1976).

Natural enemies – Mites such as *Cheyletus eruditus* and *Blattisocius tarsalis* prey on eggs and early instars. Most important of the 21 species of parasitoids are Hymenoptera, especially braconid, ichneumonid, and trichogrammatid wasps that often parasitize eggs or larval populations. Five species of Hemiptera prey on Mediterranean flour moth. Like other Lepidopera, Mediterranean flour moths are susceptible to attack by the spore-forming bacterium, *Bacillus thuringiensis*. Other pathogenic microorganisms such as polyhedrosis and granulosis viruses also can attack these moths (Cox and Bell 1991; Hagstrum and Subramanyam 2009).

Commodities infested and nature of the damage – Mediterranean flour moth is surpassed in importance only by red flour beetle as a serious pest of stored grain products. This moth prefers cereal products, especially flour, and feeds on a variety of stored commodities including cereals, nuts, dried fruits and vegetables, oilseeds and products, and dried citrus pulp (Cox and Bell 1991).

Facilities infested – Mediterranean flour moth seems more adapted to the temperate region, or Northern Hemisphere, and is less common in the United States than in Europe. It is excluded from the tropics because it cannot tolerate long exposures to high temperature. Facilities infested with Mediterranean flour moths include farm storage, grain bins, grain elevators, flour mills, feed mills, bakeries, warehouses, and tobacco curing barns. Webbing from heavy infestations can choke flour mill machinery.

Behavior

The behavior of stored-product insects is important to their survival and the ability to manage these pests. Insect mobility is important in locating food, a suitable living environment, and mating and oviposition sites. Mobility enables insects to avoid natural enemies and insecticide-treated areas and determines the number of insects caught in traps.

Many red flour beetles leave infested commodities (Hagstrum and Gilbert 1976). Few adults leave bags of flour before mating and laying eggs. The number of adults observed leaving increased from 0.4 to 24 per day as the population grew over time.

Red flour beetles actively search for feeding and oviposition sites (Campbell and Hagstrum 2002, Romero et al. 2010). Adults move an average 5.6 inches per minute after leaving flour but are moving only 26% of the time. They can travel an average of 175 feet per day. Researchers found the majority of adults in residual flour piles (62%) or seeking shelter near walls (32%). The remaining 6% of the adults moved among the piles of flour, laying eggs in 78% of the piles.

Searching for mates, male almond moths flew nearly 0.2 mile during an average 10-minute flight (Mankin and Hagstrum 1995). Females sat on the walls and released sex pheromones. Flight behavior changed as a male flew closer to a female and detected increasingly higher concentrations of sex pheromone. The male landed a short distance from the female, walked toward the female, and mated. Extensive male flight activity is evident. These insects are frequently seen flying.

Hagstrum (1984) observed that almond moth females can find residual peanuts for oviposition in an empty peanut warehouse or shelling plant. Only 8% to 20% of offspring from eggs laid on the peanuts survived. Population growth rates were low because females laid too many eggs at some locations and did not lay any eggs at others. Population growth decreased from seven- to threefold as the number of locations with peanuts increased. Female moths found only a small amount of the food during each generation, supporting population growth for several generations.

Ecology

Although insect ecology has been studied in several types of mills, more research is needed to fully understand it. The following review summarizes knowledge about species composition, abundance, seasonal trends and distribution in stored product environments. This information can be used to improve pest management programs.

Species composition – A few insect species were abundant, and many species were less common in feed, barley, semolina, and flour mills (Table 1). Feed and barley mills tended to have more species than semolina and flour mills. Thirty-one species were found in four or more of 15 mills and another 88 species of stored-product insects were found at three or fewer of these mills. The average number of species per mill was 23. Confused and red flour beetles were most prevalent and most abundant, and another 11 species were most abundant in one or more of the mills. In addition to the most abundant species listed in Table 1, warehouse beetles, *Trogoderma variabile* Ballion, and a psocid, *Liposcelis entomophilus* (Enderlein), were most abundant in Midwestern feed mills. The Mediterranean flour moth was reported in Europe, Asia, North Africa, Canada, and Wisconsin, but not in most other U.S. studies. Natural enemies were reported in six of the 15 studies.

Traps were used more frequently than visual inspection or commodity samples to study feed mills, and visual inspection or commodity samples were used more frequently than traps in flour mills. Eight or more feed mills were sampled more often (studies three through six) than eight or more flour mills (studies 13 and 14). The numbers of species found may have been influenced by sampling method and the number of facilities included in a study.

Density estimates, seasonal phenology, and population growth rate – Red flour beetle trap catches ranged from 0.2 to 2.2 beetles per trap per day at the time of fumigation (Campbell and Arbogast 2004). Numbers sharply declined after fumigation, and then increased until the next fumigation at rates of 0.002 beetles per trap per day in November and 0.004 to 0.005 from June to August.

Captures inside were higher than those outside the flour mill, and outside trap catch also declined after fumigation. Only red flour beetles generally were recovered in product samples from mill equipment and trash buckets. Over the sampling period, the number of beetles captured in traps was correlated with the number of live insects in product samples. Indianmeal moth and warehouse beetle are considered less important to the milling industry than red flour beetle. On average, fumigation reduced Indianmeal moth trap catches 4.4% and warehouse beetle by 16.7%. Trap catches of Indianmeal moth (16.1 vs. 0.7) and warehouse beetle (12 vs. 0.05) were higher outside than inside flour mills, and catches inside tended to follow seasonal trends for captures outside. Release recapture studies showed that some Indianmeal moths entered the warehouse from outside. An additional 10 species of stored-product insect pests and parasitoids were captured in traps.

In English flour mills, the Mediterranean flour moths resting on the outside of centrifugal sifter increased from early in the year until fumigation during the summer in at least one of three years at all three mills studied (Dyte 1965). Substantial numbers of larvae were found in residue samples from centrifugal sifters at one mill, but few or none were found in these residues at the other two mills. *Venturia cansescens* (Grav.), a common parasite of Mediterranean flour moths, was present in all three mills.

Over three years in two Danish flour mills, Mediterranean flour moths increased exponentially from late April or early May until mid-August (Skovgard et al. 1999). Population density in one mill was five to 10 times that in the other mill. Seasonal phenology was determined primarily by temperature and incidence of larval diapause. Trap catch approached zero during winter, but at least one moth was caught on 58 out of 61 trappings. A simulation model indicated that 95% of larvae break diapause between June 11 and September 12 and that moths realized only 1% to 3% of reproductive potential.

Distribution of insects within a facility – In an Italian feed mill, confused flour beetles and red flour beetles were most abundant in the raw-grain weighing room, the processing and bagging room, and the storage room for bagged feed (Trematerra and Sciarretta 2004). *Attagenus brunneus* Faldermann was found mainly in the processing and bagging room. Sawtoothed grain beetle and rice weevil were found most often in the raw-grain receiving area and the storage room for bagged feed. Drugstore beetle was most often found in the processing and bagging room, but some drugstore beetles were found in the raw-grain receiving area and the storage room for bagged feed. In Canada, confused flour beetles and larder beetles were collected throughout a feed mill, but more confused flour beetles were collected in the warmer grinding and tallow rooms, and more larder beetles were collected in undisturbed areas of the mixing and pelleting room and near pallets in the warehouse (Mills and White 1993).

Average numbers of insects per sample varied from 9.0 for the patent flour rebolt reel stream to 61.3 for the low-grade flour elevator boot (Good 1937). The patent and clear flour rebolt reel streams contained fewer insects because insects are sieved out. Red flour beetle was the dominant species. Lesser grain borer and rice weevil were abundant in wheat and wheat screenings but almost absent after the third or fourth break. White-shouldered house moth, *Endrosis sarcitrella* (L.), was generally found in the grain cleaning area of the mill, but less frequently in the milling area (Dyte 1965). Brown house moth, *Hofmannophila pseudospretella* (Stainton), and common clothes moth, *Niditinea fuscella* (L.), were found in the mill, but there was no evidence of them breeding in machinery.

Granary weevil eggs do not survive milling of wheat into semolina, and females do not oviposit on semolina, but females introduced into a factory will oviposit on macaroni while it is drying, and offspring can complete development (Chapman 1923).

Variation in number of species among mills and years – The number of insect species found at feed mills in five Midwestern states ranged from seven to 21 (Larson et al. 2008). Of the 30 insect species, only five occurred in every feed mill in this study. These species were foreign grain beetle, hairy fungus beetle, red flour beetle, the warehouse beetle and Indian meal moth. Two genera, *Cryptolestes* spp. and *Anthicus* spp., were captured in seven mills. The granary weevil was trapped in six of the eight mills. The remaining species were found in one to five mills. In a winter survey of eight feed mills, Rillett and Weigel (1956) found between one and 13 species per mill.

In another study, only 31 Indianmeal moths were found, mainly in flour mills that were not fumigated annually (Good 1937). Longheaded flour beetles were numerous in two mills in Oklahoma, but scarce or entirely absent in all 15 of other mills. Sawtoothed grain beetles were common in only one mill in Missouri. *Palorus* spp. and *Alphitobius* spp. were found only in mills in which some of elevator boots were located in damp, dark basements.

Very small numbers of confused flour beetles were found in two of three English flour mills. A single specimen of larval or adult cadelle was found in these two mills on fewer than four occasions (Dyte 1965). Turkish grain beetle, white-shouldered house moth and broad-horned flour beetle populations each increased in a different one of the three English mills during at least one of the three years of the study. The densities of Turkish grain beetle found in each centrifugal sifter was fairly consistent over the five years of the study. Flour mill beetle populations built up in the centrifugal sifters when the flour residues were damp.

Other food-processing facilities – In contrast to fairly extensive investigations of insect populations in mills, insect populations in food processing facilities, bakeries, peanut shelling plants, railroad boxcars, port warehouses, food distribution warehouses, groceries, and retail stores have been studied less. These inquiries also have covered species composition, insect distribution and abundance, and seasonal trends.

Cigarette beetles were trapped in 16 Japanese noodle factories, and a few drugstore beetles were trapped in nine of these factories (Suezawa et al 1987). Cigarette beetle populations peaked from May to June, in late June, in late August and in early October. None of the factories were fogged when captures were less than 25 beetles per trap, and only half of factories with higher catches were fogged. Captures were not significantly different between noodle making, drying, measuring and packing, and stock rooms. Probable sites of adult emergence were around wheat flour products and trash, and in corners of rooms and floor crevices.

Almond moth and Indianmeal moth were not uniformly distributed in a breakfast cereal factory in Australia, but were trapped more often near packing and mixing machines and conveyor belts (Rees 1999). Average trap captures ranged from 0.025 to 0.3 moths per trap per day.

Moths were abundant in only three of 35 rooms of a confectionary factory (Bowditch and Madden 1996). These rooms were used for refining chocolate and roasting nuts. High captures were near infested machinery or a result of insects being attracted to water that was present. Areas needing cleaning were readily located by inspecting around traps with high catches. Insect larvae were found in debris behind an electrical panel and two chocolate refining machines. An average of 266 days between manufacture and complaints suggest that chocolate products in Australia were stored for considerable time before being sold (Bowditch and Madden 1997). Most products were infested with one of six species of pyralids, and one was infested by the sawtoothed grain beetle.

Surveys of the factory and three distribution centers suggest that products were infested after leaving the factory.

Stored-product insect populations in bakeries in the United Kingdom included the species found in flour mills and differed by bakery section (Turner 1975, 1977, 1979). Mediterranean flour moth, confused flour beetle, broad-horned flour beetle, and Australian spider beetle, *Ptinus ocellus* Brown, were found in the dry flour section, and broad-horned flour beetle was also found in the flour silo. Moths were found in 68.5% of silos, confused flour beetles in 33%, and broad-horned flour beetle in 33%. Of sifters inspected, 68% were infested by moths, 26% by confused flour beetles, and 58% by broad-horned flour beetles. Mediterranean flour moths, confused flour beetles, broad-horned flour beetles and drugstore beetles were found in the wet dough section. Of mixers inspected, 59% were infested by flour moths, 18% by confused flour beetles, and 36.5% by broad-horned flour beetles. Provers were infested by drugstore beetles (51%), confused flour beetles (15%), broad-horned flour beetles (11%), and moths (11%). Bread coolers were infested with small numbers of shiny spider beetles, confused flour beetles and drugstore beetles. Pastry breaks were prone to moth and beetle populations under the rollers, and these species also infested cutters. Merchant grain beetles were also found in this section of the bakery. A comparison of the 1973 survey to the 1979 survey indicated there had been little reduction in insect problems during the intervening years.

The densities of insects in peanut residues at 11 shelling plants in the southeastern United States varied from 30 insects per kilogram in the winter to 580 in late summer (Payne et al. 1969). Almond moth, Indianmeal moth, red flour beetle, merchant grain beetle, and corn sap beetle made up 93% of the residual insect population, although more than 15 other species were found.

Stored-product insects were found in 81% of the railroad boxcars delivering grain products to the U.S. Gulf Coast ports, and 74% contained food residues from the previous loads (Cogburn 1973b). Red flour beetle, almond moth and lesser grain were the most abundant species.

Other parts of the marketing system – Large numbers of cigarette beetles and almond moths were recovered from food-baited traps in four port warehouses on the U.S. Gulf Coast (Cogburn 1973a). Almond moths and cigarette beetles were found in the food residues on the pallets in all four warehouses, with average densities of 6.14 and 2.18 per sample unit, respectively, and red flour beetles, sawtoothed grain beetles, and *Carpophilus pilosellus* Motschulsky were found in the food residues in three warehouses, with average densities of 4.83, 1.20, and 0.96 per sample unit, respectively. Insects were caught throughout the year, but catches were highest in August and September. Large numbers of *C. pilosellus* were found in two of these warehouses, and large numbers of red flour beetles were found in one. Among the four warehouses, the average overall density of all species in food residues from the pallets ranged from 9.4 to 44.4 insects per sample unit.

In food distribution warehouses, the numbers of almond moths and Indianmeal moths trapped in the vicinity of bird seed and chicken feed were significantly higher than those trapped near other commodities (Vick et al. 1986). A search around one trap with a high catch revealed a pallet of dog food infested with Indianmeal moths that was about six months out of date.

Indianmeal moths were abundant in eight Oklahoma grocery stores (Platt et al. 1998). Large numbers of merchant grain beetles and drugstore beetles were present in some stores. Beetle captures were higher in the pet food than the flour aisles. In five retail stores in north-central Florida, the most abundant insects were Indianmeal moth, cigarette beetle and merchant grain beetle (Arbogast et al. 2000). Indianmeal moth captures differed greatly among stores. Captures were highest near infested bags of sunflower seeds, birdseed, dry dog food, dry cat food or cat litter. Capture rates were essentially constant over the entire trapping period for both beetles and moths, suggesting well-established infestations.

In a survey of eight Kansas retail pet stores, 30 stored-product insect species were trapped (Roesli et al. 2003a). In each store, a total of 12 to 19 species were captured. *Sitophilus* spp., red flour beetle, and merchant grain beetle, *Oryzaephilus mercator* (Fauvel), were the most abundant. *Cryptolestes* spp., merchant grain beetle, sawtoothed grain beetle, Indianmeal moth, *Sitophilus* spp., drugstore beetle, and a pteromalid parasitoid, *Lariophagus* spp., were found in all eight stores. *Trogoderma* spp. and red flour beetle were found in seven stores, and cigarette beetle and red-legged ham beetle, *Necrobia rufipes*

(Degeer), were found in six stores. The parasitoids, *Cephalonomia* spp. and *Habrobracon* spp. were trapped in two stores. Insect densities in infested birdseed and pet food removed from the store ranged from 65 to 656 adults per kilogram. Five stored-product insect species were recovered from the bagged bird food and seven from the bulk food products.

Throughout the marketing system, temperature is a primary factor determining insect development, reproduction, and population trends. Species composition depends on which insects are introduced and varies widely between facilities and years. Within a facility, insect distribution generally is not uniform. These patterns of insect distribution and abundance can be important in developing the best pest management program.

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***Table 1**. Stored-product insect species found in feed, barley (B), semolina (S) and flour mills.*

				Feed mills[a]							B	S	Flour mills						
Order[b]	Family	Species	Common name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Tot
Col.	Tenebrionidae	*Tribolium confusum* Jacquelin du Val	confused flour beetle	A	A	A	*	*	*	*	A	A	*	*	A	A	A		14
Col.	Tenebrionidae	*Tribolium castaneum* (Herbst)	red flour beetle	*	*	A	*	*	A	A	*	*		*		A	A	A	13
Col.	Curculionidae	*Sitophilus oryzae* (L.)	rice weevil	*	*			*	*	*	*	*		*	*	*	*	*	12
Col.	Silvanidae	*Oryzaephilus surinamensis* (L.)	sawtoothed grain beetle	*	*	*	A	*	*	*	*	*				*	*		11
Col.	Trogositidae	*Tenebroides mauritanicus* (L.)	cadelle	*	*	*	*	*			*		*	*	*	*	*		11
Col.	Mycetophagidae	*Typhaea stercorea* (L.)	hairy fungus beetle	*	*	*	*	*	*	*		*				*	*	*	11
Col.	Laemophloeidae	*Cryptolestes ferrugineus* (Stephens)	rusty grain beetle	*	*	*	A	*			*	*		*		*	A		10
Col.	Silvanidae	*Ahasverus advena* (Waltl)	foreign grain beetle	*	*	*	*		*	*		*				*		*	9
Lep.	Pyralidae	*Plodia interpunctella* (Hübner)	Indianmeal moth	*		*	*		A	*	*					*	*	*	9
Col.	Bostrichidae	*Rhyzopertha dominica* (F.)	lesser grain borer	*	*		*	*		*	*	*		*			*	*	9
Col.	Curculionidae	*Sitophilus granarius* (L.)	granary weevil	*	*	*	A	*		*				*		*	*		9
Lep.	Pyralidae	*Ephestia kuehniella* Zeller	Mediterranean flour moth	A		*	*				*		A	A	A	*			8
Col.	Tenebrionidae	*Alphitobius diaperinus* (Panzer)	lesser mealworm			*	*	*			*				*	*	*		7
Col.	Laemophloeidae	*Cryptolestes pusillus* (Schönherr)	flat grain beetle			*		*		A	*			*		*	A		7
Lep.	Pyralidae	*Pyralis farinalis* L.	meal moth	*		*	*		*		*					*	*		7
Col.	Tenebrionidae	*Tenebrio molitor* (L.)	yellow mealworm	*	*	*	*	*						*		*			7
Col.	Laemophloeidae	*Cryptolestes turcicus* (Grouvelle)	Turkish grain beetle			*	*	*					A	*		*			6
Col.	Tenebrionidae	*Palorus ratzeburgii* (Wissmann)	smalleyed flour beetle				*	*	*		*			*			*		6
Col.	Anobiidae	*Stegobium paniceum* (L.)	drugstore beetle	*	*	*	*	*	*										6
Col.	Tenebrionidae	*Tenebrio obscurus* (F.)	dark mealworm			*	*	*			*			*		*			6
Col.	Dermestidae	*Anthrenus verbasci* (L.)	varied carpet beetle	*	*	*					*					*			5
Lep.	Pyralidae	*Cadra cautella* (Walker)	almond moth	*					*	A	*						*		5
Col.	Dermestidae	*Dermestes lardarius* L.	larder beetle			*	*		*					*		*			5
Col.	Tenebrionidae	*Latheticus oryzae* Waterhouse	longheaded flour beetle					*	*		*	*					*		5
Col.	Dermestidae	*Attagenus unicolor* (Brahm)	black carpet beetle				*	*			*						*		4
Col.	Ptinidae	*Gibbium psylloides* (de Czenpinski)	shiny spider beetle			*	*			*						*			4
Col.	Tenebrionidae	*Gnatocerus cornutus* (F.s)	broad-horned flour beetle					*					*	*			*		4

continued

Table 1. *Stored-product insect species found in feed, barley (B), semolina (S) and flour mills.*

				Feed mills[a]							B	S	Flour mills						
Order[b]	Family	Species	Common name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Tot
Col.	Anobiidae	*Lasioderma serricorne* (F.)	cigarette beetle						*	A	*	*							4
Lep.	Tineidae	*Nemapogon granella* (L.)	European grain moth			*	*				*					*			4
Col.	Tenebrionidae	*Palorus subdepressus* (Wollaston)	depressed flour beetle					*	*								*	*	4
Col.	Dermestidae	*Trogoderma inclusum* LeConte	lesser cabinet beetle	*	*	*										*			4
Total				18	14	23	23	20	15	13	20	10	5	15	5	23	18	8	
Add				9	2	7	35	2	9	10	6	1	3	17	3	9	3	5	

[a] For studies 1-15, * indicates that a species is present in that study, and A indicates that a species is one of the 1 to 5 of most abundant species in that study where 1=Trematerra and Fiorilli 1999, 2=Trematerra and Sciarretta 2004, 3=Sinha and Watters 1985, 4=Pellitteri and Boush 1983, 5=Rillett and Weigel 1956, 6=Larson et al. 2008, 7=Roesli et al. 2003b, 8=Imura 1981, 9=Trematerra et al. 2007, 10=Dyte 1965, 11=Salmond 1956, 12=Salama and Salem 1973, 13=Sinha and Watters 1985, 14=Good 1937, 15=Campbell and Arbogast 2004.
[b] Col=Colooptera (beetles) and Lep=Lepidoptera (moths).

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5 Biology, Behavior, and Ecology of Pests in Other Durable Commodities

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Other durable commodities of economic importance besides dry grains include tobacco, spices, mushrooms, seeds, dried plants, horticultural and agronomic seeds, decorative dried plants, birdseed, dry pet foods, and animal products such as dried meat and fish, fishmeal, horns, and hooves. Similar to dry grains, these commodities are typically maintained at low moisture levels that preserve quality by minimizing insect damage. Stored commodities may become infested at the processing plant or warehouse, in transit, at the store, or at home. Many arthropod pests of stored commodities are relatively abundant outdoors, but natural host plants before preadaptation to stored products remain unknown. Capable of long flight, they migrate into unprotected warehouses. Adults (larvae) crawl through seams and folds or chew into sealed packages and multiply, diminishing product quality and quantity. Infestations may spread within a manufacturing facility through electrical conduit and control panels.

The type of pest observed on a stored product depends on the commodity, but some insects vary widely in their food preferences and may infest a wide range of commodities. Not all insects feed on the product. Some might be predators or parasitoids of feeding insects or other incidental insects. These are likely temporary invaders, scavengers that feed on animal and plant by-products, materials discarded or stored by animals, items kept in warehouses, or materials that accumulate in processing facility equipment and structures. This chapter reviews the biology, behavior, and ecology of the common insect pests of stored durable commodities. Physical elements defined by the type of storage structure, insect fauna, and interrelationships in the storage environment are also discussed.

Life Histories and Behavior

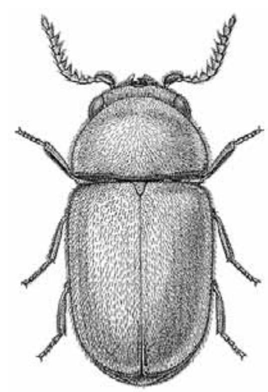

Figure 1. *Adult of the cigarette beetle, Lasioderma serricorne (F.), 2 to 4 mm long (from Bousquet 1990).*

Cigarette beetle, *Lasioderma serricorne* (F.)

The adult is 2 to 4 mm long, 1.25 to 1.5 mm wide, and light to dark brown. Antennae are sawlike and have the same thickness from the base to the tip. The head is withdrawn under the insect when the insect is at rest or dead, giving the insect a characteristic humped appearance. When disturbed, the beetle feigns death, drawing body regions closely together for a few minutes. Adults cut holes to penetrate or escape from packaged commodities but rarely feed. Larvae cause most feeding damage observed in infested commodities. *Lasioderma serricorne* is a good flier. It is active at dusk and remains so until midnight. Although capable of long flight, beetles usually are distributed through the sale of infested materials.

Climate determines the number of *L. serricorne* generations occurring per year. The insect is active throughout the year in warm buildings in temperate and subtropical regions. Development slows during the winter. In the United States, *L. serricorne* seasonal flight activity starts in late March to late May, depending on location. The life cycle of the cigarette beetle includes egg, larva, pupa, and adult stages.

When laid, the oval-shaped egg is opaque or white, turning dull yellow shortly before hatching. The female deposits eggs singly in crevices or folds within the commodity. On average, *L. serricorne* progresses through four larval instars. Larvae are scarabaeiform in shape, i.e., when at rest, bodies curl into a "c" shape. When fully grown, the larva stops feeding and builds a cocoon in a spot that provides a firm cell foundation. Uniformly white at first, the pupa gradually assumes a reddish brown color, darkening with age. Males and females look similar from the outside. Sexes differ at the tip of the pupae abdomen, which can be seen after molted skin is removed.

Temperature and humidity affect development. Optimum conditions are 32°C and 75% relative humidity (RH). Beetle development is impaired below 40% RH or above 90%, or at temperatures above 36°C. *Lasioderma serricorne* development is also affected by type of food on which the insect is reared. Under optimum conditions, it takes about 68 days for the insect to develop from egg to adult emergence on oriental tobacco; development is about 20 days less when the beetle is reared on yeast cake or a mixture of wheat flour plus yeast.

Pheromone plays an important role in the reproduction biology of *L. serricorne* by bringing both sexes together and exciting them to copulate. Seven components of the sex pheromone released by female *L. serricorne* have been identified (Chuma et al. 1985). Serricornin is the compound that elicits the strongest attraction and sexual activity in the male *L. serricorne*. Six other pheromone compounds are regarded as minor components, i.e., are less attractive to male beetles, and produced by the female in relatively lower quantities.

Commercial pheromone lure for *L. serricorne* typically consists only of serricornin. Because serricornin only captures male cigarette beetles, food attractants with synthetic serricornin that attract both females and males are being marketed to improve trap efficiency. Because of the overwhelming tobacco volatiles in the environment, additional studies are needed to determine the efficacy of the food lure in a tobacco warehouse or manufacturing facility. To be effective, pheromone lures must be changed regularly following manufacturer's recommendations.

Important natural enemies (arthropods and bacteria) recorded as attacking the cigarette beetle in storage are reviewed below.

Commodities infested – Although the name "cigarette beetle" conveys the impression that *L. serricorne* confines feeding activities to manufactured tobacco (cigarettes), the insect feeds on all cured tobacco products. The cigarette beetle probably has the most varied taste of all storage insects. Besides tobacco, the insect feeds on a wide range of dried substrates of animal or vegetable origin. Substrates that have been reported as breeding materials or food for *L. serricorne* include tobacco seed, dried figs, dried roots of various kinds, pressed yeast, dried dates, starch, bran, belladonna, dried fish, pyrethrum powder, dried cotton, cotton seed, dog food, almonds, furniture stuffing, and bookbinders' paste (Runner 1919; Howe 1957; Singh et al. 1977; Yokoyama and Mackey 1987). The cigarette beetle is also a major pest of several dried spices and herbs (Table 1), and of dried plants in botanical collections. The common food for the cigarette beetle is cured or manufactured tobacco. On tobacco, the insect prefers leaves with low nicotine and high sugar content. Beetle development is impaired on tobacco diet containing more than 8% nicotine (Milne 1963).

Lasioderma serricorne harbors the intracellular yeasts *Synbiotaphrium buchneri* or *S. kochii* or *Crytococcus albidus* in specialized tissues (mycetomes) at the junction of the foregut and midgut of the insect (Jurzitza 1979; Ryan 2001). These intracellular yeasts synthesize essential amino acids, vitamins, and sterol and enable the insect to feed on food items of relatively poor nutritional quality (Pant and Fraenkel 1950; Milne 1963). Symbionts are transmitted to the next generation superficially on the eggs. Larvae acquire them by eating the eggshells upon hatching.

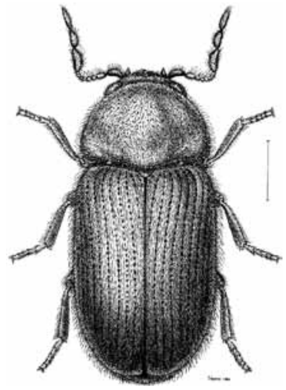

Figure 2. *Adult of the drugstore beetle, Stegobium paniceum (L.), 2 to 5 mm long (from Bousquet 1990).*

Drugstore beetle, *Stegobium paniceum* (L.)

The drugstore beetle *Stegobium paniceum* (L.) (Figure 2) is uniform brown to reddish, cylindrical in shape, and 2 to 5 mm long. *Stegobium paniceum* is virtually cosmopolitan, but its distribution is more temperate than tropical (Lefkovitch 1967). The insect received its Latin name from its occurrence in dry bread (*panis*). In Europe, it is still known as the bread or biscuit beetle. *Stegobium paniceum* attacks many pharmaceutical products and medicinal plants, from which the beetle got its common name.

Beetles are usually distributed in infested materials distributed in commerce. *Stegobium paniceum* is the only other anobiid beetle to be a serious pest of stored products, and the adults of the beetle are similar in appearance to the cigarette beetle. *S. paniceum* can be distinguished from *L. serricorne* by two physical characteristics. The antennae of *L. serricorne* are serrated, while in the *S. paniceum*, the last three segments of the antennae form a large, loosely segmented club. The other difference is that the elytra of *S. paniceum* have longitudinal rows of pits giving them a striated (lined) appearance, while those of *L. serricorne* are smooth. The larvae of *S. paniceum* are also similar to cigarette beetle larvae, but the former have shorter hairs, and the head marking ends in a straight line across the frons just above the mouthparts. The larvae typically assume a curved position when feeding in their burrows. The pupa is also similar in shape to the cigarette beetle, but proportionally much more slender. Four or five generations may occur in a year in warmer climates or heated buildings in temperate countries.

Although both sexes of *S. paniceum* are similar in appearance, the male can be distinguished from the female by a slot-like structure that is discernible on the tarsal claws of males but absent in females (Ward and Humphries 1977). This diagnostic characteristic is discernible only in specimens mounted on a slide. Similar to the cigarette beetle, *S. paniceum* life stages comprise the egg, larva, pupa, and adult stage. The female is capable of laying up to 75 eggs in a lifetime at 23°C and 65% RH (Lefkovitch 1967). The female drugstore beetle lays eggs singly in foodstuffs, and about 80% of eggs laid by mated females are fertile. Development of the beetles is possible at temperatures between 15 and 35°C and 30% RH and above. Optimum conditions for rapid development are 30°C and 60 to 90% RH (Lefkovitch 1967). The development from egg to adult emergence is completed in about 40 days at optimum conditions for rapid development (30°C and 60 to 90% RH). Adult longevity is about 85 days at 17.5°C and 50 to 70% RH.

Similar to cigarette beetles, females of *Stegobium paniceum* (L.) produce a sex pheromone that attracts males. The sex pheromone consists of two compounds: stegobinone and stegobiol (Kodama et al. 1987a; Kodama et al. 1987b). Stegobinone is the major component and the one primarily used in commercially available traps and lures. The sex pheromones of another anobiid, *Anobium punctatum* De Geer, the furniture beetle, may consist of the same isomer of stegobinone and are attractive to *S. paniceum* (White and Birch 1987). Traps baited with these compounds can be used to monitor both pest species. According to Haines et al. (1991), the natural enemies of *S. paniceum* are much the same as for the cigarette beetle.

Commodities infested – Damage due to *S. paniceum* is typically done by the larval stages. Adults might chew through packaging when they emerge from infested commodities, leaving large, round holes (Lefkovitch and Currie 1967). True to its name, *S. paniceum* feeds on herbal medicines and pharmaceuticals. The insect has been known to attack grain and grain products, spices and herbs, dried fruit, seeds, dried fish, bread, birdseed, dry dog and cat food, coffee beans, chocolate, powdered milk, and many other organic materials. It is a serious pest in museum specimens, dried spices and herbs, and has been reported to attack books, manuscripts, upholstery, and other food substrates. Similar to the cigarette beetle, *S. paniceum* can produce its own B vitamins with the aid of yeast-like organisms that it harbors at the junction of the fore- and mid-gut in structures known as mycetomes. This allows the insect to subsist on foods very low in vitamins of that group (Pant and Fraenkel 1950).

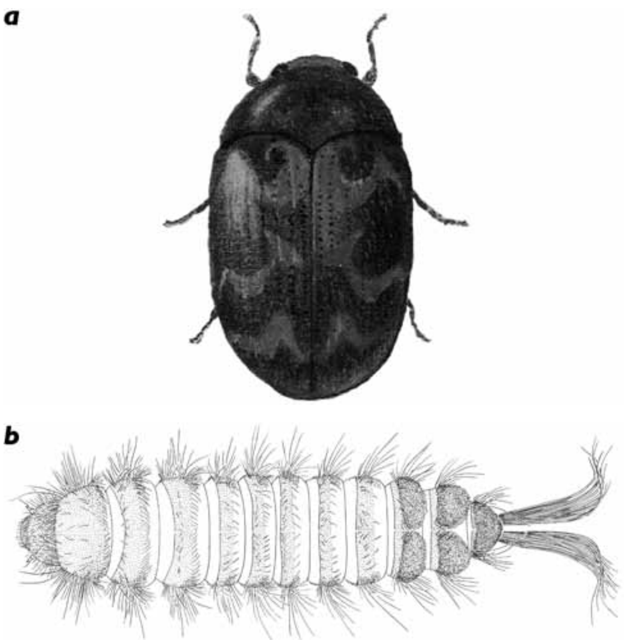

Figure 3. *Adult (a) and larva (b) of the warehouse beetle, Trogoderma variabile Ballion, 2.7 to 3.5 mm long (from Gorham 1991).*

Warehouse and other carpet beetles

Carpet beetles belong to the family of beetles known as dermestids. The beetles get their common name "carpet beetles" because they were once a common pest on woolen carpets. Although species in the family still feed on woolen items such as carpets, they are more commonly pests of fabrics, furs, stored foods, and preserved specimens and cause serious damage to these items. There are many species of carpet beetles. Those commonly found in homes, feed mills, and food manufacturing facilities belong to the genera *Anthrenus, Attagenus, Dermestes,* and *Trogoderma*. The life histories and habits of dermestid beetles differ significantly; therefore, correct identification is essential as a foundation for effective control procedures. Descriptions and keys to identification of adults and larvae of beetles in the family Dermestidae can be found in Rees (1943), and Beal (1960, 2003). This chapter will focus on *Trogoderma* spp, especially the warehouse beetle (*T. variabile*) and related species, because of the worldwide persistence of these beetles as pests of stored products, packaged goods, and handling facilities.

Adult *T. variabile* (Figure 3a) are small (about 2.7 to 3.5 mm in length), oval, and predominantly black with dense, dark-brown scales or setae covering the elytra. Adult females of the warehouse beetle produce a pheromone that excites and attracts the males. Synthetic *T. variabile* pheromone is commercially available for use in traps for monitoring the insect. Larvae are about 6.3 mm in length, light brown and cylindrical, with tufts of dense hairs protruding from the last abdominal segment (Figure 3b). Dermestidae larvae are distinct from the larvae of other stored product beetles. The larvae appear "hairy" because of a combination of setae, heavier bristles, and fine, spear-shaped setae that can entangle other insect species. The life cycle of the warehouse beetle consists of the egg, larva, pupa, and adult stage. A female may lay up to 80 eggs in her lifetime under optimum conditions (about 30°C and 70% RH). Eggs are laid singly in the food source and develop to adulthood in about 30 to 45 days. *Trogoderma* species larvae can suspend development (diapause) for a long time if environmental conditions become unfavorable (e.g., low temperatures, crowding, and starvation). For example, trogoderma dermestid beetle *Trogoderma tarsale* Melsheimer was able to survive for more than five years without food (Wodsedalek 1917). The survival of *Trogoderma* larvae through diapause makes eradication difficult.

The warehouse beetle and khapra beetle (*T. granarium*) share close physical similarities, but the latter has a limited ability to fly, so beetles caught in flight traps where both species occur are likely to be warehouse beetles (Stibick 2007; USDA-APHIS 2011). Traps for monitoring *T. granarium* should be placed at or near ground level. Species confirmation is essential for insects not captured in flight traps if there is concern about *T. granarium* activity.

Trade and import issues often are a major concern, especially with khapra beetles. The insect is difficult to control because of its ability to survive for long periods without food, preference for dry conditions and low-moisture food, and resistance to most approved insecticides. A federal quarantine restricts the importation of certain commodities into the United States from countries with known infestations of khapra beetle.

Other species within the *Trogoderma* genus include ornate carpet beetle (*T. ornatum*), larger cabinet beetle (*T. inclusum*), *T. sternale*, glabrous cabinet beetle (*T. glabrum*), and European larger cabinet beetle (*T. versicolor*). The warehouse beetle is similar in appearance to other *Trogoderma*, but diagnostic characteristics such as the the medial margin of the eye and the two-colored wing case (elytra) can be used to separate this species from the other *Trogoderma* species listed above except *T. sternale*. Unlike *T. sternale*, the basal and submedian bands of each elytron are not connected by a longitudinal band or bands, and male antennal clubs are not serrate (Bousquet 1990).

Adults and larvae of *Trogoderma* species are similar in appearance and may be difficult to distinguish by a nonspecialist. Adults of *Trogoderma* species should not be identified by color patterns alone, as species may vary in their markings. Identification should be confirmed by examination of the eye margins, shape of antennal cavities, metasternum, and other features on the adult. Other features that may be used to distinguish between *Trogoderma* species include antennae, abdominal sutures, and placement of hastisetae.

Commodities infested – Similar to other economically important families, the majority of damage by dermestid beetles occurs while the insects are in the larval stage. Unlike other stored product beetles, e.g., red flour beetles (*Tribolium castaneum* Herbest) and lesser grain borer (*R. dominica*), that can survive on grain kernels or flour alone, dermestid beetles have a variety of habits. Most genera are scavengers that feed on dry animal or plant material such as skin or pollen, animal hair, feathers, dead insects, and natural fibers. The larvae feed upon, damage, or destroy household furnishings and various materials made of leather, hair, fur, wool, and silks; dried animal remains; museum specimens and exhibits; and insect collections. The larvae are also important pests of durable commodities, including bacon, cheese, cork, seeds, cereals, and cereal products (Rees 1948). They have been detected around mills, especially in areas where flour, other insect infestations, and mold abound. With bakery mixes (cake mixes), the insect will more often be found in the ingredient, but can be quite prevalent in the mixture of flour, yeast, and dried egg. Similar patterns have been observed in processing plants producing dry pet food. The beetles will be found toward the end of the processing line, particularly between cooking, drying, and the packaging line. Besides causing damage to stored product due to feeding activities, the setae (hairs) of *Trogoderma* larvae and other dermestid beetles are an important health hazard. The setae are shed within the food product infested by the larvae and are present on larval cast-off skins after molt. Ingestion of food contaminated with larval cast skin may lead to gastric irritation and symptoms of similar to food-borne illness. Severe sensitivity to larval caste skins can lead to respiratory distress and conjunctivitis and has been attributed to cleaning equipment infested with warehouse beetles (Bernstein et al. 2009). Health risks may not only force disposal of products and ingredients, but can also lead to more serious liability and brand security issues.

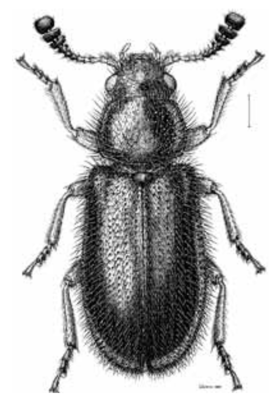

Figure 4. *Adult of the redlegged ham beetle, Necrobia rufipes De Geer, 3.5 to 4.5 mm long (from Bousquet 1990).*

Redlegged ham beetle, *Necrobia rufipes* DeGeer

The redlegged ham beetle is a member of the beetle family, Cleridae. Commonly known as checkered beetles, they are typically predators and scavengers of other insects in nature. *Necrobia rufipes* is adapted to feeding on dried meats, such as southern dry-cured hams and fish meal (Hasan and Phillips 2010). The beetle likely became adapted to human-stored animal products from wild ancestors that were scavengers on vertebrate carrion and other dried animal carcasses. Although scavenging and feeding on dead animal or insect tissues is common, *N. rufipes* has been observed to cannibalize its own live eggs and larvae and to actively prey on other arthropod species in its stored meat or cheese habitat, such as various life stages of the cheese skipper moth, *Piophila casei*, and immature of the hide beetle, *Dermestes maculatus* (Arbogast 1991).

Adults of the redlegged ham beetle (Figure 4) are approximately 3.5 to 4.5 mm in length, even-sided with clubbed antenna, pale yellowish to reddish colored legs, and a dark blue to metallic green body color. Larvae hatch from eggs laid on the surface of food, and then burrow into the food material. Mature larvae spin cocoons in which they pupate, usually in crevices between foods or in other ways isolated from other late larvae. Development from egg to adult takes about 25 days at 30°C. *Necrobia rufipes* has a cosmopolitan distribution, and is commonly found in association with *Dermestes* beetles. Pheromones have not been described for *N. rufipes*, though it may be found in traps used for other beetles, perhaps orienting to odors of food from the grain-based oils in such traps (Roesli et al. 2003). Arthropod natural enemies for *N. rufipes* have not been studied, and considering their ecological status as a predator, it is unlikely that parasitoids are commonly associated with it. Co-occurring predators and scavengers utilizing the same food resources will have some impact on eggs and other immature stages of *N. rufipes*. The impact of these is unknown though suspected to be minimal.

Commodities infested – The redlegged ham beetle is the most important of a group of arthropods that infest meats that are dried to some extent by evaporation during long-term ambient temperature storage, usually following infusion with salt solutions or smoking. It is also one of the most destructive pests of coconut meat, referred to as copra. In addition, *N. rufipes* has been found feeding on a wide variety of animal-derived foods including cheese, ham, bacon, fish, salt fish, bones, bone meal, drying carrion, as well as dried figs, palm nut kernels, and guano (Arbogast 1991). Species in the genus *Necrobia* can develop on dead fatty animal matter, sometimes on oily plant substances, or on larvae of other carrion visitors. Because of these feeding habits, *N. rufipes* can be useful in estimating the forensic status and the post-mortem interval on human cadavers. *Necrobia rufipes* has also been found associated with Egyptian mummies (reviewed in Hasan and Phillips 2010). *Necrobia rufipes* is one of the predominant pests, and a major target of pest control efforts, among arthropods infesting southern dry-cured hams in North America.

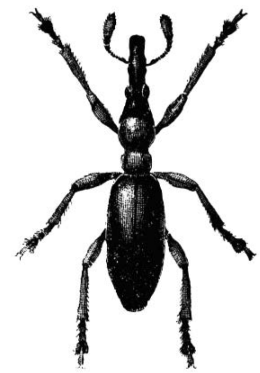

Figure 5. *The adult of the sweetpotato weevil, Cylas formicarius (F.), 6 to 8.5 mm long (from Sherman and Tamashiro 1954).*

Sweetpotato weevil, *Cylas formicarius* (F.)

The sweetpotato weevil, *Cylas formicarius* (F.), (Figure 5), is a beetle in the family of weevils that have an elongated snout, the end of which is equipped with mouthparts. The sweetpotato weevil is particularly striking in that it looks like an ant, with the antennae, thorax, and legs orange to reddish brown, a black head, and the abdomen and elytra being metallic blue. It is presumed to have evolved as an ant mimic to avoid predation. *Cylas formicarius* is a serious pest of sweet potatoes, *Ipomoea batatas*, as they mature in the field and then during storage. The pest was apparently introduced into United States from Central America or the Caribbean in the late 19th century and is now established in the southeastern United States north to North Carolina and west to Texas. Female sweetpotato weevils lay single eggs into cavities, chew in stems or tubers, and then cover the egg with a sort of fecal plug. Eggs hatch in about 6 days and the grub-like larvae tunnel in the tuber material, leaving frass in the tunnels behind them, which is the main activity of their damage to the sweet potato. There are three larval instars taking a total of about 40 days to develop; after that, the pupa develops for 7 to 10 days inside a chamber constructed by the mature larva. Adults chew a round emergence hole to the outside of the tuber and can live up to 200 days, fly very little, are active mostly at night, and become reproductively mature within days of emergence (Capinera 2009).

Cylas formicarius utilizes a female-produced sex pheromone that has been identified, synthesized, and is available commercially in lures for monitoring pest populations with traps and potentially for population manipulation via mating disruption (Jansson et al. 1991). In addition to the weevil causing serious post-harvest losses to sweet potatoes, it also represents a quarantine risk if infested sweet potatoes were to be exported from the United States to countries that do not yet have *C. formicarius* established within their borders.

Some species of parasitoid wasps have been reported emerging from sweetpotato weevil larvae collected in the southeastern United States, but no systematic studies have investigated the potential for these natural enemies to be used in biological control.

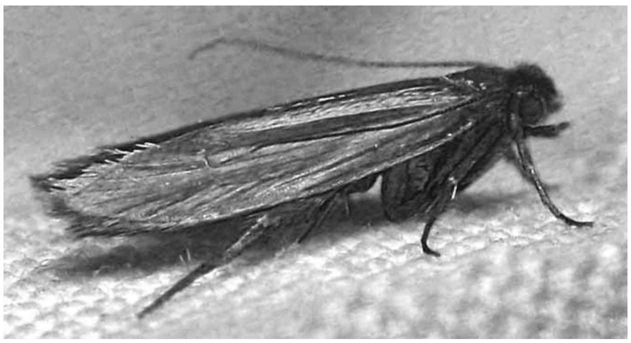

***Figure 6.** The adult of the webbing clothes moth, Tineola bisselliella (Hummel), 5 mm long (P. Kelley, Insects Limited).*

Clothes moths

The moth family Tineidae contains several species referred to as cloths moths because they are pests of fabrics made from natural animal-derived fibers. In fact, clothes moths such as the webbing clothes moth, *Tineola bisselliella,* and the case-making clothes moth, *Tinea pellionella* (Figure 6) require a diet of wholly or mostly animal products for larval development. Although dried meats, egg, and dairy products can be utilized, these moths prefer fibers from the skin and hair of vertebrates such as wool of sheep, furs from numerous mammals, bird feathers, and dried skin of all kinds. Silk generated from the silk moth, *Bombyx mori*, can also support growth and development of clothes moths. Adult clothes moths are small, buff-colored moths with a body length of 5 mm or less. Larvae generate silk while feeding. The larvae of *Tinea* make a silken case that they reside in, feed from, and carry with them, much like the shell of a snail. Development of clothes moths from egg to adult may take 40 days at 25°C (Rees 2004).

The pheromone biology of clothes moths is not like other moths, as both males and females produce attractants that facilitate mate finding at oviposition resources. These pheromones have been partially identified and are available for commercial use, but pheromone-based monitoring of clothes moths has not achieved the level of adoption as that with typical food moths such as *Plodia* and *Ephestia*. Parasitoid wasps are known from clothes moths, but none have been researched in depth or developed for commercial biological control.

The significance of clothes moths is relatively minor when considering all stored product pests, but for certain high value animal products, such as hand-woven wool carpets, expensive silk clothing, and valuable museum artifacts of animal origin (e.g., aboriginal furs or skins), clothes moths represent serious pests for which 100% control or prevention must be achieved.

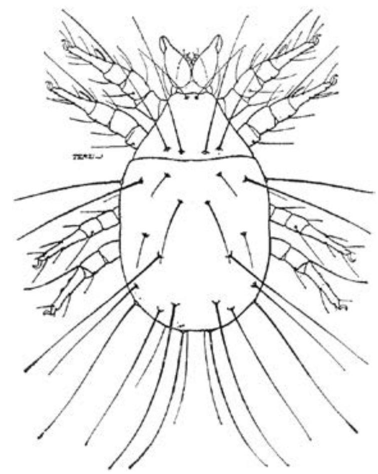

***Figure 7.** The mold mite, Tyrophagus putrescentiae (Schrank) (Source: USDA), 280 to 350 microns long (from Evans et al. 1961).*

Mold mite, *Tyrophagus putrescentiae*, Schrank

Tyrophagus putrescentiae (Schrank) (Figure 7) is one of the astigmatid mites, a group of soil-dwelling mites in the family Acaridae. The mites can be found in homes and buildings, which they invade via various insects and vertebrate hosts that have used mite-infested nests, or via movement of infested food, plant, and animal material to new locations. Structures or processing machinery may also harbor hidden infestations that contaminate product during manufacture before transportation to other sites. *Tyrophagus putrescentiae* is widely distributed throughout the world. Together with the related species *T. longior*, it is commonly referred to as the mold mite. Currently, the genus *Tyrophagus* comprises about 35 species and is worldwide in distribution. The mold mite is often mistaken for the grain mite (*Acarus siro*), or a variety of other mite genera and species, including *Tyrophagus* mites such as the cheese mite (*Tyrophagus casei*). Mite identification usually stops when the observer sees small eight-legged creatures. In the durable commodities market, species identification beyond the simple determination of "mite" is critical when attempting to determine the infestation source, leading to effective prevention and control steps against an infestation. Description and keys for identification of mite species, including storage mites can be found in Robertson (1959), Smiley (1987), and Kucerová and Stejskal (2009).

Adult mold mites are small, measuring about 28 to 350 microns long. In most cases, bodies lack segmentation and segmented somites. Their small size makes early infestation by mites difficult to detect and enables them to enter packaging and exploit food residues in very small cracks and crevices.

Females may lay up to 488 eggs during a lifetime. Population doubling may occur in as little as two to four days (Sánchez-Ramos et al. 2007). Under ideal conditions, 100 mites can render about 100 g of dog food to dust in less than four weeks. The life cycle consists of the egg, larva, protonymph, tritonymph, and adult stages. The larvae have six legs, but the juveniles (protonymph, tritonymph) have four sets of legs like adult mites. The adults and juveniles are oval, cream, and milky- or white-translucent. Development from the egg to adult takes about one to three weeks, and could take 118 days depending on environmental conditions and the food type on which the mite is reared (Kheradmand et al. 2007).

As indicated, infestations by mold mites are very common but are often difficult to detect except in occasions of severe infestations. Usually the first sign of an abundant infestation is the presence of a rapid accumulation of dust, which is made up of biomass from live and dead mites, mite eggs, frass, and food particles on or around a food product. The presence of dust suggests the likelihood of a major infestation in the adjacent area and fragmented smaller populations in adjacent areas. Mites tend to undergo rapid dispersal when conditions become unfavorable from overcrowding, food depletion, or degradation. The trigger for this dispersal has been attributed to the release of an alarm pheromone, neryl formate (Kuwahara et al. 1975), but the mechanism involved the dispersal process is not fully understood. Dispersal may also result from movement of contaminated foodstuffs, equipment, plant, and animal material to new locations.

The original food of *T. putrescentiae* is believed to be fungi. Consequently, they would appear to be preadapted to feed on a wide range of stored food and feedstuffs and many other commodities of plant and animal origin (Hughes 1976). Although the name "mold mite" conveys the impression that *T. putrescentiae* confines its feeding activities to mold, *T. putrescentiae* infest a wide range of stored products with relatively high protein and fat contents, and can be found in decaying organic matter, plant seeds, medicinal plants, and mushroom beds (Kheradmand et al. 2007). *Tyrophagus putrescentiae* also feeds on different fungi including molds (e.g., Bahrami et al. 2007) and a number of dermatophytes and yeasts (Duek et al. 2001). The mite also has been reported to feed on nematodes and other microorganisms in culture (reviewed in Bilgrami and Tahseen 1992).

The common name mold mite has led to some confusion when untrained persons are trying to determine the sources of this mite. Often there have been mistaken references to food being moldy, hence the presence of this mite. This has led to considerable confusion, particularly when infested food contains preservatives or fungistats. The role of fungi in the nutritional ecology of *T. putrescentiae* is yet to be fully understood. For example, although the presence of molds has been shown to encourage growth and development of *T. putrescentiae*, the mite would develop well on susceptible foods that are free from mold infestation (Canfield and Wrenn 2010). Mold may be required as a direct food source, or as a commensal organism providing essential nutrients or moisture to the mite in nutritionally poor foods. Mold may be a competitor for existing resources or a simple opportunist when mites begin to invade a food source. Mold and mites may coexist in an area because both types of organisms have similar favorable environmental conditions. For such a simple creature, nutritional requirements and relationships to mold and fungi may be complex and require further study.

The main ecological factors affecting the growth and development of mites are temperature, food sources, and in particular, the relative humidity of the microenvironment (Sánchez-Ramos et al. 2007). *T. putrescentiae* is particularly susceptible to low humidity because its relatively weakly sclerotized cuticle could cause the mite to desiccate at low humidities. The optimal humidity for survival appears to be 90% (Kheradmand et al. 2007). Growth and development of *T. putrescentiae* might cease at extended relative humidity below 65%. As humidity begins to decrease from optimal, mites may cluster together to reduce the impact of water vapor stress (Cutcher 1973), or may to a limited extent, rely on structures called supracoxal glands to maintain water balance through water absorption (Arlian 1992; Wharton et al.1979). Key techniques suggested for integration for management of *T. putrescentiae* includes humidity management, sanitation, freezing, stock management, as well as use of phosphine fumigation (Nayak 2006; Eaton and Kells 2009; 2011).

Commodities infested – *Tyrophagus putrescentiae* is a cosmopolitan stored product pest of significant economic and health importance. The mite infests stored products with relatively high protein and fat content such as wheat and soy flour, herring meal, bacon, cheese, dried milk, dried meats, nuts and grains, fruit, mushrooms, various seeds, and dry dog food (Robertson 1952; Hughes 1976; Arnau and Guerrero 1994; Duek et al. 2001, Kheradmand et al. 2007; Brazis et al. 2008). Fang and Zhang (2007) provide an extensive list of cases where this mite was found in plants, soil, and flowers, and this mite has been found associated with agricultural soils. Even products that would not seem to fit the above criteria, such as dried pasta, can be susceptible if storage conditions are cool and damp.

Tyrophagus putrescentiae has been shown to attack the stored product insect *L. serricorne* (Papadopoulou 2006) and to be an effective eggs predator of the field pest southern corn rootworm, *Diabrotica undecimpunctata* Howard (Brust and House 1988). The mite also has been recorded to prey on nematodes such as *Meloidogyne javanica* (Treub), and *Aphelenchus avenae* Bastin (Bahrami et al. 2007; Kheradmand et al. 2007). Although *T. putrescentiae* has been associated with beehives, its presence and significance is not fully understood. Besides damage to stored products and predation on other insects, *T. putrescentiae* is considered an important species in health and medicine. The mite produces allergens that induce discomfort in human skin and breathing. For example, the predominant allergic mite in dust and debris samples from several coalmines was found to be *T. putrescentiae* (Solarz and Solarz 1996).

Monitoring and control of mite-prone areas is a method of affecting sources of mite infestations before they have a chance to move onto food product. Specifically, reducing the number of refugia and increasing the distance between other mite sources and susceptible food product can help prevent infestations. Three methods of monitoring mites include the use of baited mite traps, equipment or product sampling, and vacuum sampling. Baited mite traps have a food item and suitable humidity that attract mites to the container. The traps will collect mites over 24 hours, though the trapping period may be longer, depending on humidity and bait consistency. These traps collect mites that have moved out of the refugia and rely on mite dispersal behavior.

Equipment or line sampling are more active practices used in food processing plants to determine if mites are harboring in the processing equipment. For equipment sampling, swab samples of food residues are taken from key areas of the processing equipment. Usually these areas exist after thermal or pressure processing steps and may include dust collection fittings, dead spaces, and areas where product flow changes direction or decreases in velocity. Equipment samples are evaluated under a microscope. Finished product samples (or line samples) are packages of product removed from the line, and inspected for mites or incubated for a period before inspection.

Vacuum samples utilize a method adapted from sampling for dust mites, using equipment set up to be used in an industrial environment. A filter of 193 x 193 nylon meshes is placed in a vacuum hose, and surfaces, cracks and crevices, and pallets can be vacuumed. Each vacuum sample covers an approximate area of 30 cm x 4 cm. Filters are inspected visually. The advantage of this sampling method is that possible refugia sites can be sampled directly. This sampling method can be used to prioritize sanitation and exclusion techniques because areas yielding mites can be directly targeted for remediation. The type of monitoring method used and the number of samples taken will depend on the susceptibility of the food product and how favorable the habitat is for mites.

Storage Ecosystems by Commodity

Tobacco

Tobacco packaging and storage

The cigarette beetle does not attack growing tobacco and is not present in tobacco fields. The insect prefers cured tobacco, thus infestation by *L. serricorne* is of major concern to tobacco manufacturers rather than growers, as the latter are less likely to hold stock longer than necessary. To improve aroma, taste, and other quality characteristics, cured tobaccos are held in storage for one to two years or more to allow for slow fermentation, or aging of the leaves under natural conditions of temperature and humidities. As a result, manufacturers often carry in storage large stocks of tobaccos in order to fulfill manufacturing requirements. Tobaccos of different crop years are often stored in the same warehouse because it is economically difficult to keep stocks in storage by crop years. Within warehouses, tobacco stored in the same lot is typically grouped together into an aisle to facilitate movement of equipment, sanitation, and related pest management activities.

In the United States, hogshead is a major container for holding tobacco while it is transported, stored, or aged. Hogshead is made from wooden staves joined together with metal and wire hoops to form a closely fitted barrel-shaped container. Between two hogshead staves are cracks measuring about 6.5 mm (Reed et al. 1941). One hogshead can hold up to 500 kg of tobacco. Cardboard boxes and bales are other packaging containers that serve the same purpose as hogsheads. A cardboard box may hold 200 or 500 kg of cured tobacco. To make a bale, cured tobacco is placed in layers in a wooden crate atop a scale that has been lined with burlap or nylon. When the desired weight (usually 30 or 50 kg) has been achieved, the tobacco is compressed into a rectangular block. The sides of the bales are stitched together and the wooden supports removed, revealing the bale. Packages offer limited barrier to entry by stored tobacco pests. Hogshead packing is vulnerable because beetles can easily migrate into the container through the cracks between the wooden staves.

Before the mid 1970s, much of the tobacco aged in the United States was stored in open or semi-closed warehouses that are merely sheds with open or partly open sides. The objective of these early designs was to maintain good air circulation and even temperatures throughout the warehouse. Controlling insects in these structures was often difficult. Tobacco warehouses became less open in the early 1970s due to the adoption of phosphine fumigation and improved leaf moisture content uniformity at packaging made possible with tobacco redrying technology. Although the primary objective of tobacco redrying is to facilitate processing of tobacco to manufacturer's grade, size, and moisture specifications, tobacco agitations and high temperatures employed during processing are sufficient to destroy all beetle stages before the leaves are packed in containers for storage (Tenhet and Bare 1951). Newly packed tobacco can become infested if containers are stored in an infested building or containers. Cigarette beetles are strong fliers, capable of using plant volatiles to locate potential food resources. In addition, female beetles release sex pheromones that attract the male for mating, building up pest populations in the warehouse or manufacturing facility. Contemporary tobacco warehouses in the United States are simple in design and vary in volume from 8,500 to 57,000 cubic meters. A major design requirement is the ability to close and seal the buildings for fumigation (USDA 1971; Ryan 1999).

Insects associated with tobacco storages

Several insect species may be found in tobacco warehouses, but very few actually feed on cured tobacco. Economically important stored product species such as *Sitophilus oryzae* (L.), *Tribolium* spp, and *Oryzaephilus surinamensis* (L.), etc., which feed on plant material and are found in tobacco storage structures, are of little importance as pests of cured tobacco and may be regarded accidental invaders (Chittenden 1897; USDA 1971). Others, such as the Tenebrionidae and Dermestidae, are largely scavengers that feed on pollens and dried plant and animal matter, including dead insects. *Trogoderma variabile* Ballion, the warehouse beetle, has been observed to cause significant damage to cigarettes. The inability of many stored product insects to survive on cured tobacco may be due to the poor nutritional content of tobacco leaves relative to other stored products such as grains, or because of the substantial nicotine and other alkaloids content of leaf tobacco. Apparently, tobacco-feeding insects are able to tolerate or detoxify these chemicals in order to survive (Self et al. 1964; Snyder et al. 1993). In addition to nutritional contributions previously mentioned, *L. ser-*

ricorne symbionts are capable of assisting the survival of the host by detoxifying ingested xenobiotic to less harmful alkaloids, which the insects then excrete (Milne 1963). *Lasioderma serricorne* is also capable of excreting most of the nicotine ingested in the form ingested, i.e., unmodified, by the insect (Farnham et al. 2006), but the mechanism for achieving this is not fully understood.

Besides *L. serricorne*, another insect that feeds on cured tobacco is the tobacco moth *Ephestia elutella* (Hubner) (Lepidoptera: Pyralidae). Although the insect is rarely encountered in tobacco storage in the United States, it is a serious pest of stored tobacco in cool temperate zones as far north as southern Canada (USDA 1971). Unlike *L. serricorne*, *E. elutella* does not attack manufactured products (Tenhet and Bare, 1951). The moth prefers tobaccos that are high in sugar and low in content, and rarely feeds on air- or fire-cured tobacco, or cigar types of tobacco (Tenhet and Bare 1951; USDA 1971). Other preferred food substrates of *E. elutella* are cacao beans, stored grains including peanuts, rice, etc., and their manufactured products. Life history and seasonal occurrence of *E. elutella* were described in early works (e.g., Tenhet and Bare 1951; Ashworth 1993).

Other insects that can feed on dried tobacco, especially in the subtropical and tropical regions, include the anobiid beetle called the larger tobacco beetle *Tricorynus tabaci* (Guerin-Meneville). *Tricorynus tabaci* has been recorded in Texas and Florida, and is occasionally intercepted in commerce (White 1971). The insect attacks cured tobacco in much the same way as *L. serricorne*, and feeds on tobacco seeds (USDA 1971; Runner 1919). *Tricorynus tabaci* is identical to *L. serricorne*, but the former is larger and black instead of brown. Another member of the genus *Tricorynus confusus* (Fall) has also been caught in tobacco warehouses in North Carolina and Virginia (White, 1971). *Tricorynus tabaci* can be distinguished from *T. confusus* by body length. The body length of *T. tabaci* varies from 3.4 to 4.6 mm long, while those of *T. confusus* vary from 1.8 to 2.6 mm long (White 1971). In addition, lateral striae are present on the elytra of *T. tabaci*, but are absent on those of *T. confusus* (White 1971).

Another insect that feeds on dried tobacco is the pyralid moth *Tulsa finitella* Walker (Tenhet and Bare 1951), but no information is available on the biology or feeding damage caused by this insect. The booklouse, *Liposcelis entomophila* (Enderlein) has been reported to occasionally cause economic damage to tobaccos in farm tobacco storages and grading buildings by feeding on leaf lamina (Mashaya 1999). Other insects, including *Mezium americamum* Laporte (Coleoptera: Ptinidae), infest tobacco seeds (Runner 1919).

A number of natural enemies attack *L. serricorne.* The pteromalid wasps *Anisopteromalus calandrae* (Howard) and *Lariophagus distinguendus* (Forest) are important larvae and pupae parasitoids of the beetle (Bare 1942). Other hymenoptera parasites include the pteromalids *Theocolax elegans* (Westwood), the enrytomid *Brachophagus* sp., and the bethylid *Cephalonomia gallicola* (Ashmead) (Haines 1991). The predatory mites *Moniezella angusta* (Banks) and *Tyrophagus putrescentiae* (Schrank) feed on the larvae and pupae of *L. serricorne* (Bare 1942; Papadopoulou 2006). Another mite, *Blattisocius keegan* Fox, and the psocid *Liposcelis divinatorius* (Mull) have been reported to feed on *L. serricorne* eggs (Rao et al. 2002). Adult and larvae of the clerid beetle *Thaneroclerus girodi* Chevr are predaceous upon the larvae and pupae of *L. serricorne* (Morgan 1913).

These natural enemies have shown little practical importance in controlling populations of stored products insects, including *L. serricorne*, because the natural enemies are often at low numbers compared to their hosts, and the natural enemies only begin to suppress hosts after the hosts have reached quite high numbers (Edde 2012). The parasitoids and predators themselves fall prey to other organisms. Besides arthropods, the bacterium *Bacillus cereus,* a noncrystalliferous, aerobic, spore-forming bacterium that has been isolated from *L. serricorne* was found to cause significant mortality of *L. serricorne* larvae (Thompson and Fletcher 1972).

Spices and herbs

The term "spices" refers to the flavored dried plant parts such as fruits, seeds, barks, and as bulb and rhizomes, while "herb" is used as a subset of spice, and is generally derived from fresh or dried leaves, and traded separately from the plant stems and leaf stalk (Peter 2001). Spices and herbs are used for flavoring, seasoning, preserving, and imparting aroma in food or beverages, and useful in the treatment of several disorders in humans because of their therapeutic properties. In this review, no distinction is made between spices and herbs. It is difficult to classify spices or herbs. For convenience, Ridley (1912) suggested that the crops might be grouped according to the parts of the plant that form the commercial product. For example, the flower bud is used in cloves; the fruit in nutmegs, vanilla, capsicums/pepper; the underground stems in ginger and turmeric; and tree bark in cumin and cassia. Spices are often dried and used in a processed but complete state, or may be prepared as extracts such as essential oils by distilling the raw spice material, or using solvents to extract oleoresins and other standardized products (Douglas et al. 2005). Important spice crops in world trade include pepper, nutmeg, cardamom, allspice, vanilla, cloves, ginger, cinnamon, turmeric, coriander, cumin, onion, paprika, saffron, sesame seeds, and the herbs sage, oregano, thyme, bay, and mints.

Packaging and storage requirements for species are as diverse as the range of plant species or plant parts from which the products are derived. For example, while dry onion, ginger, and turmeric for bulk storage are typically packed in jute or sisal sacks, wooden boxes, or lined corrugated cardboard boxes, others such as cinnamon and cassia — especially if ground — require polypropylene packaging (Douglas et al. 2005; Valenzuela 2011). Although freshly harvested spices and herbs have superior flavor compared with dried herbs, a greater proportion of the products are stored or marketed in dried form. It is essential that all material is dry to below 10% to prevent product deterioration and prolong shelf life.

The hygroscopic properties of many dried spices or herbs play an important part in the choice of packages or storage conditions. Popular packaging materials for dried spices and herbs include glass, metal, plastic, and their derivatives, and elastomeric. These containers are impermeable, reducing the possibility of insect and moisture migration into the commodities.

The storage life of spices can be maximized if the products are harvested at the proper stage of maturity, cured properly, and are free of bruises, plant pathogens, and stored under relatively cool conditions. Storing at the right environmental conditions is essential to prevent pest damage to commodities harvested as bulbs and rhizomes. For example, the recommended storage conditions for ginger include temperatures of 12 to 13°C and 85 to 90% RH (Valenzuela 2011). Activity of most stored product insect pests is limited at temperatures below 15°C. Spices and herbs are able to keep storage insect pest damage to a minimum, especially when the crop has been dried to correct specifications and stored in temperature- and humidity-controlled conditions (Douglass et al. 2005). Pest damage to some spices and herb species might be limited by the repellant or inhibitory qualities of the aromatic oils and related alkaloids contained in the crops. When plants are stored on a commercial scale, some common stored-product insect pests do cause damage, especially if the crops are stored in inferior facilities and under less than ideal management. The most frequently occurring insect species found on spices are *L. serricorne* and *S. paniceum*. The biology and ecology of the two insects were reviewed earlier in the chapter. The feeding habits of the insects are similar, and as noted, the two beetle species harbor microorganisms that enable the insects to feed on plant species of diverse chemical compositions (Howe, 1957). Other important arthropod pest species besides *L. serricorne* and *S. paniceum* that have been recorded on stored spices and herbs are presented in Table 1. The list is by no means exhaustive. The reader may refer to work by other authors, e.g., Archibald and Chalmers (1983), Hagstrum and Subramanyam (2009), and USDA (1964) for additional information on the subject.

Table 1. *Insect species associated with spices and other seasonings (modified from Hagstrum and Subramanyam 2009).*

Insect	Spice/Herb
Aglossa ocellalis	ginger
Ahasverus advena	black pepper, chili pepper, coriander, ginger, nutmeg, onion, turmeric
Alphitobius diaperinus	coriander
Alphitobius laevigatus	onion
Alphitobius viator	chili pepper, ginger
Anthicus quisquilius	ginger
Anthrenus flavipes	black pepper
Anthrenus jordicus	onion
Anthrenus oceanicus	onion
Anthrenus verbasci	black pepper, chili pepper
Araecerus fasciculatus	chili pepper, ginger, ginseng root, nutmeg, onion
Attagenus cyphonoides	chili pepper
Attagenus fasciatus	coriander
Attagenus lobatus	chili pepper
Attagenus unicolor	black pepper, chili pepper
Bruchus rufimanus	saffron
Cadra cautella	allspice, chili pepper, ginger, nutmeg, onion
Callosobruchus analis	coriander
Callosobruchus chinensis	black pepper
Callosobruchus maculatus	black pepper, coriander, ginger
Callosobruchus phaseoli	coriander
Carpophilus brevipennis	garlic
Carpophilus dimidiatus	cinnamon, garlic, ginger, nutmeg, onion, turmeric
Carpophilus hemipterus	chili pepper, garlic ginger, onion
Carpophilus humeralis	onion
Carpophilus ligneus	garlic, ginger
Carpophilus lugubris	chili pepper
Carpophilus maculatus	chili pepper
Carpophilus marginellus	ginger
Carpophilus mutilatus	garlic
Carpophilus obsoletus	garlic, nutmeg, onion
Carpophilus pilosellus	garlic, onion
Cathartosilvanus vulgaris	chili pepper
Cathartus quadricollis	chili pepper
Caulophilus oryzae	ginger
Coccotrypes dactyliperda	nutmeg
Coccotrypes myristicae	nutmeg
Corcyra cephalonica	coriander, ginger, nutmeg
Cryptamorpha desjardinsi	chili pepper
Cryptolestes capensis	chili pepper
Cryptolestes cornutus	chili pepper
Cryptolestes divaricus	chili pepper
Cryptolestes ferrugineus	black pepper, chili pepper
Cryptolestes klapperichi	chili pepper, nutmeg
Cryptolestes pusilloides	anise, chili pepper
Cryptolestes pusillus	chili pepper, nutmeg
Cryptolestes turcicus	chili pepper, nutmeg
Dermestes ater	ginger
Dermestes frischii	turmeric
Dermestes lardarius	nutmeg
Dienerella ruficollis	chili pepper
Dinoderus minutus	cinnamon, ginger
Doloessa viridis	nutmeg
Ephestia elutella	chili pepper, garlic, nutmeg
Ephestia kuehniella	chili pepper, garlic
Euscelinus sarawacus	nutmeg
Gibbium psylloides	chili pepper, coriander, ginger, spearmint, turmeric
Gnatocerus cornutus	ginger
Gnatocerus maxillosus	nutmeg
Himatismus villosus	chili pepper
Holoparamecus depressus	black pepper, ginger
Holoparamecus signatus	ginger
Hypothenemus obscurus	nutmeg
Lachesilla pedicularia	coriander
Lasioderma serricorne	allspice, anise, basil leaf, black pepper, cardamom, chili pepper, cinnamon, coriander, cumin, curry powder, garlic, ginger, ginseng root, nutmeg, onion, paprika, saffron, spearmint, turmeric
Latheticus oryzae	chili pepper
Liposcelis bostrychophila	black pepper, ginger
Liposcelis decolor	black pepper
Liposcelis entomophilus	black pepper
Lonchaea polita	black pepper
Lophocateres pusillus	chili pepper, ginger, nutmeg
Lyctus africanus	ginger
Lyctus brunneus	cinnamon

Table 1. *Insect species associated with spices and other seasonings (modified from Hagstrum and Subramanyam 2009).*

Insect	Spice/Herb
Mezium americanum	chili pepper
Monanus concinnulus	chili pepper
Murmidius ovalis	ginger
Murmidius segregatus	ginger
Nausibius clavicornis	ginger
Necrobia rufipes	chili pepper, garlic, ginger, nutmeg
Opatrum subaratum	ginger
Orphinus fulpinus	ginger, nutmeg
Oryzaephilus mercator	anise, black pepper, chili pepper, coriander, curry powder, ginger, ginseng root, nutmeg, turmeric
Oryzaephilus surinamensis	black pepper, coriander, curry powder, nutmeg, paprika
Palorinus humeralis	nutmeg
Palorus cerylonoides	nutmeg
Palorus genalis	ginger, nutmeg
Palorus subdepressus	ginger
Paralipsa gularis	pepper
Pharaxonotha kirschii	chili pepper
Phradonoma villosulum	chili pepper
Phthorimaea operculella	chili pepper
Plodia interpunctella	anise, chili pepper, garlic, ginger, nutmeg, onion, paprika
Ptinus fur	ginger, paprika
Ptinus ocellus	chili pepper, ginger, nutmeg, paprika
Pyralis farinalis	turmeric
Pyralis manihotalis	chili pepper, ginger
Rhyzopertha dominica	chili pepper, cinnamon, coriander, cumin, ginger, turmeric
Setomorpha rutella	black pepper, ginger
Sitophagus hololeptoides	nutmeg
Sitophilus oryzae	anise, black pepper, coriander
Sitotroga cerealella	black pepper
Sphaericus gibboides	chili pepper, coriander, curry, paprika, saffron
Stegobium paniceum	allspice, anise, black pepper, chili pepper, coriander, cumin, curry powder, ginseng root, onion, paprika, saffron, turmeric
Systole albipennis	anise, coriander
Systole geniculata	anise, coriander
Tenebroides mauritanicus	chili pepper, cinnamon, ginger, nutmeg, onion
Thaneroclerus buqueti	anise, ginger, nutmeg
Tinea pellionella	chili pepper, ginger, saffron
Tribolium anaphe	ginger
Tribolium castaneum	black pepper, cardamom, chili pepper, cinnamon, coriander, ginger, nutmeg, onion, oregano, turmeric
Tribolium confusum	black pepper, cardamom, chili pepper, coriander, ginger
Tricorynus herbarium	nutmeg
Tricorynus tabaci	chili pepper, garlic
Trigonogenius globosus	chili pepper
Trogoderma granarium	chili pepper, nutmeg, turmeric
Trogoderma inclusum	black pepper, garlic
Trogoderma ornatum	garlic
Trogoderma simplex	black pepper
Trogoderma sternale	chili pepper
Trogoderma variabile	black pepper, chili pepper, cumin
Trogoderma versicolor	chili pepper
Typhaea stercorea	black pepper, chili pepper, garlic, onion

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6 Molds and Mycotoxins in Stored Products

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The ecosystem within stored grain structures is limited in microbial species because of human efforts to maintain grain quality (Wicklow 1995; Sinha 1992). Of the more than 70,000 fungi species that have been described (Blackwell 2011), relatively few are found on grain. At harvest, grain contains populations of field microbes. Once the grain is placed into a storage facility, a succession of new microbial species begins to grow. Without intervention, microbial respiration will increase temperature and moisture, providing optimum growth conditions for even more diverse fungal species.

The type of grain, moisture, and temperature will influence the specific fungi that are associated with grain. The fungi on the maturing seed in the field typically require free water (liquid) for spore germination and high moisture to grow and flourish. Some of these fungi are pathogenic to the plant, while other fungi exist serendipitously. When grain is dried after harvest, most of the fungi on or in the grain before harvest will not be able to grow under the low-moisture conditions within the storage environment. Over time these fungi will slowly die off. In an ideal grain ecosystem, spoilage can be prevented if grain mass moisture is maintained at levels below that at which microbes grow. In practice, temperature and air movement continually change within the grain mass. This causes moisture to migrate, resulting in areas with moisture conditions that allow storage fungi to grow and slowly impact grain quality (Wicklow 1995; Sinha 1992; Dehoff, et al. 1984; Ayerst 1986).

The amount of water available in an environment is often measured in values of water activity (a_w) (Reid 1980). Water activity equals the vapor pressure of pure water divided by the vapor pressure of a solution at a given temperature. The equation for calculating a_w is essentially the same as for relative humidity. The two values are equal when the air and solution are at equilibrium. Unlike aquatic environments where water activity is based on the concentration of solute, in dry environments water in a gas phase is in equilibrium with the surrounding matrix, e.g., soil, lumber, or dry grain (Yanagita 1990).

Describing the water available in these environments is more complex. In most cases it is composed primarily of hygroscopic water that is strongly adsorbed to insoluble particles. The water activity in the dry environment fluctuates in equilibrium with the relative humidity of the air surrounding this matrix (grain mass)(Yanagita 1990). A moisture value often used in grain storage is the equilibrium moisture content (EMC). This value is the water activity (a_w) when the moisture in the grain is at equilibrium with the moisture (humidity) in the air spaces between the grain. Of course the temperature as well as the proportion of starch and oil in the grain greatly impact EMC values. EMC tables are available for each grain type (Tables 1a and 1b). These tables provide information about how humidity (water activity) in the air between the seeds will affect the seed moisture content at different temperatures. They also provide information on how the humidity (water activity) will change when grain temperature increases or decreases in grain stored at a particular moisture content. When using these tables, it is important to remember that the moisture limit for microbial growth is around 65 a_w. Although most field fungi and bacteria require conditions above 95 a_w, some storage fungi can grow at 70 a_w. As the humidity (water activity) approaches 90%, storage fungi grow faster. It is important to pay attention to EMC values of stored grain during summer storage.

Impact of Disease on Grain Storability

Grain quality prior to storage is a major criterion for determining whether the grain will maintain quality during long-term storage. Any breakdown in seed coat integrity allows easy entry for storage fungi. Preharvest grain disease will reduce storability. The greater the number of kernels affected, the greater the probability of spoilage during storage. Such grain must be maintained under the driest conditions and carefully monitored during the warm seasons.

Mycotoxins – There are a number of diseases that affect corn and small grains (Bockus et al. 2010; White 1999). All of them can cause seed coat damage and affect storability, but this chapter will discuss only five diseases, four in which the fungal pathogens produce mycotoxins. Mycotoxins are chemicals produced by fungi that are toxic to animals and humans. They are grouped into classes based on chemical structure. The mycotoxins of most concern in grain are produced by species of *Aspergillus*, *Fusarium*, and *Penicillium* (Council for Agricultural Science and Technology 2003). Field surveys that determine incidence and severity of disease before harvest allow the producer to make proper decisions about selling, testing for mycotoxins, and storing the grain.

Fusarium ear rot – This is an important disease of corn. The disease can be found virtually every-

Table 1a. *Equilibrium moisture content of corn kernels.*

Air Temp. (˚F)	Relative Humidity (%)													
	30	35	40	45	50	55	60	65	70	75	80	85	90	95
30	11.4	12.1	12.7	13.3	14.0	14.6	15.2	16.0	16.7	17.6	18.6	19.8	21.4	24.0
40	10.6	11.3	12	12.5	13.1	13.8	14.5	15.2	16	16.9	17.9	19.1	20.8	23.4
50	9.9	10.6	11.2	11.9	12.5	13.1	13.9	14.6	15.4	16.3	17.3	18.6	20.2	22.9
60	9.3	9.9	10.6	11.2	11.9	12.6	13.3	14.0	14.9	15.7	16.8	18.1	19.7	22.4
70	8.7	9.4	10.0	10.7	11.4	12.0	12.7	13.5	14.3	15.2	16.3	17.6	19.3	22.0
80	8.2	8.9	9.6	10.2	10.9	11.6	12.3	13.1	13.9	14.8	15.9	17.1	18.9	21.6
90	7.7	8.4	9.1	9.8	10.4	11.1	11.9	12.6	13.5	14.4	15.5	16.8	18.5	21.3
100	7.3	8.0	8.7	9.4	10.0	10.7	11.5	12.2	13.1	14.0	15.1	16.5	18.2	21.0

Table 1b. *Equilibrium moisture content of wheat.*

Air Temp. (˚F)	Relative Humidity (%)													
	30	35	40	45	50	55	60	65	70	75	80	85	90	95
30	10.9	11.3	11.8	12.2	12.7	13.2	13.7	14.2	14.8	15.4	16.2	17.1	18.4	20.4
40	10.4	10.8	11.3	11.7	12.2	12.7	13.2	13.7	14.3	15.0	15.8	16.7	18.0	22.0
50	9.9	10.4	10.8	11.3	11.8	12.3	12.8	13.3	13.9	14.6	15.4	16.3	17.6	19.6
60	9.5	10.0	10.4	10.9	11.4	11.9	12.4	12.9	13.5	14.2	15.0	16.0	17.2	19.3
70	9.2	9.6	10.1	10.6	11.0	11.5	12.1	12.6	13.2	13.9	14.7	15.7	16.9	19.0
80	8.8	9.3	9.8	10.2	10.7	11.2	11.7	12.3	12.9	13.6	14.4	15.4	16.7	18.7
90	8.5	9.0	9.5	10.0	10.4	10.9	11.5	12.0	12.6	13.3	14.1	15.1	16.4	18.5
100	8.2	8.7	9.2	9.7	10.2	10.7	11.2	11.8	12.4	13.1	13.9	14.9	16.2	18.3

Source: Postharvest Pocket Guide (1995), Purdue University Extension ID 215 where corn is grown. Most often the disease is associated with insect damage on the ear, but the pathogen can infect kernels without insect damage. Infected kernels can be scattered on the ear and appear tannish or salmon-pink. Often, white streaks referred to as "starburst" are visible on the top of the kernel (Figure 1). Fusarium ear rot is most often caused by *Fusarium verticillioides* and *F. subglutinans*. Although it is impossible to visibly distinguish these two pathogens by disease symptoms, *F. verticillioides* produces the group of mycotoxins known as fumonisins. Fumonisins have many adverse effects on animals that consume the contaminated grain. Equine (horses) are most sensitive, but swine are also affected at relatively low levels (Voss et al. 2007). The FDA has set advisory levels for fumonisin in food and feed (Table 2).

Figure 1. *Fusarium ear rot showing starburst.*

Table 2. *FDA advisory limits for fumonisins.*

Human Foods	
Product	Total fumonisins (FB_1+FB_2+FB_3)
Degermed dry milled corn products (e.g., flaking grits, corn grits, corn meal, corn flour with fat content of <2.25%, dry weight basis)	2 parts per million (ppm)
Whole or partially degermed dry milled corn products (e.g., flaking grits, corn meal, corn flour with fat content of ≥2.25%, dry weight basis)	4 ppm
Dry milled corn bran	4 ppm
Cleaned corn intended for masa production	4 ppm
Cleaned corn intended for popcorn	3 ppm

Animal Feeds	
Corn and corn by-products intended for:	Total fumonisins (FB_1+FB_2+FB_3)
Equines and rabbits	5 ppm (no more than 20% of diet)**
Swine and catfish	20 ppm (no more than 50% of diet)**
Breeding ruminants, breeding poultry, and breeding mink*	30 ppm (no more than 50% of diet)**
Ruminants ≥3 months old being raised for slaughter and mink being raised for pelt production	60 ppm (no more than 50% of diet)**
Poultry being raised for slaughter	100 ppm (no more than 50% of diet)**
All other species or classes of livestock and pet animals	10 ppm (no more than 50% of diet)**

* Includes lactating dairy cattle and hens laying eggs for human consumption
** Dry weight basis
Source: U.S. Food and Drug Administration
http://www.fda.gov/Food/GuidanceComplianceRegulatoryInformation

Gibberella ear rot – This disease of corn is caused by the fungus, *Gibberella zeae* (*Fusarium graminearum*). This disease occurs in cool, wet areas during the first 21 days after silking begins. Extended periods of rain in the fall before harvest often increases disease severity. Ear rot is most severe in fields where corn follows corn or corn follows wheat. The pathogen survives on residue left from the previous crop, and during wet conditions the pathogen releases spores into the air. The disease is easy to recognize in the field by pulling back the husk to reveal the pinkish rot at the tip of of the ear and silks that adhere tightly to the ear (Figure 2). The pathogen produces two mycotoxins in the infected kernels: deoxynivalenol and zearalenone. These mycotoxins can affect the health of many monogastric animals, with swine being most sensitive. If ear rot is present, assume that mycotoxins also are present. The FDA has set advisory levels for deoxynivalenol in food and feed (Table 3).

Figure 2. *Gibberella ear rot.*

Head blight of wheat (head scab) – Like the corn disease Gibberella ear rot, this infection occurs during flowering when the weather is wet and humid. The clearest symptoms of the disease is the early bleaching of heads when healthy plants are still green. At harvest, diseased kernels are often shriveled, lightweight, and pinkish. Both deoxynivalenol and zearalenone will be found in the shriveled kernels, but mycotoxins are often found in kernels that appear healthy. The FDA has set advisory levels for deoxynivalenol in food and feed (Table 3).

Aspergillus ear rot – Caused by *Aspergillus flavus*, this disease commonly occurs during hot, dry years in fields under drought stress. Ear-invading insects also contribute to disease development. To identify the disease, peel back the husk and look for an olive-green fungus on the ears. The fungal spores, which are the olive-green material, will appear powdery and may disperse like dust when the husk is pulled back. Symptoms are mostly observed at the tip, but when the disease is severe, kernels all the way to the base of the ear can be infected (Figure 3). The mycotoxin, aflatoxin, will be found in grain with this disease. Aflatoxin is a potent liver toxin and carcinogen. The presence of aflatoxin will affect livestock health if the grain is consumed. Feeding aflatoxin-contaminated grain to dairy cattle is a concern because the mycotoxin will pass into the animals' milk. There are strict legal limits on the amount of aflatoxin in grain and milk products (Table 4).

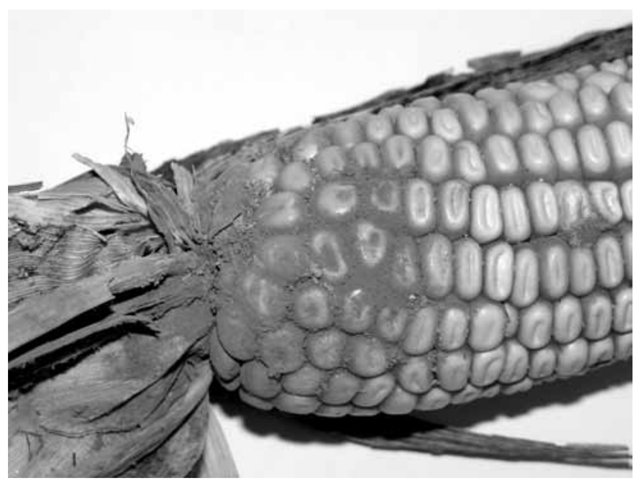

Figure 3. *Aspergillus ear rot.*

Table 3. *FDA advisory limits for deoxynivalenol.*

Deoxynivalenol/Vomitoxin	FDA Advisory Level
Humans (finished product)	1 ppm
Cattle and chickens (all grains, distillers grain)	10 ppm (not to exceed 50% of diet)
Swine (all grains and grain products)	5 ppm (not to exceed 20% of diet)

Source: U.S. Food and Drug Administration
http://www.fda.gov/Food/GuidanceComplianceRegulatoryInformation

Table 4. *Action levels established by the FDA for the use of aflatoxin-contaminated corn.*

Action Level (parts per billion)	Commodity
20 ppb	Corn for animal feed and feed ingredients intended for dairy animals
20 ppb	Corn for human consumption
100 ppb	Corn grain intended for breeding cattle, breeding swine, and mature poultry
200 ppb	Corn grain intended for finishing swine of 100 pounds or greater
300 ppb	Corn grain intended for finishing beef cattle

Source: U.S. Food and Drug Administration
http://www.fda.gov/Food/GuidanceComplianceRegulatoryInformation

Diplodia ear rot – The fungus, *Stenocarpella maydis,* causes this disease. Affected ears have grayish or grayish-brown fungus on and between the kernels and tan or brown kernels. With severe disease, the entire ear will be affected and will be very lightweight. Another diagnostic sign of the pathogen is the presence of small black specks, called pycnidia, which will be scattered on the husks, cobs, and sides of kernels (Figure 4). No major mycotoxins are associated with Diplodia ear rot.

Figure 4. *Diplodia ear rot.*

Storage Fungi

The distinction between field and storage fungi is based not on taxonomic classification, but rather on life habits. Storage fungi have adapted to grow well under dry conditions. Debris, such as dirt, chaff, and green tissues (pods and beans) are a reservoir for storage fungi and moisture. Although a few of the fungi from the field can grow under storage conditions, most will invade the grain after harvest. The fungi enter the grain through breaks in the seed coat caused by mechanical damage, insects, or preharvest diseases. Grain stored for only a few weeks at any combination of moisture content and temperature that permits even moderate invasion by storage fungi will be at high risk if kept in continued storage. Research has shown that grain moisture level will greatly influence the fungal species that can attack and grow on the grain (Sauer et al. 1992). Under the driest conditions, species such as *Aspergillus restrictus* and *A. glaucus* can grow. As the grain moisture rises to 16 to 18% in corn and 15 to 17% in soybeans, *Penicillium* species and even the aflatoxin-producer *A. flavus* can grow. All of these fungi can cause germ damage, mustiness, caking, and attract fungal feeding insects. Determination of what fungal species are on the stored grain requires laboratory examination and culturing, which may take several days to determine. Once storage fungi become established in the grain, they continue to develop at moisture and temperature levels below those required for the initial invasion of sound grain. Preventing them from infecting the grain is essential.

Blue-eye in corn – A common type of spoilage in corn, known as "blue-eye," often appears when the grain is not properly dried before storage. A blue-green line will appear on the surface of the germs, under the seed coat (Figure 5). The visible color is actually the spores of either an *Aspergillus* species or a *Penicillium* species, which has invaded the germ tissues. The spores are produced in that restricted area because the fungi are growing strictly in the germ tissues. A laboratory identification of the fungal species causing the blue-eye can provide information about why the damage occurred. In corn stored at about 20% moisture or more and temperatures of 41° to 50°F (5°to 10°C), these spore masses are often *Penicillium. Penicillium* blue-eye sometimes develops when whole ears (with cob) are stored. Some species of *Penicillium* produce the mycotoxin ochratoxin, a potent kidney toxin. Poultry are very sensitive to ochratoxin. In corn stored at moisture contents of about 14.5 to 15.5% and temperatures of 50° to 59°F (10° to 15°C) or higher, the spore masses are those of *Aspergillus restrictus* or *A. glaucus*.

Figure 5. *Blue-eye of corn.*

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7 Vertebrates in Stored Products

Stephen A. Kells

Rodents, birds, and other animals can be important pests in grain handling and food processing facilities. In addition to consuming products, they foul stored food with feces and bacteria and contaminate food processing equipment. Pests and infestation by-products can enter the food stream via equipment. They can damage structures and electronics and shorten the operational life of equipment.

Personnel can be injured when they accidentally corner or startle an animal. Rodents transmit diseases such as hantavirus, rat bite fever, lymphocytic chorio-meningitis (http://www.cdc.gov/rodents/diseases/direct.html), or rabies directly. Pathogens such as histoplasmosis can be transmitted indirectly in accumulated feces. Rodents and birds vector a wide range of bacteria that are responsible for foodborne illness (Craven et al. 2000, Liljebjelke et al. 2005), though infections are contingent upon improper food handling practices. Recent recalls linked to foodborne illness in eggs or peanuts have cited failures to control rodents or birds in the facility (Sun 2010).

Many health and food safety inspections focus on pests. Vertebrate pest activity or lapses in monitoring programs are easy to see, especially improperly maintained rat and mouse monitoring stations. Health inspectors have used these issues to gauge the adequacy of entire pest management and food safety programs.

Why Animals Are Present

Before discussing individual pests, it is important to highlight why pests might be present. Despite differences among rodents, birds, and other vertebrate pests, there are surprising similarities in why and how they infest grain handling and processing facilities. Understanding reasons vertebrate pests are present helps with decisions on how to remove or prevent them.

Food and water are the most obvious reasons birds and rodents are present around a facility. Spilled grain or food products, pooled water, and condensation attract pests. Resources that allow animals to thrive may exist on nearby properties, supporting the pest and acting as a dispersal point. For example, birds may use a nearby feedlot for food and water, then roost in a shed, on a grain bin, or inside an elevator. Pests such as mice and rats can enter a facility on an infested pallet.

With basic survival needs satisfied, animals search for shelter. A rodent infestation may start at nearby properties. Searching for food, rodents may find cracks or gaps that provide hiding places around the facility. Open doors or poor door seals permit entry into the facility itself. Birds may find sunny spots for daytime roosting or eaves, ledges, overhead conveyor, or utility corridors for shelter. Smaller birds such as sparrows use dense underbrush in forest understory to hide from predators. They find little difference between a natural forest cover and the artificial habitat created by bins, conveyors, and other industrial structures. The artificial habitat favors pest birds by limiting predators, providing clear sightlines, and making abundant food available in close to nesting sites. For mice and rats, grain storage and food processing facilities offer similarly suitable habitats with plenty of opportunities for survival, growth, and reproduction, while restricting natural predators.

The most common reason rodents and birds become a problem is failure to detect and respond to pest activity. Rats and mice prefer to avoid humans. In some cases, they may time activities when fewer humans are in the area, for example, in the evening or during shift changes. Usually the only early evidence of a rodent infestation is droppings. If fecal pellets are overlooked or ignored, the infestation will build until animals generate a complaint. By then rodents are established and require extensive efforts to remove them. Rodents found in the open usually are weaker or younger and not capable of fighting for better territory, so they are pushed to the margins of the hidden areas where they are more likely to be seen. Control tactics directed toward weaker and younger rat or mouse sightings often ignore the underlying source of the rodent infestation, which are the stronger mice or rats in hidden and more favorable habitats.

Birds also cause unforseen problems. Problems go unrecognized until birds enter the facility or feces begin to accumulate on the structure or equipment. By then, animal control procedures such as simple scaring tactics are unlikely to work because the birds must be directed to other food sources and roosting and nesting habitats. If alternate sites are in short supply, the birds will ignore scare tactics, and lethal means may be the only recourse. A bird present in a facility is exploring the area for food, water, and nesting sites. Finding these resources, a bird may call other birds to the area (through mating calls), or activity may be observed by other birds, which respond by flocking. As birds learn about the facility, numbers increase, and there is a greater chance of them entering. Predator avoidance and associative learning abilities help birds challenge facility defenses. They find new food or nesting sites within while avoiding human traffic.

The fact that humans appreciate birds in the natural environment complicates prevention and control tactics. Workers may not recognize that one or two birds in the area are actually searching the facility for resources. People tend to tolerate bird activity around facilities. In extreme cases, workers may interfere with bird control practices so they can enjoy bird activity in the area. Workers have moved traps so they become ineffective. In retail situations they have provided seed caches in quieter areas of the store. People have put food out to feed birds on sidewalks without realizing that most of the birds attracted are not native species, but species more likely to become a nuisance. Communicating with employees about the reasons for bird removal is important for early detection and successful control.

Early recognition of a problem can reduce efforts required to remove an infestation, which will avoid excessive costs and prevent damage to food products and equipment. Having employees trained to report rodent droppings or birds exploring the facility enables an earlier response and simpler control tactics. This type of training is often overlooked until animals invade the facility or there is a serious pest situation. After reviewing pests that can cause problems in grain handling and processing facilities, this chapter will look at why vertebrate pests infest facilities and how to prevent it.

Identification and Biology: Rodents and Similar Animals

Three rodent species typically cause the majority of problems in grain handling and processing facilities: the house mouse, the Norway rat, and the roof rat. Several other rodents and similar vertebrate animals may cause problems, but their presence usually is site- and location-specific. For these other animals, a brief summary of particular characteristics and behaviors that separate them from the three main pests will be provided.

House mouse

The house mouse is a small rodent weighing approximately ½ ounce and measuring 5 to 7 inches long (Figure 1). It is light brown to light grey along the back and lighter on the underside. Specific information about the reproductive ability of mice is available in the suggested readings section. It is sufficient to note that females mature within 6 to 10 weeks of birth and can produce 5 to 6 pups approximately every 20 days, with 5 to 10 litters per year. Short maturation time, and an ability to continuously produce offspring enables rapid infestation growth and quick recolonization after attempts have been made to control a mouse problem.

Mice are mainly grain eaters, but will supplement their diets with fat, meat products, insects, cereal, and vegetable-based products. This is an important consideration when planning control practices, as available food may interfere with infestation control. Also, the more complete the diet for a mouse (or any rodent) the faster they grow and reproduce. Mice do not require free water from pools, condensation or leaking taps, but they will drink readily if any of these sources are provided. Even without water, mice are efficient at obtaining water from food. Addition of fats to their diet will help them gain water when free water is scarce.

Mice and rats are territorial, with alpha males and females being strongest in the population and maintaining or defending the best locations for resources within a structure. Weaker members (betas) and weaker still (omegas) fill in the lesser territories or exist in the marginal territories. Territories are established by families of mice using pheromones deposited in the urine (Hurst and Beynon 2004). Repeated depositions of urine in specific locations result in a build-up of urine salts into pillars as the water evaporates. Such pillars will indicate a long-term sustained infestation. From a control perspective, dealing with a territorial animal means that not all individuals may be exposed to the control methods, and control practices must be planned over the long-term and in adjacent areas to ensure complete and lasting control. Further, territories may shift as new mice move into previously inhabited territories.

Norway and roof rats

The Norway rat is the most prevalent rat species in North America, with the roof rat (or black rat) prevalent in port cities, particularly along coastal regions of North America (Figure 1). Both rat species are larger than mice, with the adult Norway rat weighing approximately 16 oz. and the roof rat 10 oz. Juvenile rats may look like adult mice, but their proportional body size is different; for example, the feet, eyes, and ears can be of larger proportion compared to their body. They might look like big-footed mice as their body attempts to catch up in size with their feet. Reproductive capacity of the rats is slightly less than the house mouse, with Norway rats having 4 to 6 litters per year (6 to 12 pups per litter), while roof rats have 3 or more litters per year and 5 to 8 per litter.

The roof rat is slightly smaller and has a more sleek appearance compared to the Norway rat. The difference between roof rats and Norway rats lies in the length of the tail. A roof rat's tail will be longer than its body. Also, the tail will tend to be held off the ground. Roof rats can appear in interior cities away from port cities; these interior cities usually have distribution facilities catering to incoming goods from overseas or from places endemic with roof rats. In areas unaccustomed to roof rat infestations, they may be detected when usual rodent control practices fail and the rat seems to display odd behavior, such as

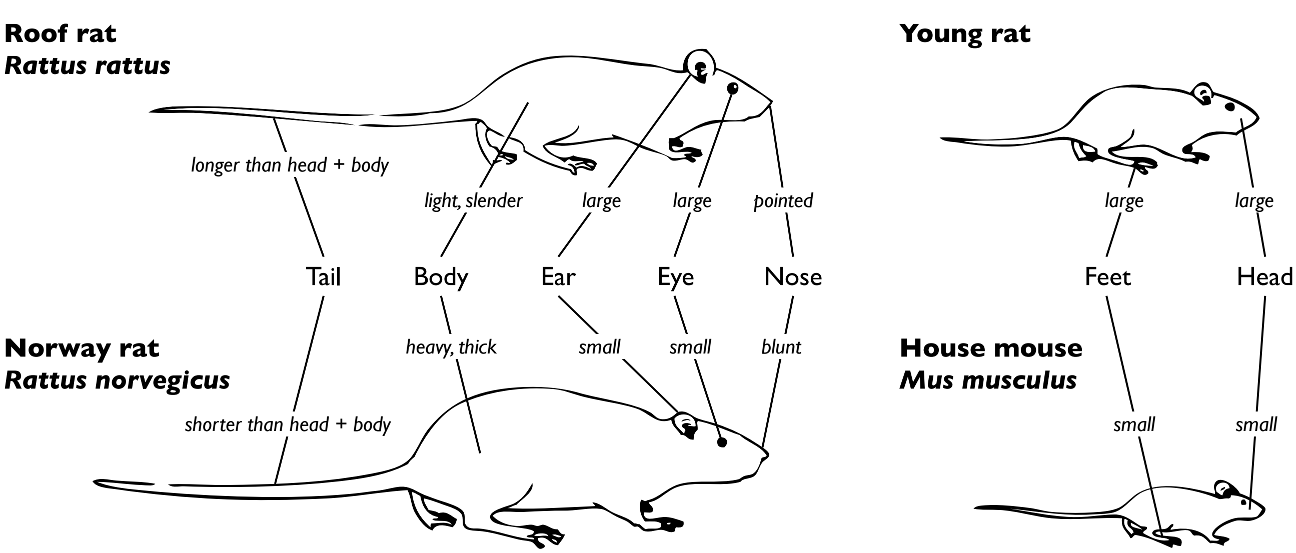

Figure 1. *Characteristics of commensal rodents (source: U.S. Dept. of Health and Human Services Centers for Disease Control).*

residing in elevated areas with little or no on-ground signs of infestation. Signs of rat activity, such as droppings and rub marks, occur in ceiling areas. Also, the rat activity may continue even though on-ground traps and devices remain untouched or avoided.

Norway rats tend to burrow in the ground for primary nesting sites and may den along the edges of concrete. Burrows and rub marks are key signs of an infestation. Burrows and other signs often are overlooked until live animals become evident. Similar to mice, rats are territorial, though home ranges tend to be larger than those of the house mouse, depending on food availability. In addition to their subtlety, signs of infestation may be spread over distances and might not be noticeable as compared to mice.

Similar to mice, rats are omnivorous. Diet can be cereal-based with some bias for meat products by the Norway rat, while roof rats have a bias for fruit and nuts. Any differences in diet are associated with the original home range of these animals: the Norway rat being ground dwelling and the squirrel-like roof rat being more arboreal (found above the ground in trees). Being omnivorous provides flexibility in food resources being used, and knowing what foods they are currently exploiting will be important when planning control.

Other mammals

An assortment of other rodents and rodent-like animals can cause trouble in grain storage and processing facilities. Usually these animals have a more obvious appearance, and it is better to contract control procedures with an experienced pest management provider or wildlife control specialist. These animals usually are present for the same reasons as the house mouse and the two rat species — availability of food and a suitable place to nest or den. Below are some key observations to consider when encountering these animals in a pest situation. Further information is available in the suggested readings.

Deer mice – Deer mice (and white-footed mice) are a similar species to house mice, but this mouse has a white underside, even along its tail, and white feet. Deer mice tend to have larger eyes and ears in proportion to their heads compared to house mice. Deer mice are quiet nesters, preferring nesting sites in less disturbed areas of a facility, usually close to the exterior building perimeter. Nests are usually in cabinets, drawers, and derelict machinery, or storage buildings at a distance from the main processing facility. Abandoned nests usually are fouled with feces and urine. Care must be taken when dealing with deer mice and their nesting material as the deer mice are a reservoir for hantavirus.

Tree squirrels – Besides their obvious appearance, tree squirrels are slightly larger than rats, with large bushy tails. Feces tend to be more rounded and less pellet-shaped. Squirrels may den inside a building, but most foraging activities will occur around the facility's exterior. In one case, a squirrel caused damage to cardboard packaging because the warehouse had considerable exclusion issues, and this animal readily entered the building.

Gophers – Otherwise known as ground squirrels (several species) are found in the upper Midwest and western states. Gophers have communal nests and form gopher towns. In these towns, gophers often can be found crouching or sitting up as lookouts. Care should be taken with control because large gopher towns may be co-habited by burrowing owls or the black-footed ferret. Both species are threatened and/or protected. In some states, gophers are considered reservoirs of plague.

Nutria – Considered "monster rats," these animals often are associated with waterways and coastal areas. No damage to food facilities has been reported, but their presence close to a facility and associated foraging may be of concern. Denning behavior may weaken levees and embankments of retention ponds.

Wood rats or pack rats – Occasionally in western areas, a rat will be found that is similar in appearance to the Norway rat, but with a hairy tail, less coarse fur, and larger ears. Wood rats are largely pests in agricultural situations and may periodically appear around grain-handling or food-processing structures. Caution should be taken when handling these rodents in plague endemic areas.

Beavers – When these large rodents are present, they may be observed denning into banks of waterways or damming nearby creeks, which results in flooding. This large rodent has a flat tail and a tendency to remove saplings from properties for a food source.

Muskrats – Occasionally, a large "rat" will be seen on the fringe of a facility or running across a road or parking lot from one body of water to another. However this animal does not attempt to enter a facility. Checking waterways, a rat-sized animal may be seen swimming low in the water with its head above, ripples from its hind legs and tail, and a large "v" spreading out as it moves through the water. In the fall, muskrats prey on ducks or other geese. Muskrat feces look like deformed pellets. Damage is similar to nutria in that muskrats may weaken improperly built embankments.

Groundhogs or woodchucks – Groundhogs are very large land rodents, approaching the size of beavers. They are found in Eastern to Midwestern states. Groundhogs usually create large burrows with much dirt excavated and mounded outside the mouth of the den. While burrowing behavior may affect foundations, concrete, or paved slabs, most concern is from the appearance of the den itself near a facility.

Skunks – Skunks are carnivores and not rodents. Occasionally they will den under buildings or pavement areas. Nocturnal in nature, skunks are black and white, and these markings can be striped or spotted. Active or recent dens have a characteristic musky odor. Skunks mainly feed on insects and grubs. In addition to being a reservoir for rabies, the greatest risk around food processing and storage facilities is safety, particularly of night-shift workers who might accidentally startle a skunk that has decided to forage around a garbage receptacle.

Raccoons – Raccoons have distinctive markings on their faces, with a black band of fur across their eyes. Raccoons are predators but can be very effective scavengers, taking advantage of garbage or handouts from people. Sometimes workers will inappropriately adopt a feral raccoon as a local pet through regular feeding. Raccoons generally are nocturnal in nature, depending on human activity and food availability. They can display aggressiveness toward people, especially when cornered. The raccoon is a potential rabies reservoir, and raccoon roundworms — an intestinal parasite that is shed in their feces — can be harmful to humans. Unfortunately, the eggs of this parasite are resilient to typical control practices, and cleanup must be very thorough.

Identification and Biology: Birds

Many species of birds may cause problems in and around facilities, depending on the region and availability of food, water, and nesting or roosting sites. In North America there are three nonmigratory bird species that are a problem around facilities. None of these species is native to this continent, but all were transported via human activity. Several migratory species also can become a problem, but the chances of infestation are less and generally confined to special circumstances. The majority of descriptions will be limited to the main three pests — English sparrows, starlings, and pigeons — and will provide an appreciation of how birds successfully use facilities. The remaining species will be mentioned with a few comments about how they may use facilities differently from the main three pest birds.

English sparrows

English sparrows are small birds about 5¾ inches (14 cm) in length. The male has a distinctive black patch under the beak and white patches on the sides of the lower head and neck. The top of the head is grey and there is a red-brown stripe behind the eyes that separates the white patches from the grey. The female is less distinctive, having a tan stripe along the head and just above the eye. The female also has a tan underside and mottled streaks of tan, red-brown, and dark brown. Unless an experienced bird watcher assists with control efforts, it is best to rely on the male coloration for a proper identification. The female English sparrow is easily confused with other sparrow species.

English sparrows become a problem where there is spilled grain, seed, or other grain products such as bread and animal feed. In urban areas, sparrows may rely on open garbage containers and handouts from people. They have been observed picking insects from the radiator grilles of parked cars and areas under light fixtures where insects have collected overnight. Sparrows will scavenge in food service areas, waiting until human traffic is low before darting in and foraging for food scraps.

Nesting sites suitable for sparrows vary and can include commercial signs, overhead furnaces, HVAC systems, seldom-used rooms and attics, and gaps under gutters or in sheet metal construction. In keeping with their normal habitat in dense forested areas, sparrows will use dense foliage as cover for nesting. They also may use dense foliage as transitional sites as they move between feeding and nesting sites.

Sparrows have the ability to learn human activity and then pattern their behavior so they avoid people in the area. They are able to learn relatively complex patterns; for example, if a facility has doors that open automatically, sparrows can learn how to move through the sensor field to activate the door. Depending on the speed of the door opening or the delay, sparrows may briefly land on adjacent shelving, then enter, or may flutter briefly in the air before proceeding. In one instance during a bird removal procedure, the birds learned to associate a dangerous situation with the color of clothes that a pest control technician was wearing. After unsuccessful attempts with a high velocity pellet rifle, whenever the technician subsequently entered the room, the birds hid and only resumed normal activity when the person left. Having the pest control technician use a lab coat that was similar to that worn by other employees resulted in the birds resuming their normal behaviors.

Birds will change their behaviors when they detect that something or someone is observing them. This type of behavior sometimes requires setting up a blind or looking indirectly at the bird; for example, having observers face someone but keep track of the bird in their peripheral vision. With the potential for birds to exhibit such learning and predator-avoidance behavior, control procedures require multiple observations to establish their daily behavior. The observer must be aware that these observations may trigger avoidance behaviors.

Starlings

The starling is larger than a sparrow — about the size of a robin (approximately 9 inches or 22 cm). Starlings are dark brown with light speckling, and males may have an iridescent green sheen on their heads. From January through June, both male and female starlings have yellow beaks.

During the summer, starlings occur in small groups, unless a particular site has an abundance of food. They may take advantage of a wide variety of food items, such as small or broken grains, pet food, garbage in urban areas, and spilled food from restaurants. They will occasionally raid nests of smaller birds if the nest is accessible to them.

As fall progresses, starlings aggregate into larger flocks-continuing to search for food but also looking for facilities that may provide heat refuges and shelter. Heat refuges are areas of buildings that give off heat, such as HVAC systems, steam vents, chimneys, poorly insulated roofs, and pollution control structures. These heat refugia will help the birds survive cold nights. Some flocks can become quite large and number more than a half-million birds. With large flocks, the movement of birds toward an evening roost can be quite impressive. In one case, a large flock of birds started moving back to a night roost at 4:30 p.m., and the constant streams of incoming birds did not stop until well after dusk (about 3 hours later). When a large flock finds a facility, feces accumulation can be quite impressive, resulting in 6 to 10 inches of feces per night coating equipment and walkways. Starling prevention and control procedures early in the fall are necessary to avoid larger populations in late- fall or winter. Previously infested sites should begin planning prevention procedures during the summer.

Pigeons

At approximately 11 inches (28 cm) in length, pigeons are larger than starlings and are mostly blue-gray with white on the underside. Their coloration can vary from gray to tan to mostly white. Males may have a green hue on the head and neck. When gliding, their wing tips are raised. Standing near them at take-off, one can hear a clicking sound as the wing-tips contact at the top and bottom of the stroke. Pigeons typically roost on ledges, but can be seen on large diameter cables.

Pigeons will eat whole grains, particularly corn and large grains. They will readily take handouts and search for other grain-based foods or vegetable material. Around large food processing plants, food spillage is a concern, but so are refuse management policies and employee training to ensure the birds are not receiving handouts.

Pigeons often have several types of roosts depending on what the area offers and the presence of predators, such as hawks or falcons. Careful observation may be required because their presence on a loafing roost may be different from a nesting or feeding site. The birds may use multiple loafing or feeding sites. Damage may occur in all three types of sites, depending on the number of birds. Some of these sites may be on adjacent properties or at a distance to the affected property; sometimes control requires a community-level response.

Other birds

Several species may cause problems with grain storage and processing facilities, and usually these birds have some type of gregarious behavior during their lifetime. For example, gulls or sparrows nesting in large colonies during the spring and summer; Canada geese foraging during summer molt; or crows flocking to a winter heat refuge for warmth. It is a matter of location and resource availability with the affected site. Facilities with flat roofs near lakes or ocean may have to contend with gulls. Geese or other waterfowl may take advantage of ponds and slow-moving rivers, where nearby grass is tender, and handouts from people are plentiful. There may be particular opportunities for combinations of food, nesting, or refugia sites that encourage bird activity. Crows (or starlings) may identify a night roost where much heat is released and in proximity to urban areas with abundant food. Sheltered sections of walls that are constructed of rough materials may encourage swallow nesting, particularly where fields have areas of clear sightlines and abundant flying insects.

When dealing with a control situation involving these other species, it is important to verify the status of the birds with state and federal wildlife officials. These birds may be protected, and depredation permits may be required before attempting control procedures. Most protected birds may be harassed by nonlethal measures as long as they have not produced eggs in a nest. There also may be local bird sanctuary bylaws that must be considered. Confirming the status of a bird with the state department of natural resources (or equivalent) is the best way to avoid issues with protected birds.

Prevention Procedures Against Vertebrate Pests

Prevention of a pest problem is the best way to avoid unexpected costs and damage caused by infestations of vertebrate pests. Prevention practices make control procedures simpler, reduce the number of pest incidences, and lessen the size and complexity of an infestation. Prevention practices are sometimes difficult to budget because they usually are planned over a longer term, and the value of the practices might not be immediately realized. To avoid major problems with vertebrate pests, six basic practices can be used. Depending on the facility and the pests encountered, one or several of these practices will help avoid vertebrate infestations.

Reviewing past documentation

The phrase "*those who ignore history are doomed to repeat it*" applies well to preventing pest infestation. Previous rodent infestations leave feces and urine spots that can help a new infestation become established. Birds may remember the location of resources or continually search an area, looking for the reoccurrence of food or harborage that previously helped them survive. Monitoring and control procedures will have documentation as a record of past infestations or sightings of animals. Using this documentation will help direct other prevention procedures to maintain a pest-free facility. This documentation is critical for timing procedures that can encourage birds to move on instead of attempting to depopulate an established infestation. Pest management documentation may help minimize costs by revealing the areas of a facility that required additional work or practices that may not have been effective. Knowledge of the facility, past experiences, employee reports, and documentation will help to determine where and when to conduct inspections.

Inspections for animals, droppings, or damage

Periodic inspections of the facility or the grounds will detect pests earlier, when infestations are smaller and more easily addressed. During an inspection for vertebrate animals, the inspector should look for the presence of the animals, evidence of pest activities, and the presence of conditions that would give animals a reason to arrive and reside in the area. Knowing what to look for and where to look is often the challenge for inspectors.

Live rodents may be difficult to detect because of their tendency to remain hidden, but they produce and distribute fecal pellets in areas where they are moving. Evidence of gnawing behavior and rub-marks will be evident long before seeing live rodents. Repeated movement of rodents in areas will cause these rub-marks when dirt and oils rub off the animals' coats and onto surfaces. An inspection for rodents should be conducted at least monthly in a grain storage or processing facility and more frequently if the facility has had previous issues with rodent activity.

Birds are more easily recognized because of their movement and songs, but they still require careful observation to determine where they are feeding and roosting. Individual birds may be just challenging the facility or they may have found materials that enable them to stay in the area. Bird droppings on and around a building indicate where inspectors should revisit during the day to observe if and why the birds are present.

Sanitation and exclusion

Grain handling and processing facilities are complex places, offering many potential opportunities for vertebrate pests. Sanitation reduces food and water availability to rodents and birds. Removing spilled grain and regrading areas to prevent pooling of water are obvious sanitation measures to prevent the initial advancement of these pests onto the grounds and around the buildings. Preventing accumulation of old equipment is another sanitation measure that denies pests hiding places next to buildings where they can continue their search for food and water. Having animals search for food and finding nothing is the best scenario, but often one that is not readily achievable. Making the food source unpredictable by cleaning up spills will force animals to search elsewhere. A worst-case scenario is one of constant and regular spillage that animals become accustomed to finding. Once there is a predictable food source, animals will change their behavior and search for shelter to make their travels easier with less energy expended to use these predictable food sites.

Exclusion is the practice of denying pests entry into areas of the facility. The classic examples include keeping doors closed and seals maintained to prevent rodents and birds from entering buildings. Many materials are available to help with exclusion, depending on the problem found and the pests of concern. Sheet metal, latex concrete patch, sealant material, metal screening, or chicken wire are items that can deny pests entry. Holes of ¼ inch or larger will permit mice to enter a facility, whereas larger rodents such as rats require ¾ inch. Use of inspections and reports of rodent activity helps to locate places where they might enter. Prevention practices should be discussed with a pest management professional who is experienced with prevention methods. If the facility is large, include personnel from facilities maintenance or engineering to ensure these practices are compatible with facility operation. Based on records of previous pest activity, routine pest exclusion, inspection, and repair can be concentrated during one to three time periods in a year. Scheduling exclusion activities makes building repairs and alterations more efficient as training, equipment, and installation practices can be scheduled within the same period.

Exclusion of birds can be more involved because of their potential to learn and tendency to change their behavior when they are aware that they are being observed. Also, exclusion procedures in one area may move birds to another part of the facility. Birds will have nesting sites, feed sites, and roosting sites. They may have transitional or observation roosts where they sit briefly between moving from one site to another. For example, they may briefly sit in a particular location after leaving a feeding site and before moving to a nesting site. Exclusion of the transitional site may not be effective in controlling a bird's use of the area. Review past activity and discuss plans with people who understand bird biology and facility operation.

Monitoring of pest activity via traps and bait stations

Rodents are very secretive, and sometimes it is difficult to detect rodent activity by inspections alone. Also, some areas in the facility will be more prone to rodent activity. Use of traps or bait stations will help detect activities while preventing rodents from gaining access to the facility. Four devices used to intercept rodents include multiple-catch mousetraps, snap traps, glueboards, and bait stations. Multiple-catch mousetraps often contain a glueboard on the inside and are termed mouse and monitoring traps (MMTs) because the traps monitor for arthropod activity in addition to limiting mouse movement within the trap.

Monitoring devices typically are placed on either side of entry doors and along walls of a facility. The number of devices in a facility often is a major question, and trap densities may be as much as one trap on either side of every door and spaced every 25 to 100 feet for interior placements and 50 to 200 feet for exterior placements. Device spacing will largely depend on previous rodent activity in the facility, the potential for rodents to explore the facility grounds, opportunities offered by the facility for food and harborage, and the thoroughness of routine inspections. In a recent study involving distribution warehouses in a retail chain, the removal of nonproductive rodent monitoring devices (and the time spent servicing these devices) permitted an increase in the amount of inspection time for the program in more active areas. This change expanded the rodent monitoring program to other areas where trap monitoring was impractical. In this program, traps were removed from areas where rodent activity was documented as nonexistent. While this work showed promise for improving rodent prevention programs in large facilities, current food safety programs and auditors may have their own standards for device placement.

In regard to device placement, rodent trap monitoring and control by traps are two different activities. Trap stations at set distances around the facility represents a monitoring activity, not a control activity. Once mouse activity is detected in monitoring traps it is important to conduct an inspection in the area and determine if additional traps are required. To ensure trap-out of a population, often 5 to 100 times more traps must be placed in the area to provide quick control.

For mice, all four devices work well, and device selection will depend on location and cost. In North America, bait stations are typically used on the exterior perimeter of buildings, and traps are used inside buildings. Traps can be used around the exterior, especially in areas where the facility is close to residential areas or if the facility management perceives an unacceptable risk of placing exterior bait stations. Exterior-placed traps may require more maintenance to ensure that they continue to work. Snap traps cost less than multiple-catch mouse traps, but are limited in the number they catch. MMTs reset themselves, so there is a greater chance of collecting more than one mouse.

Glue boards tend to be least expensive of the four device types, and often are used as supplemental monitoring points in between established MMT sites. There is a tendency to overuse glue boards without properly placing them to maximize mouse capture. Devices such as glue boards capture inexperienced or territorially stressed rodents where they are in large populations, but glue traps have limitations for experienced or more careful rodents. Glue boards should be placed in such a manner that channels movement of mice across the sticky surface, and decreases the opportunity for mice to skirt around this surface. Also, glue boards have limited use as monitors in dusty conditions.

There are fewer device types available for monitoring rats. Bait stations can be used around the exterior of a facility, and rat activity can be determined by the size of the incisor marks on bait blocks. Inside facilities, rat monitoring requires the use of nontoxic bait. One method is to use a bait station with nontoxic bait and unset traps to which the rat can become accustomed. Recent advances with bait ingredients, including fluorescent or colored dyes that are transferred to the fecal pellets, improve inspection capabilities and placement of additional traps to ensure traps are positioned within the rodent's entire home range. These products work with mice as well. The use of traps for monitoring rats is limited, as pre-baiting usually is required. Pre-baiting involves leaving traps unset, but baited so the rat will become accustomed to the trap. The trap is then periodically set once rat activity has been detected. This process is involved, but can be quite effective, especially if there are concerns about rats becoming trap-shy.

Device monitoring of birds is not practical, and therefore careful visual inspections are essential. Birds usually are quite visible, and with some initial training, workers can be asked to report birds they see perching on equipment or foraging around the structure for food or nesting material. Once comfortable with their surroundings, sparrows and other birds will begin calling, and their birdsong is an initial indication that a bird may be using the area and not just passing through. Devices to trap or bait birds will be discussed in the next section.

Control of Vertebrate Pests

There is no sure method for control of vertebrate pests, but there are a number of tactics that can be used to remove or disperse animals from the site. Quite often, failure to gain control of a vertebrate is a result of underestimating the size or complexity of the infestation. Following is a summary of common control measures used in and around grain storage and food processing facilities, as well as comments and observations on the use of these strategies. These practices are the typical responses for removal of an infestation from grain and food facilities. For a complete list of control tactics or for control of other vertebrate pests not mentioned, consult the suggested reading list.

Traps for controlling vertebrate pests

Traps are devices that hold or contain the vertebrate pest until such time that it can be removed from the facility. A number of devices are available for rodents including snap traps, glue boards, multiple-catch mouse traps, and cage traps. For larger animals, particularly skunks and raccoons, cage traps that hold living animals often are used because of the chance that nontarget animals (e.g., cats or dogs) may visit the trap. Cage traps are available and work well for birds such as sparrows and pigeons, provided they are deployed properly. Due to the urgent requirement to eliminate bird activity inside food storage or processing facilities, intercept traps in the form of mist nets may be used. Understanding animals' behaviors, movements, and biological needs is important to establish control. Regardless of the target pest, animal trapping is an active practice, not a set-it-and-forget-it scenario.

Trapping works well for many animals as long as traps are appropriately placed and enough traps are used. Most important for trapping success is that traps are placed within the normal travel range of the animal, the animal learns to identify the site as a feeding location, and enough traps are placed in the area to allow for a high probability that traps will be encountered. When trapping larger vertebrate animals such as skunks, only a few traps are required, but these traps are placed close to the den or across identified pathways the animal is using. For rats and mice, multiple trap placements are preferred, as the number of rodents and travel paths may not be as well defined. Depending on the situation and the extent and severity of the infestation, traps for rodents may number in the tens, hundreds, or thousands. Bird trapping requires a pre-baiting period to get the animal accustomed to feeding at a site that is convenient (and safe) both for the bird and the worker placing the traps. If birds identify a feeding area as suitable, only one to three traps may be required.

Pre-baiting is often necessary to avoid trap-wary or trap-shy rodents and birds. Pre-baiting is the practice of providing food in areas or on unset traps to encourage birds or rodents to become accustomed to and comfortable with the resources provided. Once they have become reliant, then traps can be set to capture the pest. Pre-baiting is critical with many animals that may cautiously approach new items in their habitat. Animals of particular concern for trap shyness include rats, skunks (and similar wildlife), and sparrows. Even mice may require a period where traps are baited but unset. For mice, this may be required after the initial trapping period when the majority of mice have been removed and a final one or two experienced and cautious mice are left. Clear communication is essential when leaving traps unset for a period of time. In one case, rattraps were distributed in a warehouse and left unset for the rat to become accustomed to their presence. An area manager became frustrated seeing all these traps sitting around unset. This manager then arranged for premature activation of these traps, which led to a trap shy rat (as rat hairs were found in a sprung trap). At this point, the only way to remove this rat was to use liquid bait as talcum tracking powder, which showed the rat clearly avoiding all snap traps. This was a costly mistake that lead to prolonged rat activity in the warehouse.

Additional measures that encourage the use of traps for birds that exhibit flocking behavior include the use of live decoy animals. Leaving an individual bird in the trap will encourage others to land near the trap and enter. For this method to work, the bird should be content and have access to food, water, and some measure of shelter from the elements if the trap is outside. The bird must be as comfortable as possible so song and calling reflect an unstressed bird.

When conducting live trapping and release of animals, it is important to consider if live-released animals will become adapted to the trap. This occurs when the trapped animal, perhaps a sparrow inside a retail center, receives a meal and water, then is released outside the building. The animals will associate temporary confinement with food and water as a way of obtaining a meal. They will come to rely on these devices knowing that, despite some brief inconvenience, they will be well fed and watered. For most birds, such as pigeons and sparrows, and rodents such as squirrels, live release may be attempted. In many cases lethal measures are necessary to prevent animals from routinely using traps as a food and water source. Such lethal measures may include a euthanization chamber (with carbon dioxide), shooting, lethal injection, or cervical dislocation (for birds). Check with local authorities to develop a euthanization management plan.

When conducting live trapping and release at a distance from the facility, careful consideration must be given to where the animal will be released. For example, pigeon release is impractical because birds must be transported more than 50 miles (approximately 80 km) from the trapping site (Williams and Corrigan 1994). Other animals may have restrictions on release; for example, raccoon release is a problem in Ontario, Canada, due to restrictions for preventing the spread of raccoon rabies. Release of trapped animals into other areas may put the animal into a place that is resource poor, into the territory of another animal, or close to another place where it can create a pest situation. With the exception of protected animals and birds, humane lethal measures are usually the best way to handle a pest animal.

Animal removal

In the pest control industry, the term "animal removal" often refers to the active removal of animals in an urgent or critical situation. Examples of this type of situation include raccoons, bats, or birds that have managed to enter a food processing facility or similar building. Restraint measures such as mist nets, capture poles, tongs, or a net or trap in conjunction with a scaring tactic may be used. Firearms are included in this section, and in food storage and processing facilities are usually limited to a quality small caliber (0.177 or 0.22) pellet rifle with a scope. Care must be taken so that galvanized roofing surfaces are not dented by stray pellets, or that stray pellets fall into exposed food streams. Special training and preparations are required before such equipment is used.

Local laws restricting the use of firearms within cities or jurisdictions, and federal or state laws pertaining to the removal of certain protected species may exist. For example, with the exception of English sparrows, starlings and pigeons, most bird species are protected under the Migratory Bird Treaty Act [(16 U.S.C. 703-712), 50 CFR 21]. Lethal removal or nest disruption of protected animals requires a depredation permit from the U.S. Fish and Wildlife Service and the state department of natural resources or equivalent jurisdictional office (www.fws.gov/forms/3-200-13.pdf). Also, animal removal requires coordination of company administration and employees to make sure the area is clear and secure.

Fumigation or heat treatments

Fumigation or heat treatments against rodents and birds in facilities are generally impractical, unless the treatment is primarily directed at insect pests as well. Fumigation of materials in trailers or shipping containers is a more realistic control method, though pest damage to foodstuff might be so severe that the contents of the trailer have to be discarded. Old or derelict equipment may be tented and fumigated if it is infested with rodents and moving the equipment would result in a large dispersal event. Fumigants are available for control of burrowing rodents, but there have been recent changes to labels regarding the use of burrow fumigants in proximity to structures.

Lethal baiting

A number of toxic baits and nontoxic pre-baits are on the market for removing animals from an infestation site or for preventing infestations in the first place. These baits are usually associated with food or water sources the animal prefers and contain lethal active ingredient. Such lethal active ingredients for rodents include anticoagulants that stop blood clotting, leading to internal hemorrhaging, a respiration inhibitor that stops cells from being able to product energy, and a vitamin D analogue that causes over-release of calcium in the body.

Bird toxicants are more diverse and include the following: DRC1339 (3-chloro-p-toluidine HCl), a kidney function disrupter; Avitrol (4-aminopyridine), a neurotoxicant; Ovotrol (nicarbazin), essentially birth control for pigeons that prevents egg fertilization; and alpha-chloralose, a compound that causes inactivity and easy capture. Avitrol acts also as a dispersant, as unaffected birds flee when observing a convulsing bird in their flock. Use of these products requires special considerations around grain handling and food processing facilities. The main consideration with rodents refers to reducing the risk of bait translocation. With birds, it is ensuring that an effective dose and proper management of affected birds has been taken into account.

All of these lethal products are regulated by the Federal Insecticide, Fungicide and Rodenticide Act, but some of these products have additional use restrictions. Recent label changes in the use of some rodenticides — particularly for use at a distance from facilities — and personnel authorized to use rodenticides can be verified by consulting the product label.

In some jurisdictions, toxicant use may be prohibited because of protected species in the affected area. For example, pigeon baiting with Avitrol may be prohibited if raptors such as the Peregrine falcon are using a pigeon flock as a food source. Some activities and formulations, such as those containing DRC-1339, may be restricted for use by only federal wildlife control personnel (USDA-APHIS-Wildlife Services) because these control methods hold a special label for certain uses. In other cases local laws or the risk of liability may restrict the use of some products, particularly avicides. An example would be the use of Avitrol around grain and food handling facilities that are close to residential areas. While Avitrol is a humane treatment against pigeons (Roswell et al. 1979), the appearance of convulsing birds in a schoolyard or residential area could be alarming.

Similar to trapping procedures, pre-baiting is an important activity. As mentioned for rodents, pre-baiting is usually employed as a means of monitoring, especially using those products that change the color of fecal pellets or have components that cause pellets to fluoresce. Nontoxic pre-baiting is not usually required to promote bait acceptance by rodents, because the modern and available active ingredients usually require only single-feeding and/or do not provide an immediate toxic response that would promote bait shyness. The use of non-toxic products is useful around facilities where there is a perceived risk to nontarget animals in the area or a risk that bait stations may be tampered with or stolen. Lethal products can be added for a short period when feeding at stations has been detected, minimizing risks.

Pre-baiting for bird control is especially critical for ensuring success. Birds must identify and become reliant on the baiting site as a feeding site and become accustomed to consuming enough bait, if baiting is to be effective. Pre-baiting also provides a method to monitor feeding behavior of the birds and how they will accept the bait, as well as monitoring to see if there are nontarget birds feeding at the site. In an interesting case where DRC-1339 was used to bait starlings at a power plant, birds readily accepted the pre-bait. When the toxic bait was used, birds avoided the bait trays. It is probable that the birds could taste the difference and avoided the traps after a few birds sampled the toxic bait. Several pre-baiting cycles interspersed with toxic bait helped ascertain that toxic bait was not being accepted at the currently formulated rate. It was likely that the birds were utilizing other areas for feeding and the bait trays placed at the night roosts represented a food source that was optional to most birds in the flock. In this case, different procedures were required to provide satisfactory control.

Deterrents Against Vertebrate Pest Activity

Deterrents are chemicals or devices that interrupt normal behavior of the animal, remove a resource the animal may have been using, or encourage the animal to seek other areas away from the site where it created a pest condition. Technically, sanitation and exclusion practices could be included in this category. This section will focus on supplementary or alternative items and practices that can be used along with basic practices of denying food and repairing building features that might encourage pest behavior. These other deterrents can be used when sanitation and exclusion are not enough or not practical to affect pest populations.

Several deterrents are available for use against birds, but comparatively fewer against rodents and other animals. This is in part because other practices (i.e., traps, baits, and lethal measures) work very well against rats and mice and other nonflying animals. From a prevention and control standpoint, nonflying animals have fewer choices than birds, which have more flexibility in building habitats, capability to use off-site areas, and resources. Because nonavian wildlife and rodents are less mobile, there is a tendency for them to challenge, ignore, or circumvent deterrents to stay in an area. This is not to imply that deterrents are ineffective against all mammalian pests, as individual animals or small groups of animals may easily be encouraged to relocate away from the site where they are being pests. For example: deer may move from a site through the use of feeding deterrents or scaring; a beaver family may move if there are deterrents to successfully completing a dam; or voles will forage elsewhere if trees and bushes are denied them by using physical deterrents such as fencing. The labor involved in installing and maintaining deterrent devices may be substantial. Allocation of effort to lethal measures might be more effective in cases where it would be difficult for pests to relocate, where they would have to contend with territorial conflicts during their move, or where they would create problems on adjacent properties and continue to be a source of future infestations on the original site.

In addition to disrupting movement abilities, deterrent products have been successful when dealing with pest birds in situations with legal and public relations issues. Although the main three pests — English sparrows, starlings, and pigeons — are not protected, other species are protected and require depredation permits. By the time a pest situation has been reported, birds are usually committed to the site or have active nests with viable eggs, requiring approval for lethal measures by the U.S. Fish and Wildlife Service and the state department of natural resources or equivalent.

Sometimes people appreciate bird activity around their spaces. This has been taken to the extreme when humans open bags of bird food in retail facilities to "help the sparrows living inside buildings," or provide food for birds on sidewalks or rooftops. Among the complications associated with trapping are that people sometimes open traps to release birds, or complain that the birds are being mistreated, even though humane trapping standards are employed. These complications are minor compared to managing collection and disposal of affected birds during lethal baiting procedures, which often lead to public relations issues, particularly if there is a residential area nearby and baited birds are able to fly to a highly visible area.

The following are common types of deterrents available for moving birds and other animals from using a site or preventing them from using a site:

Frightening

Frightening animals relies on the premise of predator avoidance and includes devices that simulate imagery of a predator in the area or create noise and flashes. Pyrotechnics such as propane cannons can be set up to ignite an explosive mixture, resulting in a sound similar to that of a gun or cannon. Pyrotechnic pistols, similar to starter pistols, can launch additional noise or flash/bang cartridges that are also available. These types of pyrotechnics can result in near-simultaneous disturbances at two places relative to the bird activity: one noise at the launch site and a secondary (much larger noise) closer to the animals or seemingly from another direction. Another audio deterrent is the use of recorded sounds that simulate birds in distress, barking dogs, and other threatening noises. The latest audio deterrents may be quite complicated, using high quality sound equipment, timing, and motion-sensing equipment. These newer devices deliver a deterrent sound that is more realistic and less predictable to the animals.

Other devices provide a visual deterrent that is less disruptive to nontarget animals and people. "Big-eyed" balloons are a common device, but models of predators and live predators (dogs and falconry) have been used to move animals away from pest situations. Some mechanisms are simple — such as shiny streamers of mylar — while others are quite complex and move or make additional noises — such as plastic owls, spiders. Other effective mechanisms can be used in combination with water sprinklers.

Avitrol, a chemical means of frightening birds was mentioned in the previous baiting section. Avitrol-treated grains are mixed per the label instructions with nontoxic grains at concentration levels between 1:9 (high) or as dilute as 1:29 (ratio of toxic to non-toxic bait). While birds are feeding on this mix, individuals consuming the toxic grains start to exhibit behaviors that cause the unaffected birds to move away from the site. The more concentrated mixture results in more birds affected, causing a faster escape response from the unaffected birds.

When frightening birds or animals away from a location, several considerations will ensure success. First, regular movement of devices around the property makes the location of sound and visual threats less predictable. Devices should not become a static part of the landscape because eventually they will be ignored. It is essential to maintain an element of randomness into the scaring program. Scaring devices should not be on a set schedule and should not occur with the same predictable activity. An element of surprise is necessary. In one case, after repeatedly scaring Canada geese away from a site, the geese began to move as soon as the vehicle came onto site and when the technician raised the starter's pistol. After the person left, the geese returned to the site. In such a case, limited lethal measures may be required. Having the birds associate a scaring measure with death reinforces the risk, causing the majority of the flock to move on. After a sound or upon deployment of big-eyed balloons, a pellet rifle may be used to dispatch a few birds. Avitrol is an excellent example of a deterrent method that mixes some lethal action to reinforce movement behavior of the larger flock.

Tactile repellents, irritants, anti-feedants

Tactile repellents (polybutenes, oils, or polymers) are available that cause surfaces to become sticky and render roosts and ledges unusable to birds. All roosting surfaces in an area must be treated, otherwise birds will find and use untreated areas. The effectiveness of sticky repellents is lost over time, especially in dusty or dirty areas. Some of the products are difficult to clean up, depending on the treated surface and the length of time the tactile repellent has been used. Newer formulations reportedly have simpler cleanup procedures involving soap and water. Mineral spirits were necessary to remove earlier formulations. Some suppliers recommend the use of water-resistant tape as a removable surface that protects a building's surfaces. These products are useful for short-term control in small areas. Repeated applications, cleanup procedures, and the risk of aesthetic damage from products not being cleaned make it uneconomical as a long-term deterrent.

Chemical irritants recently have been developed or expanded into a number of different products. Original products using capsaicin, a product of hot peppers, are available in liquid formulations to deter mammals. More current products have included active ingredients such as garlic and pepper oils in gel formulations for use against rodents. With the exemption from FIFRA of natural products that are "Generally Regarded as Safe" by the U.S. Food and Drug Administration, a number of so-called "25B exempt" products have become available. These products contain plant oils, spices, irritant oils, and other natural volatile compounds. As with tactile deterrents, these products have applications in small areas and specific situations.

There have been recent advances and registrations with deterrents containing the active ingredient methyl anthranilate. This ingredient is an extract of concord grapes and other fruits, and was originally used as a feeding deterrent against geese foraging on grass. While effective, reapplication of this product is necessary after rain, if geese are still challenging the area. More recently, methyl anthranilate was made available as an ultra-low volume or fogging agent, a gel, or for use with absorbent materials. These advances have enabled methyl anthranilate to be used in a variety of applications (indoor and outdoor), in situations where automatic reapplication is necessary, and against other bird species.

In addition to the chemical anti-feedant nature of methyl anthranilate, there are products that color-dye feeding sites (such as turfgrass) so bird behavior is reinforced with a visual cue.

Physical devices

Physical deterrents exclude birds by fencing off areas or making roosting surfaces inaccessible or unstable. The type of device used depends on the area, problems with visibility, cost, and bird pressure. Devices may be as simple as porcupine wire, wire spikes placed on ledges and other surfaces to prevent birds from putting their feet on a stable ledge. More advanced types of ledge deterrents achieve the same goal with strands of piano wire supported above the ledge or electrical shock. These advanced ledge deterrents may cost more but have a major advantage in being less visible and maintaining building aesthetics.

In cases where large birds (geese) or birds such as gulls that use soaring behavior create the pest situation, flight intercept wires may be applicable. Intercept wires (or thin cables) interrupt typical landing or take-off space. The intercept wires are heavier gauge than wires used in ledge deterrent applications. Wires typically are placed at 3- to 10-foot intervals and usually at 6 to 20 feet above the landing surface, depending on the bird species and cable support requirements. Wires should be placed to avoid interrupting human activity.

The final physical deterrent is netting. In most cases, netting is considered the most effective device to exclude birds. If multiple species of birds use the site, assessment of the situation reveals that a particular species may not move as a result of other tactics, or the area of concern is very large, netting is considered an absolute means of nonlethal control. Netting consists of a nylon, polypropylene (or other synthetic material) net, anchored into panels by a cable support system. In addition to cabling, a number of attachment devices can be used depending on building materials and the situation. The drawbacks of netting include visibility and higher material and labor costs. To manage costs, a mixture of activities and devices may provide the best effect for the least cost. Mixing strategies requires careful assessment of the pest situation to achieve maximum control.

Challenges when using deterrents

The deployment of effective deterrent measures requires an assessment of three characteristics: the size of the infestation, why pests are using the facility, and what alternative resources are available to the animals. These three issues will dictate the level of an animal's motivation for continuing to use the site and lack of willingness to relocate once deterrent measures are deployed. Once these characteristics are understood, control methods can be planned, along with alternate and contingency plans should circumstances limit use of primary methods. For example, excluding birds from a facility may require netting in key areas, while lethal measures may be required to address birds still challenging the facilities after exclusion measures have been installed. Sometimes birds will actively challenge deterrents based on motivation to use a site. If observations indicate that the animals continue to challenge or ignore deterrents, forced removal or lethal measures may be necessary.

In the pest control industry, terms such as "bird-pressure" or "rodent-pressure" are commonly used to describe motivation of animals to challenge a site, to remain on a site regardless of control or prevention measures, or to quickly reestablish infestation at that site. Animal pressure is a term that must be understood when conducting control measures, but is particularly important with the deployment of deterrent means, especially against birds. This term was developed both for describing the incidence of rodents to be found in an area and the chances that deterrent devices would successfully exclude birds from a pest situation. No scientifically formal definitions exist as to what constitutes low- versus high-pressure. Characteristics provide clues as to whether a site would be considered a low-, medium- or high-pressure situation.

High-pressure situations occur when the animals in an area have little opportunity to move elsewhere for survival or for nesting. High-pressure situations usually involve a location close to resources and limited abundance of food and water elsewhere. High pressure can also include other characteristics necessary for survival, such as availability of thermal refuges during times of cold weather. Leaving this type of site for another area requires great risk to the bird. It may have to expend large amounts of energy traveling to new food sites. Finding new nesting sites and rebuilding nests will also cause the bird to expend large amounts of energy, if displaced. In high-pressure sites, birds may actively seek alternate sites in the facility, continuing to challenge the facility or risk being killed to satisfy their currently available food, water, or nesting needs. High rodent pressure usually results from a nearby location that is overpopulated with rodents. Movement from this site causes a constant source of rodents into the grain and food storage facilities. The need for rodents to emigrate is caused by dwindling resources and increased conflict in the overpopulated area.

Alternatively, low-pressure sites for birds are "take-it-or leave-it" sites. It may be a site where birds simply take a brief rest between nesting and food sites. Lower pressure sites are observation areas, sunny spots, loafing areas, or areas to simply conserve energy after food, water, and shelter needs have been satisfied. Deterrent activities may be simple and successful because the birds simply move to another site. Low-pressure rodent areas are those with little or no emigration because there is still abundant habitat or other competing species can be displaced. The level of pressure on a site may change with the time of year or changes to other resources. A low-pressure site can become a high-pressure site in a few generations of breeding, when food becomes limited or seasonal changes occur.

Grain storage and food processing sites tend to be complex and pressure can change over the seasons. The need to find feeding, water, and nesting areas — and the energy needed to locate these resources — may cause birds to move on after a deterrent program. They will typically continue to challenge the site or attempt to reestablish as their population grows. This is different from a high-pressure situation where birds relocate within the facility area and immediately return to the site or ignore deterrent activities.

After determining the birds' motivation for inhabiting a site, a number of practices should be considered, depending on the animal pressure. Devices and strategies may be mixed with other techniques. Also, coordination of techniques on other properties may be required. In one case, a crow flock was attracted to the roof of a manufacturing plant because the heat generated there enabled birds to survive the winter. The birds were frightened off the plant roof by noise and flew into a nearby city. The city used pyrotechnics to scare them out of the urban area, and they returned to the manufacturing plant. The manufacturing plant stepped up scaring practices by employing raptors. The contractor also placed an eagle tethered to a perch on the roof. In response, the crows moved about until after sunset then made their way back to the manufacturing plant. The crows distributed themselves just out of the eagle's reach. This situation was remediated by the use of strobe lights that were moved around the plant roof after dark. This extra harassment at unpredictable times encouraged the birds to vacate the site permanently. This unusual case illustrates how deterrents can initially fail, and how the program changed once the actual bird-pressure on the site had been properly assessed.

Supplemental Reading

This chapter was produced using information pertaining to the most common pests found at grain storage facilities and food processing plants and warehouses. It addresses prevention and control of common vertebrate pests in normal circumstances and describes pest control practices typically used. For more information on particular pests or other situations, see the following references:

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8 Food Plant Sanitation, Pest Exclusion, and Facility Design

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Food processors or manufacturers can't afford to ignore sanitation, pest exclusion, and sanitary facility design. Consumers do not want insects or foreign material in their food. This chapter offers examples of ways to increase success in keeping pests out while ensuring that food products are safe and wholesome. For a complete guide to food plant sanitation, see Imholte and Imholte-Tauscher 1999.

Plant Exterior

For proper sanitation of food plants, warehouses, or storage areas, facility managers should know their neighbors. Stored product insects, rodents, and birds do not care where they live as long as they have access to food, water, warmth, and a shelter. Removing or modifying any of these critical needs stresses the population. If done well, pests will be eliminated or excluded because conditions will not allow survival. Elimination, not "control," must be the goal.

Food plant sanitation starts at the facility's exterior. A tour of the outside will reveal common situations that can cause pest problems. To see that pests' critical needs are not satisfied, food manufacturers should assess risks on adjoining properties as well as their own. Pests such as rodents are highly mobile and excellent climbers. Insects can fly or be windblown onto a property. It is important to determine neighbors' potential as pest harborage sites. Examples of situations that encourage insects and other pests are described below.

Low spots – Areas where water accumulates and becomes stagnant include obvious sites such as ditches but also places on the property or adjacent areas where low spots and holes can accumulate water. Water attracts insects, birds, and rodents. Eliminating the source will deter pests. Grounds should be smooth and properly drained.

Trash areas – Clean areas where trash, garbage, or litter accumulate to make them less attractive to rodents, flies, and birds. Place sites on a master sanitation schedule (MSS) for periodic cleaning and inspection. Approach neighbors to suggest working together to keep areas clean. If they also produce, receive, or store food and ingredients, teamwork will benefit them, too.

Collection areas near plant entries or dock areas, can entice pests into buildings. Pest-proof entries and make sure dumpsters have tight-fitting, accessible lids. Place garbage collection areas on the MSS for periodic cleaning. Cleaning may require a water source (preferably hot) and a hard, smooth, and properly drained surface under containers so water does not puddle and stagnate. Treat interiors of cleaned dumpsters with a labeled residual insecticide to aid in fly control during the summer months. It does no good to treat garbage or a dirty dumpster. Strengthen rodent control near these sites.

Landscaping – Fruit-bearing trees or landscaping, sweet-smelling flowers, nuts or seeds are attractive to insects, birds, and rodents. They provide food and potential nesting or roosting sites and should not be located near a facility. Ideally, landscaping should be designed to be minimally attractive to pests. Many facility managers realize this too late and then remove plant material around perimeters and building foundations. Even low-growing shrubs such as arborvitae planted near the foundation can become a hiding place for rodents and other vertebrates.

Flowering shrubs such as spirea attract adult warehouse beetles to feed on pollen in the flowers. Shrubs located near the building can attract the adults, which can fly into the facility and lay eggs in grain-based food products. Larvae begin feeding and start an infestation.

Parking lots and lighting – Parking lots, adjacent properties, and similar sites should be constructed and paved so water drains properly, and standing water is eliminated. Lighting should be designed so it does not attract night-flying insects. Sodium vapor lights are a better choice than mercury vapor. Wherever possible, use sodium vapor lighting for exteriors and interior areas where light may be visible from outside. These lights, known for their orange or gold color, emit low levels of ultraviolet light that is attractive to insects. Another advantage of this type of lighting is that bulbs have a low mercury content, making them more environmentally friendly than mercury vapor lights.

Ideally, do not place lighting directly on building exteriors or above personnel or dock doors. Place security lights at least 15 feet from the doorway so they illuminate, but attract insects away from the building. This ensures that areas are well lit while minimizing insect congregation at building entrances. If entrance lighting is needed, specify sodium vapor or metal halide lights because of their low ultraviolet emissions. Place photocell sensors on the lighting, so they only come on as needed.

Use insect-attracting mercury vapor lights to lure flying insects away from the facility. Place lighting away from the building and cover to project the light down. This minimizes insects from surrounding areas attracted to ultraviolet emissions (Harris 2006).

Pest control programs around perimeters – A pest control program should start at property perimeters, especially for rodents. The goal is to stress and exclude them. Typically, this involves using EPA-labeled toxic rodenticides placed securely inside commercially available tamper-resistant rodent bait stations (RBS) that are secured to the ground. In most cases, baits should be solid formulations to prevent rodents or nontarget organisms from removing them from the bait stations and taking them to another site where nontarget organisms may be killed or injured. Not only is harming nontarget organisms against the law, but it can also generate bad publicity.

Mark rodent bait stations on a schematic location map for periodic (at least biweekly and more often if rodent pressure is heavy) inspection and maintenance by trained personnel. Document observations in a log, and move bait stations as rodent activity decreases. Do not be lulled into rodent control, inside or outside of the facility, by guidelines of auditing companies that say control devices need to be placed "x" number of feet apart. Rodents may only move a few feet from their nests when food and water are easily available. They tend not to move in the open where they are exposed to potential predators. Experiment with different bait varieties to find the best one for the situation.

It is a good idea to disturb the rodent bait station before inspecting it because snakes and other vertebrates may be found there. Check for black widow spiders if known to inhabit the area. Do not place rodent bait stations in low spots where they can get wet and become ineffective. During winter it may not be possible to inspect the stations. Make sure they are working and well stocked with bait before the onset of bad weather.

It is not necessary to use toxic baits inside the bait station all the time. Nontoxic rodent attractant blocks are available that can be used as a monitoring tool to indicate rodent feeding. Once activity is noted, replace the nontoxic material with the toxic bait. Keep doing this until the feeding stops. Repeat the process as needed. This regime greatly limits the amount of toxicants used and liability associated with nontarget organisms.

Another nontoxic method of controlling rodents along perimeters is placing glue boards inside bait stations. Keep in mind that glue boards become ineffective if they get wet or dirty and may be difficult to maintain. They catch insects and other small invertebrates or vertebrates that should be monitored. A combination of methods might work best in a particular situation. Be creative as long as it is legal and works. Snap traps typically are not used outside because they are ineffective after they have been tripped. They require more maintenance because they must be checked frequently.

Other key sanitary design issues for plant perimeters and building exterior – Walls, roof, and foundation areas must be constructed to remain dry with no water accumulation. Water is not only a critical need for warm-blooded animals and insects, but it plays a key role in the survival and transmission of microbiological pests. *Salmonella*, *Listeria* and *Escherichia coli* are transmitted through water and are of particular concern to those in the food industry.

Building color can increase insect attraction. White and yellow are more attractive because of their reflective qualities. If possible, minimize the use of these colors on the exterior and in critical interior areas. If present, minimize the amount of light shining on and reflected from these surfaces.

A vegetation-free building perimeter is a must. An 18-inch band of pea gravel is also recommended. Pea-sized gravel is difficult for rodents to burrow in for nesting. Larger gravel does not collapse when moved and may not deter burrowing. Place rodent bait stations along this perimeter, with or without toxic bait, if rodent activity is observed during good manufacturing practices (GMP) inspections.

Many facilities now only place glue boards inside bait stations. The boards must be protected from weather and debris. Frequent inspection is required to remove catches before they decompose, replace glue boards, and log activity. Third party inspectors should not find decomposed rodents in traps. It will likely trigger an automatic unsatisfactory rating due to neglect or lack of disciplined checks.

If grass is allowed to grow too long and pallets are stored outside next to the foundation, pests will find shelter there. Inspect and clean pallets before moving them indoors. Birds and rodents also nest in pallets and can raise a contamination issue.

Psocids, commonly called booklice, rusty and flat grain beetles, foreign grain beetles, and hairy fungus beetles are a few common stored-product insects that can feed on mold and fungi found on wet pallets, inside or out. Wood pallets threaten sanitation and good management practices. Wood can splinter and contaminate production areas. Inspect pallets for pest evidence not only near the floor, but also several feet high in a stack. Rodent droppings can be found on pallet boards several feet up in a stack that ends along warehouse walls. If using pallets, implement a documented cleaning program. This may be even more important if pallets are stored outside and moved inside when needed.

Regulatory inspectors are now making the roof area a primary focus of inspections. Roofs are often neglected because they are out of sight. Secure and monitor roof access points from inside the plant so personnel do not use them as break areas, leaving behind food and debris. This is unacceptable from a GMP standpoint.

Roof areas should be part of a good management practices inspection. Inspections should be done monthly by a multidisciplinary team. Deficiencies should be noted for proper corrective action and to determine the cause. Act promptly to resolve issues. Similar observations noted repeatedly indicate a breakdown in the sanitation program.

Check HVAC (heating, ventilation, air conditioning) units and venting for proper functioning with no leaks. Leaks can deposit food debris on the roof that will attract pests. Roofs should be constructed of an easy-to-clean, smooth surface and must drain properly to prevent water accumulation. Roofs with a gravel base make cleaning and debris removal difficult. All HVAC utilities should be properly screened or filtered to keep out pests. Personal safety is the priority when working on the roof.

Entrance, exit, rail, or dock doors should not open directly into plant manufacturing areas. Open doors allow pests and unfiltered air into the plant. Negative rather than positive air pressure is needed inside the plant to prevent pests from being sucked in. Doors can be screened during warmer months when ventilation is needed. Emergency exit doors that open directly to the outside should have security alarms.

Doors should be tightly sealed along the bottom so rodents cannot enter. Air curtains above doors are not recommended because, more often than not, they malfunction and do not adequately keep pests out. Plastic strip doors are seldom a good option. They deteriorate and need constant repair to keep pests from getting in, adding to maintenance and upkeep costs.

Dock levelers must be fitted for pest prevention and exclusion. Rodents can easily crawl into the plant through the leveler pit when the plate is not sealed. Plates usually are equipped with brush seals or pieces of heavy rubber. Rodent mechanical multicatch traps can be placed inside the leveler pit as part of the rodent control program. Pit areas should be placed on the MSS for periodic cleaning and be part of the GMP inspection program.

Exterior food ingredient commodity storage tanks should be constructed of materials that will withstand the rigors of the outside environment and will not rust. Tanks should be smooth and cleanable, inside and out, for easy maintenance. Preferably, they should not be painted because peeling paint can become a product contaminant. Dust collection units or other HVAC ductwork must be screened or filtered to prevent pest entry. It should be watertight and non-leaking. Place sites on the MSS and preventative maintenance program to document upkeep.

Welded joints should be continuous and not stitched. Stitching creates cracks and crevices where food debris can accumulate and stored-product insects such as red or confused flour beetles or sawtoothed grain beetles can live. The Indian meal moth is another insect that can infest interior tank headspaces and HVAC units. Check these sites periodically for pests. If applicable, monitor sifter tailings coming out of the bins to detect pests and foreign material. Do not log these problems without finding the cause.

Moisture supports mold or fungi inside a dry ingredient storage tank. Precautions to prevent condensation and leaks should be designed into the system. Condensation can occur when warm ingredients are unloaded into a cold silo during cold months. This can become a problem without adequate ventilation.

External ingredient unloading sites – External food ingredient or commodity unloading sites must be designed to exclude stored-product insects such as red or confused flour beetles, sawtoothed grain beetles, foreign grain beetles, flat or rusty grain beetles, hairy fungus beetles, psocids, ants, flies and bees, or wasps. Other arthropods such as sowbugs and millipedes are attracted to moist food debris when it is allowed to accumulate around the unloading site. Surfaces adjoining railroad tracks or lots where unloading occurs should be paved and drain properly. These areas must be cleaned without using water because moist debris will decay and attract pests. Rail unloading areas should not be covered with gravel or rock, which makes cleaning spillage nearly impossible. Debris that sifts down through the gravel or rock attracts pests. Treating the track area with insecticides does not eliminate the underlying cause.

If exterior storage tanks or silos are covered with a protective head house, pest control and sanitation in these areas must be thorough. Hang insect pheromone traps for Indian meal moths, drugstore/cigarette beetles, and warehouse beetles. The traps are species-specific and effective for monitoring flying stored-product insects. Mark trap locations on a schematic map. Check traps weekly and log catches. Typically, head houses are not heated or airtight enough to be sealed easily from the inside and properly fumigated with labeled products.

Inadequate fumigation increases the likelihood of insect resistance. Resistance has already occurred in some cases. If the head house can be sealed to hold in hot air, heat can be used for insect control. The temperature should be maintained at 122 to125°F for 18 to 24 hours, giving heat enough time to penetrate the cracks and crevices. Heat treatments stress insect populations and limit reproduction.

Windows are discouraged. Left open or unscreened they allow pests to enter. Broken windows can lead to product contamination. Secure top hatch openings to tanks or silos to keep foreign material from getting into the tank. Insects adapt and can survive during the cold months even outside in a head house. They will not reproduce below 50 to 55°F, but they will survive.

Promptly remove food debris spilled during unloading. Unloading hoses should be clean, capped, and locked when not in use and stored off the ground in a sanitary location. Ideally, product protection devices such as magnets, sifters, filters, or strainers for products being unloaded should be installed before products enter the storage bin or silo. This prevents suppliers from unloading their problem into the bin. Inspect devices after each load and log observations. If contaminants are observed, act immediately to assure products do not become adulterated.

Plant Interior

Although the priority for food manufacturers should be keeping pests out of the plant, infestations inevitably occur. This section describes critical areas for pest control within the plant.

Docks and warehouses – Insect and other pest infestations often originate in warehouses. This is where food ingredients and finished products are stored, and they are located near receiving and shipping dock doors. Maximize rodent control in these areas by using nontoxic traps (i.e., snap, mechanical multiple catch, glue boards) on both sides of each door that opens to the outside. Place rodent bait stations outside along the building perimeter. Do not leave doors and windows open. If ventilation is needed, openings should be properly screened.

Seal wall openings for pipes and wiring to exclude pests. Caulking and copper wool works best. Copper wool does not rust like steel wool and prevents rodent chewing better than caulk. Do not allow birds to nest or roost near the plant. Promptly remove food spilled around docks so it does not attract pests.

Place insect light traps and pheromone traps (Mueller and Van Ryckeghem 2006) around dock and warehouse perimeters to catch flying insects. They are not a panacea because not all insects are highly attracted to them. Pheromone traps are available specifically for Indian meal moth, cigarette beetle, and warehouse beetle. Once in place, mark traps on a schematic location map and checked at least weekly. Log the catch for each trap to determine whether catches are increasing. Update maps as trap locations change.

Change insect trap light bulbs at least once a year. Their effectiveness in attracting insects decreases over time. Although it cannot be detected by humans, insects are sensitive to the drop-off in ultraviolet wavelength. Neither of these pest control devices should be used for control, but rather as a monitoring tool. Find sources of insect infestation close to to traps with high catches and eliminate them.

Keep pallet rack leg bases and I-beam bases clean and free of food in which insects can breed. Place these sites on the master sanitation schedule (MSS). These areas can be treated with a labeled residual insecticide, but debris may prevent insecticide from reaching insects. Sanitation is critical to pest prevention.

Floors – Warehouse floors should be designed for equipment and usage. Consider equipment and human traffic patterns. Will equipment be heavy? Will water or cleaning chemicals be used? Answers to these questions will determine what type of flooring will perform best and last the longest.

Wood floors usually are not a good choice. Older facilities that have them must maintain them in good condition to prevent cracks and crevices that allow food debris to accumulate and insects to breed. Keep wood floors sealed with several coats of polyurethane sealer. Concrete floors are common. Joints need to be sealed, and floor sealers do not last indefinitely. Highly acidic foods can damage concrete floors, allowing food and water to accumulate. Stagnant water can lead to insect and microbiological issues.

Phorid flies (Phoridae), moth flies (Psychodidae), dung flies (Sphaeroceridae), and fruit flies (*Drosophila* spp.) are among many flies that breed in stagnant water. They also breed under loose sections of flooring that are not properly sealed. If floors are not repaired, flies will remain, and insecticide treatment is futile. Tile floors often are a poor choice because of their construction. Seams split over time, allowing food debris and water to accumulate. Water stagnates and can lead to serious insect and microbiological issues.

Ceilings – Periodically inspect and clean ceilings and overheads. Place overheads on the MSS. Fogging with synergized pyrethrins or other labeled insecticides will not be effective on dirty overheads because insects live under built-up debris where they are protected from insecticide. Fogging is most effective when droplets hit exposed insects.

Do not overlook overhead areas as potential runways for rodents, which are excellent climbers. Do not allow condensate to accumulate in overhead areas because it becomes a source of moisture for pests. Design HVAC systems to remove condensation. Avoid false ceilings. Stored-product insects and rodents can be found in false ceilings where flour and food debris accumulate. If personnel forget to clean and inspect them, pests can take over. Fogging is ineffective if these areas are dirty. False ceiling areas must be placed on the MSS, and a pest control program (i.e., monitoring rodent and insect traps) should be implemented.

Floor drains – Floor drains can pose problems for the plant sanitarian. In dry environments, if food debris is allowed to accumulate, stored-product insects will take harborage in the drain. In wet environments, microbial concerns abound. In dry warehouses or production areas, clean and plug drains when not in use to ensure they stay clean and infestation free. Do not allow drains that are in use to dry out. Place drains on a schematic map and document cleaning dates based on an MSS.

Unplug drains while conducting a heat treatment (Chapter 15) in case a sprinkler head or two discharge. This keeps personnel from having to enter a hot room to unplug the drain while the sprinkler is on. Ideally, floor drains should be a minimum of four inches and equipped with a removable secondary strainer to prevent cockroaches, rodents, and other pests from entering the facility through the drainpipes. The strainer also prevents large accumulations of organic material from entering the drain and causing a backup. Drains should be constructed with smooth surfaces and rounded corners.

Trench drains are difficult to maintain in a sanitary manner. They should not be used except in operations where they are required because of the food being manufactured. Trench drains may deteriorate, causing the floor drain interface to separate. This allows water and food debris to get into the cracks and stagnate. Many fly species will breed in that environment and can only be eliminated by repairing the separation.

Closely monitor floor drains for pests and adequately clean and sanitize. It is important to have written drain-cleaning programs and procedures that require scrubbing the drain sides and piping into the drain. This is the only way to remove biofilms that accumulate in wet drains. Pouring sanitizing solutions into a drain will not remove biofilms. Insects will live under them and continue to breed. Utensils used for drain cleaning should be color coded and labeled ONLY for this purpose. Using drain-cleaning utensils to clean food contact surfaces will cause cross-contamination and violate good manufacturing practices. To verify that a drain is a source of an insect pest, place a plastic bag over the drain and tape it to the floor for 24 hours. Check the bag for insects. Then clean, scrub, and sanitize the drain.

High-pressure water or air should not be used in drains or anywhere else, including overheads. It can scatter debris (i.e., microbials and insects) into the general manufacturing environment and cause cross-contamination. Vacuuming is the preferred method for removing debris. In a wet environment, using a squeegee to corral large amounts of debris is preferred to using high-pressure water.

Electrical equipment – Electrical equipment and systems are extremely vulnerable to stored-product insects, especially sawtoothed grain beetles and confused or red flour beetles. If equipment is poorly designed so it does not remain dust- and water-free, it will become a pest harborage. Thousands of feet of conduit could become insect-breeding expressways. Even overhead light fixtures can become infested. They are warm, and ultraviolet light attracts several insect species. Pesticides are not recommended for use in such areas. Heat can be used to disinfest areas, but only if systems are designed to withstand high temperatures. Caution is advised in determining temperature specifications because "hot spots" can occur during a heat up. Installations must meet appropriate code requirements.

Switch gear and control centers should be installed in well-lit, pressurized rooms. They should be filled with filtered and air-conditioned air and be able to be cleaned easily without high-pressure air. No small voids should be allowed between equipment and wall, or wall and floor interfaces. Dust can accumulate and provide a breeding ground for stored-product insects. Installations should allow adequate inspection space under and around equipment. There should be no hollow areas for materials to enter and accumulate.

Control panels installed in manufacturing areas should be dust-free and watertight. Panels can be pressurized with clean, filtered air. Supporting leg bases should be designed so there are no hollow voids that could allow debris to enter from the sides or where they attach to the floor. Be cautious when using caulk as a sealant. It can become loose and create a harborage. If caulking is used, inspect it periodically to ensure it is intact.

Motor and equipment leg bases – Motor and equipment leg bases often are overlooked during cleaning. There are numerous cracks and crevices and ledges in motors where debris accumulates. They are warm, which favors breeding of stored-product insects. Clean motors at least monthly and include them on GMP inspection routes.

Equipment leg bases that sit firmly on floors also accumulate debris that can create harborage for insects if bases are not sealed to the floor. Sites are sometimes painted over and over, so crusty paint appears to be part of the equipment. Once loosened and scraped away, flour beetles or sawtoothed grain beetles might be found living there.

Windows – Making sure windows and doors are kept closed or properly screened in a food plant or warehouse can be a struggle, especially during off shifts. Because of the problems they create, it is a good idea not to have windows. Even with the most advanced HVAC units, invariably someone feels too hot and opens a window. Open windows require screens that become separate maintenance issues.

If windows or glass block windows that let light in but cannot be opened are used, do not allow any type of glass in or near food production or packaging because of the potential for breakage and contamination. Window screens used for exclusion, should be constructed of 16 mesh with 14 × 12 wires per inch. Screens should be designed for easy removal and cleaning. Reinforce those within five feet of ground level with a heavy-gauge wire and ¼-inch mesh screen to exclude rodents that can chew through conventional screening. Promptly repair holes for maximum pest exclusion.

Windows can be tinted to reduce the amount of insect-attracting light showing through. When inspecting the plant, look for dead or live insects on windowsills. Identify them to locate and eliminate the source.

Cost of Sanitation and Pest Prevention

The cost of pest control is minor compared to the cost of poor sanitation, which could easily be millions of dollars from negative publicity, brand damage, and worst of all, personal injuries to consumers. For food processors faced with a market recall, the dollars can add up quickly. Production time may be lost to do excellent work in critical sanitation and pest prevention areas, but cutting these two programs can prove more costly.

The goal should be a sanitation and pest prevention program in which prevention, rather than control, is the objective. Preventing pests from becoming an issue is the key to success. Legal requirements, such as FDA current good food and manufacturing practice, also must be met. (Code of Federal Regulations, Title 21, Pt. 110, 2006).

Over the past decade, the FDA's role in the design of new meat and poultry processing plants or remodeling of existing facilities has changed. Previously, the USDA Food Safety and Inspection Service (FSIS) required food processors to obtain prior approval of proposed drawings and equipment. Now, under the Federal Meat and Poultry Products Inspection Acts, food manufacturers are responsible for designing plants and equipment that can be maintained in a sanitary manner (CFR, Title 21, Pt. 110, 2006).

Sanitary design may cost more, but food adulterated with physical, chemical, or biological contaminants that could harm consumers is unacceptable. Adulterated food cannot be sold or shipped across state lines because FDA has jurisdiction to oversee interstate commerce. (FDA, 2007.)

Food manufacturers must design plants and equipment so they can be monitored and cleaned, not only because it is required by law, but also to protect consumers, their brands, and ultimately their business. The consequences of not doing so were illustrated by Peanut Corporation of America, a peanut processing company that was forced out of business after being found to be the source of a massive *Salmonella* Typhimurium outbreak in the United States during 2008 and 2009. Nine people died and at least 691 people in 46 states fell ill due to food poisoning from eating the company's products, according to the Centers for Disease Control and Prevention (CDC). In 2009, Peanut Corporation of America filed for Chapter 7 bankruptcy liquidation. At least a dozen civil lawsuits have been filed, and the federal criminal investigation continues.

Implementation of food safety measures — GMPs, HACCP (Hazard Analysis and Critical Control Point), integrated pest management (IPM), clean-in-place (CIP) systems, metal detectors, magnets, sifters, strainers, filters, sanitary design of floors, walls, ceilings, and drains, and audits — are costly. The return on investment is preventing the manufacture of adulterated food.

A sanitation program that relies solely on the periodic use of chemicals (i.e., fumigants) to manage pests is not feasible. Fumigations can cost tens of thousands of dollars each, yet they offer no long-term residual protection. If doors or windows are left open after fumigation, the facility can be reinfested. The goal must be to prevent infestations.

Food manufacturers must address structural defects instead of relying solely on pesticides. A 2010 survey of pest management industry personnel (Grasso 2010) reported a 6% increase in net revenue from managing stored product insects from 2008 to 2010. The number of pest management jobs for rodents, ants, and cockroaches were projected to increase from 10 to 13% during the same time period. The top four rodent pests (mice, rats, voles, and squirrels) were expected to increase revenue 13% with the average price of a rodent job at $250 in 2010.

Adhering to a Master Sanitation Schedule

Master sanitation schedules do not need to be complex. Many facilities post them so all personnel can see them and comment as appropriate. Something as simple as a grid listing periodic sanitation tasks down the left side and the months across the top will work. Initial and date tasks when completed. Do not leave blank spaces that could lead auditors to believe a task was neglected. Note the reason for the blank (i.e., plant or line down, no production). MSS are not static and should be updated as equipment and processes change in the facility or suggestions from internal or external audits are implemented. Do not include pest control records on a MSS. These should be kept separate for audit reasons.

With food manufacturing facilities becoming more automated, and fewer employees hired just to clean, production personnel are being assigned to clean the production equipment they run, as well as surrounding areas. Some plants (i.e., USDA-regulated) have designated sanitation crews because regulations require more frequent sanitation cycles. Non-USDA plants may shut down for sanitation and run for several weeks before another cycle, based on the food safety risk profile of the products manufactured. This operating procedure includes the cost of sanitation combined with the cost of production, overhead, salaries, and benefits. Many MSS tasks, such as silo or bin cleaning, can be contracted to a third party.

Once an MSS is established, it should be monitored for effectiveness. Audits, conducted by internal or external personnel, cost time and money. Some plants have an employee designated to work with external auditors to carry out inspections. If a facility supplies several customers, each will probably want one of its auditors to visit or have an outside auditing company visit the plant.

Audits take several days and can be an annual or semiannual event. For example, if a facility quality assurance (QA) manager has to accompany an auditor for two days, at a salary of $100,000 with 250 work days per year, it costs $400/day. This does not include preparation time. Most external third party audits cost at least $1,000 per day. In-house personnel need ongoing training to conduct audits. Cleaning personnel should not be assigned to audit their own areas. Independent investigators are needed to ensure there are no conflicts of interest. Fortunately, online training for conducting audits is available at nominal cost. Employees do not have to leave the plant to participate, and it is available 24 hours a day, seven days a week in most cases.

Poor sanitation and pest prevention cause poor audit scores, which will reflect negatively on the company and its business. Facilities must be inspection- or audit-ready at all times.

Most food production facilities require basic preventive food safety programs such as HACCP and environmental microbiology. Each proactive program has an implementation cost, plus periodic sampling and analysis costs. MSS support these programs to make them effective.

Future of Food Safety

Protecting the food supply is a continual challenge for food manufacturers. Widely publicized cases of foodborne illness over the last decade prompted new regulations, which shifted the focus of federal regulators from responding to contamination to preventing it.

The FDA Food Safety Modernization Act, signed into law in January 2011, authorized the FDA to require comprehensive, prevention-based controls across the food supply. As a result of this new approach, FDA is requiring food facilities to evaluate the hazards in their operations, implement and monitor effective measures to prevent contamination, and have a plan in place to take any corrective actions that are necessary.

The law also gives the FDA a new ability to hold food companies accountable for preventing contamination. In the future, food manufacturers can expect the FDA and USDA to request records (i.e., sanitation and pest control) that have not been required in the past. Companies should be prepared to produce documentation showing sanitation tasks and how they have been carried out.

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9 Chemical Control in Stored Products

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This chapter covers insecticides used as sprays in empty bins before storing new grain, as direct grain protectants in bulk-stored grains, and as surface treatments and aerosols in grain storage structures and grain products. Discussion of fumigants and fumigations, modified atmospheres, and extreme temperatures for insect management are covered in chapters 14, 15, and 16, respectively. Sampling and insect monitoring, which are essential for evaluating effectiveness of chemical treatments, are covered in chapters 18, 19 and 21.

Insecticides Used in Bulk Grains

Structural sprays

Storage hygiene or sanitation is a mandatory component of insect pest management for storage facilities. Residual grain or grain debris in and around storage environments is an important source of infestation (Reed et al. 2003, Arthur et al. 2006). All trash should be removed from the storage structure and immediate surroundings before insecticide treatments are applied as pre-binning or structural sprays. There are a limited number of chemicals for such uses and the label requirements of these products often can be confusing. Application details described here relate to those with approved U.S. Environmental Protection Agency (EPA) registrations at the time of publication. Chlorpyrifos-methyl + deltamethrin (Storicide II) can only be used to disinfest empty structures if the structure is intended for storage of the five commodities listed on the label (barley, oats, sorghum, rice, and wheat). Also, the label specifies that empty grain bins should be treated by the applicator from outside the bin, applying the spray or dust from the top opening. Pirimiphos-methyl (Actellic 5E) is labeled for direct application to stored corn and stored sorghum but is not labeled for treating empty structures. In the United States, Cyfluthrin (Tempo SC Ultra) is an effective spray for treating structures but not the commodity. This new product replaced the wettable powder formulation. Diatomaceous earth is a natural product, with or without synergized pyrethrins, composed of fossilized skeletons of diatoms from fresh or salt water. Diatomaceous earth powders, or dusts, kill insects by absorbing the protective water-proofing compounds from the exoskeleton, leading to death by desiccation (Glenn et al. 1999; Subramanyam and Roesli 2000). Several diatomaceous earth dusts are available worldwide. Insecticidal efficacy varies among formulations, product sources, and insect species (Korunic 1998, Subramanyam and Roesli 2000).

Grain protectants

Protectants are chemical or nonchemical materials applied directly to raw commodities as they are loaded into a storage structure. They can be applied to farm-stored grain or small-scale commercial storages using a small tank sprayer (Figure 1) as grain is transferred to an elevating screw auger (Figure 2). Grain loaded into large-scale commercial structures is treated as it moves along a conveyer belt or where the grain is diverted into a storage bin. Generally, chemical protectants that are subject to regulated residue tolerances should be applied once during the storage period to uninfested commodity. Protectants that are exempt from a residue tolerance, such as diatomaceous earth, can be applied multiple times, but it is rare to find commodities treated repeatedly with protectants. Several protectants are registered in the United States. Some of the older protectants have been cancelled due to regulation (1996 Food Quality Protection Act). Others that are legally registered for use are no longer recommended because insects have developed high levels of resistance.

Figure 1. *Small tank sprayer for applying grain protectants (photo courtesy of F. H. Arthur, USDA-ARS-CGAHR).*

Figure 2. *Wheat being loaded into a small bin. The protectant insecticide is often applied as the grain is falling into the auger boot (photo courtesy of F. H. Arthur, USDA-ARS-CGAHR).*

There have also been changes in the way protectants should be applied to commodities. Before 1997 it was acceptable to use any suitable handheld sprayer. Some current labels require closed systems for mixing chemicals for applicator safety. Check labels for specific products and application instructions.

Storicide II is labeled for direct application to barley, oats, sorghum, rice, and wheat. It contains 3 parts per million (ppm) chlorpyrifos-methyl and 0.5 ppm deltamethrin. In the United States, Storicide II replaced chlorpyrifos-methyl, which was labeled at 6 ppm on these commodities. Tolerances for chlorpyrifos-methyl applied at 6 ppm were revoked in 2004. Chlorpyrifos-methyl is not effective against the lesser grain borer, *Rhyzopertha dominica* (F.), but the addition of deltamethrin to chlorpyrifos-methyl makes the formulation effective against this species and many other species, at least in the United States where resistance to deltamethrin has not been detected.

Actellic 5E is labeled for use on corn and sorghum at 6 to 8 ppm. The insect growth regulator (IGR) methoprene (Diacon II), is labeled at 1 to 2.5, and 5 ppm for all stored grain. In general, methoprene is effective against externally feeding stored-product insects and the lesser grain borer (Athanassiou et al. 2011a,b) but is less effective against internal feeders, particularly weevils (Arthur and Throne 2003). Methoprene is not effective against psocids (Athanassiou et al. 2010). There are a number of commercial formulations of diatomaceous dusts than can be applied directly to stored grains at varying label rates. Generally, the efficacy of most of these formulations decreases as grain moisture content or relative humidity increases (Subramanyam and Roesli 2000). Although diatomaceous earth is a food-safe material among compounds considered generally regarded as safe, application of effective concentrations of diatomaceous earth to entire grain masses can reduce the bulk density, or test weight, of the grain and reduce its value at the time of sale. In some countries (e.g., Australia) grain intended for export cannot be treated with diatomaceous earth, because it alters physical properties of the grain.

Several insecticides should be mentioned, which are rarely used today as structural sprays or grain protectants. Malathion, first registered in the United States in 1958, received extensive use as a structural spray and grain protectant. During the 1990s many agricultural chemical companies removed malathion formulations from the stored-product market. These products are being replaced with the insecticides previously mentioned because of widespread resistance in major stored-product insect species.

Synergized pyrethrins are a mixture of natural pyrethrins, derived from chrysanthemum flowers, plus the enzyme-suppressing synergist piperonyl butoxide, PBO. Although there are several active labels for commercial formulations of synergized pyrethrins for treating structures and commodity, these products are rarely used. To date, stored-product insects have not shown signs of resistance to synergized pyrethrins. *Bacillus thuringiensis* (*Bt*) (Dipel), is a naturally occurring pathogen that produces a parasporal crystal, which is toxic on ingestion by moth larvae. It is labeled as a surface application to the top of a grain mass primarily to control the Indianmeal moth, *Plodia interpunctella* (Hübner). This product is also effective against other moth pests found in grain. A total of 36 isolates of *B. thuringiensis* specific for beetles tested on the lesser grain borer provided less than satisfactory control (Beegle 1996). Dipel is exempt from a residue tolerance. Grain manager surveys indicate that this product is not used extensively to control moths in grain. Moths can develop high levels of resistance within a few generations of exposure to *Bt* (McGaughey and Beeman 1988). There are no *Bt* formulations registered in the United States to control stored-product beetles.

Concerns about human safety, insect resistance, and environmental impacts require a grain protectant that is highly effective against insects but safe to humans and the environment (Hertlein et al. 2011). One such product is Spinosad, which is derived via fermentation from a naturally occurring soil actinomycete, *Saccharopolyspora spinosa* Mertz and Yao. Spinosad is extremely effective against the lesser grain borer. This insecticide is registered in the United States for use on all grains at 1 ppm, but commercial formulations have not been released pending acceptance of international tolerances (Codex 1 ppm; U.S. 1.5 ppm) by Japan and Australia (Hertlien et al. 2011). The widespread global launch of Spinosad as a grain protectant is anticipated in the near future. Once released, the commercial formulation will be called Contain.

General surface treatments

Surface treatments are insecticides that can be applied over a wide surface area as liquid contact insecticides. Most of the commonly used surface treatments discussed below also can be used as spot or crack and crevice treatments to limited areas. A number of less common insecticides can be used on a limited basis as spot or crevice treatments. These minor use compounds will not be discussed in this chapter. The present discussion is limited to general surface treatments. Perhaps the most common conventional insecticide used as a general surface treatment is cyfluthrin (Tempo SC Ultra). Most of the previous research with this insecticide has been with either emulsifiable concentrate (EC) or wettable powder (WP) formulations (Arthur 2000). In general the red flour beetle, *Tribolium castaneum* (Herbst), and the confused flour beetle, *Tribolium confusum* (Jacquelin duVal), are more difficult to kill than other stored-product beetles (Arthur 2000, 2008). The order of susceptibility varies among insecticides, within the same or different classes of insecticides (Arthur 2008). The neonicotenoid chlorfenapyr (Phantom) was originally labeled for termites, cockroaches, and nuisance ants. Recently the label was expanded to include stored-product insects (Arthur 2009).

Efficacy of surface treatments can be adversely affected by the presence of a food source. When adult red flour beetles were provided with a flour food source either during or after exposure to cyfluthrin WP, survival increased relative to the survival that occurred when beetles were not given food (Arthur 1998). Similar results occurred in studies with chlorfenapyr (Arthur 2008). In other studies in which red flour beetles were placed on whole wheat kernels, dirt, or sawdust after they were exposed to cyfluthrin WP, survival increased then as well compared to survival without extraneous material (Arthur 2000). The presence of food and trash may provide harborage sites where adult beetles can escape exposure to insecticides, in addition to providing a nutritional or physical means to increase their tolerance to exposure (Toews et al. 2009, 2010).

The insect growth regulators hydroprene (Gentrol), methoprene, and pyriproxyfen (NyGard) are currently labeled in the United States as general surface treatments for controlling stored-product insects. Insect growth regulators normally do not give control of adults, although there is evidence of sublethal effects such as reduced fecundity after exposure (Daglish and Pulvirenti 1998). Hydroprene is the most volatile of the labeled insect growth regulators and gives less residual control than either methoprene or pyriproxyfen (Arthur et al. 2009).

Aerosols

These insecticides are liquid formulations that are atomized and dispensed as fine particles ranging from 5 to 50 microns in size, and often resemble a dense fog (Figure 3). Aerosols do not penetrate through packaging materials, bulk food products, or deep into machinery, and should not be confused

Figure 3. *Dispersion of pyrethrin aerosol inside a food storage facility. The aerosol was dispensed from an application system installed in the ceiling, and the insecticide was dispensed outward from the nozzles. (Photo courtesy of F. H. Arthur, USDA-ARS-CGAHR.)*

with fumigants, which are toxic gases that have excellent penetrating ability. There are several insecticides that are labeled in the United States for aerosol applications.

Dichlorvos (Vapona or DDVP) is an organophosphate insecticide that has been used since the 1970s. It has excellent vapor toxicity for exposed insects but little residual activity. Pyrethrins or pyrethroids, used either alone or in combination with insect growth regulators, are also used in pest management programs. Several field studies have shown increased survival of adult confused flour beetles when given food either during or after exposure to pyrethrins (Arthur 2010), hence, sanitation and cleaning are also important aspects of pest control programs when aerosols are used. Species differences between insects also must be taken into account when using aerosols. For example, the Indianmeal moth is a common pest in milling and retail environments. Mature larvae can be difficult to control with insecticides (Mohandass et al. 2007), including aerosol formulations of pyrethrin or pyrethroids (Jensen et al 2010ab). Inclusion of an insect growth regulator such as methoprene may give increased control of larvae compared to using a pyrethroid alone (Jenson et al. 2009, 2010ab). Incorporation of an insect growth regulator into the aerosol mixture will also give residual efficacy for beetle control (Arthur 2010). Methoprene also can be used to fog space above the stored grain to control flying insects.

Conclusions

Insecticides are important components of insect pest management programs for stored grains, mills, processing plants, and retail stores. Sanitation can help improve insecticidal efficacy and reduce economic costs associated with pesticide applications. Biological and environmental factors such as insect species and life stage, environmental temperatures, formulation type, coverage, and application method can influence efficacy of an insecticide.

Disclaimer

This paper reports the results of research only. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by Kansas State University or the U.S. Department of Agriculture (USDA). The USDA is an equal opportunity provider and employer. Consult pesticide labels for specific requirements and current uses of the particular insecticide formulation.

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10 Drying, Handling, and Storage of Raw Commodities

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The goal of postharvest grain drying, handling, and storage operations is to preserve the harvest quality of the grain and to add value by removing impurities and identifying and segregating lots with special characteristics when appropriate. For agricultural products, quality loss may occur due to poor drying techniques, improper handling, or lack of proper storage environments resulting in deterioration from cracking, splitting, mold growth, insect damage, sprouting, loss of germination, or dry matter loss from respiration. Large grains such as corn — especially when dried at high temperatures — are particularly susceptible to physical damage during handling. Physical damage also makes grain more susceptible to invasion by storage fungi and insects.

Grain Quality Characteristics

All postharvest operations attempt to maintain the initial quality of the harvested grain. During storage, grain must be protected from deterioration or attack by molds, insects, rodents, and birds. Drying and handling operations must prevent physical or chemical deterioration. The physical protection provided by modern grain storage structures should eliminate serious bird and rodent damage. Molds and insects cannot be physically excluded from grain with current storage designs. They can be controlled through grain temperature and moisture management.

End-use quality

The definition of grain quality varies depending on the intended end-use of the grain. For hard wheat, the ultimate criteria may be loaf volume for baked bread; for soft wheat, the objective may be cookie spread. Soybeans are processed for protein and oil content. Corn has many uses and applications. For the ethanol industry, the amount of starch available for fermentation is a critical quality factor. Ethanol producers may have other quality concerns because they sell co-products such as dried distillers grains (DDGS) with minimal or no mycotoxin content; mycotoxins are more concentrated in the distillers grains than in the incoming corn (Bennett and Richard 1996; Murthy et al. 2005).

Milling is an important processing step for many grain products, so milling characteristics are often important quality parameters for hard, soft, and durum wheat; corn; and rice. Specialized end uses may focus on one grain quality parameter — for example, high oil content in corn and soybeans — to provide energy and amino acids in livestock and poultry diets.

Grain grading

Originally, U.S. grain grading standards did not focus on product quality characteristics of interest in today's specialty grains markets. Early grain standards were developed to facilitate trade, describe physical properties and storability of the grain, and characterize product yield and grain quality. Initial grading standards addressed deterioration issues that adversely affect product quality. Over the years standards have changed as rapid measurement technologies have been developed that emphasize product quality characteristics.

Some standards relate to specific product quality issues. For example, insect damaged kernels (IDK), addressed in Federal Grain Inspection Service (FGIS) wheat standards, pertain to potential milling problems of insect fragments in the flour. FGIS added tests to address characteristics of interest to buyers such as protein content of wheat and oil and protein content of soybeans.

Sampling

Quality measurement, or grading, of a grain sample assumes that the sample is representative of the quality of the lot sampled. A representative sample is critical. Without it, the grade assigned is meaningless. The FGIS recommends continuous diverter-type samplers for the most representative samples. The agency requires the use of specific grain probes: a grain trier, which is a gravity fill probe, and a vacuum probe. The probe must be long enough to reach the bottom of the truck or other container. The sample must be collected using an approved probing pattern. Explicit probing patterns require up to nine probe locations on shallow flat-bottom trucks. More probe locations are required for grain on barges (USDA-GIPSA 1995).

Nonofficial sampling in the grain industry often involves using two or more probes to obtain a useful sample quickly. There is not as much assurance that such a sample is representative. For nonofficial sampling, simulating a diverter-type sampler by crosscutting a stream of flowing grain is recommended (Hellevang et al., 1992; Maier, 1993). See USDA-GIPSA (1995) for complete sampling recommendations.

Grain Quality Degradation

Preserving grain quality is a problem in many parts of the world (Gras et al. 2000). Quality never improves during storage. The best a manager can hope for is to preserve the initial quality as closely as possible. Grain and feed can be stored for a long time if storage conditions are managed correctly and material is in good condition to begin with. When degradation occurs, swift intervention is needed to minimize product damage and loss of market value.

Influences

The main reasons for grain quality decline are under drying (storing grain with unsafe moisture and temperature levels), overdrying, grain respiration, insect and rodent damage, and mold or other bacterial contamination (Kazazis 1980; Wilcke et al. 2000). Proper grain moisture and temperature management is essential for reducing damage to the stored crop. High humidity and temperature conditions promote insect infestation and mold development. Generally, the drier the grain in storage, the higher the storage temperature can be before mold begins to form. Each grain or seed variety has its own safe storage moisture, temperature, and equilibrium relative humidity (ERH).

Drying damage

Overdrying grain causes cracking, darkening, and seed damage. Although drying damage often is associated with corn, oilseeds such as soybeans, rape, and canola also can be damaged when overdried. Seeds shatter during handling when dried to less than 6% moisture. Drying damage is not always visible. For example, overheated wheat may look normal, but contain denatured protein that affects performance in making flour. Reducing heat during drying will minimize or prevent damage.

Handling damage

Mechanical handling can damage grain and seeds, reduce quality, and encourage other unfavorable conditions such as moisture hot spots due to poor aeration through accumulated trash and fines. Damage can occur because of high velocity impact, kernel stress cracks during drying and cooling, and very dry or very cold grain. Proper selection and sizing of handling equipment such as augers and drag conveyors is essential for reducing kernel damage. Augers must be operated at the rated capacity and speed for the grain handled. Larger, slower augers can reduce handling damage. Bearing-supported augers make it much easier to operate at rated capacity under variable incoming flow rates. An accumulating bin over the intake hopper for the auger also can provide a constant feed rate by keeping the intake full. Level control switches allow the auger to run periodically at or near full capacity to minimize mechanical damage.

Bucket elevators cause less damage to grain when drop heights are less than 40 feet. Above this, grain damage is much more likely to occur. Grain decelerators can be installed in downspouts to reduce the grain velocity and subsequent damage. Properly installed and operated pneumatic conveyors reduce grain damage. Large drop heights, sharp spout turns and transitions, and misalignments increase grain velocities, turbulence, and high impact and damage grain, particularly cracked or brittle seed.

Storage damage

Mold and insects are the primary causes of damage to stored grain. Grain in poor condition because of improper management is a prime target for mold growth and insect population increases. Damaged kernels, excessive fines, trash, and improper drying create conditions for spoilage. Pockets of fine material impede aeration distribution, allowing insects to multiply, which increases moisture and temperature. Mold forms under high moisture, high temperature conditions. Cleaning grain before storage, spreading grain to reduce fine concentrations, and properly managing aeration systems helps reduce pockets of high moisture grain and minimizes mold and insect activity.

Grain Management During Handling and Storage

The key to maintaining grain quality during storage is the proper moisture and temperature management. Becoming familiar with the interaction between these two conditions and how they control grain storage is essential to successful grain and seed storage. Improper management provides favorable conditions for insect infestation and mold damage. Toxins caused by molds and kernel damage caused by insect infestation reduce product value. If damage is extensive, the product may not be marketable. Molds and insects thrive at temperatures between 60° and 100°F. The higher the grain moisture, the more damage these temperatures will cause. If grain is kept cooler, moisture content can be higher. If storage temperatures are expected to be high, as is the case with summer harvested crops, grain must be at lower moisture content to store successfully. Fall-harvested crops can be stored at higher moisture content because of low ambient storage temperatures that continue through the fall and winter months. The lower the moisture content, the longer grain can be stored successfully. Table 1 shows expected storage periods for grain held at various moisture contents.

Temperature management is affected by moisture migration during storage. Convection air currents caused by temperature differences between ambient conditions and the grain cause moisture migration as warm moist air meets cool grain. Differences in temperatures surrounding grain bins due to shading, temperature differences between day and night, and cold weather cause moisture problems within bins. Grain is a good heat insulator. The center of the grain mass (or bulk) stays warmer longer than grain near the bin walls. When the center of the grain is warmer, convection air currents move down through the wall area of the grain and push the concentrated warmer air up through the center of the grain. The warmed rising air absorbs moisture and deposits it on cool grain near the surface of the grain at the middle of the bin. Moisture diffusion also can occur between warm and cool grain.

Between the convection currents and moisture diffusion, high moisture problems occur at the top, middle surface of the grain bulk. This is the area where fine material collects under the fill point and aeration is least effective. It provides an ideal place for molds and insects to multiply and infest the grain. Proper use of aeration fans can reduce temperature differences within the bin and cool grain to desirable temperatures. Knowledge of the interaction between ERH and equilibrium moisture content (EMC) — the ability of grain to accept and release moisture as determined by the temperature, moisture content, and relative humidity — will help managers know when to efficiently operate aeration systems. Comparing grain temperatures between the grain near outer walls and the center of the bin will also provide a basic guide on when to aerate. When outer grain is more than 10°F cooler than center grain, aeration should be considered. A 3- to 5-foot temperature probe is essential for aeration management.

Facility site selection

Many factors must be considered when selecting a site for a new grain handling facility or expanding an existing one. The purpose of the facility and place in the company's expected growth plans must be

Table 1. *Suggested grain storage moisture in the midwestern U.S. (% wet basis). Moisture values are for good quality grain that is aerated to control temperature. Reduce moisture content by about one percentage point for grain that has low quality at time of storage. (MWPS AED20).*

	Storage period (months)		
Crop	Up to 6 months	6 to 12 months	More than 12 months
Barley and oats	14	13	13
Buckwheat	16	13	13
Canola	10	8	8
Corn, sorghum	15	14	13
Edible beans	16	14	13
Flaxseed	9	7	7
Soybeans	13	12	11
Sunflowers (confectionery)	10	9	9
Sunflowers (oil type)	10	8	8
Wheat, including durum	14	13	13

carefully evaluated. When locating or expanding a facility consider the following:

- What are the space requirements for the immediate need as well as for future expansion plans?
- Is there adequate electric power available or is electric service economically feasible?
- Is there adequate drainage? (Flood plains are unacceptable sites.)
- Are access roads adequate both in size, number, and condition?
- What are the restrictions on fuel and pesticide storage, and chemical use within state regulation guidelines?
- Are there noise level limitations? Neighbors or possible future housing developments?
- Are there fugitive dust and fine material drift concerns beyond legal limits?
- Is the soil structure adequate for the increased weight of equipment and grain storage?
- Is there room for equipment and truck entrance and exit?
- Is groundwater near the surface?

With new bin design tending toward larger bins and silos, consulting with a reputable grain bin distributor and construction company is essential. Choose a company that has experience not only in the grain storage industry but experience in building these facilities in your geographic location. They will be familiar with weather issues, soil structures, water and drainage issues, and local code and standard requirements.

Bin layouts

The following equipment and buildings should be considered in planning the facility:

- Bins (steel bins, flat storage, or concrete silos) and room for future construction
- Handling and cleaning equipment
- Dryer
- Truck scales
- Feed processing equipment and storage buildings
- Fuel storage
- Chemical storage
- Electrical service and boxes
- Maintenance and management buildings
- Adequate road access and roads within the facility large enough for trucking, combines, trailers, tractors, and loading and unloading equipment.

Focus should be on the efficiency of equipment movement around the site and the safety of moving equipment and material throughout the facility. Some situations may call for remote sites that are close to crop production with a central collection point for processing or shipping. Other operations will require one central location that handles all of the operation's grain and feed processing. The road structure for each situation is critical. A seasonal storage facility may not need to be as extensive as a central handling location. Central storage facilities require careful planning of layout with respect to conveyors, overhead catwalks, downspouts for filling bins, distributor access, dust control equipment, and unloading access.

Safety and groundwater and drainage considerations are paramount when designing pits, tunnels, catwalks, driveways, placement of buildings requiring chemical application such as fumigants, and location of electrical control boxes. Management office buildings and equipment requiring computer support or network connectivity should be identified early so that cabling or remote wireless communication can be established, whether provided by satellite access, underground cabling, or telephone lines. Examples of site and bin layouts are available through consulting engineers and university planning services. The larger the facility and the more expansion anticipated, the more essential planning becomes. A bin layout that will not allow larger trucking access to accommodate an increase in operation size will be a big negative management factor in the future.

Storage

Grain can be stored in a variety of structures. The decision about which kind of structure to use is influenced by the type and volume of grain to be stored, the frequency of loading and unloading, the availability of facility space, and soil and climatic conditions. The goal of storage is to keep the grain in the best condition possible. Individual kernel or seed quality cannot be improved during storage but, cleaning grain can improve the overall quality of the stored and marketed product. Maintaining the least amount of damage and loss of quality depends on the storage facility and the management of the grain. Generally there are five categories of storage units: metal bins, concrete silos, flat storage buildings, hopper bottom bins, and temporary storage areas.

Metal bins

Round metal bins are the most common structure type for storing grain in farm storage facilities. They are relatively easy to build with aeration and loading/unloading equipment, and are relatively low cost compared to concrete structures and flat storage buildings. Metal bins come in a large range of diameters, heights and volumes. The life of these bins is considered to be 20 to 25 years. The frequency of loading and unloading the bins as well as the quality of maintenance and management has significant impact on the structure's integrity. Large metal bins are prone to collapse when unloaded or loaded on one side. Roof collapse is possible if proper maintenance and management of roof venting is not maintained during aeration. The larger the bin diameter, the greater the risk is for problems to occur. Sometimes several smaller bins are a better option than a single large bin. The sizes and number of bins available provide greater flexibility in the selection of bins for storage.

Concrete silos

Dry grain may be stored in upright concrete silos. These tall-roofed silos may be constructed of tile with external steel hoops (ensilage silos) as well as slip-formed reinforced concrete. Aeration can be installed using bottom duct work. The static pressures encountered with tall columns of grain are high. Therefore, it is essential that fan vendors be consulted to insure proper sizing of aeration equipment for deep silos.

An alternative to high static pressure vertical aeration is to use four-duct cross-flow aeration, which greatly reduces fan power, static pressure and "compression heating" of cooling air. Cross-flow aeration requires full silos or special control management of supply and exhaust vents. Four-duct cross-flow aeration uses two fans on opposite ducts. One fan operates at a time with three exhaust ducts (exhausting through the opposite nonoperating fan), then the operating fan is switched by a timer so each fan operates 50 percent of the time — an hour or two of air movement in each direction. This method eliminates the dead air zone in the center of the silo and provides full, uniform air distribution to all grain at all depths. (Navaro and Noyes 2002)

Concrete silos should be unloaded from the bottom center. Offset loading and unloading can cause instability, cracking, and failure in the silo walls. Before loading silos, an inspection of the integrity of the silo walls should give managers a good idea of the safety and feasibility of using the silos, especially if the silo has been in place several years. Unloading from the bottom of these silos may cause bridging of the grain, especially if grain is out of condition or moist. Bridging can cause engulfment hazards for workers entering the bin and unloading failure before the bin is emptied. Upon inspection of the top surface of the grain, a shiny appearance should be present if some of the grain has been unloaded. If the surface is dull and dusty, workers should suspect a grain bridge has occurred and a gap or cavern exists under the top surface of the grain. Workers entering a concrete silo must use confined space entry procedures. They should use the buddy system for communication, operate the aeration system to provide fresh air, check the oxygen and dangerous gas levels in the silo headspace, wear safety harness tied off securely outside the silo, and have good lighting.

Flat storage

Flat storage structures are rectangular low-level buildings that generally contain only one kind of grain stored for a year or more. The advantage to flat storage is that the building can be used for other purposes such as machinery or supply storage. A major disadvantage is that it is more difficult to get even distribution of air for aeration as the grain pile is relatively shallow and peaked in the middle unless a mechanical spreader is available to level the top surface. This peak causes complications in distributing air evenly through the grain. Unless aeration ducts are built flush with the floor, ducting must be moved out of the way of unloading equipment as the structure is unloaded. Another method of unloading this storage is an unloading u-trough auger installed in the concrete floor.

The use of existing warehouse type storage buildings for flat storage poses structural problems. The walls of the building must be strong enough to withstand the excessive load from grain pressure on the walls. Reinforcement of the walls and flooring is essential to prevent deformation, cracking, or failure. Fabricated L-shaped bulkheads reinforced by diagonal steel rods from floor to wall sections of the bulkheads are used to keep grain pressure from walls. Check Midwest Plan Service (http://www.mwps.org/) for grain bulkhead plans.

Hopper bottom bins

The advantages of hopper bottom bins are ease of unloading and self-clean out. Gravity does the work as long as grain is dry and in good condition to flow from the 45-degree bin hopper. Hopper bins are used when grain must be moved frequently. Examples are overhead load-out bins and wet holding bins. Elevated hopper bins require extra support legs and are typically more expensive than flat bottom bins, but multiple uses and labor savings makes them affordable. Aeration involves perforated round or half-round ducts mounted down the slope of the cone bottom with a small vane-axial fan connected to the end or side of the duct through the hopper. Large hopper storage bins may use one large fan connected to three to four ducts inside the hopper by an exterior transition duct.

Temporary storage

Temporary storage is used when crops exceed available space in permanent bins. Different forms of temporary storage have become common for storing corn and milo. Temporary storage may consist of a pile of grain placed on the ground or on a plastic tarp and left uncovered for a short time, or covered by tarps for a longer period until marketed or permanent storage space is available. Storage may consist of short bulkhead walls with aeration system ductwork set on the ground. The material is piled inside the bulkhead walls with a tarp covering the pile held in place by negative pressure of the aeration system.

Uneven aeration and pockets of wet grain and insect activity can cause spoilage and fermentation in the pile and reduce grain quality. The advantage of temporary storage is that walls can be disassembled and stored when they are not needed. Piles can be moved and the area cleaned for other uses when the storage area is not required. Temporary storage is less expensive but provides greater risk of losing product quality in storage and during unloading when the covering is removed.

Another popular temporary storage method is the use of long, white UV-resistant plastic hermetic tubes. Grain is sealed inside the specially designed strong tubing, filled, and unloaded by machines specifically suited for such grain handling. Grain stored in grain tubes should be cleaned and at a recommended moisture content for medium to long-term storage (Table 1). Hermetic grain tubes are relatively inexpensive but are not reusable. Grain tubes are typically about 8 to 10 feet wide and 3 to 4 feet high when filled. They can be up to 200 feet long.

In hermetic storage, grain respiration gradually consumes the oxygen, which slows the respiration and eventually suspends biological activity. Insects in hermetic storage cause oxygen to be depleted faster, Insects die from lack of oxygen, and the entire storage remains in a carbon dioxide storage atmosphere. Grain tubes evolved from haylage tubes developed in New Zealand and Argentina. Grain managers should inspect the tubes for bird or animal damage every week or two, and monitor the internal gas content for carbon dioxide (CO_2) versus oxygen (O_2) levels until time to market the grain.

Sanitation, aeration, and monitoring

Insect infestation is a major contributor to spoilage in stored grain. Good housekeeping and integrated pest management (IPM) practices can help reduce infestations in bins. Removing old grain, fines, and dust when bins are empty reduces the residual habitat for insect populations before new grain is loaded into the bin. Vegetation and trash should be removed from around the outside of bins. Dust, grain, and fines should be removed by vacuuming or sweeping walls, floors, and under perforated floors if possible. Moldy grain attracts and harbors insects. When new grain is placed on top of old, insect infestation is certain. Infestations increase temperature, producing moist hot spots that lead to mold and grain spoilage. Cleaning of harvesting and handling equipment such as augers, conveyors, carts, wagons, and grain buggies is as important as cleaning empty bins. Empty bin insecticides can be applied to empty storage bins and will help to reduce holdover populations of insects. Applicators should follow label instructions and federal/state regulations. Insecticides do not replace good storage housekeeping.

Along with sanitation and insecticide treatments, managing grain moisture and temperature can help minimize insect populations and keep stored grain from spoiling. When grain temperatures are below 70˚F, insects cause less damage and reproduce more slowly than they do in 70˚ to 85˚F grain. Below 60˚F, most insect activity stops. Well-managed aeration using cool outside air can reduce grain temperatures. Aeration fans should be operated until the cooling front travels through the entire grain mass. The amount of time required depends primarily on airflow capacity of the aeration fans. Besides fans, grain condition and fine distribution (peaked versus level), which affects airflow within the grain, are critical.

Generally, for 60 lb/bu grain, the cycle time will be approximately 15 hours of fan operation/cfm/bu. At the minimum of 0.10 cfm/bu, it will take about 150 hours. At the recommended 0.2 cfm/bu, cooling time is about 75 hours. Once the temperature front has progressed through the entire grain bulk, fans are turned off until the average fall or winter air temperature drops another 10˚ to 15˚ F. In the case of some oilseeds and summer harvest grains that tend to "sweat" or self-heat for a period of time after harvest, fans should be operated continually until this phase is complete, generally about a month. Then aeration should follow the method mentioned for lowering temperatures until the grain reaches 30˚ to 35˚ F for winter storage in the northern United States or 35˚ to 40˚F for the central United States. Aeration fans should be covered to prevent insect entry until fan operation is required to cool the grain. Sealing fans is vital to keep cool air in the grain mass from moving out of the bin and pulling warm air down into the grain mass. Fan airflow can be directed up or down. Both directions have advantages and disadvantages, which will be discussed in detail.

Leveling equipment

Leveling the surface of the grain during loading is essential for providing the best air distribution during aeration. Peaks in the grain increase air flow resistance. Forced airflow tends to move around the peaked area instead of through it. More spoilage will occur because of higher temperatures, moister grain, and more insect activity in this center core area under the fill point, where fines and moist weed seeds concentrate. It is important to level the grain surface and spread fines, trash, and small seeds.

Electrically-powered grain distributors (auger types) in drying bins and dry grain storage bins, when properly adjusted, level the grain surface and spread fines evenly, distributing them uniformly throughout the bin. Grain spreaders reduce grain peaks to a rounded surface where the center may be 3 to 5 feet higher than grain at the sidewall. Without some form of distributor or rotary spreader, or a method called "coring" the grain, fines tend to accumulate in a cylindrical column down the center of the bin. In this dense core, grain fines and moist weed seeds fill the kernel spaces, which impedes air flow and harbors insect populations. Electric spreaders are commonly found in bins larger than 24 feet in diameter. In smaller bins, gravity-powered spreaders and grain cones help reduce concentrated fines by spreading fines across much of the surface. Gravity cone spreaders typically leave a donut shaped concentration of fines, which is preferable to peaked grain with a core of fines. If a spreader is not used, the core can be removed by operating the unloading auger until an inverted cone diameter of one-third to one-half the bin diameter is achieved at the top of the bin. This will lower the peak, loosen the center, and remove some of the fines from the center of the grain. Removing grain by coring at intervals while filling the bin (producing an inverted cone of about one-quarter bin diameter at each interval) helps prevent the center concentration of fines, provides some grain cleaning, and removes the peak, which greatly improves aeration uniformity and speeds cooling.

Unloading

Grain can be unloaded from a bin directly into transport vehicles or into another bin for mixing or comingling with other products. Depending on the kind of bin, layout of the facility, and type of grain being handled, load-out equipment can vary widely to include augers, belts, and hopper-bottom gravity fed cones. Unloading the bin evenly is important, so it does not collapse because of eccentric loading. The larger and taller the bin, the greater the risk for bin collapse during unloading.

Unloading grain is faster if grain can flow from the bin. A sweep auger is not required to move grain to the load-out gate if grain is in good condition and not clumped.

Conveyors

Grain conveyance systems vary widely in configuration, but they are all designed to move material from point A to point B. Selection of the type of conveyance system is should be aimed at reducing grain loss and damage during transfers. Common types of conveyors are augers, belt conveyors, flight (drag) conveyors, bucket elevators, and pneumatic conveyors.

Augers

Portable or permanently installed augers move grain horizontally and up inclines. Augers are relatively inexpensive and come in many sizes. Higher energy requirements are a disadvantage of larger capacity augers but they move material quickly. Compared to other conveyance systems, augers move less material per horsepower, but they are simple, easy to maintain, and adaptable to different materials and conditions. Auger power requirements are determined by the diameter, length, pitch of the flighting, speed (rpm), exposed flighting intake length, incline, and physical properties of the grain. Capacity is not affected by the length of the auger but by the diameter and operation speed of the auger. Augers range from from 4 to 16 inches in diameter). Higher grain moisture also decreases the amount of material the auger will convey and increases the power required. The handling capacity of an auger varies by grain type. Manufacturer literature contains information to assist in selection of the appropriate auger.

Belt conveyors

Belt conveyors have a higher capacity per horsepower than augers. Drawbacks are that they are limited to shallow angles of incline, expensive, require permanent installation and require extra floor space. Their primary advantage is gentle conveying, causing minimal grain damage compared with other methods of handling grain. Belt conveyors are used primarily in large facilities and in facilities that handle seed grain, edible beans and soybean seed, or other products that cannot tolerate rough handling.

Mass flow or bulk conveyors

Bulk flow conveyors consist of a housing or trough that contains flights that scrape or push the material along the conveyor path. The flights are usually made of low friction plastic or composition material. These conveyors are gaining in popularity for on-farm operations and used heavily in commercial elevators, particularly in handling seed. Although more expensive, bulk flow "drag" conveyors are reliable and highly efficient, using relatively less horsepower to move grain than augers or belt conveyors .

Bucket elevators

Bucket elevators, or "legs", have vertical conveyor belts equipped with cups for scooping and elevating grain. They are common in bulk grain storage facilities. Elevator legs are at the center of the operation, with most of the grain handled through the leg. They consist of two metal vertical rectangular housings which enclose a belt that supports closely spaced buckets or "cups" bolted to the belt. This belt runs vertically between top and bottom wheels. Grain flows into the cups near the base of the leg and is lifted to the top of the leg where it is centrifugally discharged as the cups rotate over the head drive wheel. Elevator legs can handle almost all kinds of wet or dry grain, meals, processed materials, and feed. Legs can receive or deliver grain to most of the other conveyors in the facility. They require less relative power than most conveyors, are quiet, and have a long service life. Lubricating bearings during routine maintenance reduces the possibility of hot bearings, which can cause grain fires or explosions. Other safety mechanisms should be in place such as power load indicators and leg back-stop mechanisms.

Pneumatic conveyors

High-capacity permanent or portable pneumatic conveyors are gaining popularity in commercial grain- handling facilities. Systems are equipped with positive or negative pressure conveyors. Some mobile units use both positive and negative pressure to vacuum grain before discharging it into a truck or transfering it into another storage. Operators should watch for plugged airways in these conveyors. These systems have a lower initial cost than a bucket elevator but require more power to operate. They often offer less capacity for the same amount of power as a bucket elevator. The advantage of a pneumatic conveyor system over a bucket elevator is flexibility in more easily reaching any bin location. Sharp turns should be avoided to minimize grain impact damage. All 60- to 90-degree turns should use large radius elbows.

Portable pneumatic conveyors can be used as the central handling system on several storage sites located several miles apart where each site has permanent pneumatic tubing that can be quickly connected to the mobile conveyor as needed. Suction-pressure conveyors should have a vacuum and pressure gauge installed on the inlet and outlet of the rotary lobe blower. This allows the operator to fine-tune total pressure to keep the blower from overheating and warping the rotor lobes. Filters must be used to keep grain dust out of the blower. Dust quickly wears down lobes and housing, increasing lobe tip clearance and destroying blower performance through excess bypass air leakage.

Identity Preservation of Commodities

Identity preservation (IP) involves grain industry programs that begin at harvest by segregating grain with specific characteristics from other grain. After initial segregation, the IP program maintains the purity of the grain through segregated handling until it reaches its intended use. Segregation of grain with desirable attributes has increased substantially in the grain industry over the last twenty years. It is common to distinguish identity preservation programs from grain segregation. Identity preservation is a program that identifies a specific grain or seed trait and keeps it labeled and segregated until sold as a specialty grain. Although segregation is a key part of identity preservation grain handling, it does not include all the specific components, such as labeling the trait throughout the system and carrying the identity though until the grain is sold based on that special trait.

Before growth in identity preservation grain handling, traditional grain handling operations were usually *commodity gain* handling operations. Commodity grain is the standard grain flowing through the system that is not known to have special characteristics that command a higher price. For example, “number two yellow corn” is a standard for commodity corn. Much of the corn grown in the United States meets the criteria for U.S. Grade No. 2 corn. Even today there is much more grain handled as a commodity than as a specialty crop with its specific identity preserved until sale.

The commodity grain marketing system developed because of the economies of scale inherent in the large bulk handling systems developed and perfected during the 1950 and 60s. The motivation for IP grain handing is also economic. Grain dealers found that in some markets a premium (higher price) can be obtained for grain with a specific quality attribute that differentiates it from the usual commodity grain quality. That desirable quality attribute increases value to the buyer who is willing to pay a higher price for the IP grain.

When processors are willing to pay a sufficiently higher price so handlers recoup the additional expense of segregated handling plus enough additional profit to make the identity preservation program worthwhile, identity preservation is economically viable. Identity preservation efforts also may be influenced by the desire to avoid commingling that would be viewed as "contamination." Avoiding the commingling of genetically modified (GM) crop varieties into grain that is intended to be GM-free is an example. Often these scenarios are perceived negatively because the economic incentive is a severe price penalty for excessive commingled grain of undesired characteristics. This is in contrast to positive scenarios where the focus is on the economic gain expected for grain with a special attribute.

Some of the earliest identity preservation programs were *passive* programs. In passive programs either the processor or a grain handler obtains grain with specific characteristics even though the grain came into the grain handling system without being identified in advance and segregated from other grain from the outset. The method of finding the special grain may have been fairly secretive in the early days of these practices. (See Christensen and Meronuck (1986) for a discussion of quiet identity preservation buying practices that were known to them at the time.) Some buyers worked more openly, looking for grain with special characteristics, finding processors willing to pay extra for it, and passing on a bit of the extra profit to their source.

Grain commingling usually is an unintentional introduction of other grain during normal handling operations that directly reduces the level of purity maintained in grain moving through the system. For example, if white corn enters a facility that is 99% pure (contains 1% yellow corn), but another 1% of yellow corn gets commingled during handling in that facility, the color purity is reduced to about 98%. Whether intentional or unintentional, unwanted material introduced by commingling propagates through the grain handling system until it is removed or consumed (Herrman, 2002).

The starting point for an IP program is early in the process — if the program addresses the genetic purity of the crop the effort starts with proper field and seed selection, and evaluating pollen drift so that a high genetic purity level is available at harvest. The field should be selected to avoid volunteer plants with the wrong genetics. The seed must be the correct high purity variety, and pollen drift must be accounted for by segregating harvested grain from borders of the field subject to pollination from crops with the wrong genetics. Nielsen and Maier (2001) discuss these issues in detail.

Once harvesting and handling of the crop begins, there is potential for commingling as grain passes through each piece of equipment. All equipment should be thoroughly cleaned of residual grain after the previous year's harvest is complete. This greatly reduces the possibility of insect-infested grain or grain of the wrong genetics being commingled with the new grain at harvest. Commingling data from grain harvesting equipment indicated that up to 185 lb (84 kg) of residual grain remained in some combines where it could commingle with new grain at harvest (Hanna et al. 2009). That amount is sufficient to cause 1% commingling, or "contamination," of 9 tons of grain that was 100% pure originally. Thorough cleanout could theoretically reduce commingling in equipment to zero, but in practice some grain remains after cleaning, perhaps on the order of 1 to 2% of the original residual grain after thorough cleaning. Other items such as grain carts, trucks, trailers, augers, dump pits, legs, dryers, and holding bins have the potential to add additional commingled grain — including insect-infested grain — to the new grain if not thoroughly cleaned (Nielsen and Maier 2001).

Some studies (Hurburgh 1994; Wheeler 1998; Herrman et al. 1999; Maltsbarger and Kalaitzandonakes 2000; Hurburgh 2003) have estimated the opportunities, revenues, benefits, and costs associated with segregation and identity preservation. Other studies (King 1995; Bullock et al. 2000; Herrman et al. 2001; Krueger et al. 2000; Herrman et al. 2002) have investigated the impact of design configuration on the flexibility of elevator facilities in handling specialty crops and on their ability to maintain product identity. Nielsen and Maier (2001) identified key areas in an elevator that provide challenges for identity preservation: receiving pits, storage bins, legs, and other conveyors.

Commingling and residual grain levels have been measured for a receiving pit and elevator boot, grain cleaner, weighing scale, and grain scalper for a research elevator (Ingles et al. 2003). They found that the highest mean cumulative commingling of 0.24% occurred in the grain cleaner, followed by 0.22% in the inline weighing scale, 0.18% in the receiving pit and elevator boot, and 0.01% in the grain scalper. They also found that the largest amount of residual grain in any equipment was 120 kg in the elevator boot. Ingles et al. (2006) evaluated commingling during grain receiving operations in three different receiving pits at a country elevator. They found commingling levels varied significantly among the pits and produced a maximum of 1.3% commingling when receiving 10 t loads. To reduce commingling in handling equipment, grain elevators should either clean the equipment thoroughly between loads of different grains or designate dedicated equipment for handing each type of specialty grain being handled. The second approach, using designated equipment, can be extended to dedicating an entire facility to a specific grain — an approach sometimes used for food corn.

When an elevator has decided to use an identity preservation program where more than one type of grain is received, the inbound grain must be channeled to the appropriate location when it reaches the elevator. In some cases the desired quality characteristic, such as high protein content, is tested for and any grain meeting the specification is routed to a different receiving pit and storage bin. This is the same approach that might be used to check for insect-infested or wet grain and route it for treatment or drying so it does not get commingled with clean or dry grain.

Safety

Accident and entrapment conditions

There are three ways in which people become trapped in grain. All are associated with moving grain during bin unloading and are especially dangerous when grain is out of condition. The three ways are grain bridge collapse, vertical grain wall avalanche, and grain flowing to an unload conveyor, which creates a funnel that pulls a worker under the grain surface. Flowing grain acts much like quicksand; a victim can become entrapped and engulfed in 2 to 3 seconds. Suffocation occurs when the weight of the grain around a victim's chest precludes him from breathing. If someone is trapped in grain above the knees, it is doubtful that the worker or others can pull him out of the grain. Rescue procedures and equipment should be readily available to secure victims from further engulfment until trained rescue personnel arrive.

Lockout/tagout procedures

Lockout/tagout procedures are established to control hazardous energy. OSHA Standard 29 CFR1910.147 gives the minimum requirements for these procedures. The purpose of the procedure is to reduce the likelihood that equipment will be energized while personnel are working inside the bin or the area where equipment is installed. Each qualified maintenance person must have a unique key, hasp/lock and tag that can be placed on equipment which will prevent the equipment from being energized as long as the lock is in place. If a lock is not available or the equipment cannot be locked, a tag may be used to notify users that the equipment cannot be energized until the tag has been removed by the person placing it on the equipment.

Any time a worker must enter a grain bin, lockout/tagout procedures should be employed. This secures the equipment (e.g., unload conveyors) that could cause grain to move and subsequently present a hazard for entrapment and engulfment. Managers must become familiar with the OSHA regulations and use the examples to set forth their facility's safety program.

During grain bin accident rescue operations, lockout/tagout must be a part of the procedures for securing the facility before entry into the bin by rescuers. An extra step for security would be to place an employee by the lockedout/taggedout equipment to monitor the area making sure no one violates safety procedures.

Coffer dams

Coffer dams are placed around a victim who is trapped in grain to keep the grain from continuing to engulf the victim. Once the coffer dam is in place, grain between the victim and the coffer dam can be removed using a vacuum or scoop until the victim is able to free himself or be safely lifted or pulled from the grain. Coffer dams are available commercially or can be constructed of readily available plywood or sheets of metal. The idea is to place a boundary between the victim and the grain to relieve the pressure of the grain entrapping the victim.

Emergency preparedness and training

All grain handling facilities are responsible for keeping their employees informed of safety regulations and prevention measures. Every employee should have an awareness level of knowledge about the hazards of handling grain and the causes of grain entrapment or engulfment. Along with elevator personnel, local fire departments and first responder units should have knowledge of the grain facilities within their jurisdiction. They should also be provided with the basic skills of stabilizing a victim until specially trained crisis teams can arrive at the scene of an accident to affect the recovery or rescue. This level of training would include methods of handling coffer dams, safe bin entry procedures, air quality monitoring, and victim stabilization.

Awareness level training should include information about what causes grain to go out of condition, the different ways a grain bin accident can occur, lock out/tag out procedures, safety procedures for entering a grain bin when it is necessary, bin entry permit requirements, and procedures for initial response in the case of a co-worker or individual accident. Advanced training should include high angle rescue techniques, stokes basket techniques, bin emergency unloading methods in addition to all of the information from the lower-level training.

Condition awareness

Many of the conditions requiring grain bin workers to enter bins and risk a dangerous situation are caused by grain going out of condition. Workers may enter the bin because grain has become stuck to walls, formed clumps that clogged unloading equipment, or formed a crust on the surface causing a bridge with a cavity under the surface to occur when grain was unloaded from the bottom of the bin. Each of these situations can entrap a worker who becomes covered by an avalanche from the wall of grain or falls through the crusted surface into the cavity below. Augers can cause limb amputation and even death if workers become entangled in the equipment while attempting to remedy unloading/recovery stoppages. The message here is that if the grain is kept in good condition, there are few reasons to chance entering the dangerous environment inside the bin.

It is important that rescue teams understand how grain can go out of condition so that they know what working conditions they will encounter when entering the bin during a rescue. Knowledge of potential air quality issues, possibility of fumigant presence, and the presence of molds and grain dust that may cause allergic reactions is important. Knowing that grain acts like a combination of a solid and a flowing liquid product at times is essential so workers are aware of the possible dangers. Monitoring grain temperature and conditions regularly gives workers and rescue units a hint of the conditions to expect when entering the bin. Temperature hot spots and moldy clumps of grain cause many accidents. These conditions can be monitored and remedied many times without entering the bin if managers are aware of their presence.

Drying

Those involved with the management, operation, and design of drying systems need to understand the principles of drying and how a particular situation may dictate the desired final moisture content for storage of grain and selection of a drying method. The following presents a broad overview of these principles and considerations.

Purpose of drying systems

Drying is usually the most economical choice for successful storage of grain and seed products, especially in the long-term. Economic considerations that influence drying and storage system selection include the following:

- Opportunity for earlier harvest, which reduces the potential for weather- and pest-related field losses while maintaining the quality and quantity of harvested grain and seeds.
- Reducing the net price penalty (dockage) from the sale of high-moisture grain and seeds.
- Increasing options regarding when, where, and for what purpose the grain may be sold or used for feed.
- Greater total farm efficiency from better utilization of labor, equipment and other resources associated with shortening harvest and possible double cropping or fall planting.

- Risk associated with processing and maintenance of grain between harvest and time of sale.

Moisture content

Grain comprises moisture and dry matter. The "wet basis" moisture content of grain is defined as the percentage of total weight of the sample that is water; that is:

$M_{wb} = W_w \times 100/W_t$ where M_{wb} is the percent moisture content on a wet basis and W_t is the total sample weight comprised of water (W_w) and dry matter (W_{dm}).

The "dry basis" moisture content of grain is the ratio (expressed as a percentage) of the water in the grain to the dry matter; that is:

$M_{db} = W_w \times (100)/W_{dm}$, where M_{db} is the percentage moisture content on a dry basis.

Wet basis readings are used in the grain industry (and in this chapter). Dry basis readings are used primarily in scientific research and professional journals. Conversion from one basis to another may be made using the following equations:

$M_{db} = [M_{wb}/(100 - M_{wb})] \times 100$ and
$M_{wb} = [M_{db}/(100 + M_{db})] \times 100$

Bushel

In producing, marketing, and utilizing grain, the quantity involved is usually stated in terms of bushels. The term "bushel" can have different meanings depending on the situation in which it is applied. By definition, the bushel is a volume measure containing 1.25 cubic feet. For trading purposes it is usually designated for each type of grain as a unit weight for a certain moisture content as specified by USDA Grain Standards (often called a "dry bushel"). Sometimes a bushel may refer only to a weight without regard to moisture content (called a "wet bushel").

Shrinkage

Shrinkage refers to the loss of grain weight and volume associated with drying (and to a lesser extent handling in the form of dust, foreign material (f.m.) shrunken and broken kernels (s.b.) and trash). Shrinkage is an important economic consideration when buying and selling grain.

Dockage

Dockage refers to the reduction in price associated with failure to meet the standards in place at the time of the sale. Excess moisture usually is the largest component of dockage — in effect, the penalty associated with the difference between buying and selling wet bushels and dry bushels.

Airflow

In drying grain, airflow is usually expressed in terms of cubic feet of air per minute per bushel (cfm/bu). It is important to recognize in grain drying systems that cfm/bu decreases non-linearly with increases in the height of the grain column through which the drying air passes.

Air-water vapor properties and mixtures

Grain drying depends on air-water vapor mixtures and properties as well as grain moisture content. The following properties are all interrelated mathematically so that any two of these can be used to compute the remaining ones — dry bulb temperature, wet bulb temperature, dew point temperature, humidity ratio, vapor pressure, relative humidity, enthalpy, humid volume and specific volume. All are important when analyzing the drying process scientifically, which is beyond the scope of this chapter. Changes in the air-water vapor state during the drying process can be visualized graphically and computed for design purposes using a psychrometric chart.

For purposes of this chapter, it is especially important to consider the following air–water vapor properties.

Vapor pressure – Vapor pressure is the pressure exerted by the water vapor in a given sample of air. If the air is saturated with water vapor — that is, it contains all the water vapor it can hold under the existing conditions — the pressure is referred to as the *saturated vapor pressure*. Both the dry air and the water vapor components of any air-vapor mixture produce partial pressures related to the mixture temperature and the relative concentration of the components. Total vapor pressure is equal to the sum of the component partial pressures and, in an unpressurized environment, is equal to the prevailing atmospheric pressure.

Relative humidity – Relative humidity is defined for a given dry bulb temperature as the ratio of the vapor pressure of the water vapor contained in an air-vapor mixture to the vapor pressure of an air-vapor mixture that is completely saturated (air having a relative humidity of 100%).

Enthalpy (heat content) – Enthalpy is the amount of heat energy contained in an air-vapor mixture per unit weight of dry air. It is usually expressed in terms of btu/lb dry air and includes both sensible and latent heat components. Sensible heat is that heat associated with a dry bulb temperature increase of an air mixture. Latent heat, as used in air-vapor mixtures, is the heat required to change the state of water (liquid to vapor or vapor to liquid) without changing its temperature.

Grain equilibrium moisture content

Drying and storage relationships for various grains are directly related to their equilibrium moisture properties. Because grain is hygroscopic, it will exchange moisture with the surrounding air until the vapor pressure of the moisture in the grain and that of the air reach a state of equilibrium. If grain comes to equilibrium with air moving through it at constant environmental conditions, the grain moisture content is referred to as the equilibrium moisture content (EMC) corresponding to the existing air conditions. If the grain is surrounded by a limited amount of air (such as in interstitial spaces of a grain mass in storage bins), the air will reach moisture equilibrium with the grain without any significant change in the grain moisture content. The relative humidity of the air in this situation is referred to as the equilibrium relative humidity (ERH) corresponding to the existing grain moisture content at the prevailing temperature. All equilibrium moisture properties are a function of temperature; that is, the properties change with changes in temperature. Equilibrium moisture properties are specific for each type of grain.

Equilibrium moisture properties are important in analyzing drying and storage systems and in developing storage and drying recommendations. Especially noteworthy is that most storage fungi cannot grow and reproduce in grain that is in equilibrium with air at a relative humidity (ERH) less than 65%. Many molds are limited at 70% ERH. The activity of storage insects greatly decreases at relative humidity below 50% (most insects cannot maintain body moisture eating very dry grain), although this is not commonly used as a control tool for stored grain insects.

Grain drying fundamentals

In most grain drying systems, ambient air is heated and passed through grain so that a relatively high vapor pressure gradient is produced between the moisture in the grain and the moisture in the drying air. This differential causes moisture to move from the grain to the air that is flowing past the kernel where it is then exhausted from the grain mass to the outside atmosphere. In the most simplistic drying situation, the grain and the air that surrounds it are in equilibrium before the introduction of heated air, and the properties and rate of flow of the heated air entering the grain mass remain constant during the drying period. In such a situation, the heated air transfers its heat to the grain and creates a new equilibrium moisture content based on the new differential vapor pressure. The drying air begins absorbing moisture from the first kernels that the air contacts. This process continues until the drying air, falling in temperature and increasing in relative humidity, can no longer add additional moisture because it is in equilibrium with the remaining grain mass. Simultaneously, the transfer of moisture from the grain to the drying air becomes increasingly more difficult as the grain dries, so much so that stress cracks can occur if the grain is dried too quickly or is overdried.

Effectively, the above process produces a drying front and a drying zone. All grain behind the trailing edge of the drying zone would be in a new, stable equilibrium moisture condition with the heated air. The grain ahead of the drying zone would remain essentially in its initial equilibrium moisture condition. The grain in the drying zone would range from highest moisture content at the start (leading edge) of the drying zone to driest at the end (trailing edge) of the drying zone.

The simplistic drying situation described above seldom happens for very long. In practice, the grain being dried varies in temperature and moisture content during harvest, gradually losing moisture in the field during harvest. It may contain differing levels of fines and trash that influence the distribution of airflow. Heat is lost or gained in the grain mass because of changes in ambient air conditions surrounding the mass. Properties of the ambient and heated air also change during the drying process as daily weather changes occur. Some generalizations should be considered when evaluating the drying process:

- If there is sufficient variation in the temperature and relative humidity of the drying air relative to the grain mass, some zones in the grain mass may experience heating, cooling, drying or rewetting relative to other zones.
- Safe storage conditions are reached when all the grain has been dried to a safe equilibrium moisture content (65 to 70% ERH or lower), either by passing the drying front completely through the gain mass or by thoroughly mixing the grain so that the overdried and under-dried grain can equilibrate to a safe storage moisture condition in an acceptable amount of time.
- Drying is most efficient when the drying air has come into full temperature and moisture equilibrium with the grain as it passes through the grain mass.

Efficiency, design considerations, and management

Measuring efficiency in grain harvesting, handling, drying and storage systems has many dimensions. The goal is to optimize the entire system rather than a particular component such as drying. Important design and management considerations include:

- Drying capacity increases with increases in drying air temperature and airflow as does the potential for over drying and associated grain quality reductions.
- Drying efficiency alone is usually measured by dividing the sum of energy required to heat the drying air and to force this air through the grain by the theoretical amount of energy required to evaporate that same amount of water. Sometimes only the numerator is used as the basis for comparison.
- Overdrying and inefficient use of airflow reduces drying efficiency.
- Efficient design of grain harvesting, handling, drying and storage systems begins with determining a daily harvest rate that properly balances the composite set of equipment needed to both harvest and safely secure the entire crop.
- After determining the daily harvest rate, the next design key is to determine the allowable drying time for successful storability, which depends on a combination of grain temperature and moisture content.
- The final choice for a type of drying system is based on a combination of daily harvest rate and allowable drying time linked with individual values and resources concerning such things as cost, marketing, risk, flexibility, convenience, and future expansion.

Basic grain drying systems and techniques

While there is no guarantee that past trends will continue, the average daily harvesting rate has increased for many years in magnitude and importance as a design factor. This has generally shifted the selection of grain drying systems away from comparatively lower temperature in-bin drying systems to higher temperature external drying systems. Contributing to this trend are advancements in sensor and control technology that have enhanced energy efficiency in the higher temperature dryers.

The assumption in the discussion that follows is that each of the drying systems, including those using bins, is adequately designed and equipped with drying/cooling fans, perforated floors, grain spreaders, venting systems and handling equipment for efficient loading and unloading. Inadequate venting can be especially problematic for in-bin drying, or cooling when moisture removed from the grain is restricted from efficiently exhausting from the bin, resulting in condensations on the roof or bin walls causing rewetting of parts of the grain mass.

Note also that the choice of drying system and technique is based on individual situations; no single type of drying system will work well for everyone. Accordingly, the following options are offered that reflect possible needs of producers and commercial grain managers extending from relatively low to relatively high daily harvest receiving rates.

Natural or ambient air drying

Natural air drying is a process where unheated air is forced through the grain mass until the grain reaches equilibrium moisture condition with average ambient air conditions. Drying with natural or ambient air can be accomplished only if the air temperature and relative humidity conditions allow a net moisture transfer from the grain to the air, which may be problematic. The potential for natural air drying is enhanced because the energy inefficiency from operating the drying fan results in a temperature rise in the drying air of 2° to 3°F. Other than heat from the fan operation (fan motor heat and mechanical heat of compression), energy for evaporating the moisture from the grain comes from the energy contained in the ambient air. Natural air drying is a basic form of solar drying.

Natural air drying is usually the most energy efficient method for drying grain. It is also the slowest and usually becomes slower over the harvesting period because air temperature generally decreases as does airflow rate per bushel as the bin is filled. Because of slow drying, natural air drying also has the greatest potential for grain spoilage because drying capacity often lags harvest capacity, and weather losses or harvested wet grain may mold while waiting to be dried. Consequently, natural air drying requires the highest level of management if spoilage and aflatoxin problems are to be prevented.

Low temperature drying

Low temperature heated air drying of grain is the process by which relatively low amounts of energy are added to the drying air, raising its temperature approximately 10° to 15°F above ambient conditions. Usually, electricity is the thermal energy source; hence the term "electric drying" is sometimes used instead of "low temperature" drying. LP gas and solar energy also may be used as thermal energy sources.

The low temperature drying method is assumed to always have potential for drying grain within the accepted moisture contents associated with long-term storage. This is contrasted with natural air drying where outside air conditions may not allow adequate drying for extended periods of time.

Low temperature drying is a relatively high risk drying system requiring substantial management ability. Generally, it is preferable to natural air drying because drying can occur in most types of weather. When used successfully, low temperature drying results in high quality grain. Its susceptibility to failure during high temperature – high relative humidity conditions during harvest limits its application to warm to hot, low humidity or cooler geographic regions.

Layer drying

In-storage layer drying is a process whereby the grain is dried in layers in the storage structure with the entire grain depth ultimately being dried in place. The process begins when the initial grain layer is placed in the drying bin. The drying air establishes the drying front that moves through the grain. Additional layers of wet grain are added periodically so that a depth of wet grain always precedes the drying front. As the drying bin fills, each successive layer is thinner. The quantity of grain that can be placed in any one layer is limited to that which can be dried before excessive mold growth or aflatoxin develops in the top of the layer. This drying technique is used most successfully in grain systems where relatively slow harvest rates are acceptable and harvest volumes are low to moderate.

Layer drying offers the advantage of low heat input, making it one of the most energy-efficient drying methods in terms of the amount of heat required to remove moisture from the grain. The drying air temperature should be limited to no more than a 20°F rise above ambient conditions in order to prevent excessive overdrying. A criticism of layer drying is that the bottom 15 to 25% of the grain is always overdried. A control mechanism for limiting the drying capacity of the air, and hence the final equilibrium moisture content of the grain, is to place a humidistat in the plenum chamber. The control level for the humidistat normally ranges from 50 to 60% relative humidity (Rh) depending on the type of grain, with 55% being a typical setting.

Layer drying necessitates superior management skills. The system leaves little margin for error because of its relatively low reserve drying capacity.

Batch-in-bin drying

Batch-in-bin drying refers to the process where the grain is dried in a drying bin each day in a batch, usually 2.5 to 4 feet deep, then cooled and moved to a storage bin in time for the next day's harvest. When storage bins are full, the drying bin may be filled and the grain dried in layers. No wet grain storage is needed with this technique because the batch size constitutes one day's harvest. The basic principle behind the operation of a batch-in-bin dryer is to force high volumes of air through a relatively shallow grain depth in order to obtain rapid drying, allowing the producer to accommodate larger harvest rates than with other in-bin drying methods. A batch-in-bin system allows drying flexibility in that the drying depth may be varied based on day-to-day operating conditions. As a result, the producer is able to adjust the harvesting schedule if necessary.

Batch-in-bin drying air temperature typically ranges from 120° to 160°F, with 140°F being a recommended average drying temperature for shelled corn. When designing batch-in-bin systems, it is desirable that the fan/bin combination dry the daily 8 to 10 hour harvest in about 16 hours. After drying is completed, the cooling process will usually require another 2 hours. Handling will also require 2 additional hours for a total of 20 hours of activity each drying day. The remaining 4 hours provide catch-up time in case of breakdowns, harvesting delays, etc.

With a good fill leveling system, drying can begin after ½ to ⅔ of the day's harvest is binned. Two drying bins allow the operator to alternate filling, so that unloading the bin into storage bins is less critical. Two bins provide more flexibility and drying capacity to handle wetter grain during the early part of the harvest. Batch-in-bin drying is often unacceptable from a labor and management perspective because the system requires attention on a 20- to 24-hour basis and the grain must be handled twice before going into storage. Management skill is not as critical as with other in-bin drying methods because the operator has many learning experiences per harvest season and can make daily adjustments in system operations.

Operators must recognize that deep batch-in-bin drying results in drier bottom grain mixing with wetter surface grain for an "average" storage moisture. In 15% average moisture dried corn, bottom grain may be 11 to 12% while upper grain may be 17 to 19%, depending on the initial moisture of the corn. Thus, good mixing of the entire batch during transfer is essential, as mixed kernels will equilibriate to within 1 to 2% from the average moisture in storage.

Automatic batch/continuous flow

Automatic batch and continuous flow are two popular high-speed grain drying techniques. Both dryer types are similar in appearance and operation. Both also require wet grain storage ahead of the dryer, and some facilities may require a surge bin for temporarily holding dry grain that exits the dryer. The basic principle in both dryer types is to force high quantities of air (50 to 125 cfm/bu) through 12- to 24-inch grain columns to obtain high drying rates. The automatic batch units usually self-load, dry, cool and unload a fixed amount of grain into storage per batch, whereas continuous flow units meter cool-dry grain from the drying chamber continuously. Automatic batch dryers are classified as stationary bed dryers. Continuous flow dryers may be categorized into three types:

1. **Cross-flow –** Drying air is blown across the grain column similar to automatic batch driers.
2. **Counter-flow –** Drying air and the grain move in opposite directions, and
3. **Concurrent-flow –** Drying air and grain move in the same direction.

The main advantage of an automatic batch or continuous flow drying unit is its greater drying capacity compared to bin drying. Most are completely automated, thus reducing labor for loading and unloading. They are available in many different sizes to accommodate a wide range of drying needs. They are somewhat portable which allows for relatively easy replacement associated with either wear-out or expansion of capacity. The main disadvantage of these drying units is relatively low energy efficiency. But advances in electronic control systems and the addition of heat- recapture systems have improved the energy efficiency of these dryers by 35 to 50% compared to non-energy saving models.

In-bin continuous flow

In-bin continuous flow drying most often utilizes the grain bin as a combination wet-holding and drying bin. Wet grain from the harvest is loaded directly into the drying bin. As the grain becomes dry, it is removed from the bottom of the drying zone by either gravity (for systems with drying platforms near the roof) or by a tapered sweep auger (for floor supported systems); thus, to some extent, this system is a "counter-flow" dryer in that grain and air are moving in different directions.

In-bin continuous flow systems have several advantages over other in-bin drying systems. The use of higher drying temperatures increases the drying capacity without overdrying the bottom grain layers because the dried grain is continually removed at the desired final moisture content. The drying capacities of in-bin continuous flow units are similar to automatic batch-continuous flow dryers but usually have greater drying efficiency.

Combination drying systems

Combination drying is an approach to drying where both high-temperature processes and in-bin drying (natural air, low-temperature or layer) procedures are used. The high-temperature method is used to dry relatively wet grain to a sufficiently low moisture content so that in-bin drying can be used to successfully complete the drying process before spoilage would occur.

The advantages of combination drying relate primarily to risk, drying fuel energy savings, facility expansion cost, and enhancement of grain quality as compared to using only high temperature drying. Combination drying offers a low risk method of utilizing in-bin drying. Drying efficiency is less than most in-bin drying methods but greater than high-temperature processes. Combination drying requires a relatively high level of capital investment and management if purchased as a unit because two complete drying systems are included. It may represent a relatively inexpensive way of adding drying capacity to an existing system. Keep in mind that in combination drying, both the high temperature and bin driers are sized smaller than if each was designed to do all the drying.

Supplemental aids to drying

A supplemental aid to drying is some secondary combination of equipment and management that enhances the drying process. Examples are the following:

Stirring devices

Stirring devices are used to enhance in-bin drying performance. These devices are machines suspended from the top of the bin at the roof eave level with one or more small vertical augers extending through the grain mass to within 1 to 2 inches of the drying floor. The augers move continually through the grain mass lifting grain kernels from the bottom of the bin toward the surface, mixing them with kernels in the upper layers in order to constitute a continuous mixing effect in the grain mass.

Stirring devices may be used to enhance most in-bin drying systems. Continuous lifting and mixing reduces the moisture gradient in the drying bin and practically alleviates overdrying of the bottom grain. Stirring loosens the grain density by about 10% (operators can only fill 85 to 90% of the grain depth below the eave), which significantly reduces the resistance to air flow in the bin, which in turn provides a proportional increase in the fan airflow and drying rate.

Dryeration

"Dryeration" is the process by which high temperature grain (mostly used in corn drying), taken directly from a dryer, is systematically tempered (no aeration), and then cooled in order to extract additional moisture from the grain without using any additional fossil fuel for direct heating of the drying air to dry grain to final moisture. Under proper management and representative conditions, approximately 2 points of moisture content may be removed through *dryeration*.

Dryeration operates as follows: (1) Hot grain is transferred from the dryer into a specially sized hopper holding tank immediately after being dried at high temperatures and thus contains excess (stored) heat; and (2) The hot grain then tempers for several (4 to 10) hours after which the stored heat is slowly removed using relatively high aeration airflow rates (preferably 0.5 to 0.75 cfm/bu) and latent heat rather than sensible heat transfer mechanisms. Because high temper drying stops before the final 2 to 2.5 points are removed, and the hot grain tempers before being cooled slowly for 8 to 12 hours, high grain quality is maintained and drying energy efficiency is increased while the external drier capacity is increased by 75 to 100%. The primary disadvantage of dryeration is that the logistics of this process are somewhat more difficult to manage than with a conventional high temperature drying system, and additional equipment costs may be incurred to install dryeration bins and fans. Doubling the capacity of an existing dryer often makes dryeration economically attractive for the farm and commercial grain industries when compared to adding another new dryer of the same size with wet holding tank plus the necessary electric power and other handling equipment. Moreover, dryeration may result in a premium final grain quality.

Theoretically, dryeration has the potential of 3.5 % moisture removal in high temperature corn drying. The development of insulated continuous-flow dryeration tempering and cooling bins minimizes management issues while further improving the efficiency to 2.5 to 2.75% removal during the temper/cool process.

In-bin cooling

In-bin cooling is an alternative to conventional dryeration. In this process the grain is cooled and stored in one bin so that extra handling is not required, and logistical management is not needed with regard to scheduling. As with conventional dryeration, air is blown upward through the grain, with the hotter grain being added on top of existing grain. The fan begins operation after the floor has been sufficiently covered with warm or hot grain. Fans are operated continuously until the grain reaches the average daily temperature.

Typically, this process is used with a system that had been employed previously for in-bin drying (natural air, low temperature or layer drying) so that little additional investment is needed. It offers another advantage in that any of these in-bin techniques may be used to further dry the grain, thus becoming a combination drying method.

Disadvantages of in-bin cooling, as compared to using an intermediate bin for *dryeration*, relate primarily to a lack of tempering time, which results in reduced moisture removal, lower quality, and possible condensation under the roof and along bin walls. It is also important that sufficient roof venting be in place to prevent moisture from condensing in the bin and rewetting the grain mass.

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11 Grain Aeration

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Aeration is the forced movement of ambient air by fan power through a grain bulk to improve grain storability. Aeration is primarily used for cooling, but additional objectives are to equalize grain temperature throughout the bulk, promote limited drying, and remove fumigant residues and odors. Aeration is distinguished from "passive" or "natural" ventilation, which takes place in corn cribs, where sidewall wind pressures force ambient air through the grain, causing slow natural drying of damp unshelled corn, or in grain bins where roof wind forces create suction convection currents between roof vents and base fan openings. Aeration flow rates should be distinguished from recirculated fumigation, which uses very low airflow rates, and from drying, which uses very high airflow rates compared to aeration.

Aeration is widely used in stored grain management programs in the United States. Pioneering engineering work of U.S researchers such as Foster (1953), Robinson et al. (1951), Shedd (1953), and Holman (1966) and research on technological aspects of aeration by Hukill (1953), and more recently by Cuperus et al. (1986), Arthur and Casada (2005, 2010), and Reed (2006), form the basis of modern grain aeration systems. Aeration technology is used to modify the grain bulk microclimate to reduce or eliminate the development of harmful or damaging organisms in the grain by reducing and maintaining grain temperatures at safe levels below humidity levels which support microflora activity. Aeration helps sustain favorable storage conditions for the safe preservation of grain quality.

Substantial storage losses can be caused by microflora that flourish in moist grain and insects that can be destructive if preventive measures are not taken. These losses should be considered a result of interactions between components of the ecosystem, affected by grain and ambient weather conditions. Interactions between damaging pests, the grain, and other physical components of the system form a dynamic infrastructure, with each component continuously affecting the others. The role of aeration in this ecosystem is to uniformly "condition" the stored grain to a desirable low temperature and maintain desirable conditions in the grain bulk by moving the sufficient air volumes of suitable quality through the grain mass (Navarro and Noyes 2002a).

The purpose of this chapter is to guide grain managers on the concept of using aeration to preserve grain quality and manage insect populations in conventional farm and commercial grain storages.

Aeration Objectives

The objective of aeration is to maintain the quality of bulk grain in storage. Although aeration can improve storage conditions, aeration does not improve intrinsic quality attributes of grain.

Cooling the grain bulk for pest suppression – Cooling grain is the primary objective of grain aeration (Reed and Arthur 2000, Reed and Harner 1998a) when discussing pest suppression.

Stored grain insects are of tropical or subtropical origin and require fairly high temperatures, typically 75° to 90°F (24° to 32°C) for development. Grain-infesting insects are sensitive to low temperatures. Stored product insect development is generally stopped below 60°F (16°C); there is little insect survival above 110°F (43°C). In the southwestern and south-central U.S., temperatures of wheat, rice, and sorghum at harvest can range from 90° to 110°F (32° to 43°C), depending on the specific crop and location. During fall harvest in the northern U.S., grain temperatures around 50° to 65°F (10° to 18°C) are typical.

At temperatures below 70°F (21°C), population growth of most storage insects is significantly suppressed. Grain temperatures of 60° to 70°F (16° to 21°C) are considered "safe" for insect management, because feeding and breeding are slow. Complete life cycles at these temperatures take three months or more, so insect population growth remains insignificant. Insect damage caused under these low temperature conditions is minimal (Flinn et al. 1997).

The crucial control parameter for mite pests is not temperature, but establishing an equilibrium relative humidity (ERH) below about 65%. About 12.5% moisture content (MC) for wheat at 77°F (25°C) suppresses mite development (Cunnington 1984, Navarro et al. 2002). Temperatures required to suppress mite development in damp grain (14% to 16% moisture content wet-basis) are obtainable in temperate climates. Maintaining low uniform grain temperatures is too expensive at the bulk periphery when mean ambient temperatures are favorable for mite development. Although cooling moist grain is unlikely to prevent moderate mite infestation, aeration is expected to minimize "hot spots" and heavy mite populations associated with them.

Suppression of microfloral growth – Low temperatures are required to prevent mold damage in moist grain. Temperatures below 40°F (5°C) are needed for the suppression of most mold development. For suppression of *Penicillium* molds, temperatures must be below 0°C. Most fungi do not grow at relative humidities below 70%, which is equivalent to roughly 13% moisture content for cereal grains at typical storage temperatures. The moisture content threshold is lower for oilseeds. In practice, mold growth is dependent mainly upon interstitial air humidity. Although cooling grain may not seem like an efficient method for controlling mold, at lower grain temperatures, mold damage is reduced.

Maintenance of seed and grain quality – Low kernel temperatures are desirable for better maintenance of seed and grain quality. Studies have shown that the lower the temperature (within certain limits), the longer the seeds maintain full viability. A rule of thumb (Harrington 1973) states that a seed's life span in storage is doubled for each 9°F (5°C) decrease in temperature (within the range of 32° to 122°F (0° to 50°C) and for each 1 percent decrease in seed moisture (within the range of 5% to 14%). Seeds are commonly stored with equilibrium relative humidity from 30% to 40% with good results. For extended storage times of seeds, Vertucci and Roos (1990) recommend the best storage moisture content is between 19% and 27% equilibrium relative humidity.

Equalization of temperature throughout the grain bulk – Because of self-insulating properties, grain placed in storage during summer harvest retains initial harvest temperatures for a long time before cool weather arrives in the fall (except for grain near bin walls, exposed conical base, or the surface). It is recommended that harvest heat be removed by nighttime suction aeration as soon as ambient temperatures are 15° to 20°F below internal grain mass temperatures to minimize insect activity at or near the grain surface. The initial cooling should be followed by additional aeration when generally lower ambient temperatures will allow cooling the entire grain mass below 70°F.

Prevention of moisture migration in the grain bulk – As the ambient temperature drops during the cool season, the surface (and peripheral) layers of the grain become considerably cooler than the internal grain mass. Temperature gradients are established in the grain bulks that can lead to convection currents that circulate air through the intergranular spaces. In large bulks, the cold dense air settles along the outer walls. The warmer air (which contains more moisture than cool air) moves toward the colder upper surface of the grain bulk. When the warm air reaches the cool layers of the grain bulk, moisture condenses and creates wet layers or spots in the grain. Recent studies (Montross et al. 2002, Montross and Maier 2001) suggest a new moisture equilibration theory for the mechanisms involved in this moisture movement in a non-aerated grain mass. Using the finite-element model they developed, additional large-scale trials will be required to demonstrate the effect of significant temperature gradients on moisture condensation due to convection currents that carry moisture into the cool layers of the grain bulk. On the other hand, the traditional natural convection hypothesis suggests that the natural convection currents in the grain bulk alone are sufficient to cause large amounts of moisture to "migrate" to cooler layers or the cooler surface grain, where the air cools to "dew point" and deposits excess moisture, slowly increasing the grain moisture content in the upper parts of the grain bulk.

Prevention of head-space and down spout condensation – Under-roof condensation is a different natural process than moisture migration within the grain bulk. Condensate that drips on the grain involves moisture in humid air, which accumulates in the head-space above the grain bulk and condenses on the under-surface of the bin roof. Bins with sufficient roof vents and open eave gaps (spacing of ½ to 1 inch) between sidewall and roof, generally have enough natural ventilation to avoid under-roof condensate. Condensate is especially problematic in bins with eave gaps that are permanently sealed to prevent fumigant gas losses and easy grain access for insects.

Prevention of biological heating of dry grain – In grain bulks where infestation is localized, insect populations develop in small pockets of grain. The lesser grain borer and the three primary weevil species found in grains in the United States — the rice weevil, the maize weevil, and the granary weevil — are characteristic species that develop localized infestations in bulk grains, creating hot spots. Temperatures of heavily infested grain undergoing widespread heating are typically about 100˚ to 110˚F (38˚ to 43˚C). When heavy infestations are discovered, the grain should be fumigated immediately to stop insect activity. Then aeration should be used to cool the grain bulk.

Prevention of spontaneous heating of moist grain – In warm moist grain (equilibrium relative humidity greater than 70%), respiration can become very intensive due to mold development. High levels of respiration produce a phenomenon called "spontaneous heating." Heating of the grain bulk is detrimental to grain quality. In spontaneous heating, hot spot temperatures can easily reach 135˚to140˚F (57˚ to 60˚C) creating steep temperature gradients between heated and surrounding cool grain. In bulks containing oil rich seeds such as cottonseeds, soybeans, and sunflower seeds at sufficiently high moisture conditions, very high temperatures are generated and "spontaneous combustion" can occur, starting a fire. Do not operate aeration fans if fire is detected (by the smell of smoke or burning grain in the exhaust air stream) in a grain bulk.

Limited grain drying by aeration – A small, but significant drying effect (from ¼% to ½% moisture loss per aeration cooling cycle) is typically experienced, and during long-term aeration (multiple cooling cycles) up to 2% moisture reduction may occur while cooling large grain bulks. Because of the very low flow rates during aeration, the drying front moves slowly, and this small drying effect is usually limited to the grain near the entrance of the aeration air. This grain moisture loss is reflected in a corresponding shrinkage or market weight loss in the grain bulk. This must be considered in grain management as a cost for keeping grain safe for marketing. Aeration moisture shrinkage as well as "invisible" handling loss will affect facility records significantly and should be considered when grain receipt and delivery records from storage facilities or sites do not tally.

Removal of fumigant residues and odors – The release or desorption of fumigants at the end of a fumigation can be achieved with relatively low air flow rates. The aeration system can be operated intermittently (in pulses) to flush gas vapors from the grain bulk and storage. Aeration systems can be operated for 10 to 15 minutes every two to three hours to allow interstitial air space to reach equilibrium with the concentration of the fumigant in the grain. Thus, the aeration system can be operated several times to ventilate the storage. Storage odors also can develop in a grain bulk due to hot spots containing insects or moldy grain. Sour odors result from anaerobic activity in the process of fermentation at high moisture contents (above 18% for cereals). At moderate moisture levels (14% to 18% moisture content for cereals), musty odors in grain are usually caused by the growth of certain molds. Other odors occasionally found in grain are considered commercially objectionable foreign odors (COFO) because they are odors that are foreign to grain and render it unfit for normal commercial usage. Most odors can be reduced using aeration; however residual odors may linger after repeated aeration cycles. Commercial applications based on pilot laboratory studies have used aeration combined with ozone treatment to reduce off odors in grain (personal communication Carlos Campabadal).

Aeration System Design

In a typical aeration system, the basic components are a bin with perforated in-floor or on-floor ducts; a fan connected to the plenum or duct system to force the air through the grain; and one or more roof vents for exhaust or air intake. Many variations of the typical aeration system are used in practice.

Resistance of grain to airflow – Cereals, oilseeds, and granular animal feeds have an intergranular porosity or void space that ranges between 35% and 45% of the bulk volume. Two different grain types may have similar porosities but the surface area per unit volume for small-seeded grain would be larger than for the large-seeded grain, e.g., sorghum seeds are smaller and the kernel surface area is larger than for maize. At the same superficial airflow rate (i.e., the same cfm/bu), the specific air velocity through sorghum is much higher than through maize, which has large intergranular void openings and shorter interstitial path lengths for airflow. The increased velocity over larger surface areas and the longer air paths through smaller interstices cause the higher resistance for sorghum than maize even though the percent air volumes in the masses are about the same. In a typical aeration operation, the resistance (expressed in inches of water static pressure) to airflow through the grain is the most significant design factor.

Airflow path in the bulk – Many of the recommendations on design and operation of ducts for grain aeration systems are empirical rules for duct spacing and air velocities in the ducts. The aim is to keep air paths through the grain as nearly equal in length as possible. If there is a path that is significantly shorter than the others, an excessive amount of air will flow through the shorter air path. The longest path should be less than 1.5 times the length of the shortest path, though larger variations in path lengths may be used with satisfactory results in small dry grain bins.

Fan characteristics – The performance of fans is graphically represented by plotting airflow rate on the ordinate, and static pressure on the abscissa. The graph of this relationship between airflow rate and airflow resistance for a specific fan is called the system curve. Fans with certified (measured) fan performance curves should be used for designing grain aeration systems. The performance of similar size fans from different manufacturers can vary widely. For example, against a resistance of 2.4 inches of water (600 Pa), fan A provides a measured flow rate of 1,695 cfm (800 L/s), fan B, 2,755 cfm (1300 L/s), and fan C, 5,509 cfm (2600 L/s), which at this airflow resistance is more than three times higher than the airflow rate of fan A (5,509/1,695 = 3.25). A high-speed vane-axial fan may be suitable for corn, but a low-speed centrifugal fan may be needed for sorghum or wheat on the same size bin because of higher static pressure required for the airflow rate for which it was designed.

Aeration System Design Considerations

Airflow rates – For upright storages (concrete silos and tall steel bins) airflow rates of 0.05 to 0.10 cfm/bu [3 to 6 (m^3/h)/tonne] and for horizontal storages airflow rates of 0.10 to 0.20 cfm/bu [6 to 12 (m^3/h)/tonne] are typically used. Higher airflow rates (0.20 to 0.25 cfm/bu), which will cool grain faster, are needed in southern regions with limited cool weather conditions. Central U.S. systems may find that 0.15 to 0.20 cfm/bu works well, while 0.1 to 0.15 cfm/bu in northern states may be sufficient due to early long periods of cool weather.

Aeration speed is analogous to grain quality insurance. Slow cooling may cost less, but if grain spoils, slow cooling is false economy. Good aeration economy is what provides grain managers with high quality grain in any geographic location.

Because airflow and power requirements for grain depths exceeding 100 ft (30 m) become excessive, reduced airflow rates of 0.03 to 0.05 cfm/bu [2 to 3 (m^3/h)/tonne] may be required. Doubling the airflow rate triples the required static pressure while fan power is increased by over four times.

An excellent alternative to consider on concrete silos with strong roof structures is to use a two-fan, "push-pull' system. With a roof-mounted fan pushing air down and a duplicate-base mounted fan pulling air down, each fan only has to overcome the resistance of half the grain depth. Higher airflow can be achieved at reasonable static pressures and costs.

Air duct velocities – To minimize friction loss in ducts, a compromise between duct diameter and air velocity is made. In aeration ducts, maximum velocity should be at or below 2,000 ft/min (600 m/min). For transition and supply ducts up to 20 ft (6 m) long, velocity could be 2,500 ft/min (750 m/min) or less. Transition ducts should have a taper (slope) of 20° or less. For 45 to 90° elbows, the centerline radius of curvature should be at least 1.5 times and preferably 2.0 times duct diameter. Joining two 45° elbows to make a 90° elbow is acceptable practice.

Air distribution systems – The ratio of length of the longest airflow path to the shortest airflow path should be 1.5:1. Positive pressure systems have a more uniform airflow distribution and are preferred over negative pressure systems in horizontal storages. The exit velocity from the perforations should not exceed 30 ft/min (9 m/min).

Intakes and exhaust – In general, roof vents should be equally spaced around the circumference of the roof at about ⅓ to ½ the distance up the slope from the lower edge. Bins with sealed eaves need roof ventilators spaced around the roof , which provide at least 1 square foot of roof vent opening per 800 to 1,000 cfm of airflow with a minimum of two vents per bin. Bins should have at least one vent near the peak to provide natural ventilation from lower vents to upper vent. This will minimize moist air accumulating in bin peak and going up downspouts. Downspouts should have gravity flap valves to minimize moist air entry during pressure (up-flow) aeration, which causes condensate dripping into the grain. One or more vents should be located near the peak to minimize moist air condensation in down spouts used for filling the storage. The vent cross section area should be sized preferably for an air velocity of 1,000 ft/min (300 m/min), with a maximum velocity of 1,500 ft/min (450 m/min). The pressure difference between the headspace of a storage bin or silo and outside should not exceed 0.12 inch water column (30 Pa) during either pressure or suction aeration. Higher pressure differences may cause structural damage and is an indication of inadequate exhaust area.

Estimate static pressure and fan power requirements – To select the proper aeration fan for the system to be operated at a specific airflow rate [cfm/bu - (m^3/h)/tonne], knowledge of static pressure requirements is essential. Figure 1 provides static pressure (inches of water column) and fan power requirements (hp/1,000 bu) vs. depth (ft) for wheat, maize (shelled corn), sorghum and soybeans, respectively (Navarro and Noyes 2002a).

A Windows program called FANS (Minnesota Extension Service 1996), provides valuable design assistance for fan type, size, and power selections and static pressure required based on desired airflow, bin diameter, grain depth and grain type. This software contains performance data on over 200 fans listed by manufacturer and fan horsepower. The National Institute of Agricultural Technologies of Argentina (INTA) has also developed software, named AireAr, for sizing and selecting grain aeration fans (Bartosik et al. 2009). The user can select, round flat bottom or coned bottom, and between leveled grain surface or grain peak, and enter its dimensions as well as the grain depth.

Aeration System Operation

Direction of air flow – The question of whether air should be pushed or pulled (sucked) through grain is a subject of controversy that has caused much discussion. As with most processes, there are significant advantages and disadvantages in selecting a specific aeration method. The designs of aeration systems involve many variables, so it is important to recognize when the advantages of up flow versus down flow, or pressure versus suction, outweigh the disadvantages. Either pressure or suction airflow could be used in most grain storage structures, and most aeration systems can be adapted for pressure or suction airflow depending on the specific situation.

There are two conditions where pressure airflow should be used: (1) in regions where aeration roof vents can become iced over because of freezing rain or heavy snow and (2) when warm grain has been loaded on top of cool grain. Suction systems are not used in the central and northern U.S. Corn Belt because of the many roof collapses that occurred from 1950 to 1970 before the grain industry recognized that suction airflow was not satisfactory.

Situations that are frequently encountered conform to the following guidelines:

- Suction airflow provides quick early cooling of the top of grain where insect populations are heaviest.

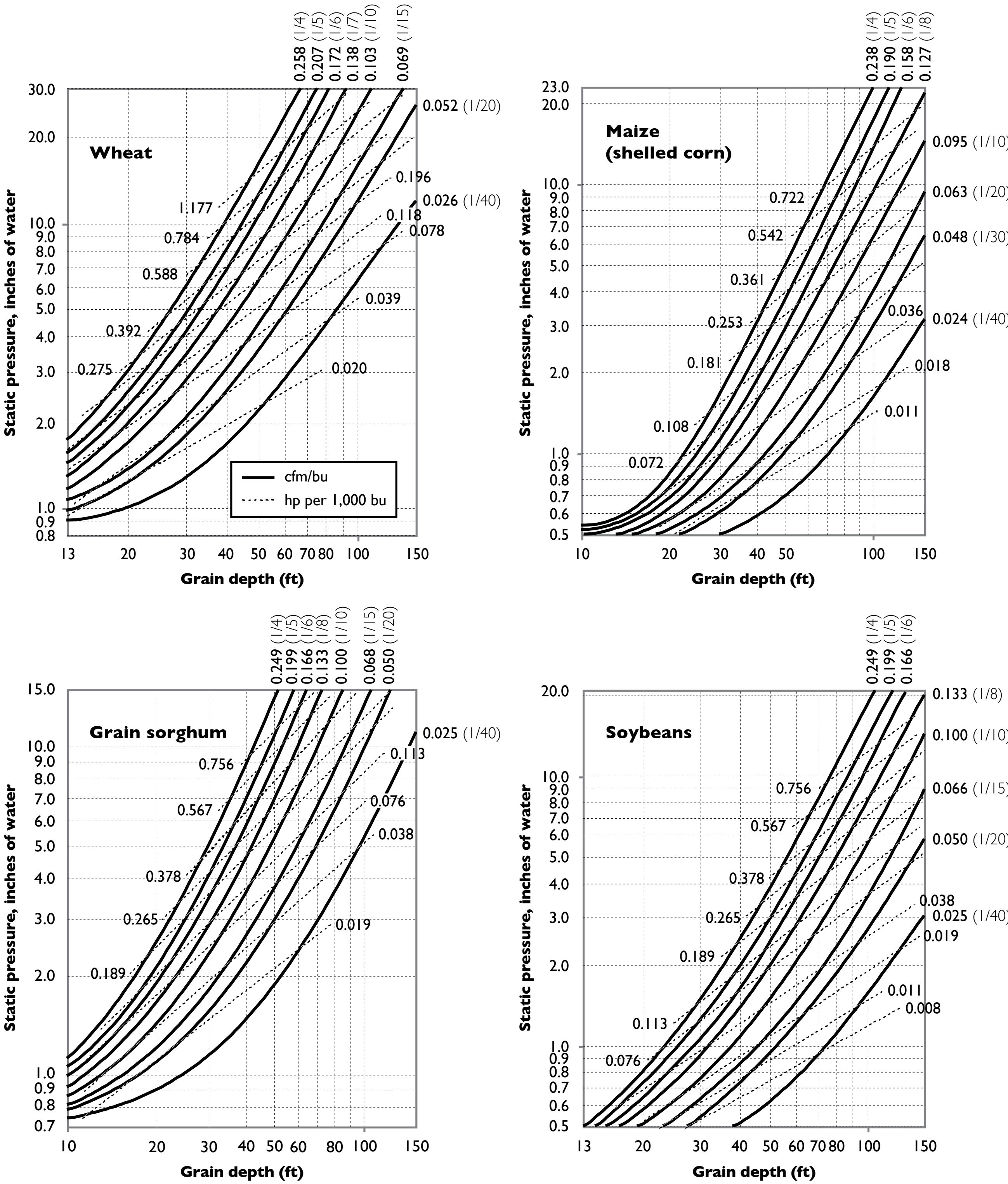

Figure 1. *Static pressure developed at different airflow rates (solid line, cfm/bu) and fan power requirements (dashed line, hp/1,000bu) for aerating wheat and soybeans (bulk density 60 lb/bu), shelled corn, and sorghum (bulk density 56 lb/bu). A fan static efficiency of 50% was assumed in the calculation of fan power (compiled from Navarro and Calderon 1982).*

- Suction airflow should be used to aerate warm grain when aeration is started during cool weather, for grain stored in metal bins, or to prevent excess condensation under the headspace roof.
- Suction airflow should be used in tropical or subtropical humid climates when cool weather conditions are marginal for insect control.
- Pressure airflow should be preferred in large flat storages for uniform airflow.
- Pressure airflow is required when loading warm grain on top of grain already cooled such as (a) when loading warm grain from a dryer on top of aerated grain in a storage bin or (b) when loading warm grain delivered to an elevator on top of a bin that has been previously cooled.
- Pressure aeration can usually be performed regardless of the air humidity because the mechanical fan compression heat reduces the relative humidity of air entering the grain mass somewhat, depending on storage and fan systems. Heat of compression adds about 0.75 to 1°F per inch static pressure.
- Pressure airflow minimizes or eliminates the risk of roof collapse from icing of aeration vents.

Aeration control equipment – Essentially, aeration controllers are electrical system control devices designed to provide automatic starting and stopping of aeration fans based on selected temperature and humidity levels deemed suitable for the aeration program. Existing control systems may be categorized as follows: simple mechanical time controllers; thermostats without relative humidity control; complex electro-mechanical controllers with humidity control; temperature difference controllers; wet bulb temperature controllers; proportional time controllers; and microprocessor and computer-based temperature monitoring and aeration control systems.

Selecting aeration controllers – Use of automatic aeration controllers that minimize excessive aeration will result in savings by more precise minimum cooling cycles, which will reduce grain market weight loss, grain damage due to spoilage (self-heating) and insect infestation, end-use quality loss, and aeration fan electrical operating costs (Reed and Harner 1998b). As long as grain temperature control is the primary objective, a simple low-cost electromechanical aeration controller may suffice to control all the fans at one installation (assuming all fans are either suction or pressure). The payback on such a low-cost ($500 to $1,500) aeration controller is usually less than one year.

For systems where grain has to be dried in storage (in-bin drying), conditioned to a specific end use (e.g., popcorn to optimize popping volume) or market moisture content (e.g., soybeans harvested too dry), or where weather conditions are highly variable, a microprocessor-based aeration and low-temperature drying controller is preferred. The payback on such a controller ($1,500 to $3,000) is usually less than one year when critical end-use quality factors are considered.

Operating aeration based on humidity controls may reduce the aeration fan operating time excessively. If humidity control is used, the aeration management plan must provide adequate fan operating time to complete the aeration cycle within a target time; fan-operating time should be monitored and the control scheme modified as needed during the aeration season to insure adequate, timely grain cooling.

Monitoring ambient air and use of computer aid to predict aeration system performance – One reason automatic aeration controllers have often been abandoned by stored grain managers soon after installation is the inadequacy of the fan control strategy to accommodate local weather conditions. Before implementing any automatic control strategy, local historic weather records should be evaluated to determine whether a planned strategy guarantees sufficient fan operation to achieve desired control objectives. Ten years of historic weather records are a minimum for evaluation; 20 to 30 years is recommended (Arthur et al. 1998, Arthur and Siebenmorgen 2005).

Computers are an ideal platform with which to model grain storage management systems and strategies (Arthur et al. 2001). Computer models can be utilized to study the physical and biological parameters involved in grain storage and establish realistic operating parameters to implement best stored-grain-quality management practices. Numerous computer programs have been developed throughout the world for this purpose.

Time required for cooling – A family of curves to describe several variations of temperature change

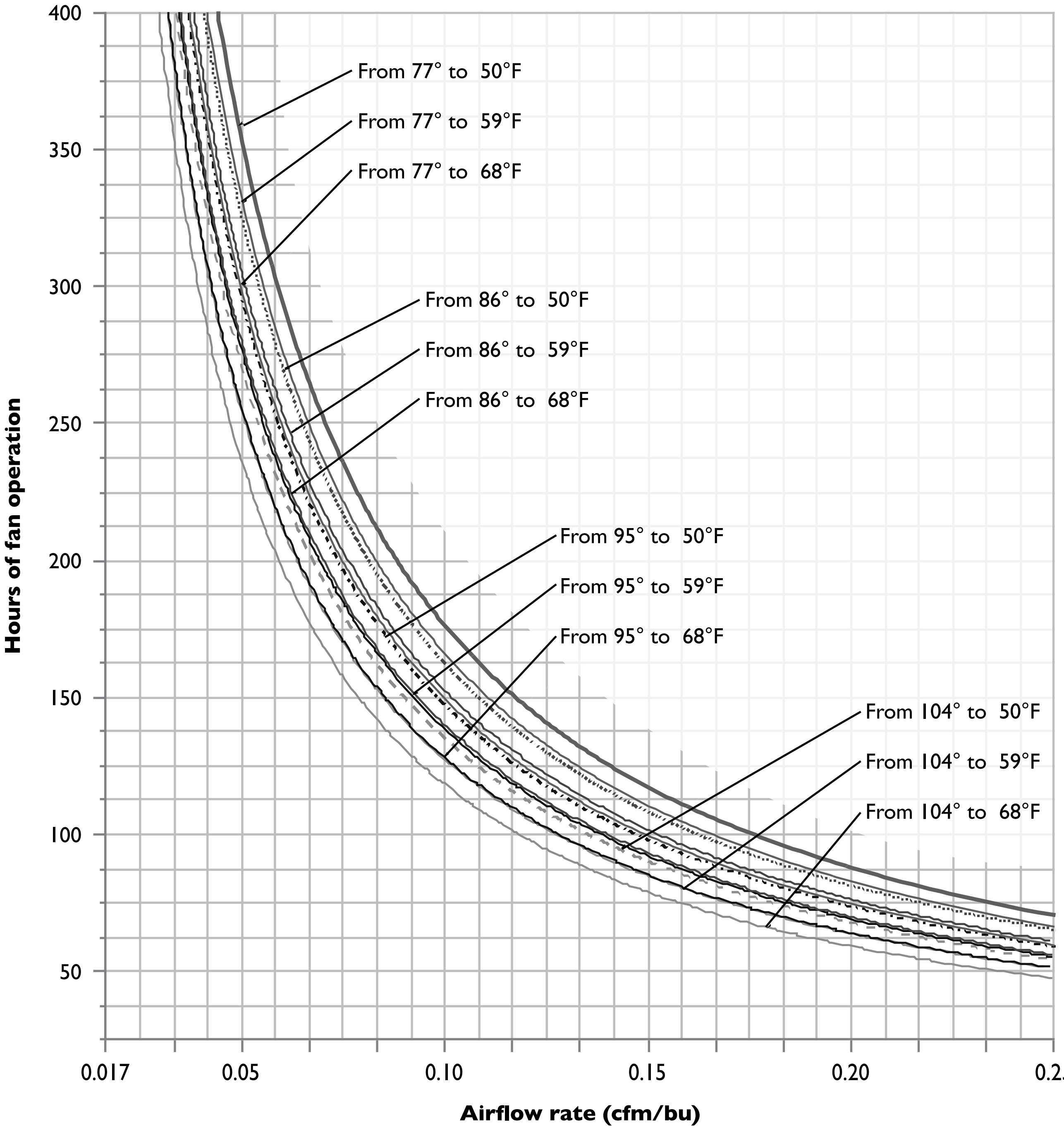

Figure 2. *Calculated family of curves showing the aeration time needed for reducing wheat (at 12% moisture content wet-basis) temperature from 77°, 86°, 95°, and 104°F to ambient temperatures of 50°, 59°, and 68°F at 64% relative humidity (Navarro and Noyes 2002a).*

from 77°, 86°, 95°, and 104°F (25°, 30°, 35° and 40°C) to ambient temperatures of 50°, 59°, and 68°F (10°, 15° and 20°C) at 64% relative humidity is presented in Figure 2. This family of curves clearly indicates that by reducing or increasing the airflow rate beyond certain limits, the aeration time needed to cool grain satisfactorily may exceed practical limits.

At a low airflow rate, below 0.017 cfm/bu [1.0 (m^3/h)/tonne], the aeration time will exceed 600 to 700 h, which is not practical for grain cooling, especially in geographical regions with marginal ambient temperature conditions. If airflow rates are increased above 0.15 cfm/bu [10 (m^3/h)/tonne], cooling capacity becomes progressively less effective. At higher aeration airflow rates, which are needed where the hours of cooling weather are marginal, for each increment in airflow rate, the cooling time becomes less pronounced (the lines are asymptotic).

The initial grain temperature and ambient air conditions are the primary factors that influence the curves shown in Figure 2.

Steel bin roof venting – Moisture condenses inside cold spouts and runs back onto the surface grain. Installing one or two vents close to the center fill point will help minimize condensation in the bin fill pipe. In pressure aeration, the roof vent system must be designed with sufficient cross-sectional area to allow adequate exhaust or inlet air volume to maintain vent throughput velocities of 1,000 to 1,300 fpm (300 to 400 m/min).

The vent opening area should be divided into several equally spaced vent units based on the customary design practices in the area.

Roof exhaust fans to minimize condensation – To minimize humid exhaust air roof condensation during up-flow or pressure aeration, high volume propeller type roof exhaust fans can be installed. Roof exhausters should be sized to provide a total air volume of 1.5 to 2 times the aeration fan system airflow in order to draw in excess ambient air to dilute moist exhaust air, lowering the dew point of the total air mass exhausting through the roof fans. When roof fans are used, fresh air is pulled in through the roof vents, mixed with the cooling air moving upward through the surface grain and exhausted through the roof fans. Thus, the drier, diluted air mass that contacts the under side of bin roof sheets is less likely to experience condensation.

If roof vents are mounted about ⅓ of the roof slope distance from the peak, roof exhaust fans should be spaced about ⅔ to ¾ of the roof slope distance from the peak, and mounted symmetrically around the roof. If two fans are used, they should be placed opposite each other on the roof. Three fans should be spaced 120 degrees apart, four fans, 90 degrees apart, six fans at 60 degree intervals and eight fans, 45 degree angular spacing.

A major problem can occur when roof fans becomes imbalanced, the vibration can cause serious structural damage to steel bin roofs, causing water leakage and grain spoilage. Roof mounted fans must be checked for fan blade balance and vibration before each storage season, as well as periodically during the aeration season.

Chilling Grain with Refrigerated Air

There are some storage situations where ambient air conditions are not suitable to cool grain. For these situations, refrigerated air units for chilling grain have been developed for commodities that justify the added expense of refrigerated aeration. In refrigerated aeration, ambient air is passed through the evaporator coil and a secondary reheat coil of the refrigeration unit, and then is blown into the grain bulk using the existing aeration system. Passage through the secondary reheating coil adjusts the air relative humidity to 60% to 75% to match the target moisture content of the dry grain. The amount of reheating and the final air temperature are adjustable by the operator to achieve the desired aeration conditions.

Evaluation of Aeration System Efficiency

Aeration efficiency includes uniform air distribution through the stored product, sufficient airflow to maintain temperature and moisture, and minimal energy loss due to improper selection of fans, motors, and ducts. Aeration systems may perform less efficiently than originally planned; low system efficiency often goes undiscovered until long periods of aeration have failed to produce the desired cooling results. Many factors may be involved in the malfunction of an aeration system. The main problems are faulty system design, improper system operation, excessive dockage accumulation in certain regions of the grain bulk, faulty fans, rusted out sections of transition ducts causing air leaks, molded grain layers from moisture migration which restricts airflow or gradual duct blockage by foreign material and fines.

Aeration system efficiency should be tested when a new installation is first operated or any time measured cooling times are longer than those calculated initially. Aeration system efficiency should be rechecked after any major change, such as installing a new fan, improving aeration ducts, or when storing grain different than the type or quality of the grain for which the aeration system was designed. Measurement of the airflow rate and static pressure of the system are important procedures in evaluating the aeration system efficiency.

Measurement of static pressure – The U-tube manometer is probably the simplest device for measuring static pressure. The U-tube is a glass or plastic tube partially filled with water or special gauge oil (for low temperatures) in which the pressure is read directly in inches, cm or mm of water column. The reading is taken by measuring the difference in the liquid levels of the two parallel tubes to determine the aeration system resistance pressure. The internal diameter of the tube should be at least 0.2 to 0.24 inch (5 to 6 mm), and the walls perfectly clean. A small diameter hole (0.06 to 0.2 inch) (1.5 to 5 mm) should be drilled in the side of the airflow transition or connection duct (Figure 3). This static pressure access hole should be connected to the U-tube with a flexible connecting tube. One end of the U-tube must be open to atmosphere when reading static pressure.

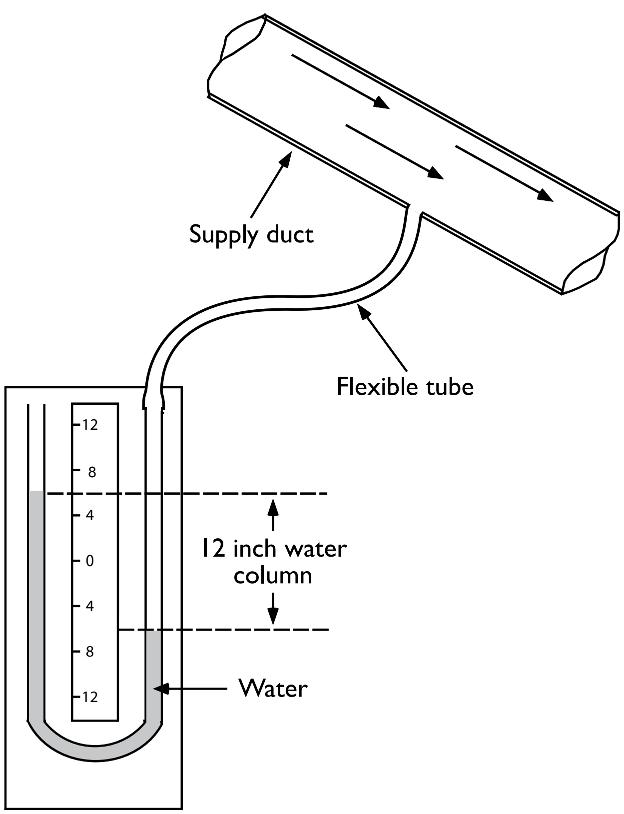

Figure 3. *Static pressure measurement using U-tube manometer.*

Measurement of airflow rate – For convenience in the United States, the unit of measure for airflow used here will be (ft^3/min)/bu (cfm/bu). The volume of airflow may be determined by multiplying the average velocity (ft/min) by the cross-sectional area (ft^2), at the same point of airflow measurement. The unit volume of air, ft^3/min (cfm), divided by the unit of grain volume (bushels = 1.244 ft^3) of the commodity will give the airflow rate in cfm/bu.

A straight section of the supply duct, at a specified distance (usually in numbers of pipe diameters, e.g. 10 pipe diameters of straight pipe) downstream from the fan provides a preferred airflow measurement position. But, in practice, convenience governs the position at which measurements are made to determine airflow rate; air velocity readings can also be taken in front of the fan entry orifice, a roof door opening or roof vent in vertical bins. Thermo-anemometers (also called hot-wire anemometers), if properly calibrated, are suitable for airflow measurement. They are suited primarily for measuring relatively low velocities such as 10 to 2,000 ft/min. Windmill or rotary vane anemometers are also used for taking a series of grid pattern readings across fan openings to determine the average air velocity entering or exiting the fan; the average air velocity multiplied by the fan opening cross-section area gives an estimate of air volume.

Fan efficiency – Although fans are selected on the basis of performance ratings and the recommended fan selection range is supplied by most manufacturers, their "installed" operating performance and efficiency may be substantially different than that listed in the manufacturer's fan performance charts. Therefore, during the first operating stages of a new installation fan efficiency should be evaluated. With the difficulties and inaccuracies that may occur in determining fan efficiency under field conditions, early fan performance testing provides an excellent initial evaluation to ensure that the fan performs as designed. Such evaluations may be performed in an installation where the required power to operate the system is significantly greater than those specified in Figure 1. Standard fan performance data obtained from tests conducted at officially approved "certification" laboratories are sometimes available and should be more accurate than field evaluations under similar static pressures.

Using modern aerodynamic science and technology, manufacturers have developed, high performance fans with efficiencies as high as 80%. Conversely, poorly designed, improperly manufactured, or poorly selected fans may have efficiencies as low as 15% to

20%. Low fan efficiency will result in aeration system failure and serious monetary losses.

Air distribution throughout the bulk – As air from the aeration system is dispersed through the aeration ducts into the grain mass, airflow near the duct surfaces is relatively high. But in regions at floor level farthest from the ducts, in corners and on the floor half way between aeration ducts in flat-bottomed structures, airflow rate is considerably reduced, thus, in flat storage warehouses and large flat bottom bolted steel bins an overall increase in airflow rate is recommended to provide adequate airflow to the floor areas that are farthest away from aeration ducts.

Example: A 40 ft diameter flat bottom bin has a floor surface area of 1,256 sq ft; at a depth of 20 ft level full, contains 25,132 cu ft or about 20,000 bu of grain. Although an airflow rate of 0.1 cfm/bu might be minimally sufficient for flat bottom bins with aeration ducts which cover only 6% to 8% of the total floor area, it is advisable to use 50% to 100% more aeration airflow. Thus, using a minimum area of aeration duct, design airflow of 0.20 cfm/bu is recommended, so the airflow to be produced by fans is 4,000 cfm. To limit air velocity to 30 ft/min (the recommended maximum duct entry or exhaust air velocity), the minimum aeration duct surface needed would be 133 sq ft (about 10% of the total bin floor area).

Due to higher particle surface friction, smaller size and lower mass, dockage with higher moisture has less spreading capability, so it accumulates directly below the loading port, forming a column of a dense higher moisture mixture of grain and high dockage (column of fines) that causes increased resistance to airflow. Where feasible, cleaning the grain before storage to remove foreign material, fine particles and dockage is encouraged. A mechanical spreader to distribute fines with the grain is recommended, to minimize the center column of fines.

By measuring the pressures developed in the bulk of the grain, a low pressure/low airflow map of the grain can be made to locate the high dockage spots (Navarro and Noyes 2002b). In up-flow aeration, higher pressures are encountered below the spot with very low pressures within and immediately above it. A method of minimizing the development of these dense central hot spots in grain where grain and fines are not mechanically distributed is by “coring” (operating the unload conveyor to withdraw the column of grain and fines directly under the fill point) the central dense column of grain and fines where high dockage accumulates in the grain bulk.

Uniform spreading to eliminate a column of dockage and foreign material at the center of bins is part of best grain storage practice. Suitable distribution of all the grain components during the loading process is desirable for satisfactory aeration of grain bulks. Grain spreaders or distributors are installed just below grain bin loading ports. Grain spreaders are usually mechanically powered devices designed to spread the mixture of grain, dockage and foreign material across at least half of the bin diameter. Even inverted cone sheet metal spreaders which have a center opening to allow a minor part of the grain flow to drop through the center will help spread dockage and fine material, minimizing the central column of fines. Performance of grain spreaders varies for different designs and even the best do not distribute fines completely uniformly (Chang et al. 1983).

Efficacy of Aeration for Insect Control

Field trials – As mentioned previously, the optimum temperature range for development of most stored grain insects is about 75° to 90°F (24°C to 32°C) (Fields 1992), but the preferred lower and upper limits vary with species. However, about 60°F (16°C) is the lower limit of development for most of the important pest species in the U.S. Aeration generally involves cooling to or below this threshold, often in a series of steps or time cycles depending on the initial temperature of the grain when it is loaded into storage and the ambient temperatures at the time (Arthur and Casada 2005)

In the U.S., grain crops such as wheat, corn, rice, and sorghum are harvested and stored at different times of the year. As ambient temperatures cool, the top surface and peripheral regions of the grain mass will begin to cool, while most of the grain mass will retain heat and cool much more slowly. This allows for not only insect pest population development but also promotes mold and fungal development because of the temperature differences within the grain mass. Depending on the specifics of the crops, the geographic region, and the size of the storage bin, it may take weeks or even months for temperatures in the central section of the grain to be cooled to the developmental threshold of 60°F (Arthur et al. 2011).

Automatic control systems – During the last 20 to 30 years several new studies have refined aeration through the use of various types of controllers, which essentially set activation temperatures so that fans will operate only when ambient temperatures are within these set points, thereby cooling the grain through a progressive cooling front that moves either upward or downward in the grain mass (often referred to as pressure or suction aeration, respectively). Grain temperatures can be monitored so that once the grain mass is cooled, the fans can be turned off. This allows for a stepwise progressive cooling approach, which can be especially useful for stored wheat. An important point that should be monitored on pressure aeration systems is that the aeration fan adds several degrees of heat to the air (heat of compression, about 0.75 to 1°F rise per inch of static pressure), so the grain does not receive humid ambient air as it does in suction aeration. The air temperature increase due to the *heat of compression* must be considered when using pressure (up-flow) aeration, especially when cooling small grains in deep bins.

An initial cooling of the wheat mass from harvest grain temperatures in the 90°s to the mid-70°s, followed by cooling to 60°F in early autumn, will likely result in lower insect populations compared to waiting two to three months longer before cooling the grain to 60°F (Arthur and Casada 2005). Because the majority of insects infest grain near the grain surface, suction cooling at night during the summer can effectively cool the top 3 to 6 feet of grain by 15° to 20°F within three to five weeks of harvest in most regions, thus dramatically slowing insect population buildup.

Although aeration can be accomplished through manual means, controlled aeration is a low-cost management option and can cool stored grains more effectively than can be accomplished manually, thereby resulting in lower insect pest populations.

Manual control strategies – In the past two decades, TV and Internet weather information has become more accurate and accessible. Grain managers who prefer to manually control their aeration systems now have excellent predictive weather data to use for manually operating their control systems. By watching Internet weather on hourly predictions, aeration fans can be operated during optimum ambient weather conditions.

Producers and small elevator grain managers can keep track of the start and stop times they use each day, and thus can develop fan operating time data to allow them to estimate when a cooling front should be complete. At 0.1 cfm per bushel with fines spread and surface rounded (not peaked), an aeration front can be expected to break through in about 50 to 75 hours with the trailing edge (completion) in 125 to 150 hours. At 0.2 cfm per bushel, the times will be about half of the times for 0.1 cfm/bu. Suction aeration system operators can monitor exhaust air at the fan discharge to document the exhaust air temperature profile to see when the leading and trailing edges of the cooling zone pass. Although not as convenient, pressure (up-flow) cooling exhaust temperatures can be monitored at roof doors, fill points or roof vent exhausts. If a thermometer with long remote bulb is used, the temperature readings may be available at the side of the bin wall ladder near ground level.

Models predicting efficacy – Historical weather data can be used to help predict cooling patterns in different geographical regions of the U.S., and can be integrated with insect population models to show how aeration can help limit insect pest populations (Arthur et al. 2011, Arthur and Siebenmorgen 2005, Arthur and Flinn 2000). These predictive models are useful tools for demonstrating the impact of aeration on insect pest populations in grain and in commercial silos, and how aeration can be integrated with other control options (Flinn et al. 2007).

Although aeration has been utilized in grain management for many years, new research is refining methods and techniques. Management concepts originally developed for stored wheat and stored corn are being applied to other grains (Arthur et al. 2008). Some modifications may be necessary because of the peculiarities of the rice system compared to wheat and corn, but a web-based expert system has been developed that allows user groups to examine how aeration could be useful for rice stored in the different geographic regions of the south-central U.S. (Arthur et al. 2011). Initial cooling cycles in warm-weather regions of the U.S. may help reduce insect pest populations, even if the target of 60°F cannot be initially achieved (Butts et al. 2006). Airflow direction may also be important, and a recent study showed that overall insect populations in the upper surface zone of stored wheat were lower in suction versus pressure aeration (Arthur and Casada 2010).

Compatibility with Other Pest Management Methods

Aeration is a vital component for insect pest management in stored grains, but it has limitations. Residual grain in and around storage bins can be important sources of infestation (Reed et al. 2003), and if initial populations are excessive, the effectiveness of aeration will be limited unless those populations are eliminated through fumigation. Depending on the pest species, the grain crop, and the geographic area of the United States, grain protectants and/or fumigants might be required along with aeration to prevent economic damage (Flinn et al. 2004). Yearly variations in temperature cycles may also be important, and although historical weather data can be used to help produce guidelines, it may not be possible to define absolute rules that will be applicable to each and every storage situation.

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12 Insect-Resistant Packaging

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Food and beverage packaging make up more than $70 billion of the U.S. packaging market and more than $200 billion worldwide (Wilkinson 1998). Paper and board, the most common type, is also the most susceptible to insect attack. Widespread use of susceptible food-packaging materials is important because losses from insect infestation are the sum cost of growing, harvesting, transportation, processing, and packaging (Mullen and Mowery, 2000). Package type (rigid or flexible) ability to be resealed and maintain food quality, cost and availability of materials, and consumer acceptance are all important package design considerations.

Besides maintaining quality, packaging must compete with many similar products for consumers' attention. Excessive packaging can result in needless expense, while inexpensive packaging can encourage insect infestation, microorganisms, and reduce quality. Packaging manufacturers have modified packaging to address safety concerns such as tamper-resistance. They are beginning to modifiy packaging to address environmental issues raised in the manufacture and disposal of packaging materials (Connolly 2011a). Replacing the paperboard carton with a film-overwrapped tray will reduce the use of paperboard by 150 tons (Connolly, 2011a). Customer convenience also is important. It does little good to use difficult to open can when a zippered plastic pouch will do (Kindle 2001).

Any comprehensive study of insect control in the food industry must consider the elimination or prevention of insect infestation. Most foods are presented to the consumer in packaging that has been exposed to infestation. In the 1950s and 1960s pesticides were used to protect against infestation. Then it was discovered that pesticides can migrate through paper and paperboard. Over the past few decades it has become clear that the use of toxic chemicals on consumer packaging is no longer a viable option.

Many consumers have experienced opening a box of crackers or a bag of flour to discover a thriving colony of Indianmeal moths, flour beetles, or other insects. Even worse is the experience of eating a bowl of breakfast cereal and finding small wriggling insects floating in the milk. Although food processors may take all possible precautions to package an insect-free commodity, they often have no control over the product during shipping and storage. Consumers are especially sensitive to these problems, and manufacturers are concerned with providing high-quality products that meet their needs. Consumers usually hold the manufacturer responsible for the insect infestation, regardless of where or how the package became infested (Highland 1984). Manufacturers know that if the consumer finds an insect in a cereal package, it can make a lasting and often irreversible impression, and can result in the loss of a customer. A pet food manufacturer recently reported $1 million in losses in one year in one product line because of insect infestation.

Many companies have implemented package-testing programs to improve resistance to insect attack (Mullen and Mowery 2000). Insect-resistant packaging is the most common way to prevent insect infestation without using insecticides or repellents (Mullen and Highland 1988). Insect infestation is often the result of transportation problems or prolonged storage under less than optimal conditions in the warehouse or on a grocer's shelf.

Since 1990 insect-related losses in pet food have declined because of insect-resistant packaging. Packages are designed to protect food products for several years as they make their way to the consumer. Unfortunately, there is no perfect package that provides the protection needed for all products under all conditions. Packages must be tailored to fit the specific product. The product value, length of time it must be protected, the economics of delivering a high-quality product to the consumer, and other factors must be considered when designing and developing insect-resistant packaging.

Biology of Stored-Product Insects

Most stored-product insect pests are cosmopolitan. They have become established throughout the world via international trade (Highland 1977). To survive, many species infest packaged foods where they have ample nourishment for offspring and are protected from lethal chemicals. Because of distribution practices, contaminated products can often be moved from one geographical location to another. In local warehouses and retail stores, infestations can spread from package to package. While food products can become infested at any point in the marketing channel, they are most likely to become infested during extended storage. Some products are more susceptible than others. They can serve as insect reservoirs and lead to infestation of other products (Highland 1984). Dry pet foods and birdseed are often infested. Most pet foods are packed in multiwall paper bags that are not insect resistant because they lack adequate seals and closures. Food also may become infested during shipment in trucks, railcars, and ships, retail storage, or in the home.

How Insects Enter Packages

Highland (1984, 1991) separated package pests into penetrators and invaders (Table 1). Invaders typically have weakly developed mouthparts at both the larval and adult stages (Wohlgemuth 1979). They account for more than 75% of infestations (Collins 1963). Invaders enter packages through openings caused by mechanical damage, defective seals, or holes made by other insects (Mullen and Highland 1988). Newly hatched larvae cause the most damage because they can fit through holes as small as 0.1 mm wide (Wohlgemuth 1979). Typical insect penetration into food packaging materials is shown in Brickey et al. (1973) and illustrated in Figure 1. Most infestations are the result of invasion through seams and closures and rarely occur through penetrations (Mullen 1997). 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 through holes less than 1.35 mm (Cline and Highland 1981).

Penetrators

Penetrators can chew holes directly into packaging materials. They are most dangerous at the larval stage, though some beetle species also can be dangerous as adults (Wohlgemuth 1979). The lesser grain borer, *Rhyzopertha dominica* (Fab.); the cigarette beetle, *Lasioderma serricorne* (Fab.); the warehouse beetle, *Trogoderma variabile* Ballion; the rice weevil, *Sitophilus oryzae* (L.); the cadelle, *Tenebroides mauritanicus* (Linnaeus); and the larvae of the rice moth, *Corcyra cephalonica* (Stainton), are good penetrators capable of boring through one or more layers of flexible packaging. Under some conditions larvae of the Indianmeal moth, *Plodia interpunctella* (Hübner), are also good penetrators and may be the most serious pests of packaged foods (Mullen and Highland 1988, Mueller 1998). The warehouse beetle is more specialized in the food products it infests and is often found in dry pet food and pastas. It can create an additional problem for the consumer because cast off skins of larvae can cause allergic reactions. The drugstore beetle, *Stegobium paneceum* (L.), is a strong penetrator that infests a wide variety of foods (Highland 1991).

Invaders

Species classified as invaders enter packages through existing openings. Common invaders include the sawtoothed grain beetle, *Oryzaephilus surinamensis* (Linnaeus); the red flour beetle, *Tribolium castaneum* (Herbst); the confused flour beetle, *T. confusum* Jac-

Table 1. *Classification of pests that commonly infest packaged food[1].*

Penetrators	Invaders
Red Flour Beetle (*Tribolium castaneum)*	Red flour beetle (*T. castaneum*)
Confused Flour Beetle (*T. confusum)*	Confused flour beetle (*T. confusum*)
Warehouse beetle (*Trogoderma glabrum)*	Merchant grain beetle (*Oryzaephilus mercator)*
Rice weevil (*Sitophilus oryzae*)	Sawtoothed Grain Beetle (*O. surinamensis*)
Almond moth larvae (*Cadra cautella*)	Almond moth larvae (*C. cautella*)
Indian meal moth larvae (*Plodia interpunctella)*	Indianmeal moth larvae (*P. interpunctella*)
Lesser grain borer (*Rhyzopertha dominica*)	Squarenecked grain beetle (*Cathartus quadricollis*)
Cadelle (*Tenebrodes mauritanicus*)	Flat grain beetle (*Cryptolestes pusillus*)
Drugstore beetle (*Stegobium paniceum*)	Rice moth larvae (*Corcyra cephalonica*)

[1] Adapted from Highland 1984

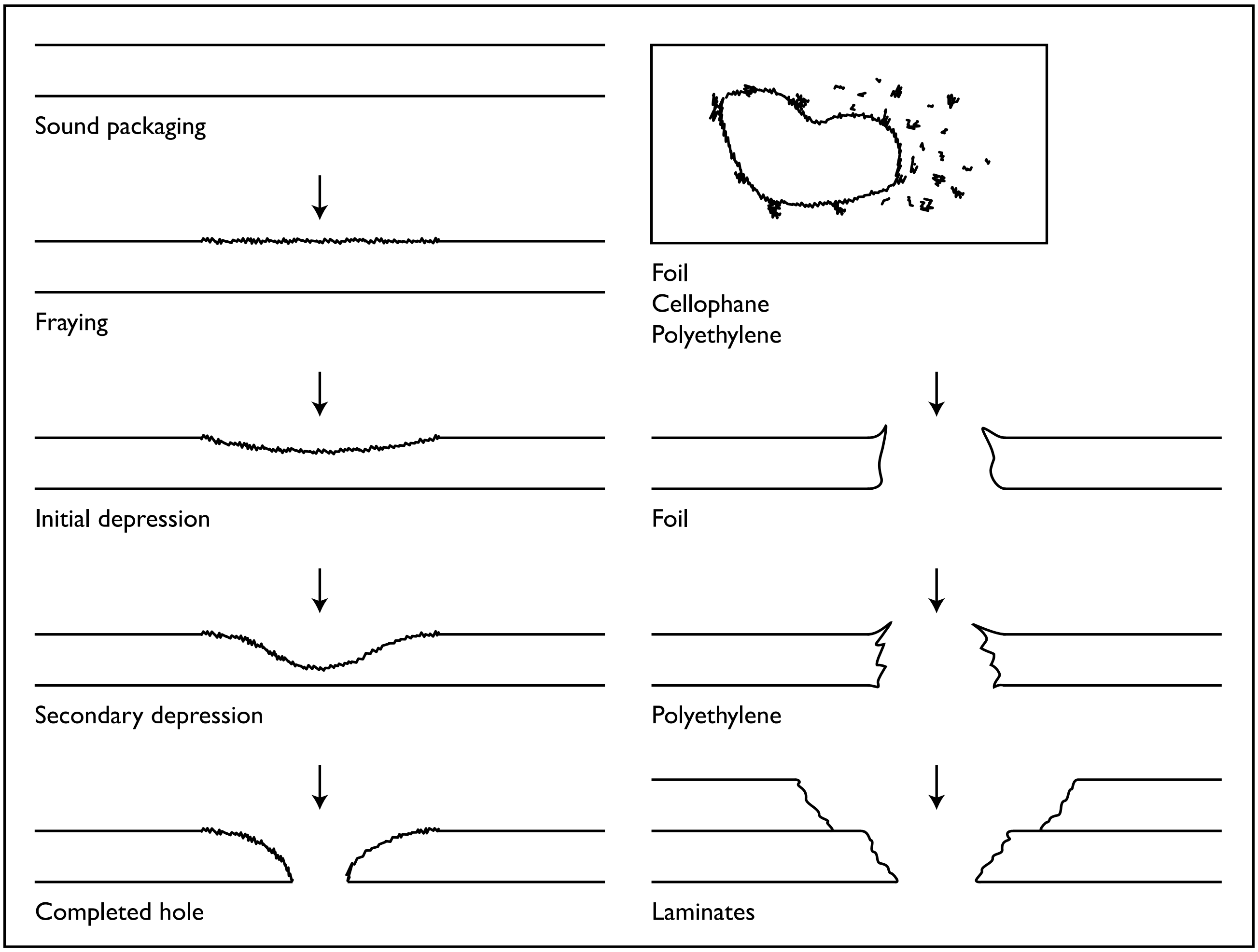

Figure 1. *Direction of insect penetration into food packaging adapted from Brickey et al. 1973.*

quelin du Val; and the flat grain beetle, *Cryptolestes pusillus* (Schoenherr) (Mullen and Highland 1988). The most important invaders are the larvae of the genus *Tribolium* (flour beetles), the genus *Oryzaephilus* (grain beetles) and freshly hatched moth larvae (Wohlgemuth 1979).

Although invaders and penetrators classifications are often used to describe packaging pests, the groups are artificial. Under certain circumstances invaders can become penetrators and vice-versa. Larvae of the Indianmeal moth and the almond moth penetrate packages. They are generally classified as invaders, but in certain situations, they can be penetrators as well (Mullen and Mowery 2000). Both penetrators and invaders exploit package flaws or other existing openings to reach food. Some invaders can chew into weak packaging materials such as paper and cellophane.

Considering how important insect infestation of stored food products is to the industry, disproportionately little has been done to describe the behavior and mechanisms by which insects invade packaged goods. Although invaders are assumed to enter packages through existing openings, little information is available to support this belief.

Mechanism of Entry

Aside from adult stored-product moths, which do not feed, most stored-product insect adults and larvae feed to sustain themselves. When faced with consumer food packages both invaders and penetrators will take advantage of any opening in a packaging material to gain entry. Openings may be the result of the chewing, of rips, tears, or punctures from normal wear and tear during handling. Package openings or vents may have been created by the manufacturer to allow pressure equalization and to avoid the bursting or shrinking during shipment over changing altitudes and temperatures.

In most cases, insect pests enter through existing openings created from poor seals, openings made by other insects, or mechanical damage. Most infestations occur because of invasion through seams and closures, and rarely through penetrations (Mullen 1997). 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. These refuges provide a safe place to lay eggs and give hatched larvae an ideal location for invading packages.

Odor Escape Through Openings

Stored-product insects identify packaged consumer food products through olfaction. When an insect "smells" food, it will try to reach it. The vent holes made to reduce bursting also allow odors to escape and provide a point of entry. Small stored-product insect larvae can enter packages through tiny openings (Barrer and Jay 1980) and enlarge openings to gain access. Barrer and Jay (1980) determined that the odor of kibbled wheat, when diffused into a 10 m^3 cage through 10-1 mm diameter holes, strongly attracted gravid free-flying *Ephestia cautella* (Walker) females seeking oviposition sites. When *E. cautella* females cannot gain direct access to the grain, they oviposit near the opening through which the food odor is escaping, possibly to allow larvae access to the grain upon hatching (Barrer and Jay 1980). Mated female sawtoothed grain beetles have been shown to have a more rapid response to the odor of carob distillate than virgin females (White 1989). It has been speculated that mated sawtoothed grain beetle females respond more rapidly to food odor due to the greater effort expended in egg production (White 1989).

Insect age also affects response to food odor. White (1989) determined that two-day-old sawtoothed grain beetles showed a significant preference for the odor of carob distillate, which increased up to 16 to 20 days old. Honda et al. (1969) showed that newly emerged *Sitophilus zeamais* Motschulsky less than 10 days old are more sensitive to attractants from rice than older weevils.

Package Design

With the exception of canned food, most nonperishable food items are shipped in consumer-sized packages susceptible to insect attack (Mullen 1994). Seals and closures often can 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. Sharp folds and buckles should be avoided because they weaken the material and provide easier pest access (Wohlgemuth 1979). Insect resistance can be improved by wrapping packages with materials such as oriented polypropylene films (Mullen and Mowery 2000). In research comparing wrapped and unwrapped snack bars subjected to infestation by larval Indianmeal moths, bars with perfect shrink wraps remained uninfested for 28 days compared to those with flaws in the shrink wrap (Davis and Pettitt 2002).

To maximize effectiveness, wrappers should fit tightly around the package. If wrappers are not completely sealed, insects often enter at the corners of folded flaps. If the wrapper is sealed tightly, insect movement will be restricted, reducing the chances of infestation. Although it is impossible to avoid vulnerable spots, it is important to be aware of the problems they can cause.

Odor barriers are another way of discouraging insect infestation (Mullen 1994). Food odors may be prevented from escaping the package through the use of barrier materials, so the package is "invisible" to invading insects. Flexible packaging with acrylic PVdC (polyvinylidene chloride) or EVOH (ethylene vinyl alcohol) can improve odor retention (Sacharow and Brody 1987). These materials have been used with some success. Any flaw in the package will negate the odor-proof qualities of the package (Mullen and Highland 1988). Studies reported by Mullen (1997) showed that when odor barriers were used to protect a commodity, only packages with flaws became infested.

Packaging Materials

Food products are packaged in a wide variety of paper and plastic materials. New materials are constantly being added to the list and are too numerous to discuss in detail. Paper is one of the most widely used products and one of the most easily penetrated. Paper often is used with foil and polyethylene to form multiwall packages. This type of packaging is found in pet food bags. Paper offers little resistance to insect penetration, but it provides excellent strength, serves as a moisture barrier, and can be grease proof.

Bags with a heat-sealable inner layer can be sealed, but the outer plies must be folded and glued. The sealed end flaps of these packages provide insects with a protected area in which to deposit eggs. When young larvae emerge, they often have little trouble entering through existing openings in commercially sealed packages. Tiny openings in most flexible packaging allow odors to escape and attract pests. Often openings are large enough to permit the first instar larvae of most stored-product insects to enter.

An airtight package can create other problems. Changes in air pressure or temperature can cause the package to swell or shrink (Wohlgemuth 1979). To avoid this small ventilation holes are created to allow pressure to equalize. Vent holes compromise the seal and provide access for insects. This can be avoided by creating a tortuous path for the insects to follow. One of the simplest methods for creating a tortuous path is the use of a double heat seal so there are vents at opposite ends of each seal. This method has been shown to allow for pressure equalization while limiting insect infestation.

Cellophane is one of the oldest plastic films to be commercialized. Desirable physical characteristics include transparency, clarity, and heat sealability. Many of these attributes were lacking until nitrocellulose was developed in 1927 (Sacharow and Brody 1987). Studies on cellophane-wrapped packages conducted at the USDA Grain Marketing and Production Research Center in Manhattan, Kan., have shown that both dry cat food and raisins packaged in cellophane were susceptible to penetration by a variety of stored-product insects including the Indianmeal moth, *P. interpunctella*, the warehouse beetle, *T. variable,* and the cigarette beetle, *L. serricorne*.

Of the flexible packaging materials in use today, paper and cellophane are probably the least resistant to insect penetration. Depending on environmental conditions, some insect species can penetrate kraft paper in less than a day (Highland 1984). Adding multi-ply construction adds little resistance.

A recent study comparing standard commercial multiwall paper bags, reverse printed multiwall, and woven poly reverse printed bags to increase resistance to infestation to the Indianmeal moth illustrates the need for research to develop better packaging (Vardeman unpublished), as illustrated in Table 2.

Table 2. *Percentage of bags infested by package type and the average number of Indianmeal moths (IMM)found within each bag.*

Packaging	% Bags Infested	Avg No. IMM/ Bag
Standard multiwall (MW)	30	2
Reverse printed multiwall (RPP)	80	4
Woven-poly reverse printed (WPP)	90	12

Polyester (PET), first developed in 1941, has good resistance to insect penetration, but its use in packaging has been limited because of higher cost, less coverage per pound of material, and limited shrink properties (Sacharow and Griffin 1973). In recent years there has been a dramatic increase in the use of PET and metalized PET in flexible packaging (Highland 1978). Polyvinylidene chloride (PVDC), a good odor barrier when used alone, is a poor barrier to insects. Laminates containing polyester and saran provided very good protection against insect penetration when the polyester side was exposed to insects (Rao et al 1972). This material is used today in packaging for refrigerated or frozen products.

Flexible polymer films used in packaging can be penetrated by one or more species of insects. MRE (meals ready to eat) military rations, are packaged in 10-mil polyethylene. They are resistant to penetration, but under extremely crowded conditions red flour beetle adults have been known to penetrate these packages. Even laminates can be susceptible to insect attack. Plastic has several advantages over paper. It can ensure that the contained materials will remain in the original condition. Plastic packages can be colorful, attractive, and made into different sizes and shapes.

Work done at the USDA in Manhattan, Kan., has shown that many plastic materials resist infestation by most stored-product pests. Recently, stand-up plastic pouches have become popular. The pouches have been shown to be resistant to insect penetration. Zippered stand-up pouches made from a polyester/foil/nylon/polypropylene laminate offer an extremely strong and lightweight package, (Connolly 2011b) and excellent insect resistance. Earlier studies by Cline (1978) showed that insect survival in airtight plastic pouches was reduced and that no insects survived in unpenetrated packages after 12 weeks. VanRyckeghem (2011) listed several common packaging materials and their insect penetration resistance (Table 3).

Repellents

Repellents, as the word implies, have the characteristics of repelling insect entry or movement across a treated surface. The use of repellent coatings on packages to prevent insect infestation is an area in which additional research is needed. In 1978 Highland listed the development of repellent treatments as a priority.

Through the years many repellent formulations have been tried with little, if any, success. Studies conducted by the senior author included natural and synthetic compounds. These compounds included Neem oil, methyl salicylate, DEET derivatives, and insect growth regulators. Many of these compounds were effective in laboratory choice tests. Food odors from the packages either greatly reduced or completely eliminated effectiveness of the repellent treatment. Another problem is the migration of the repellant compound through the packaging material. Recently, methyl salicylate (Repellcoat) was patented (Radwan and Allin 1997) and received approval by both the EPA and FDA as a package treatment. This was significant because it represents the first such approval and should make it easier for other materials to be approved. In 2009 the EPA approved ProvisionGard, which uses the IGR methoprene and is now being considered for use in many package applications. ProvisionGard has been shown to be effective in reducing the entry of Indianmeal moth into bulk shipping packaging by 99.5%.

Summary

Packaged foods face many challenges before they are consumed. These include package flaws during manufacture, improper handling during shipment, inadequate storage conditions, lack of proper product rotation, and improper sealing in the home. Increased restrictions on pesticide use and emphasis placed on sanitation may be hindered by demanding production schedules, so development of insect-resistant packaging is of increasing importance to both the consumer and the manufacturer. The consumer is assured of insect-free food, and the manufacturer is protected against loss of goodwill and lawsuits arising from insect infestations in packaging. Future research in this area will lead to the development of more effective packaging methods to ensure that packaged foods remain insect-free until consumed.

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Table 3. *Resistance of common packaging materials to penetration by insects.*

Complete resistance	Vacuum sealed jars and cans
Insect proof	Polycarbonate, polyethylene terephthalate (PET), polyester nylon plastics
Insect resistant	Cellulose acetate; polyamide; polyethylene (250 microns to 10 mils; polypropylene; Polyvinyl chloride
Susceptible	Acrylonitrate; polyactic acid (biodegradable plastic); polyethylene (125 microns)
No resistance	Ethylene vinyl acetate; kraft paper; corrugated paperboard; paper/foil/polyethylene; polyethylene (25 to 100 microns = 1 to 4 mils); polyvinyldene chloride (Saran)

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13 Resistance Management

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Grain storage managers implement an integrated approach to controlling insect pests by using a range of tactics such as sanitation, cooling, drying, and grain cleaning. Chemical treatments, including fumigants and residual insecticides, remain the most effective tools for controlling insect pests and are key elements in integrated approaches. These tools enable grain storage managers to maintain food security, access markets, implement effective quarantine systems, protect the supply chain, and provide consumers with high quality food.

Health, safety, environmental, and economic considerations severely limit the range of chemicals that can be applied to grain. In recent years authorities around the world have reduced the number of chemicals available. Chemicals that can be applied to grain are rare and costly to develop.

In addition to these pressures, insects targeted by the chemicals are rapidly developing resistance to the few alternatives available. The remaining chemicals must be managed carefully to ensure effective grain protection now and in the future.

This chapter briefly summarizes our knowledge of the status of resistance to grain protection chemicals in stored-product insect pests. It describes factors that influence rate of resistance development or selection, including genetics, mechanisms of resistance, gene flow, relative dominance, fitness, and the effects of human activities. The chapter concludes with a discussion of how resistance management tactics can be applied to a real-world situation to show the challenges of managing resistance in stored-product systems.

Resistance Management in Stored Product Insect Pests

Pesticide resistance is an increased tolerance to a pesticide that has a genetic basis. As a heritable trait, the development and spread of resistance will be influenced by the selective pressures of pesticide use, the mode of inheritance, fitness costs associated with individuals carrying resistance genes, and movement of pests on geographical scales. Insecticides from a range of chemical groups and several fumigant gases have been used to control insect pests of stored products. In most cases, at least one major pest species has developed resistance to these compounds somewhere in the world, and that same resistance often develops in different parts of the world. Resistance development patterns in stored product insects from one country show potential for resistance development in other countries.

Insecticides have been used mainly as grain treatments (disinfestants and grain protectants); surface treatments for bag stacks, floors, and storage structure walls; and aerosol treatments. Since the mid-20th century these insecticides have been drawn mainly from the organophosphates (OPs) (malathion, chlorpyrifos-methyl, and dichlorvos), the pyrethroids (bioresmethrin, deltamethrin, and beta-cyfluthtin), and from the juvenile hormone analogues (JHAs) (methoprene and hydroprene).

The history of resistance development to insecticides from all of these groups has been well documented in Australia and demonstrates both the propensity of stored products insects to develop resistance and the potential for resistance to develop elsewhere in the future (Table 1). The lesser grain borer, *Rhyzopertha dominica* (F.), is of particular concern given that it is a major pest of stored products and clearly has the potential to develop resistance to OPs, pyrethroids, and JHAs.

Parallel development of insecticide resistances in different countries is well illustrated in the scientific literature. Champ and Dyte (1976) reported that malathion resistance was present in many countries around the world, and resistance to newer insecticides has since been reported from a range of countries as the following examples show. OP-resistant *R. dominica* have been reported from Australia, the United States, and Brazil (Bengston et al. 1975, Zettler and Cuperus 1990, Guedes et al. 1996). Similarly, pyrethroid-resistant maize weevils, *Sitophilus zeamais* Motsch., and *R. dominica* have been reported from Australia and Brazil (Samson et al. 1990, Collins et al. 1993, Guedes et al. 1994, Lorini and Galley 1999).

The principal fumigants used in stored product protection have been phosphine and methyl bromide. Resistance has been detected predominantly in phosphine, with examples from many species from many countries since the 1970s. One key feature of fumigation is that concentration and exposure period can both be altered to maximize fumigant efficacy. This has implications for the detection, measurement, and impact of phosphine resistance (e.g., Collins et al. 2005), with insects carrying resistance genes often controllable in practice.

The global survey of Champ and Dyte (1976) showed that phosphine resistance has been present in many countries for several decades. Subsequent published surveys focusing on specific geographic regions have further demonstrated the extent of phosphine resistance (e.g., Attia and Greening 1981, Zettler et al. 1989, Herron 1990, Zettler and Cuperus 1990, Benhalima et al. 2004).

Different levels of phosphine resistance can occur within a species. In the case of *R. dominica,* for example, at least two levels of resistance appear to exist: weak resistance, with resistant adults about 30 times more resistant than susceptibles when fumigated for 48 hours; and strong resistance, with resistant adults hundreds of times more resistant than susceptible insects (Collins et al. 2002, Lorini et al. 2007). Similarly, at least two levels of phosphine resistance have been reported for *S. oryzae* and *Tribolium castaneum* (Herbst) (Daglish et al. 2002, Jagadeesan 2011). As with resistance to other insecticides, phosphine resistance trends in one country show the potential for resistance development in other countries. The presence of strongly resistant insects in countries such as Australia, Brazil, and the Philippines should be of concern to countries that do not yet have strong resistance. Also, the prevalence of strongly resistant *R. dominica* in Brazil is a warning to countries where strong resistance is rare or has not been detected.

Although biologically derived insecticides have seen some use in agriculture, this has not been the case for stored-product protection. This does not preclude their future use and the potential for insects to develop resistance to these biopesticides should they be adopted. The potential of stored product insects to develop resistance to biopesticides is well illustrated by a study that demonstrated that native populations of the Indianmeal moth, *Plodia interpunctella* (Hubner), could develop resistance to the bacterium *Bacillus thuringiensis* within a few generations (McGaughey 1985). Spinosad is a bacterium-derived biopesticide that has been registered as a grain protectant and is likely to be widely used (Hertlein et al. 2011). Although there is no evidence of the potential of stored product insects to develop resistance to this biopesticide, resistance has developed in other agricultural pests (e.g. Moulton et al. 2000).

Cross-Resistance and Multiple Resistance

Cross-resistance is when resistance to a given pesticide causes resistance to another pesticide without the insect having been exposed to the latter pesticide (Scott 1990). For example, *R. dominica* that are resistant to one organophosphate have a tendency to be resistant to other organophosphates. A similar situation occurs with pyrethroid resistant *T. castaneum* and *R. dominica* (Collins 1990, Guedes et al. 1996, Daglish et al. 2003). In the application of pesticides for the control of stored-product insect pests, avoiding the use of pesticides that share cross-resistance is important. Failure to do so hastens the development of resistance.

Table 1. *Examples of field-derived insecticide resistances detected in Australian stored-product beetles.*

Type	Species	Insecticide tested	Reference
Benzene hexachlorides (BHCs)	*Sitophilus oryzae* and *S. zeamais*	Lindane*	Champ and Cribb (1965)
	Tribolium castaneum	Lindane*	Champ and Campbell-Brown (1969)
Organophosphorus compounds (OPs)	*Rhyzopertha dominica*	Malathion*	Greening et al. (1975)
		Chlorpyrifos-methyl Pirimiphos-methyl	Bengston et al. (1975)
		Dichlorvos*	Greening et al. (1975)
	T. castaneum	Malathion*	Champ and Campbell-Brown (1970)
	Oryzaephilus surinamensis	Fenitrothion* Chlorpyrifos-methyl*	Collins (1985)
Pyrethroids	*T. castaneum*	Bioresmethrin* Cyfluthrin Cyhalothrin Cypermethrin Deltamethrin Permethrin d-Phenothrin	Collins (1990)
	S. zeamais	Deltamethrin	Samson et al. (1990)
	R. dominica	Bioresmethrin*	Collins et al. (1993)
		Bifenthrin	Daglish et al. (2003)
Juvenile hormone analogues (JHAs)	*R. dominica*	Methoprene*	Collins (1998a)

*In commercial use at the time of the cited study.

When an arthropod has more than one mechanism of resistance, it is said to have multiple resistance (Georghiou 1965). For example, certain resistant strains of *P. interpunctella* are resistant to *B. thuringiensis* by altering the target site on which the toxin of this bacterium binds and reducing the number of target sites available (Herrero et al. 2001).

Mechanisms of Resistance

Four main mechanisms insects can use for resistance to pesticides are described below (Soderlund and Bloomquist 1990, Mota-Sanchez et al. 2002).

Metabolic resistance – Insects can develop an increased ability to detoxify and/or metabolize (breakdown) a pesticide by producing higher amounts of enzymes. Enzymes usually used to break down insecticides are cytochrome P450-dependent monooxygenases, hydrolases, or glutathione-*S*-transferases. This type of resistance is called metabolic resistance, and it is the most common mechanism of resistance. For example, higher levels of glutathione-*S*-transferase have been found in resistant strains of *T. castaneum* (Cohen 1986).

Target site resistance – Pesticides work by attaching themselves to target sites. Unless the pesticide molecules attach to these target sites, insects are not affected or killed. Some insects resist pesticides by having genetically altered target sites so that pesticide molecules are unable to attach to them, rendering the pesticides ineffective. This mechanism of resistance is called target site insensitivity. For example, one way *P. interpunctella* is resistant to

B. thuringiensis is by target site alteration to the toxin of this bacterium (Herrero et al. 2001).

Penetration resistance – Insects have a hard material called the cuticle covering the surface of their bodies. Pesticides that kill insects by contact must penetrate the cuticle and get inside the insect. Some insects have developed barriers against pesticides and can slow the absorption of chemicals into their bodies. This mechanism of resistance is referred to as penetration resistance, and it is not pesticide-specific. When penetration resistance is present alone, it confers weak resistance. For example, resistance to pirimiphos-methyl in certain strains of *T. castaneum* is by reduced penetration through the cuticle (Walter and Price 1989).

Behavioral resistance – In some cases the behavior of insects results in reduced exposure to pesticides. For example, Guedes et al. (2009) found higher rates of flight take-off in a resistant strain of *S. zeamais* exposed to surfaces treated with deltamethrin. Presumably this behavior has been selected to increase the insect's chance of survival by reducing the amount of time it spends on treated surfaces.

Genetics and Ecology of Resistance

Effective management of resistance requires an understanding of its causative processes. Insecticides act on genotypic variation (mutation, recombination, gene flow) to select for resistant phenotypes. How the selection process operates is determined by the population genetics and ecology of the organism in relation to its environment, including human activity. An understanding of factors such as the inheritance and relative dominance of resistance genes, relative fitness of genotypes in the presence and absence of insecticides, insect movement and mating systems, and human impacts is essential for sustainable resistance management.

Where investigated, insecticide resistance in insect pests of stored products has most often been attributed to a single autosomal gene. For example, in *T. castaneum*, DDT (Erdman 1970) and lindane/cyclodiene resistance (Beeman and Stuart 1990) are each mediated by a single autosmal gene, and resistance to the organophosphate malathion is also associated with a single gene but is multiallelic, with alleles for "specific" (carboxylesterase) and "nonspecific" resistance (and susceptibility) occurring at the same locus (Beeman 1983, Beeman and Nanis 1986). Single genes are also responsible for resistance to malathion, lindane, and dieldrin in *Plodia interpunctella* (Attia et al. 1981, Beeman et al. 1982) and DDT/pyrethroid sex-linked resistance in *S. oryzae* (Champ 1967, Heather 1985).

Multigene resistance also occurs. At least two major genes control resistance to organophosphates in *O. surinamensis* (Collins 1986), pyrethroids in *T. castaneum* (Collins 1998b, Stuart et al. 1998), and high phosphine resistance in *T. castaneum* (Jagadeesan 2011) and *R. dominica* (Collins et al. 2002). Further detailed genetic and molecular analysis of *R. dominica* (Schlipalius et al. 2002, 2008a) revealed the presence of two loci, *rph1* and *rph2*, responsible for phosphine resistance in this insect. *Rph1* controls the "weak" resistance phenotype by providing moderate resistance to phosphine, whereas *rph2* by itself confers only very low-level resistance. *Rph2* was not discovered in the field until *rph1* had become common. When combined in the same individual, mechanisms controlled by *rph1* and *rph2* synergize to produce a much higher level of resistance known as the "strong" resistance phenotype. Mau (2008) compared the genetics of phosphine resistance in strongly resistant *R. dominica* strains from three widely separated locations in Australia, and concluded that resistance in each strain was derived independently from others despite genetic analysis being consistent, with two major genes being responsible for resistance in each case.

How genes are expressed in the phenotype is known as dominance. When a pair of alleles is required to express resistance in the phenotype, the allele is a recessive factor. When an allele can phenotypically express itself in the heterozygote as well as the homozygote, it is referred to as a dominant factor. It is important to understand that dominance is not fixed and is dependent on the environment in which it is expressed or how it is measured. For example, resistant homozygotes and heterozygotes may survive a certain insecticide dose, making resistance dominant, but at a higher dose only the resistant homozygotes may survive, making the resistance recessive.

Most knowledge of the dominance of resistance in insect pests of stored products is derived from classical analyses of the inheritance of resistance. Very few resistances are expressed as either fully dominant or recessive. Most are intermediate, i.e., partially expressed in the heterozygote. For example, resistance to insecticides such as malathion (carboxylesterase) (Beeman 1983), fenitrothion (Collins 1986), pyrethrins (Prickett 1980), and pyrethroids (Collins 1988b, Stuart et al. 1998, Heather 1985) are often semi- or incompletely dominant, whereas resistance to phosphine is incompletely recessive (Bengston et al. 1999, Collins et al. 2002, Daglish 2004).

The bioassay methods used in these analyses, such as exposing insects to insecticide-impregnated papers or to very short exposures of fumigant (FAO 1974; 1975), are intended for rapid diagnosis of resistance but, because they do not reflect field application of chemicals, have limited relevance to resistance management. On the other hand, some analyses (Collins 1986, 1998b) used bioassays that mimicked use of insecticide so that conclusions about the effect of a range of doses on the dominance of phenotypes can be made.This may not be an issue with phosphine, as it has been shown (Daglish 2004) that degree of dominance (and resistance factor) of phosphine resistance in *R. dominica* and *S. oryzae* adults was constant over a range of exposure periods up to 144 hours. Whether this finding holds true for longer exposure periods is not known. A second potential problem with laboratory bioassays is that they are overwhelmingly carried out on adult insects and there is a general assumption that dominance will be the same for other life stages. This is not necessarily the case as it has been shown that both relative tolerance and relative dominance vary with life stage in *T. castaneum* (Collins et al. 1997).

Insects possessing resistance genes are often assumed to suffer a fitness cost (i.e., lowered reproductive success), which explains the initial absence or rareness of the resistance. From a resistance management perspective, a fitness cost would mean that the frequency of resistance would decrease during periods when the pesticide is not used. Despite the development of resistance to phosphine and a range of insecticides in stored product insects, relatively few studies have investigated potential fitness costs associated with these resistances. These studies have variously concluded that there is no fitness cost, there is a fitness cost, or there is even a fitness advantage. Heather (1982) compared the population growth rates of malathion-resistant and susceptible *S. oryzae* and overall found that resistant populations were no less or more fit than susceptible populations, and nor were population crosses between resistant and susceptible populations. In contrast, Arnaud et al. (2002) reported that malathion-resistant *T. castaneum* had a higher fecundity and were therefore more fit than susceptible insects. Schlipalius et al. (2008a) concluded that strongly phosphine-resistant *R. dominica* suffer no fitness disadvantage, after a population of resistant-susceptible cross was reared in the absence of phosphine selection, and the frequencies of resistant, susceptible, and hetetrozygote individuals determined after 5, 15, and 20 generations. Using a similar approach Jagadeeesan (2011) concluded that strong resistance in *T. castaneum* came with a fitness cost, but weak resistance did not. Several studies in which various physiological or ecological parameters were compared in resistant and susceptible populations have demonstrated fitness costs to insecticide- or phosphine- resistance in various stored product pests (Pimental et al. 2007; Sousa et al. 2009). Clearly, no general conclusions can be drawn about the fitness of resistant stored product insects, and so studies on specific species and resistances are needed.

The fact that studies using different approaches can support contradictory conclusions raises the possibility that expression of fitness in laboratory studies is so situation-specific that different approaches will often lead to different conclusions. Using more than one approach in fitness studies may be advisable to maximize the likelihood of obtaining information that is useful for resistance management.

Understanding genetic structure of populations and gene flow in stored product pests may provide insights into the development and spread of resistance, and the scale on which resistance management should be applied. Studies like these must rely on molecular tools such as resistance markers and neutral DNA markers. No information is available on the frequency of pesticide resistance genes in wild stored product insects, although the discovery of the molecular basis for the inheritance of phosphine resistance in several organisms raises the possibility of resistance markers being developed for phosphine resistance (Schlipalius et al. 2008a; Jagadeesan 2011). Several studies have investigated the levels of genetic differentiation in *T. castaneum* using neutral DNA markers. Drury et al. (2009) reported relatively low levels globally indicating considerable gene flow, as did Semeao et al. (2010) for the United States and Puerto Rico. Although anthropogenic movement is likely to contribute to gene flow, Ridley et al. (2011) showed that dispersal through flight is important for this species at least on a district scale. No information is available on population structure and gene flow in *R. dominica*, but Mau (2008) showed that strong phosphine resistance evolved independently in Australian populations from three widely separated geographical origins. The lack of information on population structure and gene flow in stored product pests represents an impediment to understanding how resistance develops and spreads and how it should be managed.

Resistance Monitoring and Detection

Resistance monitoring is undertaken for a number of reasons including early warning of resistance, feedback on the success of management activities, diagnosis of control failures, and information on the likely impact of new resistance. Reliable methods of detecting and measuring resistance and an understanding of how results relate to control failures are the foundation of an effective resistance-monitoring program.

The most common method of testing for resistance is to expose the insect to the toxicant and observe and quantify the response, known as bioassay. Standard bioassay methods have been published for testing for resistance to the grain protectants malathion and lindane (FAO, 1974, Busvine 1980) and the fumigants methyl bromide and phosphine (FAO,1975) in a number of stored product pest species. These methods are based on exposure of adult insects to a “diagnostic concentration” of chemical for relatively short periods of time, 5 to 6 hours and 20 hours, respectively.

The grain-protectant test was designed to provide a result on the day of testing. Diagnostic or discriminating concentrations are developed from the responses of “susceptible” or wild-type strains of insects believed to represent the insect genotype before any selection with the chemical had occurred. The diagnostic dose is usually a single dose used to separate putative resistant from susceptible insects. Choice of diagnostic doses requires careful consideration of the range of responses of populations of target insects and analysis of their response data. Second-level diagnostic doses have been developed in situations where higher-level resistance (a second mechanism) is suspected, or where current resistance levels are too weak to challenge field control (Daglish and Collins 1999). A detailed discussion of bioassay and the statistical analysis of response data is beyond the scope of this chapter. The reader is referred to Robertson et al. (2007) and Stanley (2008) as starting points.

The FAO-published methods provide an international standard that can be used to alert researchers to the presence of resistance in an insect population. They do not reflect how chemicals are used by industry, so they give no indication of the impact of any given resistance on control in the field. For example, the protectant assay exposes insects to chemical impregnated into a filter paper, whereas grain protectants are applied as liquids to grain or industrial surfaces of various types and are expected to remain active for several months.

The phosphine exposure assay is short compared with industry practice of about 5- to more than 20-day fumigations. Resistance tests typically expose only adults, while the treatment is usually aimed at controlling all life stages. (An obvious exception is that treated grain assays must be used to test for resistance to juvenile hormone analogues [e.g., methoprene] because these protectants affect the immature stages and cause negligible parental mortality). For these reasons, other assays that better model field uses have been developed (Collins 1990, Daglish and Collins 1999, Collins et al. 2005). These assays are particularly important in the confirmation and characterization of resistance.

Sampling strategy (reviewed by Venette et al. 2002) should be considered carefully before undertaking a monitoring program. In the early stages of resistance development, resistance gene frequencies are relatively low, and homozygote-resistant insects will be virtually absent in the population (Mackenzie 1996). Thus, the probability of detection of resistance genes will be low (Roush and Miller 1986). If the primary aim of monitoring is discovery of new resistance, then a strategy, such as F2 screen, that maximizes the likelihood of detection could be used (Andow and Onstad 1998). In later stages of resistance development, when gene frequencies are relatively high, the primary aim of monitoring may be to provide information to a management strategy. In this case, a sampling and detection strategy that provides rapid diagnosis may be more appropriate.

Detection is also influenced by the relative dominance of resistance genes. Most resistance in stored-products insects is semi- or incompletely dominant (Prickett 1980, Stuart et al. 1998, Beeman 1983, Heather 1985, Collins 1986, 1988a) or close to recessive (Bengston et al. 1999, Collins et al. 2002, Daglish 2004) so that the overlap of responses between susceptible and heterozygous genotypes further diminishes the sensitivity of the bioassay method.

A potential solution to the two major drawbacks of traditional bioassay — long response time and low sensitivity — is the development of either biochemical or molecular testing methods. A PCR (polymerase chain reaction) diagnostic has been developed for cyclodiene resistance in *T. castaneum* (Andreev et al. 1994), and genomic methods have been used to identify the major genes responsible for phosphine resistance in *R. dominica* and *T. castaneum* (Schlipalius et al. 2008a, Jagadeesan 2011). The advantages of these techniques are that they can identify resistance in heterozygotes, live or dead, they avoid the need for culturing insects and they provide accurate unambiguous results in less than a day at a reasonable cost (Schlipalius et al. 2008b). The major disadvantage is that this type of test can detect only known resistance genes.

In conclusion, resistance monitoring is an important part of keeping the proportion of susceptible organisms in a population as large as possible. It enables the assessment of pest population status, understanding of potential risks, evaluation of whether a resistance management program is achieving its goals, and the prediction of future trends (Stanley 2008).

Resistance Management Principles

Pesticide resistance management is a strategy for applying any pesticide or pesticide class as infrequently as possible to delay the development of resistance to it. Resistance management expects resistance to develop and acts to mitigate the rate at which it develops. This section presents information on possible ways of maintaining the pesticide susceptibility of stored-product insect pests.

A practical resistance-management strategy relies on three major components.

Information about the system – Information is required on the state and condition of grain and grain storages in the system and on the occurrence of insect infestation. In addition, there must be information on strengths and frequencies of resistance in insect pest populations. The latter provides early warning of the emergence of new resistances and the occurrence of known resistance. This allows researchers and industry time to assess the situation, avoid control failures, and implement remedial action. Accurate, detailed information permits effective planning and provides feedback on the success of resistance-management tactics.

Tactics that reduce the rate of selection – Tactics that reduce the rate of selection are likely to be the most successful in the long term. This can be achieved by reducing the frequency of use of the selecting agent, by reducing the number of insects exposed to the selecting agent, and by maintaining sources of susceptible genes. For example, cooling grain reduces insect population growth, reducing the need to fumigate. Chemical and physical hygiene treatments reduce population numbers, decreasing the number of insects potentially exposed to the selecting agent. The existence of untreated refuges maintains sources of susceptible genes.

Tactics that destroy resistant insects – In a situation where resistance has already evolved, tactics that destroy resistant insects are essential for practical resistance management. These can be either higher doses of the current material (e.g., phosphine), alternative chemicals, or physical methods such as heat disinfestation. These tactics are used to eliminate resistance foci, that is, instances where resistance has been detected (resistant homozygotes present), and destroy undetected incipient resistance (heterozygotes present). Manipulating chemicals through rotating them in time or separating their use geographically facilitates the destruction of resistant insects.

Resistance Management Tactics

Reducing Selection

Minimize applications

Theory – The more often a pesticide is used, the more insects are exposed to selection, and the more likely that resistance will evolve (Tabashnik 1990). Reducing the use of the pesticide will reduce the rate of selection.

Practice – Fumigants, especially phosphine, are used widely in the grain industry, exposing a potentially very large population of insects to selection. In addition, they are often used repeatedly on the same parcel of grain, or in stores where insect populations are maintained in harborages, so that the same population is serially exposed to selection. The aim should be to reduce the overall dependence on these materials and limit repeat fumigations. This will require the use of alternative disinfestants (chemical and non-chemical, such as heat), more effective disinfestation systems, expanded use of nonchemical controls, or expanded use of protectants. To avoid calendar-based fumigation, the industry requires better insect detection systems that allow monitoring of whole bulks.

Storage hygiene – Reduce the number of insects exposed to selection

Theory – Storage hygiene refers to the removal and disposal of all residues of grain, grain dust, dockage, etc., from storages and associated equipment. Grain insect pests can survive for long periods and even multiply on only a small amount of this material. If high levels of cleanliness are maintained inside storages, then the likelihood of insects that carry resistance genes surviving from one storage season to the next is greatly reduced. In addition, if grain residues are removed from the outside of storages and storage equipment, then the risk of infestation from these sources by insects carrying resistance genes is also reduced. Maintaining strict hygiene standards reduces the risk of insect populations becoming resident in a silo and from being repeatedly subject to selection with pesticide.

Practice – Good hygiene reduces general infestation pressure and is the basis for effective integrated pest management. High standards of hygiene require an investment in time, training, equipment, and the determination to do a thorough job.

The practice of applying insecticidal sprays to storage structures will increase the likelihood of effectively controlling insects and provides some residual effect but risks selection for resistance to insecticides used. Diatomaceous earth treatments should be used instead of chemical protectants wherever practicable. Diatomaceous earths are not effective where significant numbers of insects are already present in the grain or in high humidity situations, such as ports.

Grain cooling – Reduce the number of selection events

Theory – Low temperatures can slow insect development and reproductive rates significantly, and inhibit population growth. Reducing the insect population growth rate should reduce the number of treatments such as fumigations required on any parcel of grain and, in some cases, may permit no chemical use.

Practice – In many cases, such as tropical and subtropical regions, cooling alone will not ensure insect-free grain but may be sufficient for some segregations such as feed. In practice, feed can come out of any storage and is a potential source of infestation in a common grain path. With effective monitoring, cooling should reduce the number of fumigations required on any parcel of grain. Note that cooler grain may require longer fumigation times or higher fumigant concentrations for effective control. Note that in many situations, storages cannot be cooled economically.

Provide untreated refuges

Theory – Refuges or areas of untreated habitat (grain, etc.) serve as sources of large numbers of insects, both susceptible and resistant (Onstad 2008). If resistant insects have lower fitness relative to susceptibles, then in the absence of chemical selection, the presence of refuges will result in an increase in the relative frequency of susceptible genes. Early in a resistance episode, susceptible individuals greatly outnumber resistant insects. Refuges also function as a reservoir from which susceptible genes may flow through insect movement and interbreeding into insect populations that are under selection, to reduce the frequency of resistance genes in the populations.

Practice – This tactic is often a key part of resistance-management strategies for field crops. This tactic is difficult to implement in the grain industry because it contradicts storage hygiene and market requirements for insect-free grain. Nevertheless, refuges may exist in other parts of the environment. The potential advantages to be gained because of differences in fitness between resistant and susceptible insects may not be realized in the grain storage system because differences in fitness between resistance genotypes often are not demonstrated.

A possible variation of this tactic would be to reduce use of a particular pesticide in certain sectors of the industry to create "refuges" from selection. For example, farmers could be encouraged to use non-chemical control technologies including hygiene, cooling, controlled atmospheres, diatomaceous earth, and alternative chemicals (where markets permit).

Destroying resistant insects

High doses – Make resistance recessive

Theory – Application of doses high enough to control resistant heterozygotes (insects carrying one copy of the resistance gene or genes) will delay the evolution of resistance because these insects do not survive to reproduce (Roush and Daly 1990). This tactic requires reliable distribution of adequate concentrations of the chemical treatment in a closed system. If resistant homozygotes (insects carrying two copies of the resistance gene(s)) survive such treatments, resistance will rapidly increase in frequency.

Practice – This tactic requires implementation very early in resistance development because using high doses that would control only heterozygotes could result in rapid selection for resistance in insect populations where resistant homozygotes are already present.

A practical way to apply this tactic is to aim to control homozygote-resistant insects. This can be done with phosphine because the dosage (concentration and exposure period) of this fumigant can be varied. Fumigation in a silo proven to be sealed will allow concentrations to be held at the required concentration for long enough to ensure destruction of resistant homozygotes (Daglish et al. 2002, Collins et al. 2005) and minimize the opportunity for insects to escape the toxicant. To be effective, this tactic requires optimal application of phosphine and the avoidance of under-dosing. A risk with this tactic is the possible selection for even higher levels of resistance in target species.

Manipulating chemicals – Rotate in time or separate geographically

These tactics require two preconditions to be met to be successful. First, the mechanisms of resistance that develop with each of the components should be different and independent (i.e., no cross-resistance). Secondly, the frequency of resistance genes in the target populations must be low and should not occur together in the same individual (Roush 1989). In addition, each tactic relies on its own set of assumptions.

Theory – Rotation in time tactic involves the rotation of two or more pesticides to which the insects do not show cross-resistance. Rotations assume, at least at the beginning of the resistance episode, that individuals that are resistant to one pesticide have substantially lower fitness than susceptibles, so their frequency declines between applications of that chemical, and that there is a large gene pool of susceptible insects that will readily mate with resistant insects and dilute the resistance-gene frequency, or both (Tabashnik 1990). The latter relies on the presence of large areas of untreated habitat. Decisions on when to rotate ideally should be made on the basis of the length of insect generations so the period of selection of any pesticide does not extend beyond one generation. Rotations also need to be coordinated over a large area so insects functionally belonging to the same gene pool are not simultaneously selected for resistance to the different pesticides used in the alternation.

Practice – Currently, alternative fumigants and grain protectants are limited. Even when potentially available, they are further limited by issues such as environmental and health concerns, cost, and grain-handling logistics.

Most of the conditions described for success of this strategy cannot be met in the grain industry. For example, evidence to date suggests that resistance to phosphine does not decline between applications. Frequency of weak phosphine resistance is often already high in insect populations, and strong resistance genes are present in most regions, so large populations of susceptibles are not available. Further research is needed on these aspects.

Alternative fumigants or grain protectants have value in that they can be used to control undetected incipient resistant populations and to control known resistance outbreaks. In the former, the alternative would be part of a predetermined rotation. In the latter, the alternative would be used when resistance to phosphine has been diagnosed.

Conclusion

The previous discussion of feasible resistance management tactics reveals that grain storage managers have a limited number of options that can be implemented to manage resistance to chemical treatments. Management is restricted, in particular, by the lack of viable alternatives.

A practical resistance management strategy that could be implemented immediately would include:

- Limiting the number of repeat treatments (fumigations) on the same parcel of grain.
- Ensuring highest standards of application. For fumigation this means use of sealed silos so that recommended minimum concentrations and exposure periods are met to avoid under-dosing.
- Strong emphasis on use of nonchemical control technologies including hygiene, cooling, controlled atmospheres, and diatomaceous earths to minimize the use of essential materials such as phosphine across the grain industry.
- Use of alternative chemicals such as protectants and structural treatments (including diatomaceous earth) where acceptable and effective.
- Introduce limited strategic use of alternative fumigants and other chemicals when available.

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14 Fumigation

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Fumigation is the practice of using gaseous pesticides applied directly to commodities or to part or all of a structure, including vehicles used to store, handle, process, or transport raw commodities or finished food products. A fumigant is a toxic chemical or mixture of compounds that kills pests as a volatile gas within a range of temperatures. For purposes of this book we consider fumigant gases that are targeted at killing arthropod pests and rodents infesting grains, grain products, other durable stored foods, and stored seeds for planting. A highly toxic fumigant such as methyl bromide can be used to kill weed plants and seeds, fungi, snails, and nematodes in addition to arthropods in some use contexts. Because fumigants act in the gaseous stage, they are ideal for penetrating commodities and protected parts of buildings and food containers. These areas are inaccessible to contact by other pesticide formulations, including aerosols, which are actually fine mists of liquid materials.

Fumigants are the most effective control measures for stored product insect and mite pests. When properly applied, they deliver a high level of mortality and leave no chemical residue on grain or food to pose a health concern. In addition to being effective insecticides, fumigants are among the most dangerous to use for applicators, for human bystanders and for nontarget organisms. Of all insecticides, fumigants belong to the most dangerous group of pesticides, Category 1 U.S. EPA. Packages are marked with a skull-and-crossbones (Figure 1).

Almost every year one or more people die in the United States from misuse of registered fumigants or unauthorized entry into fumigated spaces. It is critical that applicators receive thorough training and certification from government regulatory agencies before using fumigants. Insecticides with residual toxicity — those that can be applied to a commodity or a surface in a building and kill insects on contact for several weeks or months following application — are covered in Chapter 9 of this book. More detailed and technical reviews of fumigation for stored products have been given in previous publications (e.g., Bond 1989, Walter 1991, Thoms and Phillips 2004). The objective of this chapter is to summarize the characteristics and application methods for the fumigants registered for use on stored products and associated structures and buildings in the United States.

Overview of Available Fumigants

Table 1 gives a summary of the physical and chemical properties of the five fumigant gases covered in this chapter. Despite what might seem an adequate number of fumigant insecticides to meet the needs of the pest control and food industries, each compound has particular characteristics or a regulatory status that make it more or less applicable to any given situation. For example, methyl bromide is highly effective at killing all life stages of most pest species in a short period of time, but it is currently being phased out and banned under the international Montreal Protocol and U.S. Clean Air legislation. Ethyl formate may be relatively safe and easy to use but its effectiveness as a toxin may be limited.

Table 1. *Physical and chemical properties of commonly used fumigants currently registered or proposed in the U.S. for stored products.**

Fumigant (chemical formula)	Molecular weight	Specific gravity air = 1	Boiling point (°F)	Flammability by volume in air (%)	Water solubility ppm	Odor as gas	Incompatibility	
							Liquid or solid	Gas
Methyl bromide (CH_3Br)	94.94	3.27 @32°F	38.5	Nonflammable	15,444 ppm	None (sweet odor in high concentrations)	Contact of liquid with aluminum, magnesium, zinc, and alkali metals may result in liberation of toxic gases, and possible fire and explosion. Liquid incompatible with plastics, like polyvinyl. Liquid may react with sulfur compounds to create malodors.	In high concentrations, gas may react with sulfur compounds to create malodors. Decomposes in flame, glowing filament to produce HBr.
Sulfuryl fluoride (SO_2F_2)	102	2.88	-67	Nonflammable	750 ppm @77°F	None (sulfur odor in high concentrations)	Contact of liquid with glass, metals	Decomposes in flame, glowing filament to produce HF
Phosphine (PH_3)	34.04	1.21 @39.2°F	-125	1.79% by volume of air	416 ppm @63°F	Garlic-like odor due to contaminant; ammonia in certain formulations	Solid metal phosphide formulations can spontaneously ignite if contacted by water, acids, or chemicals.	Can corrode copper, brass, copper alloys, and precious metals such as gold and silver. Can react with metallic salts on photographic film.
Carbon dioxide (CO_2)	44.01	1.53	-109.3	Nonflammable	88%	Odorless	None	Various elastomers
Propylene Oxide (C_3H_6O)	58.08	0.86	34.2°C	Extremely flammable	40.5%	Irritant	Aluminum, copper, brass, bronze	Anhydrous metal chlorides, acids, bases, clay-based materials
Ethyl Formate ($C_3H_6O_2$)	74.08	0.92	54°C	Flammable liquid	1,000 ppm	Sweet, fruity	Decomposes slowly in water	Generates flammable hydrogen when mixed with alkali metals or hydrides

* Excerpted from Walter 1991.

Readers who would like to learn more or who seek to become fumigant applicators can pursue training and education provided by universities, professional associations, and fumigant manufacturers and distributors. Because fumigants act to kill insects and rodents in the gaseous state, their mode of action is believed to begin with respiration. Arthropod life stages most susceptible to fumigants are those that are most physically active — the larvae/nymphs and adults that take in a lot of toxic gas through breathing. Less active life stages, such as pupae and embryos in eggs, are less susceptible to fumigants.

Methyl bromide

Methyl bromide (MeBr, CH_3Br) has a long history of use in the agricultural sector as a broad spectrum biocidal fumigant. It is applied primarily to control pest populations in soils, commodities, processing facilities, and commercial marketing channels. MeBr predominates in gaseous form at normal atmospheric temperatures and pressures. It diffuses homogeneously within the headspace or pore space of treated substrates (e.g., grain, nuts, etc.) to reach pests and achieve uniform exposure, a highly coveted characteristic. The gas is stored in, delivered in, and released from metal canisters and cylinders of various volumes at 100% concentration (Figure 1).

Figure 1. *The skull-and-crossbones symbol (top) is used on labels for Category 1 insecticides, the most dangerous category assigned by the USEPA. Methyl bromide (bottom) comes in containers of various sizes.*

MeBr was identified as a chemical that contributes to the depletion of stratospheric ozone, and its production and use are subject to regulation under the U.S. Clean Air Act. As one of the original signatories of the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer, the United States ratified the Protocol in 1988. Amendments to the Clean Air Act were enacted in 1990 to include Title VI on Stratospheric Ozone Protection to ensure that the United States would satisfy its obligations under the protocol. For developed countries including the United States, consumption was frozen at 1991 "baseline" levels until 1998, and then reduced incrementally until an intended 100% reduction, or phase-out, was reached by a target date of 2005. Before 1991, the United States used roughly 27,000 metric tons (MT) annually (Ragsdale and Vick 2001). Of this about 75% was used for soil fumigation, 11% for commodity treatments, and 6% for structural fumigation, with the remainder used as feedstock in industrial chemical production. In keeping with the schedule set by the Montreal Protocol and a commitment to a gradual reduction, MeBr usage in the United States has declined significantly (Figure 2, Johnson et al. 2012).

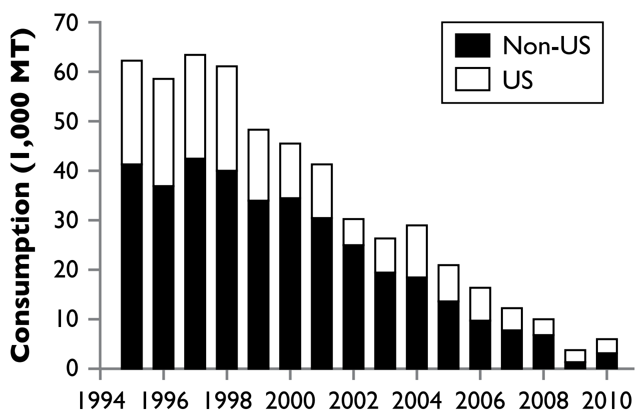

Figure 2. *World and United States consumption of methyl bromide 1995-2010. Quarantine and pre-shipment applications are not included (Source: Johnson et al. 2012).*

The Montreal Protocol and the U.S. Clean Air Act allow yearly requests for critical use exemptions for MeBr use in scenarios where no technical or economic alternatives are available (Table 2, USEPA 2011a). Since 2005, more than 90% of the critical use exemption allowance goes to preplant soil fumigations, with strawberries alone taking up 30 to 66%. Postharvest MeBr uses involve the direct treatment of commodities in marketing channels that are not subject to domestic and international quarantine

Table 2. *United States critical use exemptions for methyl bromide (MT)*.*

	2009	2010	2011	2012
Postharvest				
Mills and processors	291.4	173.0	135.3	74.5
NPMA food processing structures	54.6	37.8	17.4	0.2
Commodities	45.6	19.2	5.0	2.4
Dried cured pork	19.0	4.5	3.7	3.7
Total	410.6	234.5	161.4	80.9
Preplant				
Strawberries – field	1,269.3	1,007.5	812.7	678.0
Tomatoes – field	1,003.9	737.6	292.8	54.4
Peppers – field	549.0	463.3	206.2	28.4
Cucurbits	407.1	303.0	195.7	59.5
Orchard replant	292.8	215.8	183.2	18.3
Forest nursery seedlings	122.1	117.8	93.5	34.2
Ornamentals	107.1	84.6	64.3	48.2
Eggplant – field	48.7	32.8	19.7	6.9
Nursery stock – fruit, nut, rose	25.3	17.4	8.0	1.6
Sweet potato slips	18.1	14.5	11.6	8.7
Strawberry runners	7.9	4.7	6.0	3.8
Total	3,851.3	2,998.9	1,893.8	942.0
Grand total	4,262.0	3,233.5	2,055.2	1,022.8

* Values are those exemptions granted by the Parties to the Montreal Protocol (Source: USEPA 2011a).

requirements. Postharvest uses take less than 10% of the total critical use exemption allowance, with mills and processors receiving 71 to 92% of this. Postharvest critical use exemptions are not expected to continue for the United States past 2015.

Also exempt from the Montreal Protocol are quarantine and pre-shipment uses of MeBr as well as emergency uses, although the latter have not yet been granted. Quarantine and pre-shipment uses of MeBr refer to those required by regulatory entities to ensure pest-free commodities. The intent of quarantine and pre-shipment MeBr fumigation in the United States is to enhance the distribution and safety of commodities, promote and retain access of U.S. commodities to domestic and foreign markets, and protect the United States and its trading partners from the threat posed by pests. As the overall agricultural use of MeBr declines, quarantine and pre-shipment applications constitute a growing percentage of the total, and there is pressure to end the exemption under the Montreal Protocol. MeBr alternatives for quarantine and pre-shipment use must be consistent with international phytosanitary standards (IPPC 2011), generally requiring dose response data and confirmatory treatments that kill sufficient numbers of insects to provide the required security (usually Probit 9 or 99.9968% mortality) for each pest of quarantine concern (Couey and Chew 1986).

Unlike critical use exemptions, the amount of MeBr used for quarantine and pre-shipment is relatively difficult to track, as there is no single source for these data (Schneider and Vick 2002). Amounts used under USDA Animal and Plant Health Inspection Service (APHIS) supervision are given in Table 3, but additional MeBr is used by industry and supervised by state and local regulators with few records taken. Best estimates indicate U.S. imports require roughly twice the MeBr that exports do, with Chilean imports receiving more than 60%. Among the commodities treated, grapes receive the most MeBr for quarantine treatments, followed by logs.

The elimination of MeBr for quarantine and pre-shipment applications would require specific analyses of the technical efficacy and economic feasibility for each application scenario and alternative. Alternatives acceptable for one quarantine pest and commodity may not necessarily be applied to other applications without sufficient data to support the regulatory allowance. Gradual adoption of these alternatives (such as sulfuryl fluoride or phosphine) will help reduce the use of MeBr for quarantine and pre-shipment treatments, but issues of cost, product quality, and the acceptance by quarantine regulatory agencies must be addressed. Of particular concern is the treatment of domestic products or imports requiring fumigation upon arrival at port and inspection facilities. Because these quarantine and pre-shipment fumigations are generally time-sensitive and may involve large amounts of product to be treated, most MeBr alternatives are not currently acceptable.

Preventing the release of MeBr into the atmosphere following chamber fumigations may extend quarantine and pre-shipment use. Several commercial recapture systems are available, and research continues to develop commercially viable processes to contain, destroy, or reuse MeBr and alternative fumigants after use to reduce agricultural effects on air quality. To address this situation in a manner that minimizes nontarget effects on human and environmental health, the USDA has established research initiatives to reduce or eliminate the emission of fumigants and other agriculturally derived volatile organic compounds (VOCs) into the atmosphere (Civerolo et al. 1993).

Phosphine – hydrogen phosphide

Hydrogen phosphide gas has the chemical formula PH_3 and is commonly referred to as phosphine. Phosphine is by far the most commonly used fumigant for bulk-stored cereal grains, oil seeds, and other bulk dried commodities due to its low cost and relative ease of use. Phosphine can be purchased in various formulations that vary in method of application, rate, and efficiency of gas delivery to the target pest insect. Phosphine has a specific gravity of 1.21 (Table 1), similar in density to air, which allows it to spread and penetrate well through commodities and structures. The toxic mode of action of phos-

Table 3. *Quarantine use of methyl bromide in the United States.*

	2005	2006	2007	2008	2009	2010
Total MeBr Usage (metric tons)						
Export*	101.3	113.8	113.8	87.1	71.5	56.5
Import	213.5	245.1	233.7	248.9	251.1	252.4
Total	314.8	358.9	347.5	336.0	322.6	309.0
Commodity Type						
Fresh fruits and vegetables	190.8	216.7	210.1	215.8	224.7	210.3
Propagative plant material	1.0	0.9	0.5	0.8	0.8	0.6
Cut flowers and greenery	2.2	4.7	4.9	5.3	5.5	5.0
Other**	120.8	136.5	132.0	114.2	91.5	93.1
Total	314.8	358.9	347.5	336.0	322.6	309.0
Country of Origin (Import only)						
Chile	148.7	166.1	154.5	149.4	164.9	150.6
Peru	20.9	25.8	32.3	37.6	36.6	34.3
Costa Rica	9.4	11.0	12.6	16.3	9.6	10.9
Italy	9.1	7.1	6.8	10.1	8.5	11.2
China	4.5	9.3	9.7	9.8	7.7	7.8
All Others	20.9	25.8	17.8	25.8	23.8	25.8
Total	213.5	245.1	233.7	248.9	251.1	240.6

* Data from APHIS methyl bromide use database, includes only APHIS supervised treatments; amounts supervised at the state and county level are not included in the table.
** Includes tile, steel, and logs.

phine is not well understood but is generally believed to interfere with metabolism of oxygen at the cell membrane. Oxygen must be present for phosphine to be toxic. It is not recommended to use phosphine in combination with low oxygen controlled atmosphere treatments that would reduce the efficacy of the gas.

Phosphine fumigants are registered for more than 50 raw commodities, processed foods, and nonfood items in the United States, and can be used in one of several formulations or delivery methods. The most common formulations of phosphine are as metallic phosphide salts that react with moisture in the air to generate phosphine gas. Aluminum phosphide (AlP) and magnesium phosphide (MgP) react with water molecules according to the following chemical reactions.

$$AlP + 3H_2O \rightarrow Al(OH)_3 + PH_3$$

$$Mg_3P_2 + 6H_2O \rightarrow 3Mg(OH)_2 + 2PH_3$$

Aluminum and magnesium phosphide can be purchased as pellets or tablets (Figure 3) that can be incorporated directly into the commodity to release gas throughout a grain mass, or the phosphide salt can be commercially formulated as a powder or granule in a ventilated linen "sachet" or pressed as a thin layer on a metal plate. As the reaction formulae indicate, one molecule of AlP reacts with three molecules of water to generate one molecule of phosphine, PH_3, but MgP generates twice as much phosphine in its reaction. Both reactions are limited in their rate by the ambient temperature and the water vapor available through humidity in the air.

Application labels for these formulations indicate that application should be done when the commodity air temperature is above 40°F. The minimum ideal conditions for reaction of phosphide salts to yield phosphine gas are 80 to 90°F and 70% RH or higher. With all conditions being equal more phosphine is generated at a higher rate from MgP compared to AlP. Applicators often choose MgP for commercial fumigations that require treatment to be done in one or two days, while treatment of bulk stored commodities for which treatment time is not critical will utilize AlP. The application label for phosphide salts will report a range of doses that can be effectively applied to a commodity or space. The effectiveness of phosphine fumigation, as with fumigants using other active ingredients, is determined by the concentration of the gas, the temperature at which the

Figure 3. *Pellets (left) and tablets (right) of aluminum phosphide that generate 0.2 and 1.0 g, respectively, of phosphine each when fully reacted.*

fumigation is conducted, and the length of time the gas can be held on the target pest. Gas concentration is a function of gastightness of the structure or space being treated and the total amount of fumigant added to the structure or commodity. When consulting application instructions that recommend a range of treatment doses, it is recommended that the applicator use a higher number of pellets or tablets to maximize the total amount of phosphine gas that could be generated and counteract any loss of gas that may occur in a leaky structure.

Phosphine also can be delivered directly as a gas to a commodity or structure from a phosphine generator or from one of several formulations of hydrogen phosphide gas released from a pressurized gas cylinder. A phosphine generator requires that a phosphide salt be reacted with water in a highly controlled and contained reaction vessel from which the gas is released into the treatment area (Figure 4). Phosphine in cylinders may be composed of PH_3 dissolved at about 2% in carbon dioxide, all of which is released into the commodity or structure, or nearly pure phosphine gas from a cylinder can be precisely and rapidly mixed with air upon release from the tank and then delivered directly to the treated commodity or space (Figure 4). Phosphine gas concentrations of more than 18,000 ppm can spontaneously combust and explode in a normal atmosphere, so rapid dilution in air is essential during a treatment.

Current USEPA registrations for cylinder-based phosphine are very specific and strict as to the method and instrumentation used for releasing the gas.

Phosphine fumigants have some drawbacks that may preclude their use in specific situations. Flammability or explosion of solid and gaseous formulations of phosphine products is a safety hazard, as discussed. Spontaneous ignition of phosphine gas, if the gas concentration exceeds 18,000 ppm, rarely happens but could occur if large numbers of phosphide pellets or tablets quickly generate gas in a small-volume space. Dangerous high concentration situations may be more likely when using cylinderized pure PH_3 gas that is not properly mixed with a diluting gas. Phosphide pellets and tablets are prone to smoldering. Ignition and fires can occur within buildings or grain masses when they are deposited in piles in which the pellets are touching each other or when standing water is present. As with spontaneous combustion under high concentration, fire hazard from "piling" can be avoided by proper application.

A common drawback of phosphine that dictates the places and structures that can be fumigated — though not a direct human safety concern — is that the gas is highly corrosive to certain metals that it contacts. These metals include gold, silver, and most importantly, copper. Electrical appliances, wiring, lighting, and especially electronic equipment with

Figure 4. *A phosphine generator (left). Cylinder-based phosphine at 2% in carbon dioxide (center) and 100%* PH_3 *being diluted immediately in air (right).*

integrated circuits, computer chips, and similar devices with copper and other conductors of electricity are at risk of being damaged under phosphine fumigation and may not work properly after the fumigation. This corrosive factor, more than any other, is why phosphine fumigation is rarely applied to buildings such as flour mills, food plants, climate-controlled warehouses, and other buildings that have extensive electrical wiring, light fixtures, telephones, computers, and electrically powered and computer-processor controlled equipment that could be damaged by the gas. Grain bins, grain silos, bag stacks, barges, ship holds, and buildings with minimum electrical equipment are thus ideal for phosphine fumigation because the gas is relatively inexpensive and easy to apply.

Sulfuryl fluoride

Sulfuryl fluoride (SF) has been used for more than 50 years, under the trade name Vikane gas fumigant (Dow AgroSciences, Indianapolis, Ind.), for control of structure-infesting pests including drywood termites, other wood-destroying insects, and most recently, bedbugs. Vikane does not have food tolerances, so food must be removed or sealed in airtight containers before fumigation. Another SF product, trade name ProFume gas fumigant, registered in the United States in 2004, has EPA-approved food tolerances and is labeled for fumigation of more than 50 commodities, food processing and storage structures, stationary vehicles, and permanent and temporary (e.g., tarped stack) chambers. ProFume was developed by Dow AgroSciences at the request of the food processing industry as a postharvest fumigant replacement for MeBr, which is being phased out under the Montreal Protocol as an ozone-depleting substance.

Sulfuryl fluoride (ProFume) is formulated as 125 pounds of liquid (99.8% SO_2F_2) packaged under pressure in steel cylinders (Figure 5). SF is an inorganic molecule. It is nonflammable, nonexplosive, and as a gas is considered relatively inert and nonreactive. SF has been used for more than 50 years to fumigate more than 2 million buildings, including museums, research laboratories, medical facilities, and historical structures for control of structure-infesting pests. Similarly, extensive research to develop ProFume documented that SF does not impart odor or off-taste to commodities and does not alter handling and baking characteristics of grain.

Figure 5. *Cylinder of ProFume gas fumigant (sulfuryl fluoride, Dow AgroSciences).*

Sulfuryl fluoride is a colorless, odorless gas at working concentrations. The mode of action involves breakdown of SF into fluoride anions, which in excessively high concentrations can interrupt processing of stored fats and carbohydrates required for normal metabolic functions. For these reasons, detailed procedures to ensure worker and public safety are included on ProFume labeling, and a comprehensive product stewardship program including mandatory training has been developed by Dow AgroSciences for fumigators who use ProFume (see safety section, this chapter).

A computer program called the Fumiguide (Dow AgroSciences) is used to calculate dosing for ProFume based on the pest species, exposure time, temperature, volume, and fumigant confinement (called half-loss time, HLT) (Figure 6). When ProFume concentrations are measured during fumigation, the program will use this information to calculate an actual HLT, accumulated and predicted dosage, and to update instructions on exposure time and if additional fumigant is required. In some commodity substrates, SF may form trace fluoride residues for which food tolerances have been established. The accumulated (concentration × time) dosage of ProFume should not exceed 1,500 oz-hours/1,000 ft^3 based on these food tolerances.

The SF is released through an introduction hose into the fumigated space, with the applicator and fumigant cylinder located outside the fumigated space. The high vapor pressure (15.2 times normal atmospheric pressure at 68°F) and low boiling point (-67°F) of SF result in the liquid fumigant expanding instantaneously to a gas upon release from the introduction hose.

During this expansion, ambient air temperature is cooled. Moisture condensation and potential damage to surfaces can result if fans are not used to blend air in the fumigated space. Fans serve as heat exchangers when releasing SF. The length and inside diameter of the introduction hose control the release rate of SF and the fan capacity (cubic feet per minute, or CFM) controls the rate at which air is mixed throughout the fumigated space. The labeling for ProFume and the Fumiguide (Figure 6) provide directions on the required hose specifications to obtain the appropriate release rate of ProFume in relation to fan capacity; e.g., 1 pound of ProFume released per minute per 1,000 CFM fan capacity.

Fumigating tarped sacks of commodities may not have space for fan placement. In these conditions, SF should be introduced very slowly by using a long, narrow inside diameter hose to prevent condensation. Long introduction hoses, up to 500 feet, are commonly used when fumigating large structures with ProFume. During release of SF, the cylinder valve is fully opened by one complete turn to prevent flow restrictions that could cause frost damage to the valve and hose. In buildings, the introduction sites should be large, open spaces to provide a large reservoir of ambient air for temperature stabilization.

Carbon dioxide

Carbon dioxide (CO_2) is toxic to insects and many other pests when held at high concentrations for adequate time periods and suitable temperatures. CO_2 in normal air occurs at a fraction of a percent concentration, but concentrations of 20% or higher can be toxic to air-breathing animals through direct action on tissues. CO_2 as a fumigant for pest control must be applied on site and delivered into a gas-tight structure where it can be held for several days. Because CO_2 is at low concentration in normal air, it cannot be easily concentrated from air for use, as nitrogen can be for low oxygen treatments (see

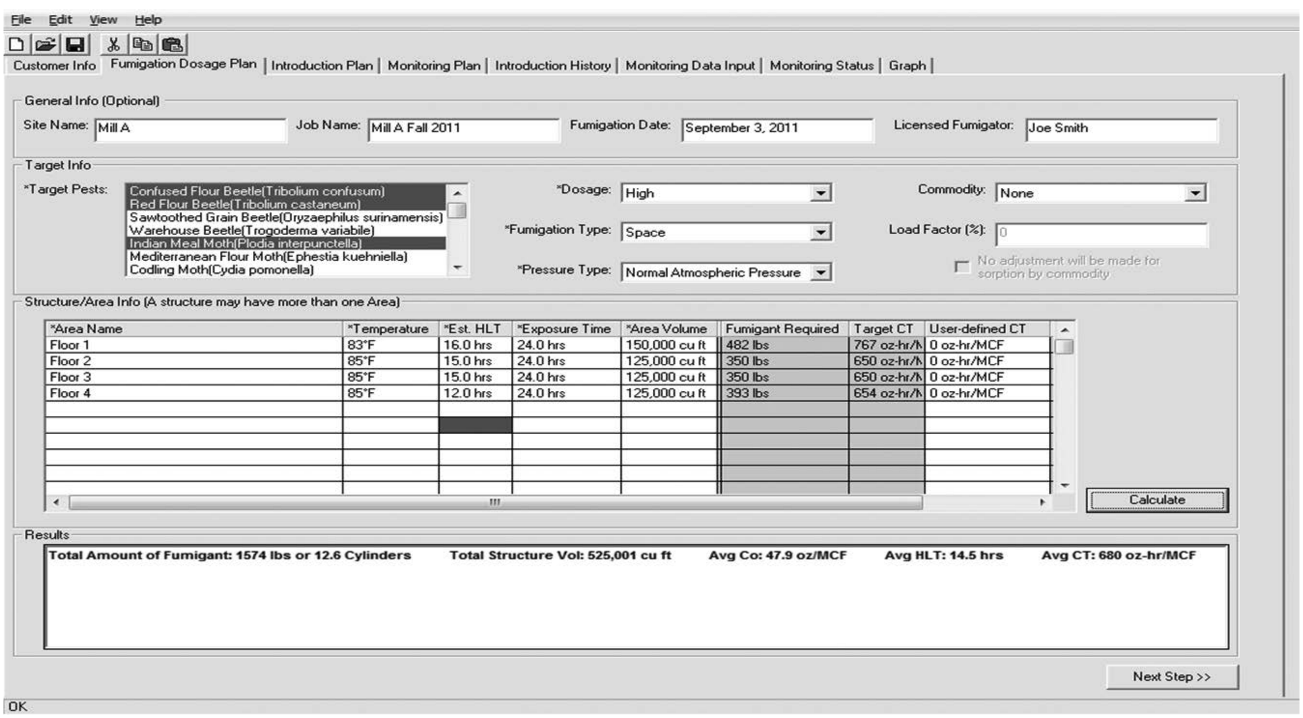

Figure 6. *Screenshot from the ProFume Fumiguide, a computer software tool for logging relevant information for a specific fumigation treatment and to calculate proper application dose of ProFume to a structure. The Fumiguide logs a record of past fumigations of the same structure for more precise fumigations of that structure in the future.*

Chapter 16). Instead, CO_2 must be manufactured or collected as a combustion product from some primary industrial activity, concentrated as a gas or liquid in large tanks, and then applied to the fumigation site. Because CO_2 used in pest control is mechanically or synthetically generated for this purpose, rather than simply extracted from existing air, it must meet regulatory standards as an insecticide.

Despite the initial perception of CO_2 being a "natural" fumigant, because it is an atmospheric gas, it has several chemical and practical features that limit its commercial use. Positive aspects include its effective toxicity when used properly, lack of harmful residues in commodities or structures, and immediate dilution and toxic neutralization when diluted in air during ventilation or aeration of a treated structure. Negative aspects include the relative high cost of performing an effective CO_2 treatment due to large quantities of gas needed to impart toxicity, long hold times relative to other fumigants, and the apparent environmental drawback of releasing quantities of a greenhouse gas into the atmosphere after use. Unless a CO_2 fumigation is specifically required, more practical and cost-effective fumigants are probably available.

Propylene oxide

Propylene oxide (PPO) is presently approved by the U.S. Food and Drug Administration (FDA) as a microbial sterilant for spices, cocoa powder, and processed nut meats (except peanuts), but it has yet to be registered as a fumigant insecticide. PPO has physicochemical characteristics that make it exist predominately in a liquid form at room temperatures and pressures. It is flammable at concentrations in normal air at or above 3%. To facilitate its safe and effective dispersal as a gas throughout commodities and structures, it is often delivered with the aid of a propellant, e.g., a 98% dilution in CO_2 (2% PPO + 98% CO_2), or it can be applied under low pressure in special chambers (Isikber et al. 2004). If the structure to be fumigated can be placed under vacuum, still more PPO will be driven into the gas form. Elevating temperatures above ambient conditions is not typically used as a way to drive more PPO into a gas form. PPO is highly flammable. Ignition sources must be removed from the space or structure being fumigated.

As a fumigant, PPO has shown potential to control storage pests (Isikber et al. 2004) with one recent test indicating PPO is toxic to two species of postharvest insects at relatively low doses (Creasy and Hartsell 1998). PPO is generally most effective against the egg stage of a species, which is contrary to the action of most other fumigants (Ferguson and Pirie 1948, Navarro et al. 2004, Ryan and Bishop 2003). Research is under way to engineer more applications for PPO to fill the void created by the regulations that restrict MeBr use.

Ethyl formate

Ethyl formate (EF), also known as ethyl methanoate, is a fruity smelling ester molecule (Table 1) that occurs naturally in several foods. It is used as a food additive and can be insecticidal at high concentrations. EF is designated a GRAS (generally recognized as safe) compound by the FDA with a current Occupational Safety and Health Administration permissible exposure limit of 100 ppm (300 milligrams per cubic meter (mg/m^3) as an 8-hour time-weighted average concentration. Like PPO, EF is flammable (rated 3 by the National Fire Protection Association) and exists predominantly as a liquid at room temperatures and pressures, so similar strategies are used to facilitate its dispersion into the fumigated commodity and structure.

Ethyl formate has been shown to be an effective fumigant for control of various arthropods, including thrips, aphids, Pacific spider mites, and omnivorous leafrollers (Simpson et al. 2004, 2007). Scenarios where ethyl formate has been demonstrated to be effective are those where the targeted pests predominantly reside on the surface of the commodity. Due to EF's flammability, a commercial formulation named Vapormate has been proposed. It contains 16.7% EF by weight dissolved in CO_2 and is applied from a pressurized cylinder (Ryan and Bishop 2003, Finkelman et al. 2010). To date no commercial product has been registered in the United States or elsewhere. Ethyl formate penetrates poorly — relative to MeBr, PH_3, and SF — to target internal feeding insects. This limitation is exacerbated with commodities that contain water because EF decomposes in water at a rate that is directly related to temperature. Formulation in CO_2 may aid in penetration. Of course, the "benefit" of this decomposition is that the residues formed from fumigation with EF are not typically of regulatory concern. Research efforts are under way across the globe to incorporate EF as much as possible into scenarios where it is effective, particularly quarantine and pre-shipment scenarios where control of surface pests is required on fresh produce. As with PPO, fumigant applicators are encouraged to contact distribution source and respective manufacturers for the most up-to-date applications, allowances, and restrictions.

Commodity Fumigations

Cereal grains, oil seeds, legumes, and other plant products

Phosphine is by far the most commonly used fumigant applied to bulk commodities for disinfestations in the United States and throughout the world. Aluminum phosphide (AlP, see page 6, previous section) is the common formulation applied to bulk cereal grains and many other stored products. A typical application label for AlP pellets and tablets lists 31 raw agricultural commodities, ranging from popcorn to wheat; 24 processed food products such as candy, flour, nuts, and "other processed foods"; and several nonfood products such as feathers, tobacco, and seeds. Tablets of AlP are larger than pellets and generate 1.0 gram of hydrogen phosphide gas when fully reacted, which is five times that generated from each of the smaller pellets.

The application rates of AlP to commodities such as wheat or corn are given in broad doses and exposure time periods to allow for variation in the temperature and the gastightness of the structure being fumigated. Fumigation below 40°F is not allowed, because the temperature would be too cold to provide adequate reaction of the phosphide salt to yield the hydrogen phosphide gas. Temperatures up to 53°F require 8 to 10 days of exposure, while those above 68°F can be completed in 2 to 3 days.

The maximum number of pellets allowed to be added to a bulk commodity is 900 per 1,000 bushels; while up to 180 tablets can be added to the same size bulk. When treating spaces that are empty or that house product, the maximum number of pellets is 725 per 1,000 cubic feet or 145 tablets in the same volume. The labels permit application of a range of pellet or tablet numbers for various structure or commodity situations, such as vertical concrete silos, sealed round steel bins, rail cars, warehouses with finished products, barges, and such. If there is any chance that the structure being fumigated is not well sealed, it is recommended that application of AlP be done near the highest dosage rate.

Homogenous distribution of phosphine gas, or any fumigant gas, in a structure or bulk of stored commodity is important for an effective fumigation. Placement of pellets of AlP in a bulk of cereal grains or oil seeds must be well planned after the applied dose (number of pellets or tablets) is calculated to allow for the best distribution of gas.

An automated gas recirculation system is a preferred feature (Figure 7). It allows gas from a phosphide source to be drawn from the top of a grain mass or structure and returned to the bottom of the mass and distributed so it can be evenly upward through a grain mass as it rises. Recirculation requires that the majority of phosphide pellets or tablets be deposited at the top and bottom of the mass, and the active system can move the gas to the other spaces of the grain mass.

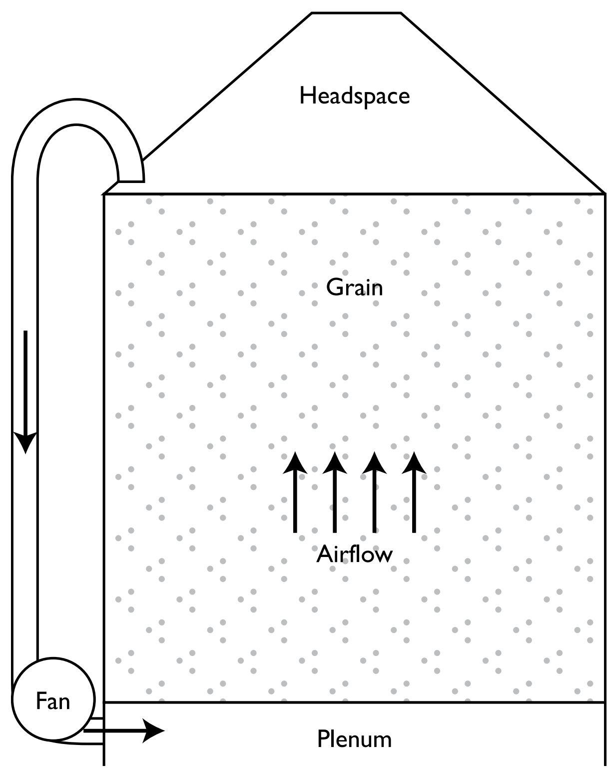

Figure 7. *Recirculation or "closed-loop" fumigation system depicted in a storage bin. Phosphine gas generated from aluminum phosphide inside the grain bin is accumulated near the roof, collected from the headspace, and drawn with a suction fan through a pipe or flexible tube to the base of the bin. Gas is pushed back into the bin at the bottom where it can rise up through the grain mass for even thorough coverage (Jones et al. 2011).*

For structures lacking active recirculation, the pellets or tablets need to be distributed at various depths in the mass, with the majority being in the lower half of the grain. Such a distribution is best accomplished when the grain is loaded into the structure, and pellets are added while loading. The intricacies of proper phosphide application, recirculation, and gas distribution are beyond the scope of this chapter but are covered further by Reed (2006) and Walter (2006).

Magnesium phosphide (MgP) also generates PH_3 gas after reaction with humidity in the air, but the rate of generating gas is much faster than that of AlP. Thus MgP is often the fumigant of choice when treatment time is critical for commercial activity and the fumigation must be expedited. Otherwise, AlP is adequate and typically recommended when there are no time constraints on the space or commodity being treated and hold time for the gas can be maximized.

Methyl bromide, sulfuryl fluoride, and carbon dioxide represent other fumigants that are legally available for treating grain, oilseeds, and other bulk agricultural products. Methyl bromide is the most toxic of the fumigants available, and it remains currently labeled in the United States for treating all the commodities and structures considered here, but its availability is limited, and future use threatened with the current phase-out and ultimate ban under the Clean Air Act. With reduced availability, the cost of MeBr has also increased. These factors provide practical reasons why a fumigator may chose something other than MeBr. Nevertheless, there may be a need to use MeBr, such as a required short treatment time, so the applicator should be skilled with the use of this material. The high toxicity of MeBr is good for killing insects and other pests but also threatens killing the germ of grain and other seeds if concentration or exposure time is too high. Dead germ results in poor storage quality, so application of MeBr must be done carefully.

Sulfuryl fluoride is registered in the United States for fumigation of grain and grain products. As with MeBr, SF is applied from gas cylinders and may be viewed as easier than applying pellets or phosphine tablets. Special training and experience are required. Sulfuryl fluoride does not affect germ quality and has a unique chemical structure and mode of action that is different from those of other fumigants, including phosphine. SF represents a viable alternative to phosphine for situations in which pest populations are suspected or known to be resistant to phosphine (e.g., see Chapter 13).

Dried fruits, nuts, and similar durable commodities

An estimated 9 to 20% of durable commodities are destroyed or contaminated by pests after harvest (Pimentel 1991). This requires food handlers and processors to implement pest management programs tailored to commodity-specific scenarios. In particular, insect and microbiological pests can seriously affect production, commercial market access, food safety, and subsequent profits. The dried fruit and nut sector is concerned with disinfesting raw products of field pests within hours or days after harvest and controlling storage pests in processed “stored product” amenable to (re)infestation and microbial colonization. The existing infrastructure and logistical constraints of commercial production and consumer demand dictate that fumigation be used for this protection. The standard fumigant for years, MeBr, is no longer obtainable due to the Montreal Protocol and the U.S. Clean Air Act.

At present, phosphine and sulfuryl fluoride (SF) are registered fumigants being considered as alternatives to MeBr for postharvest treatment of insect pests in dried fruits and nuts. Postharvest use of SF on dried fruit and nuts, which has nearly the same infrastructural requirements as MeBr, has increased consistently since its registration in 2004. The majority of the dried fruit and tree nut market have transitioned from MeBr to SF since 2009. Phosphine in its various commercial forms (pellets, generators, cylinders), has been used in a postharvest capacity to treat dried fruit and nuts for decades, and new application technologies have been developed to reduce fire hazard and decrease the exposure time required for insecticidal efficacy.

Alternative fumigants such as ammonia, ozone, methyl iodide, ethane dinitrile, ethyl formate, and carbonyl sulfide have been researched and proven effective in certain situations; however, work continues on these to develop more efficacy data, industry acceptance, and registrations for their use on foodstuffs, including dried fruits and nuts. Because of the relatively serious postharvest pest pressure that accompanies commercial dried fruit and nut production, U.S. industries have been at the forefront of researching viable alternatives to MeBr. The majority of dried fruit and nut industries have successfully incorporated MeBr alternatives, including phosphine and SF, into routine treatment regimes for pest control. Certain other U.S. dried fruit and nut industries still request critical use exemption allowances for MeBr due to industry-specific technical and economic limitations of phosphine and SF, which are briefly described below.

Disinfestation of fruit and nut pests originating in the field

With respect to field disinfestations, which are primarily conducted in chambers or controlled-atmosphere rooms, several dried fruit and nut industries are granted critical use exemptions for methyl bromide because of a need to treat rapidly (within hours), particularly during peak harvest periods that coincide with the highest-value product and market demand (e.g., California walnuts and dates intended for holiday markets in December). Since 2009, there has been nearly a complete conversion from MeBr to SF for treatment of in-shell and shelled walnuts, using vacuum or normal atmosphere fumigations. Numerous studies report that for post-embryonic life stages of postharvest insect pests, SF is generally more toxic than MeBr for a given species (Kenaga 1957, Thoms and Scheffrahn 1994). Insect eggs are relatively more tolerant to SF than to MeBr, often requiring many times the dosage required to control adults of the same species (Walse et al. 2009).

The recently developed Horn-Diluphos System (HDS) safely and rapidly delivers 100% phosphine (Vaporphos), achieving levels approximately 10,000 ppm within hours, even under commercial cold-storage conditions (Horn et al. 2005). With the HDS, the use of phosphine as a MeBr alternative for field disinfestations is expected to increase across the world, particularly for dried fruit and nuts that need to be marketed shortly after harvest (California walnuts and dates) or are preferentially treated at temperatures below 50°F to avoid phytotoxicity and quality damage. Research is under way in the United States and abroad to engineer phosphine fumigations to be efficacious in the shortest time possible through the integration of physical (e.g., vacuum) and chemical approaches, such as the use of mixtures containing other physiologically active gases (oxygen and nitrous oxide, for example).

Stored product disinfestations

With respect to stored product treatment of dried fruits and nuts, alternative strategies to overcome the need to use high ovicidal dosages for SF would be to conduct two, time-separated fumigations: one to kill all postembryonic life stages and most eggs, and a second fumigation about 2 weeks later, after surviving eggs have hatched, to kill larvae that survived the first fumigation while in the egg stage. Attention must be stringent so multiple fumigations with SF or modification of exposure intervals on the same commodity do not exceed the cumulative maximum "CT" dosage (1,500 oz-hour/1,000 cubic feet) allowed by the label.

Phosphine is routinely used to disinfest many types of dried fruit and nuts as well as other durable commodities stored in a variety of containment devices, including silos, chambers, ship hulls, bins, or under tarpaulins. When applied at recommended doses (500 to 2,000 ppm), complete mortality of all insect life stages is species-specific and typically requires exposures of 2 to 7 days, as compared to 2 to 3 hours needed for MeBr. From both a technical and economic perspective, phosphine use is not without limitations due to logistically challenging time and volume requirements, as well as corrosion issues that are prohibitive to many U.S. industries. Applicators must be mindful that the development of phosphine-resistance in target insect populations can occur when environmental factors, concentration, temperature, and hold-time goals are not properly achieved.

Agronomic and horticultural seeds

Seed treatment is much like that for cereal grains and edible beans in that the same products are labeled, and the doses, temperatures, and hold times are the same. The economic value of seeds for agronomic and horticultural crops are many times higher than the value of food-commodity crops, so seed managers must be more vigilant to damage caused by insect infestation and the potential damage from excessive fumigation that can result in seed sterility. Methyl bromide is by far the most toxic of the gases considered in this chapter, and as a general biocide it poses the highest risk for seed viability if used in that context. As mentioned, mortality of seeds can occur if MeBr is applied at a high concentration for a long period, and thus can represent a serious loss for commercial agronomic and horticultural seeds compared to commodity grains. Seeds are fairly tolerant of high doses and long exposure to phosphine, but care should also be taken in these situations to avoid seed sterility. Sulfuryl fluoride (SF) is gaining wide acceptance for seed treatments due to flexibility in using short duration fumigation exposures to meet shipping schedules, seed tolerance to SF concentrations applied, and lack of adverse effects on expensive computerized equipment used to process seeds. Carbon dioxide is relatively safe for seeds, but is less effective for controlling arthropod pests compared to MeBr and phosphine, as CO_2 treatments need to be conducted by someone with expertise using this compound as a fumigant.

Dried animal products

Products considered here include dried milk, cheeses, dried meats, dried fish, animal skins, wool, leather, feathers, bone meal, silk, and any other product derived from vertebrate or invertebrate animal bodies or their products. The pest species of insects and mites important for animal products are also discussed in Chapter 5 and include the cheese mite, redlegged ham beetle, warehouse beetle, and related species in the beetle family Dermstidae, and the common species of clothes moth from the moth family Tineidae. The currently registered fumigants MeBr, phosphine and SF can all be used on these pests but will vary in effectiveness depending on the specific pest.

The product being treated may be affected negatively by the fumigant. Current registrations relative to product should be checked before treatment. For example, permitted critical use exemptions of MeBr for fumigation of southern dry-cured ham product to control cheese mite and ham beetle remained constant in 2011 and 2012 (Table 2). Since the critical use exemptions of MeBr for treatment of ham and cheese will eventually end, fumigation with phosphine is being evaluated as an alternative. Limited, positive research exists on quality effects of fumigants on commercial stored animal products (e.g., Sekhon et al. 2010), so the applicator must work from experience and with precautions to quality effects as well as attention to treatment efficacy.

Processed foods and value-added products

Numerous processing facilities of human and pet foods, and warehouses holding value-added food products relied on MeBr as the “fumigant of choice” at varying frequency for decades before the current phase-out and ban of this product under the international Montreal Protocol and U.S. Clean Air Act. In the 1990s it was estimated that more than 220 commercial wheat flour mills in the United States and Canada produced flour for bread-making, and that these facilities conducted between one and three MeBr fumigations each year. The use of MeBr has fallen dramatically since the official ban in 2005 and the current year-to-year use by the pest control industry following the critical use exemption regulations.

Phosphine is considered by many as an impractical substitute for MeBr in most flour mills and food processing plants because of the risk of corrosion and damage to electronic devices, combined with the quick turnaround time needed for most mills that operate nearly around the clock to meet business requirements. Many mills and food processors have substituted nonfumigation practices to manage insect pests, or they use a combination of fumigant alternatives with occasional MeBr fumigation as allowed or available in a given year under the critical use exemptions. Others have converted to using SF as an effective, noncorrosive substitute for methyl bromide, while still others have converted to using heat treatments at a regular frequency for large-scale general pest control activities (see Chapter 15). Large finished-product warehouses and regional food distribution centers can typically use IPM and nonfumigant pest control methods since they have many employees and many nonfood products for which fumigation would not be necessary. The pest control and processed food industries in North America continue to operate with dramatically lower levels of MeBr than those used before 1993. At this writing there is “some” MeBr still being used, SF has been widely adopted, heat treatments are being adopted and highly refined, and improved methods of IPM and fumigant alternatives allow the flour milling and food industries to meet customer needs and quality standards.

Factors Affecting Fumigation Efficacy

Concentration, time, and temperature

Understanding the relationship of fumigant concentration, exposure time, and temperature during fumigation is critical for determining the proper dosage for control of the pest of interest. For SF and MeBr, the dosage of the fumigant is calculated by the “CT concept” as follows:

Dosage (D) = Concentration (C) × Time (T)
or
D = C × T (CT)

The units for C = ounce (oz) of fumigant/1,000 cubic ft (ft^3), which are equivalent to grams (g) of fumigant/cubic meter (m^3).

The unit for T = hours (hrs), which equals exposure time defined as the number of hours the target pest is exposed to the fumigant.

Therefore, CT is the product of Concentration (C) and exposure Time (T) expressed as oz-hrs/1000 ft^3 or g-hrs/m^3.

D = C × T = oz-hr/1000 ft^3
or
g-hrs/m^3 = oz-hr dosage

If you increase the exposure time, less gas will be required to achieve the dosage level (CT) for control. Contrarily, if you decrease the time of exposure more gas will be required to get to the appropriate dosage (CT) for control.

Phosphine differs from the previous model because the relationship of dosage and toxicity to insects is not linear. Phosphine is most effective over longer exposure times of 1 day or longer. In general, longer exposures to phosphine even at low concentrations result in better efficacy than shorter exposures at higher concentrations.

Knowing the target pest is critical because different pest species as well as life stages require different fumigant dosages for effective control, and this varies by fumigant. For SF the postembryonic stages are most susceptible, while the egg stage is most tolerant. For phosphine the egg stage is also primarily the most tolerant stage, but depending on species, temperature, and exposure duration, pupae have also been shown to be the most tolerant stage. For MeBr the most tolerant stage are pupae, but in a study looking at susceptibility of red flour beetles, the only life stage that had survivors was large larvae (Hartzer et al. 2010).

Temperature is also a critical factor to consider for a successful fumigation. Arthropods are cold-blooded, so temperature affects their metabolism. In cool temperatures, i.e., 68°F (20°C) and below, insects move and respire at a lower rate, so fumigant uptake is less. As temperatures drop, more fumigant is required. Eventually, it is too cold to fumigate to get the control desired, or the fumigation becomes economically unfeasible. The labeling for ProFume states it should not be applied for insect control if the temperature is below 40°F (5°C). In fumigated spaces with higher temperatures — for example, 78 to 86°F (25 to 30°C) — insects have increased metabolism, which will improve fumigant intake. Less fumigant is required when the temperature is higher, and often, higher temperature fumigations are more efficient. Planning fumigations during the warmer seasons and during the warmer times of day can positively affect the temperature and overall effectiveness. In addition, fumigators can use permanent built-in heating systems or temporary leased heaters to increase the temperature in the area to be fumigated. The exception to the temperature factor is when target pests are rodents. They are warm-blooded animals and do not require increased fumigant as the temperature decreases.

Other factors

Other factors that can affect fumigant dosage include atmospheric pressure, insect diapause, and formulation of phosphine. Vacuum fumigations conducted at lower atmospheric pressure in specially designed chambers can improve penetration of the fumigants SF or MeBr into commodities and provide control at lower dosages. Vacuum fumigations generally are not conducted with metallic phosphides, but as stated in the previous section on dried fruit and tree nuts, testing is under way. Some insects, including stored product moth larvae and beetle larvae, can undergo a dormant state known as diapause. This dormant state is generally less susceptible to fumigants. Formulation has been shown to affect dosage rate of phosphine, as less cylinderized phosphine is required to achieve control in comparison to AlP pellets.

Gastightness, persistence, confinement, and sorption

To reiterate what is discussed throughout this chapter as key to a successful fumigation: maintain adequate gas concentration for a sufficient hold time by ensuring good seals for gastightness, proper starting concentration, and maintenance of the desired concentration throughout the exposure. The term "sorption," used frequently when discussing fumigation of a raw agricultural commodity, gives the impression that the commodity acts like a sponge, absorbing the fumigant into the commodity, then desorbing back into the air space. In fact, researchers have rarely been able to recover presumably absorbed gas from a fumigated commodity. Thus "sorption" must be thought of as any loss of gas other than from leakage, probably due to chemical breakdown or reactivity with surfaces, that ultimately results in a lower concentration and less persistence of active gas in the treated space. Monitoring gas levels with appropriate detection equipment is key to knowing the delivered concentration of a fumigant.

Tolerance and/or resistance within and among pests

Variation exists within and between pest species as to their level of susceptibility to a given fumigant pesticide. In general, because fumigants act in the gas stage, one generalization is that life stages or species with low levels of respiration, such as the egg stage or the pupal (pre-adult) stage, are more difficult to kill under fumigation conditions that would easily kill more highly respiring larval and adult stages that are active and breathing in fumigant gas. Among species, variation in tolerance exists that is not easily explained by respiration. It may be related to an inherent ability due to natural detoxification or other physiological differences. Among grain insects, it is well know that the lesser grain borer, *Ryzopertha dominica*, is more difficult to kill with fumigants and other insecticides compared to other common grain insect species. Genetically based, heritable resistance to fumigants, especially phosphine, has evolved in certain populations of grain insect species (see Chapter 13), which poses challenges for effective phosphine use in the future. Genetic resistance to other gases — such as MeBr, SF, or CO_2 — has not been reported. Fumigators must be aware that variation exists in tolerance and susceptibility to fumigants for various reasons. Such phenomena provide additional justification for applying fumigants properly for the most effective result only when applications are clearly needed.

Safe Use of Fumigants

Human injury during fumigation can occur from overexposure to the fumigant or mechanical injury during fumigation. The wide spectrum effectiveness of fumigants makes them potentially lethal to humans. Fumigant application usually involves physically demanding work, such as climbing ladders and lifting heavy equipment in potentially dangerous environments, including grain bins, at heights, and near industrial equipment. For these reasons, it is critical for fumigators to follow federal, state, and local safety regulations when fumigating.

The fumigator should carefully read and understand the fumigant labeling — which may include an applicator manual — and always have a copy of this labeling readily available at the fumigation site. All fumigant labeling provides product-specific information about safety equipment and procedures required to prevent overexposure, first aid, note to physicians on treatment, and an emergency number. For any type of overexposure, fumigant labeling recommends immediate medical attention. This is essential because the onset of acute adverse symptoms can be delayed for a day or more, even in life-threatening exposures. There is no antidote to overexposure to fumigants; physicians can only treat the symptoms.

Inhalation exposure

Overexposure to a fumigant by inhalation is of greatest concern for fatal exposure. Acute and lethal exposures to fumigants cause pulmonary edema (fluid in the lungs) in humans, resulting in death by respiratory failure or cardiovascular collapse. General symptoms of overexposure to fumigants can include:

- Nausea
- Slowed body movement, slurred speech
- Abdominal pain
- Numbness of hands and feet
- Difficulty breathing

Inhalation exposure is prevented by wearing a self contained breathing apparatus or supplied-air respirator when fumigant concentrations exceed the permissible exposure limits established on product labeling. The permissible exposure limits vary by fumigant and are 5 ppm for MeBr, 1 ppm for SF, and 0.3 ppm for phosphine. A full-face cartridge respirator is not permissible respiratory protection to prevent inhalation exposure to MeBr or SF, but can be worn with phosphine when concentrations are at or below 15 ppm.

The Occupational Safety and Health Administration (OSHA) has specific and detailed regulations on use and maintenance of respiratory protective equipment. These regulations require employees to be trained in the proper use and maintenance of the equipment per manufacturer's directions, be fit-tested for the respiratory equipment, and have an evaluation by a health care professional to determine fitness to wear respiratory protection. OSHA regulations are available for viewing and printing at no charge at *www.osha.gov*.

Airborne concentrations of phosphine and SF should be monitored after introduction where workers are present, using appropriate detection devices. The purpose of monitoring is to determine when and where workers need to wear respiratory protection, and to seal leaks from the fumigated space.

Dermal exposure

Fumigant overexposure to skin or eyes is another concern for fumigators. Any dermal exposure to fumigants in the liquid or solid phase during application should be avoided. MeBr can produce chemical burns. SF and phosphine/inert gas mixtures produce frostbite-type burns due to rapid evaporation of these materials from skin or eyes. Spent dust from metallic phosphides can be very irritating to the eyes.

Dermal exposure to fumigants packaged in cylinders is prevented by wearing long-sleeved shirts and pants during fumigant introduction. Rubber gloves and rubber boots should not be worn when applying these fumigants. Cloth or leather gloves should be worn when handling metallic phosphides and their spent dusts. With the exception of metallic phosphides, fumigant labels require eye protection, such as goggles or full-face shield, to be worn during fumigant introduction. When introducing fumigants using an introduction hose connected to a pressurized cylinder, eye protection also can prevent potential mechanical injury if the hose accidentally bursts or disconnects.

Fumigant labeling requires two persons trained in fumigant use to be present when there is the greatest potential for worker exposure — during fumigant introduction, reentry into the fumigated structure before aeration, the initiation of aeration, and after reentry when testing for clearance.

Transportation

All fumigants are classified as hazardous materials by the Department of Transportation (DOT) and as a result have extensive regulations regarding their transportation. These regulations include vehicle placarding, driver licensing, vehicle safety kits, inspections and maintenance logs, and fumigant documentation. Hazardous materials must be secured within the vehicle so they do not move during transport. Fumigants should always be transported in a separate air space from vehicle occupants. Cylinders must be transported and stored in an upright position with the valve cover and safety bonnet attached. Fumigators should check with the state's DOT enforcement agency to confirm current transportation requirements for fumigants. An exception to DOT regulations may be obtained from the supplier (e.g., Degesch America Inc.) for transporting small quantities of their metallic phosphide formulations.

Storage and handling

Fumigants should be stored in a locked, vented enclosure that is posted as pesticide storage. It is advisable to not store fumigants in an occupied building, unless the storage area has a separate ventilation system that provides constant aeration during building occupation in case fumigant leaks from storage containers.

Fumigation workers should receive verified training on general safety procedures and proper handling of all equipment they will use at a fumigation site. This training could include CPR and first aid, along with OSHA requirements on proper use of ladders, working at heights, or around power lines and industrial equipment, and lifting heavy equipment. At each fumigation site, fumigation workers should be updated on additional precautions and safety equipment (such as bump hats) that they may need to work safely at that location and what to do in case of an emergency. Any specialized equipment, such as boom lifts, used to prepare the building for fumigation should only be operated by personnel trained to use the equipment.

Confined space entry restrictions have numerous requirements that must be met before workers can enter concrete or steel grain bins to do work to prepare for fumigation, such as cleaning or sealing of bin intervent systems. The extent and cost of these confined entry requirements may preclude some companies from allowing workers into bins, thus sealing before fumigation can only be done externally and may not be optimum.

EPA requires all fumigation areas be posted with warning signs. The information on the warning sign (skull and crossbones, English/Spanish signal words, date of fumigation, fumigant name, and name, address, and telephone number of the applicator) is standardized by EPA. Other requirements for warning signs can vary by product use pattern. Warning signs are placed on each side of a structure, including both sides of railcars by ladders and on all entrances of a fumigated structure, including doors of fumigation chambers and railcar hatches. Warning signs are placed before fumigant introduction and are removed only after testing with approved clearance detection devices has demonstrated that fumigant is aerated per label requirements.

Doors to fumigated structures must be locked during fumigation. In addition, labeling for ProFume requires barricading or secondary locking to prevent unauthorized persons from entering the fumigated space. At food storage and processing sites, site employees may participate in preparing the facility for fumigation. At these facilities, which can be large and complex, it is imperative for the fumigator to ensure all personnel have exited the area to be fumigated before reentry deterrents are applied, and the fumigant is introduced.

Low-level exposure

Low-level, nonoccupational exposure to fumigants can occur from other sources, such as bystander exposure to fumigant dissipating onto neighboring properties during fumigation and aeration, or off-label exposure of commodities. Potential bystander exposure to fumigants is minimized by preventing excessive leakage from structures during fumigation and controlling the fumigant's release during aeration. Fumigant contamination of commodities is prevented by ensuring that the fumigant is labeled for the commodity and the applied dosage does not exceed the label rate or tolerances for the commodity. Spent dust from metallic phosphides must not contact processed food or commodities (with exception of brewers rice, malt, or corn grits used in the manufacture of beer).

The availability of fumigants in the future is dependent upon fumigators practicing stewardship in handling these products today. Increased concern about public safety since the September 11, 2001, terrorist attacks on the United States emphasized the importance of security when managing fumigants. Fumigant inventory should be carefully tracked. Containers should be secured to prevent unauthorized access when stored or transported. Background security checks should be conducted on new employees.

Detection equipment

Detection equipment serves different objectives during the fumigation process. Gas leak detectors, such as continuous monitoring halogen leak detectors for MeBr and SF (TIF detectors, Miami, Fla.), are used to determine where fumigant may be leaking from confined spaces. Leak detectors indicate the presence of fumigant at concentrations above the permissible exposure limits set by EPA, and other gases can interfere with readings, depending on the leak detector. Leak detectors are important tools to identify areas requiring additional sealing to improve confinement.

Detection equipment capable of accurately measuring low concentrations of fumigants is mandatory to confirm fumigant clearance before reoccupation of a treated structure or handling/processing of a treated commodity. Fumigant detectors provide either point-in-time measurements or continuous readings, depending on the type of gas detection sensor used. Commonly used single reading detectors for measuring low concentrations of MeBr and phosphine are color diffusion detector tubes, available from numerous manufacturers (Matheson Gas Products, Rutherford, N.J.; Draeger Safety, Pittsburgh, Pa.; Sensidyne, Clearwater, Fla.; RAE Systems, San Jose, Calif.). These tubes utilize a pump to draw a specified volume of air through a tube containing a chemical reagent. The reagent changes color in the presence of the fumigant. The length of the stain or intensity of the color is proportional to the fumigant concentration. Some ambient gases, high temperatures, or humidity can affect the readings. These colorimetric tubes are simple to use, do not require calibration, are single-use only, and have a limited shelf life.

A variation of the color diffusion detector tubes is available for phosphine (Draeger Safety, Pittsburgh, Pa.). The system uses chips containing capillaries filled with reagent for a colorimetric reaction. An optical analyzer reads the reaction, and the concentration is digitally displayed. This technology is more accurate than the color detector tubes because the amount of air samples and analysis of color reaction is automated.

A badge that directly measures exposure to phosphine (e.g., Draeger Safety Inc., Pittsburgh, Pa.; Scott Instruments, Exton, Pa.) can be worn by workers to verify any exposure to phosphine. The badges operate by direct diffusion exposure. The intensity of the color on the badge is directly proportional to the gas concentration and exposure time. The user compares the badge color to a dose estimator wheel to determine total exposure.

Continuous reading electrochemical sensors are available to detect low concentrations of phosphine and are useful for monitoring worker exposure. Electrochemical sensors function like a chemical battery, generating current proportional to the amount of gas passing through the catalytic electrode. They respond slowly after saturation with high concentrations of fumigant. These electronic detectors are portable, battery-operated, and typically have a digital display of gas concentration (Examples: Pac Series, Draeger Safety, Pittsburgh, Pa.; PortaSens, ATI, College Oaks, Pa.; ToxiRE, RAE Systems, San Jose, Calif.). Gases, such as carbon monoxide, can interfere with the detection of phosphine by certain sensors, so these electrochemical sensors maybe used to monitor aeration before final clearance testing with color diffusion tubes.

The photoionization devices measure the electrical charge of UV-ionized gas samples and are available to detect MeBr and phosphine (example: MiniRAE, RAE Systems, San Jose, Calif.). High fumigant concentrations need to be diluted before reading using a dilution probe. Other gases can interfere when measuring MeBr, and phosphine can cause coatings to form on the photoionization device lamp. Coatings need to be removed by cleaning.

It is important to confirm that the detection equipment used to verify fumigant clearance is approved for use on the fumigant label. Currently, only two clearance detectors are approved and manufactured for use with SF; the Interscan (Interscan Corp, Chatsworth, Calif.) and the SF-ExplorIR (Spectros Instruments, Miss.). The Interscan analyzes the gas sample in a furnace, releasing SO_2 that is measured by a sensor. SO_2 and other gasses, such as H_2S, HCN_2, and Cl_2, can interfere with the Interscan sensor. These gasses do not affect fumigant measurement by infrared wavelength absorption, the method of detection used by the SF-ExplorIR.

Equipment for detecting fumigants is rapidly evolving. Fumigators should contact fumigant manufacturers for information on the latest technology approved for use with a specific fumigant.

The Fumigation Management Plan

The EPA initiated the requirement of a fumigation management plan to be written, on file, and followed during phosphine fumigations along with the agency's re-registration eligibility decision for phosphine products issued in the late 1990s. At this time, a fumigation management plan is required for fumigation with ProFume and likely will be required for MeBr following completion of its registration review at EPA. A fumigation management plan is an organized, written description of the required steps involved to help ensure a safe, legal, and effective fumigation. The plan helps those involved with fumigation comply with pesticide product label requirements. Federal and state regulators, along with distributors and product manufacturers, provide templates that assist a fumigator in writing a fumigation management plan for the specific job. The process of writing the plan familiarizes the fumigator with the specific pesticide label for the product being applied and ensures that the fumigator is knowledgeable about the specific facility, commodity, and characteristics of the fumigation. The fumigation management plan is to be placed on file with the fumigation company for future reference. Relevant sections of fumigant labeling should be reviewed by appropriate company officials (supervisor, foreman, and safety officer) in charge of the site. Labeling may require local fire companies and/or other emergency agencies in the area to be notified before the fumigation. Fumigation management plans are revised each time the same facility is treated, so the plan allows for a collective learning experience about each specific fumigation and should enhance safety, efficiency, and effectiveness.

The Future of Fumigation

Stored product protection using fumigant insecticides is subject to changes in label registrations, specific procedures, fumigant application methods, and information about controlling pest populations, among other variables across various levels of government. At this writing the effective and common chemical fumigants available for treating stored products and associated structures in the United States include phosphine, SF, and MeBr. Methyl bromide continues to be phased out under the Montreal Protocol, and more specifically for the United States, the Clean Air Act. MeBr is still allowed in many situations up to an annual cap guided by critical use exemptions, but its use for general stored product protection is expected to end within the decade, leaving the stored product industry with phosphine and SF. With only two effective synthetic fumigant active ingredients available, alternatives should be considered, and fumigants should be used only when needed as tools in carefully monitored IPM programs.

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S156 – 14 September 2012

15 Extreme Temperatures

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Extreme temperatures, at or above 50°C and at or below 15°C, can be used to disinfest commodities and structures. Controlling stored-product insect populations with extreme temperatures offers a number of advantages. These techniques are environmentally benign, no registration or special licenses are required for application, and to our knowledge, insects do not develop resistance, as they do to chemical pesticides. A number of challenges prevent the widespread adoption of these techniques. They require extensive capital investment (grain chillers or heaters), treatments may be limited to certain times of year (winter for aeration, summer for heat treatments), and equipment or products may be damaged if techniques are used improperly (Fields 1992, Beckett et al. 2007).

The responses of stored-product insects to extreme temperatures are well documented (Fields 1992, Mason and Strait 1998, Burks et al. 2000, Beckett et al. 2007). Three temperature zones are significant for growth or death of stored-product insects. At optimal temperatures (25 to 32°C), insects have maximum rate of increase. At suboptimal temperatures (13 to 24°C and 33 to 35°C), development slows, and at lethal temperatures (below 13°C and above 36°C), insects stop feeding, develop slower, and eventually die. The more extreme the temperature, the more quickly they die (Table 1). These are general guidelines. Each insect species, stage, and physiological state will affect the particular response to temperature (Fields 1992). No stored-product insects can survive freezing. The target insect freezing point is the temperature that needs to be obtained to kill the insects instantly. The insect freezing point varies by species, stage, and physiological state between -4.0 and -22.0°C (Table 2). Insects die before they freeze. As temperature decreases, it takes less time to control insects (Fields 1992, Burks and Hagstrum 1999). Fields (1992) summarized times and temperatures required to control specific life stages of stored-product insects.

Low Temperatures

Commodities

Three methods to reduce temperature of bulk-stored grain are turning, ambient air aeration, and chilled aeration (Fields 1992, Mason and Strail 1998, Burks et al. 2000). Once cooled, grain will remain cool even with high outside air temperatures, because bulk grain is a good insulator. Turning bulk grain does little to reduce overall temperature because there is little opportunity for heat transfer, even in winter. Hot spots, or isolated pockets where grain heats up because of insect or microorganism activity, will be broken up. The disadvantages of turning grain include energy cost, empty bins needed to receive grain, and grain breakage, which is a problem particularly in maize.

Ambient air aeration is the most common method of cooling bulk grain. Aeration is discussed in depth in Chapter 11, Grain Aeration. Aeration often is used to dry grain, but cooling requires smaller fans and weaker air flows. Automatic aeration systems simplify the operation by starting the fans when ambient

Table 1. *Response of stored-product insect pests to temperature.*

Zone	Temperature range (˚C)	Effects
Lethal	above 62	death in < 1 min
	50 to 62	death in < 1 h
	45 to 50	death in < 1 day
	35 to 42	populations die out, mobile insects seek cooler environments
Suboptimal	35	maximum temperature for reproduction
	33 to 35	slower population increase
Optimal	25 to 32	maximum rate of population increase
Suboptimal	13 to 24	slower population increase
Lethal	5 to 13	slowly lethal
	3 to 5	movement ceases
	0 to -10	death in weeks, or months if acclimated
	-15 to -25	death in < 1 h

Adapted from Fields 1992.

air is cooler than the grain. Drying grain to below the moisture content required by grading authorities can be a commercial concern. Grain dries the greatest amount at the warmest temperatures.

Chilled aeration (Figure 1) is the most expensive cooling method, but it allows chilling regardless of outside air temperature. It is used commercially in 50 countries to cool about 80 million tonnes of grain annually (Maier and Navarro 2002). Grain is chilled to protect it from mold, insects, and to maintain germination. Chilled grain can be safely stored at higher moisture contents than warm grain. It takes six times more energy to reduce moisture content by 6% than to cool grain from 25 to 5°C. Air is dried and cooled before it is pushed through the grain bulk. Depending on the grain bulk and chilling unit, it takes 2 to 21 days to bring the grain temperature down to 15 to 20˚C, and a second chilling may be required after 2 to 6 months. It takes about 5 kilowatt hours per tonne (kwh/t) to cool grain from about 30 to 15˚C. The costs in the United States were estimated to be $1.50/t compared to $2.90/t for fumigation and aeration (Rulon et al. 1999).

Figure 1. *Grain chillers rom Burks et al. 2000).*

Insects in finished products also can be controlled with low temperatures. Packaged finished product often requires extremely low temperatures or extremely long durations to reach temperatures required to kill insects (Table 3) (Mullen and Arbogast 1979). For certain high value items, flash freezing with liquid nitrogen to obtain -18˚C is recommended. This method has been used for many years to disinfest herbs before processing (Adler 2010).

Structures

In Canada and the northern United States, winter temperatures are sufficiently cold to control insects in structures (Fields 1992). Typically this requires outside air temperatures of -17˚C for three days. As with heat treatments of structures described below,

Table 2. *Insect freezing temperatures, or the lowest temperature at which insects can survive. All stored-product insects die when frozen. Mortality will occur at higher temperatures.*

Insect scientific name	Insect common name	Stage	Insect freezing point (°C)
Alphitobius diaperinus[a]	lesser mealworm	adult	-9.4 to -12.3
Cryptolestes ferrugineus	rusty grain beetle	adult	-16.7 to -20.4
Cryptolestes pusillus	flat grain beetle	adult	-14.0
Ephestia kuehniella	Mediterranean flour moth	larval	-16.9 to – 21.7
Gibbium psylloides	hump beetle	adult	-10.7
Oryzaephilus surinamensis	sawtoothed grain beetle	adult	-13.7
Plodia interpunctella[b]	Indianmeal moth	larval	-7.4 to -16.0
		pupal	-5.0 to -22.0
		adult	-22.5
Rhyzopertha dominica	lesser grain borer	adult	-15.2
Sitophilus granarius	granary weevil		-15.0
Sitophilus oryzae[c]	rice weevil	adult	-22.0
Stegobium paniceum[d]	drugstore beetle	larval	-6.5 to -9.0
		pupal	-4.0
		adult	-15.2
Tenebrio molitior	yellow mealworm	larval	-7.7 to -14.9
		pupal	-13.3
		adult	-7.7 to -14.9
Tineola bisselliella[e]	webbing clothes moth	egg	-22.6
		larval	-13.0 to -16.2
		pupal	-16.9
		adult	-18.8
Tribolium castaneum[c]	red flour beetle	adult	-12.3 to -16.0

[a] Salin et al. 1998
[b] Fields and Timlick 2010; Carrillo et al. 2005
[c] Burks and Hagstrum 1999.
[d] Abdelghany et al. 2010
[e] Chavin and Vanier 1997.
Adapted from Fields 1992.

Table 3. *Chilling times for selected commodities. Commodities were exposed in a 0.76-m^3 freezer filled to capacity.*

Commodity	Freezer setting (°C)	Time to 0°C (h)	Time to equilibrium (h)
Cornflakes (28 1.45-kg boxes)	-10	7	30
	-15	6	30
	-20	5	35
Flour (7 45-kg bags)	-10	55	160
	-15	29	130
	-20	25	145
Elbow macaroni and peas (15 11-kg cases of each)	-10	29	130
	-15	18	95
	-20	19	100

Adapted from Mullen and Arbogast 1979.

to achieve control, product must be removed from equipment and equipment must be opened up. Good air circulation within the building is needed to insure that sufficiently low temperatures are achieved. Water must be drained from the facility to prevent pipes from freezing and cracking.

Such extreme cooling is not possible in most facilities during much of the year, but any cooling of structures, equipment, and finished product will reduce insect growth and population size in the long run. For example *S. oryzae* held at 29°C and given sufficient food will increase approximately 10,000-fold in three months. Insects held at 25.5°C will increase by 1,500-fold, and those held at 18.2°C by only fivefold (Birch 1953). Food processing equipment can produce a considerable amount of heat and food, causing ideal conditions for insect development and population growth.

High Temperature

Commodities

Heat has also been used to disinfest perishable and dry, durable food products. High temperature treatments are used for disinfestations of dried fruits and nuts, perishable commodities (fruits) (Hansen and Sharp 1998), and grains (Beckett et al. 2007). In heat treatments of fresh commodities, nuts, dried fruits, or grains, heating rates are from 1 to 15°C/minute, and high temperatures of 60 to 85°C control infestations in a few minutes. During heat treatments, it is important to ensure that end-use quality is not reduced.

A number of systems are used to heat commodities (Beckett et al. 2007). The Australians developed a 150 tonne per hour (t/h) continuous-flow fluidized bed process that heats grain to 70°C for 2 minutes before recooling the grain. A spouted-bed process with a capacity of 8 t/h is an option for farms. A few studies have shown that grain dryers greatly reduce insect populations. Not all grain reaches temperatures required to kill insects, as is the case in thermal disinfestations units built specifically to control insects. Some modifications to the dryers could increase the efficacy of control (Qaisrani and Beckett 2003, Bruce et al. 2004). Irradiation of commodities and finished products with nonionizing radiation from microwaves, radio waves, and infrared has been studied extensively. Insects have higher water content (80%) than commodities (5 to 20%), causing insects to heat faster than the commodities they infest. Microwaves have greater power, but radio waves can penetrate deeper into products than infrared radiation. No commercial units exist to disinfest commodities using microwaves, radio waves, or infrared radiation.

Heat Treatments

Structures

Heat treatment of grain-processing structures (flour mills) is a 100-year old technique (Dean 1911) that involves raising the temperature of a room, equipment, or an entire facility to 50 to 60°C to control insects, primarily stored-product insects (Heaps 1994, Mahroof et al. 2003a b, Roesli et al. 2003, Beckett et al. 2007). The duration of the heat treatment depends on the site. Whole facility heat treatments typically last 24 hours. Depending on the facility, treatment times of 30 to 36 hours are not uncommon. Spot treatment of empty bins or equipment can be completed in as little as 4 to 6 hours (Tilley et al. 2007). There is renewed interest in exploring heat treatments as an alternative to methyl bromide. This structural fumigant has been phased out in the United States, Canada and Europe, except for certain critical uses, because of its adverse effects on stratospheric ozone levels (Makhijani and Gurney 1995).

At temperatures between 50 and 60°C, large differences exist between susceptibilities of the life stages (Table 4). Heat tolerance of a stage varies with temperature. Tolerance to heat at temperatures of 50 to 60°C is more important than at temperatures below 50°C (Mahroof et al. 2003b; Boina and Subramanyam 2004; Mahroof and Subramanyam 2006; Hulasare et al. 2010). These studies were based on laboratory experiments at fixed temperatures. Heat tolerance of life stages of a species has not been determined during commercial heat treatments. Experiments should be designed to confirm laboratory findings with field data. The heat tolerance of life stages confirmed under laboratory conditions at fixed temperatures could not be confirmed under field conditions (Mahroof et al. 2003a; Yu et al. 2011), perhaps due to heating rate influencing heat tolerance among life stages, an area for further research.

Table 4. *Time for 99% mortality (LT_{99} with 95% confidence levels) of heat-tolerant stages of four stored-product insect species at constant temperatures between 50 and 60°C.*

Species	Stage	Temperature (°C)	LT_{99} (95% CL) (minutes)	Reference
Red flour beetle	young larvae	50	433 (365-572)	Mahroof et al. 2003b
		54	82 (60-208)	
		58	38 (29-76)	
		60	42 (34-66)	
Confused flour beetle	old larvae	50	90 (82-102)	Boina and Subramanyam 2004
		54	56 (49-67)	
		58	38 (30-71)	
		60	24 (20-33)	
Indianmeal moth	old larvae[a]	50	34 (29-43)	Mahroof and Subramanyam 2006
		52	34 (26-67)	Yu et al. 2008
Cigarette beetle	eggs[b]	50	190 (170-220)	
Drugstore beetle	young larvae	54	39 (36-43)	Abdelghany et al. 2010
		50	234 (176-387)[c]	
		55	10.8 (6.6-13.8)	
		60	4.8 (4.2-4.8)	

[a] Fifth instars
[b] Time-mortality relationships were based on egg hatchability data.
[c] This value is a LT_{90} (95% CL)

High temperatures that do not kill insects can adversely affect reproduction. Red flour beetle, *Tribolium castaneum* (Herbst) pupae exposed to 50°C for 39 minutes or adults exposed for 60 minutes resulted in surviving adults from these insects having significantly reduced oviposition, egg-to-adult survival rate, and progeny production (Mahroof et al. 2005).

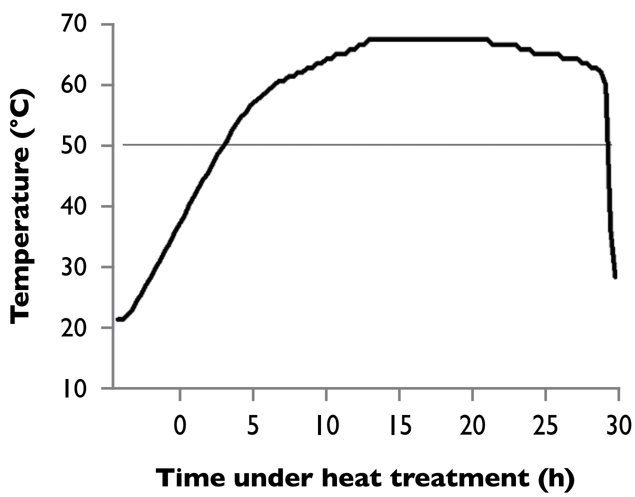

Figure 2. *Temperature during a heat treatment in a flour mill using propane-fired heaters.*

In facility heat treatments, heaters are used to gradually heat the air in the structure. A long treatment period is necessary for the heat to penetrate wall voids and equipment to kill insects harboring in them. A typical heat treatment may last 24 to 36 hours (Mahroof et al. 2003b; Roesli et al. 2003; Beckett et al. 2007) with heating rates generally around 3 to 5°C per hour (Figure 2). In effective heat treatments, the time to reach 50°C usually takes about 8 to 10 hours, depending on the time of year and the leakiness of a structure. During heat treatments, it is important to remove all food products and packaging materials (bags) from the facility. Equipment should be opened and thoroughly cleaned of food product where possible. Unlike fumigants, heat does not penetrate deeply into flour, grain or grain products. It is important to ensure there is no damage to the equipment, uninfested materials stored within the facility, and the structure are not damaged. Electric heaters, forced-air gas (direct-fire) heaters (Figure 3), or steam heaters (Figure 4) are used to conduct a heat treatment. Two basic approaches to facility heat treatment are positive pressure or recirculation (Table 5). With forced-air gas heaters, the building is placed under positive pressure during a heat treatment, and the entire air within the building is exchanged four to six times per hour. The number of air exchanges when using electric and steam heaters may be one or two per hour. The forced air also allows heat to reach gaps in the building and equipment much better than electric or steam heaters. Forced-air gas heaters can use natural gas or propane as fuel. They have air intakes outside the heated envelop, and nylon ducts are placed within the facility to introduce heated air. Because hot air has a tendency to stratify horizontally and vertically within a facility, several fans should be placed on different floors to redistribute heat uniformly. Fans should be directed to areas that are difficult to treat such as corners, along walls, dead-end spaces, and areas away from the heat source. During heat treatments, fans should be moved to eliminate cool spots (less than 50°C). In addition to food-processing facilities, heat treatment can be used in empty storage structures (bins, silos), warehouses, feed mills, and bakeries.

Figure 3. *Propane-fired heater (Temp-Air) heater (source of heat for studies in Figure 2).The door is sealed with plywood, and a flexible fabric duct delivers heated air through a hole cut in the plywood.*

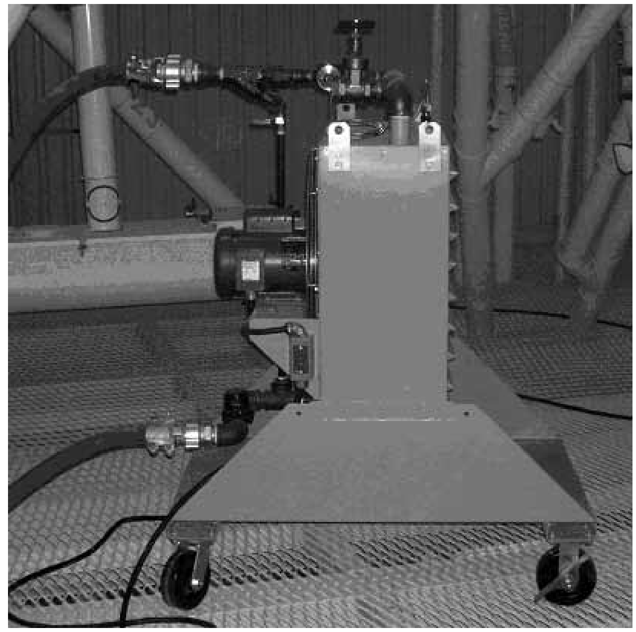

Figure 4. *Portable steam heater (Armstrong International, Inc.) used in heat treatment (Fields 2007).*

Dosland et al. (2006) gave step-by-step instructions for conducting and evaluating a facility heat treatment (see checklist, pages 186–88). Calculating how much heat energy is required after accounting for heat losses due to exposed surfaces, equipment, and infiltration is an important aspect of conducting an effective heat treatment. Research at Kansas State University and discussions with heat service providers shows that the amount of heat energy should range from 0.074 to 0.102 kilowatt hour per cubic meter (kwh/m^3) or 8.0 to 10.0 btu per cubic foot. During a 2009 heat treatment of a K-State flour mill

Table 5. *Differences between forced-air heaters using positive pressure and recirculation.*

	Forced-air heaters, positive pressure	Recirculation
Description	• Heaters external to building. • Building has positive air pressure, with 4 to 6 air exchanges per hour. • Patented process by TempAir.	• Heaters inside building. • Heaters permanently installed or portable. • Many are steam heaters. • Used by Quaker Oats for more than 50 years.
Advantages	• More even heating than recirculation. • Can be faster than recirculation.	• Takes less energy than forced air. • No moving or storage of heaters (fixed heaters only).
Limitations	• Open flame. • Takes more energy than recirculation.	• Some heaters are explosion proof. • Chimney effect that stratifies air in top of floors or upper part of building. • Infiltration of cold air from outside. • Needs more fans than forced air.

the heat energy used was as high as 0.16 kwh/m^3. An indirect method of determining whether or not adequate heat energy is being used is based on 50°C being attained within the structure in 6 to 10 hours.

To gauge heat treatment effectiveness, identify critical areas in the facility. These are places where insects can hide and breed or where temperatures cannot reach 50°C, which can be identified through inspections. Temperature sensors should be placed in these areas. During the heat treatment infrared guns and thermometers can be used to determine areas that have attained sufficient heat (50°C) or that are too hot (65°C). Monitoring temperatures during the heat treatment is needed to adjust equipment so all areas of the facility are heated sufficiently.

Insect bioassays are another method to determine the effectiveness of heat treatments. Commercial companies sell cards or vials with insects of different stages. Some bioassays have food in the container, which makes it more difficult to determine if insects are dead. This reduces the exposure temperatures, but it provides better quality insects and is more representative of the insects that are found in the mill. The use of live insects to gauge heat treatment effectiveness provides valuable information, but in some facilities bringing in live insects may be prohibited. Bioassay results are only available after the heat treatment is completed. Temperature monitoring provides immediate information needed to control an effective heat treatment.

Insect populations within a facility should be monitored before and after a heat treatment. Ideally, traps should be used throughout the year. Trapping for a minimum of four weeks before and 16 weeks post-treatment will show how effective the heat treatment was and potential centers of insect activity. At least 35 traps should be used inside the facility and five outside the facility. In some facilities such as flour mills, it is possible to sample rebolt sifter tailings to determine insect load. The rebolt sifter should be monitored daily, and the number of live and dead insects counted. Subsamples or a single rebolt sifter can be used as long as sample collection is consistent.

Heat treatments can reduce insect populations, and the duration of insect suppression is related to sanitation and exclusion practices followed by the facility. The doors and windows should be tightly closed to prevent outside insects from coming into a facility. Insects can be brought into a facility on raw materials. Care must be taken to inspect all materials to ensure that they are insect free. Inspection, sanitation, and exclusion practices can help extend the degree and duration of insect suppression obtained with a heat treatment.

Summary

Extreme temperatures, above 50°C and below 15°C, can be used to disinfest either commodities or structures. Using extreme temperatures has a number of advantages: no insecticide residues, no licenses needed for application, and no resistant populations. Among the challenges are that an extensive capital investment may be needed, treatments may be limited to certain times of the year, and extreme temperatures may damage equipment or products if used improperly. Heat treatment involves raising and maintaining temperatures of empty grain storage structures, warehouses, and food-processing facilities between 50 and 60°C to kill stored-product insects. The duration of heat treatment is application-specific and may vary from six hours for an empty storage facility to up to 34 hours for an entire food-processing facility. Laboratory and commercial trials with high temperatures during the last decade have provided information about responses of insects at various life stages to heat, heat distribution within a treated area, and techniques necessary for gauging effectiveness of commercial heat treatments. Insect responses are species, stage, and temperature-specific. Air movement and strategic fan placement are important for eliminating cool spots (below 50°C) and uniformly heating a treated area. The use of heat and cold treatments for commodities and structures are described.

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Checklist for Heat Treatment

Before heat treatment

____Appoint site heat-up planning team (including an engineer). Select a team leader to coordinate the heat treatment.

____Identify specific areas to be heated and make a site plan. Determine local heat and air sources.

____Identify heat sensitive structures and supports, including roofs. If protection or engineering assurances cannot be developed, then do not conduct a heat treatment because of possible damage to structures.

____Identify and develop measures for protecting heat-sensitive equipment within the facility. Contact manufacturer if in doubt as to which equipment is heat-sensitive.

____Identify sealing materials needed inside and outside the heat zone to exclude pest harborages.

____Determine air movement plan, circulation equipment, fan placement, and type and number of fans needed. Identify energy sources, location of temporary electric panel to plug-in fans and extension cords to spread out the electrical load for air movement.

____Establish a fire protection plan. Check the insurance carrier for coverage for any damage to structure or equipment.

____Repair damaged doors, windows and other openings that would allow heat to escape. This would not be a major issue when using forced-air gas heaters. Wide open areas around forced-air gas heaters need to be closed with plywood or polyethylene to reduce or eliminate cold air infiltrating from outside. Eliminate major drafts from unheated areas

____Notify corporate safety, engineering, and regional personnel of intent to conduct a heat treatment.

____Notify local (city and county) fire and police departments.

____Notify construction contractors or other persons who may be using the facility so equipment, materials and supplies may be removed.

____Use 4 to 6 mm polyethylene sheet to seal off exhaust fans, dust collectors or air make-up systems that exhaust to the outside.

____Remove heat-sensitive products or raw materials from the area to be heated. Examples are vitamins, shortenings, sugar, and some packaging materials. Many products are sensitive to the high temperatures used during heat treatments.

____Empty storage structures (bins/silos). Grain or grain products (flour, etc.) are good insulators, so heat will not penetrate into the bulk and insects may survive if the stored product is infested. Alternatively, if the stored product is insect-free, bin entry and exit points must be sealed so that insects do not migrate into these storage structures. Make sure that high temperatures do not alter the quality or the end-use of the stored product.

____Empty garbage cans and vacuum cleaners. Bagged, bulk raw, or processed products should be placed in a trailer and fumigated with phosphine to kill residual infestation.

____Remove pressurized containers and cylinders from the heated area. Label fire extinguishers with proper location for emergency “near-by use” during heat treatments. Remove or empty beverage vending machine.

____Where possible, remove electronic equipment. Unplug equipment that cannot be removed. Back up computer programs. An experiment run at the Kansas State University heat workshop in 1999 showed no adverse effects on computers after they were subjected to a 34-hour heat treatment.

____Empty and remove all trash, waste, and product containers.

____Check the sprinkler system and head sensitivity for 141°C. If heads activate at lower temperatures, replace them. One option is to drain the sprinkler systems and post a fireguard during the inactivation period. Check systems for tripped heads and refill slowly before activation.

____Turn off older sodium or mercury vapor lights during heat treatment. Check with engineering staff or supplier regarding heat tolerance of these lights. Identify alternate lighting plans to minimize plant power usage.

____Check bearing and belt types and loosen where necessary.

____Check lubricant type and reservoirs, and provide for expansion during heating.

____Identify plastic-type material, including PVC piping and Tygon tubes, and monitor these for possible damage during heat treatment. Check pneumatic line plastics connectors for any adverse heat-related effects.

____Double check temperature limitations on all solid-state equipments such as electronic controllers, small computers, or photoelectric sensors. The best information source is the equipment supplier. Protect sensitive equipment by placing it a cool zone during the heat treatment. Develop floor-by-floor and area-by-area checklists for preparation of sensitive equipment within heat treatment zones.

____Take precautions about magnets that may be deactivated as a result of exposure to high temperatures (50 – 60°C). Contact the manufacturer for maximum temperatures.

____Establish an employee safety plan that covers heat illness warning signs, use of the buddy system (people working in teams of two), tips on proper clothing, drinking, eating, heat stress first aid room outside heated area, first aid kit, emergency phone numbers, employee heat tolerances (based on physicals), and cool vests.

____Identify and provide appropriate personal protective equipment (PPE) such as bump caps with cloth lining and cloth gloves. It is advisable to wear light, loose fitting clothing.

____No metal or glass such as buttons and glasses, which are good heat conductors should be in direct contact with skin.

____Establish temperature-monitoring plan, including key locations to be monitored manually or with remote temperature-measuring devices. Calibrate all monitoring tools with reference to a standard mercury thermometer.

____Identify all areas adjacent to heated areas. Spray surfaces, especially floor-wall junctions and doorways, with a residual insecticide to prevent insect migration to unheated areas.

____Determine numerous locations on the plant layout for placement of test insects. The cages should have an insect that is a problem within the facility, and temperatures should be measured near the test insects. It is important to use the most heat-tolerant stage of the insect. The best procedure is to expose all stages (eggs, young larvae, old larvae, pupae, and adults) of the insect species.

____Thoroughly clean accessible equipment, leaving no more than 1 cm thickness of food products. Close equipment after cleaning. Proper cleaning is essential to an effective heat treatment because grain or stored product is a poor heat conductor.

____Elevator and conveyor boots are good sources of insect populations. Areas under the elevator buckets are good harborage points for insects because broken, damaged grain becomes trapped or encrusted in these areas. Opening the boots of bucket elevators and conveyors and directing fans to these areas helps kill residual insect populations. Sometimes elevators may be run for a few hours before shutdown so that all areas of elevator (belts, cups, and screw conveyor) are exposed to lethal temperatures.

____Identify the person responsible for turning off plant power, if necessary.

During heat treatment

____Before heaters are turned on, walk through the facility with the heat treatment team to determine whether the facility is ready for the treatment. Determine whether the level of sanitation is adequate and ensure that all the critical items have been removed from the facility.

____Measure the temperature from as many locations as possible within the facility to identify cool (less than 50°C) as well as overheated areas (greater than 60°C).

____If the heat treatment is provided as a service by a private company, that company is responsible for the operation of the rental power, heating equipment, and assisting with temperature and humidity monitoring. Facility maintenance personnel should monitor specific structures and heat-sensitive equipment, in addition to providing oversight during heat treatment.

____Numerous industrial strength fans, capable of withstanding 50 to 60°C, should be used to circulate the hot air within the facility. Circuit breakers on the temporary electrical panels for fans should be industrial strength so they do not trip. This will cut-off power to the fans and reduce air flow necessary for uniform temperature distribution.

____Record temperature and humidity at predetermined locations and intervals. This can range anywhere from a minute using microprocess-based temperature sensors to every hour if done manually using infrared thermometers.

____Check areas near test insects regularly. Remember that insects exposed to sudden heat shock appear dead but may come back to life if they are removed from the heated areas. Insect test cages with adults removed during heat treatment should be kept at room conditions for 24 hours before insect mortality is assessed. All pre-adult stages should be reared to adulthood for mortality assessments.

____Designate an office as a heat-treatment command center with phone, first aid kit, temperature log sheets, fluids (water or other hydrating beverages), and emergency phone numbers.

After heat treatment

____Discontinue heating after the desired exposure time and temperature are achieved. Keep fans running after shutting down the heaters to facilitate cooling. In the case of forced-air heaters, the blowers may be left running after burner is shut down, forcing outside cool air into the facility for cooling.

____Uncover roof and wall vents, air intakes, and other openings for exhaust air. Open screened windows.

____Turn on plant power when temperature cools to less than 43°C.

____Recover test insects and temperature-sensing equipment or charts. Record insect mortality.

____Treat areas where survival occurs in insect test cages with a residual insecticide.

____Start the exhaust fans in heated areas. Monitor temperatures during the cool-down period.

____Replace fire extinguishers at proper locations, and return plant to normal fire-protection standards. If sprinkler system was drained, check each sprinkler head before activation. Refill slowly.

____Remove portable power or heater equipment and begin reassembly of plant equipment to prepare for normal operation.

____Remove all sealing equipment and complete post-treatment cleanup. Flush the initial food material within the processing system for about 10 to 20 minutes and dispose of it as trash. A large number of insect fragments may exit processing equipment in the initial flush. Check flushed material and record information on the types and number of insects present.

____The heat treatment team should review treatment activity and effectiveness and list suggestions to improve a future application. Subsequent heat treatments are more effective than first ones. Modifications often are needed due to the uniqueness of the structure and training of personnel.

____Prepare a detailed post heat-treatment report. This report should serve as a baseline for future heat treatments.

____Adverse effects observed should be investigated and a plan developed to prevent such occurrences in the future.

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16 Controlled or Modified Atmospheres

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Atmospheric manipulation for the protection of stored products such as grains has been researched extensively for more than 30 years (Adler et al., 2000; Calderon and Barkai-Golan, 1990; Jay, 1984; Navarro, 2006). Processes such as airtight or hermetic storage have been used successfully to maintain grain quality in South America (Argentina), the Middle East, India, and North Africa. Modified atmospheres (MA) or controlled atmospheres (CA) offer an alternative to the use of conventional residue-producing chemical fumigants for controlling insect pests attacking stored grain, oilseeds, processed commodities, and some packaged foods. These atmospheres also prevent fungal growth and maintain product quality.

The development of this technology has come about mostly over public concern about the adverse effects of pesticide residues in food and the environment. Although this method has become well established for control of storage pests, its commercial use is still limited to a few countries. More recent investigations have attempted to integrate modified atmosphere application into the 21st century version of raw product and manufactured food storage and transportation (Navarro 2006).

MA is proposed to serve as the general term, including all cases in which the atmospheric gases' composition or their partial pressures in the treatment enclosure have been modified to create conditions favorable for insect control. In a MA treatment, the atmospheric composition within the treated enclosure may change during the treatment period. In a CA treatment, atmospheric composition within the treated enclosure is controlled or maintained at a level and duration lethal to insects. The results are the creation of processes for managing food preservation that are residue-free, relatively safe to apply, and environmentally benign (Navarro 2006).

The purpose of this chapter is to discuss the concepts and variations of MA and CA, their impact on pests and on the quality of the product being treated, the structures where they may be considered for use, and their compatibility in commercial settings.

MA Hermetic Storage

A type of MA that can be applied for the protection of grain is *hermetic storage*, also termed *sealed storage* or *airtight storage* or *sacrificial sealed storage*. This method takes advantage of sufficiently sealed structures that enable insects and other aerobic organisms in the commodity or the commodity itself to generate the MA by reducing oxygen (O_2) and increasing carbon dioxide (CO_2) concentrations through respiratory metabolism. Respiration of the living organisms in storage (insects, fungi, and grain) consumes oxygen (O_2), reducing it from near 21% in air to 1 to 2%, while production of carbon dioxide (CO_2) rises from an ambient 0.035% to near 20% (White and Jayas 2003). This environment kills insect and mite pests and prevents aerobic fungi from growing (Weinberg et al. 2008). Elevated CO_2 and depleted O_2 levels will generally maintain stored grain quality for long periods of time. Grain with excessive moisture may be invaded by lactate-forming bacteria and yeasts (White and Jayas 1993). Hermetic storage has been in use for several thousand years preserving grains in airtight pots or containers (Adler et al. 2000). The key to successful hermetic storage is airtightness and control of condensation. In modern times, storage size has increased from small family storages to large bulks representing many producers or a portion of a country's total production. In the 1960s and 70s, large aboveground hermetic storage in some African and Asian countries was discredited because of severe condensation problems, particularly in metal structures (Navarro et al. 1994). Semi-underground storage has been used successfully in Argentina, Kenya, and Cyprus; Australia and Israel have successfully used bunker storage systems from the 1980s.

With recent improvements in materials and construction of flexible, nonporous bags and liners, a variety of size options offer protection for products from 25 to 1000 kg up to 10,000 to 15,000 tonnes (Navarro 2010). Commodities including cereals, oilseed grains, pulses, cocoa, and coffee can be stored safely for many months, maintaining high quality and limiting molds and mycotoxins. Plastic structures suitable for long-term storage systems, as well as intermediate storage of grain in bags or in bulk have been developed and applied.

Storage systems based on the hermetic principle include the following:

- Bunker storage in gastight liners for conservation of large bulks of 10,000 to 15,000 tonnes;
- Flexible gastight silos supported by a weld-mesh frame of 50 to 1,000 tonnes capacity for storage of grain in bulk or in bags;
- Gastight liners for enclosing stacks of 5 to 1,000 tonnes capacity, called storage cubes or Cocoons, and designed for storage at the farmer-cooperative and small trader level or larger commercial and strategic storage facilities;
- Silo Bags of 200 tonnes capacity for on-farm grain storage directly in the field. This technique was originally used for grain silage, and involves storing dry grain in sealed plastic bags; and
- Small portable gastight containers of 25 kg to 2.5 tonnes, called SuperGrainbags, which are suitable for seed storage and man-portable and bagged commodities. These structures enabled the application of modern MA technology worldwide to provide quality preservation and insect control.

CA Under Normal Atmospheric Pressure

Gas supply from pressurized cylinders – CA is a modified gas composition, usually produced artificially, and maintained unchanged by adding desired gases (CO_2 or nitrogen [N_2]), supplied from pressurized cylinders or other means. This supplementary introduction of gases is carried out when their concentration in the sealed container drops to below the desired level.

The objective of CA treatment is to attain a composition of atmospheric gases rich in CO_2 and low in O_2, or a combination of these two gases within the storage enclosure or treatment chamber. These set concentrations are maintained for the time necessary to control the storage pests. A widely used source for production of such atmospheric gas compositions is tanker-delivered liquefied CO_2 or N_2, when the target CA gas composition is less than 1% O_2 or high CO_2 concentration. For large-scale application of N_2 or CO_2, vaporizers are essential. These vaporizers consist of a suitably designed receptacle with a heating medium (electricity, steam, diesel fuel, or propane), a super-heated coil with hot water jacket, and forced or natural draught.

Combustible gases – Exothermic gas generators or gas burners are available for on-site generation of CAs. They work by combustion of hydrocarbon fuel to produce a low O_2 atmosphere containing some CO_2. Their CA composition is designed to allow the presence of approximately 2 to 3% O_2, with CO_2 removed through scrubbers. Several adaptations are required for use in the grain industry, i.e., tuning equipment to obtain an O_2 level of less than 1%; utilizing the CO_2 generated to full advantage; and removing excessive humidity from the atmosphere generated. Combustion of propane and butane yields approximately 13% and 15% CO_2, respectively. The CA generated is more toxic than a N_2 atmosphere deficient in O_2 because of the presence of CO_2. The combined effect of CO_2 and low O_2 results in greater insect mortality.

On-site N_2 generators – Commercial equipment, called pressure-swing adsorption systems, use the process of O_2 adsorption from compressed air passed through a molecular sieve bed. For continuous operation, a pair of adsorbers is provided that operate sequentially for O_2 adsorption and regeneration. Nitrogen at a purity of 99.9% can be obtained through regulation of inlet airflow; this method of N_2 generation is an expanding new approach in CA-generation technology. Equipment is now being manufactured that is rated to supply an outlet flow of 120 m^3/h at an outlet purity of 98% N_2.

Ozone – Ozone can be generated and used to kill insects, although it reacts with caulking in bins and may bleach grain. Ozone also lowers levels of microflora on seed. It is suggested for use in railcars at low temperatures and low humidity (McClurkin and Maier 2010). It is also effective in killing insects at 1800 ppm for 120 minutes and can be applied in specially modified augers (McDonough et al. 2010).

CA Under Altered Atmospheric Pressure

Vacuum or low pressures – In a low-pressure environment there is a close correlation between the partial pressure of the remaining O_2 and the mortality rate. Until recently this treatment could only be carried out in specially constructed rigid and expensive vacuum chambers. A practical solution has been invented that uses flexible liners. To achieve the low pressures in the flexible liners, sufficiently low pressures (25 to 50 mm Hg absolute pressure) can be obtained (using a commercial vacuum pump) and maintained for indefinite periods of time by continued operation of the pump.

High-pressure carbon dioxide treatment – CO_2 treatments can be significantly shortened to exposure times that may be measured in hours using increased pressure (10-37 bar) applied in specially designed metal chambers that stand the high pressures. Because of the high initial capital investment, these high-pressure chamber treatments may be practical for high-value products such as spices, nuts, medicinal herbs, and other special commodities.

Effects of CA on Insects Under Normal Atmospheric Pressure

Effects of low oxygen levels – Insects can tolerate low levels of oxygen for prolonged periods. Using N_2 to replace O_2 must result in O_2 being below 2%, preferably 1% for rapid death. This effect is reversed below 1% O_2 in N_2 where adult rice weevils, *Sitophilus oryzae* (L.) (Navarro et al. 1978) showed tolerance, increasing the lethal exposure time by apparently closing their spiracles. In particular, *S. oryzae* adults are killed more quickly at 1.0% O_2 rather than at 0.1 or 2% O_2 under the same conditions. *Tribolium castaneum* (Hbst.) in N_2 showed significant differences in adult mortality between 0.1 and 1.0% O_2 (Navarro 1978). Adults are generally most susceptible to treatment, and *S. oryzae* or *Rhyzopertha dominica* (F.) was found to be more tolerant than *Tribolium* spp. The lowest level of tolerance to lack of O_2 was attained around the 1% concentration level. Therefore, Annis (1987) concluded that O_2 levels of 1% are needed to kill insects in 20 days (Table 1).

Table 1. *Suggested provisional dosage regimes for control of all stages of the 12 most common insect species of stored grain, using modified atmospheres at temperatures between 20° and 29°C* (Navarro and Donahaye 1990).*

Atmospheric gas concentration	Controls most common grain insects including *Trogoderma granarium*	Exposure period
	yes/no	days
<1% O_2 (in nitrogen)	yes	20
Constant % CO_2 in air		
40	no	17
60	no	11
80	no	8.5
80	yes	16
CO_2 decay in air from >70 to 35%	no	15
Pressurized CO_2 at >20 bar	**	<0.35

* Data, except those on pressurized CO_2, compiled from Annis 1987.

Effects of high carbon dioxide levels – Elevated CO_2 levels cause spiracles to open resulting in insect death from water loss. Above 10% CO_2 spiracles remain permanently open. Toxic effects are entirely through the tracheae, not the hemolymph; CO_2 has direct toxic effects on the nervous system. In some cases, CO_2 can acidify the hemolymph leading to membrane failure in some tissues (Nicolas and Sillans 1989). Elevated, but sublethal CO_2 levels, for prolonged periods can have deleterious effects on insect development, growth, and reproduction (White et al. 1995, Nicolas and Sillans 1989). Atmospheres containing about 60% CO_2 rapidly kill stored-product insects. At 26°C, about 4 days of exposure would be sufficient to kill all stages (including eggs) of most stored-product insects (Table 1).

High carbon dioxide and low oxygen levels – Atmospheres with 60% CO_2 and 8% O_2 are very effective at killing internal seed-feeding insects, while low O_2 atmospheres are more rapid in killing external-feeding insects (Banks and Annis 1990). High CO_2 levels, even with 20% O_2,rapidly kill insects because of CO_2 toxicity. CO_2 levels must be at 40% for 17 days, 60% for 11 days, 80% for 8.5 days at temperatures above 20°C, or 70% declining to 35% in 15 days at 20°C (Annis 1987). Higher temperatures accelerate CO_2 toxicity as insect metabolism is elevated. Even low levels of CO_2 (7.5-19.2%) for prolonged periods sharply increase immature and adult mortality (White et al. 1995).

Effects of temperature and relative humidity on controlled atmosphere fumigation – Insect mortality increases more rapidly as temperatures rise and their metabolism speeds up. Cool temperatures slow rates of mortality while lower relative humidities (RH) hasten toxic effects, notably in high CO_2 atmospheres because of desiccation of insects (Banks and Fields 1995).

Development of insect tolerance to controlled atmospheres – Bond and Buckland (1979) were the first to show that stored-product insects have the genetic potential to develop tolerance to CAs, when they obtained a threefold increase in tolerance to CO_2 by *Sitophilus granarius* (L.) after selecting for seven generations. Navarro et al. (1985) obtained a similar level of resistance for *S. oryzae* exposed to hypercarbia by selection over 10 generations. *Tribolium castaneum* populations were exposed to high levels of CO_2 (65% CO_2, 20% O_2, 15% N_2) (Donahaye, 1990a) or low levels of O_2 (0.5% O_2, 99.5% N_2) (Donahaye, 1990b) and 95% RH for 40 generations. Selection pressure in both bases was between 50% and 70% mortality each generation. At 40 generations, the insects exposed to high CO_2 levels had an LT_{50} (lethal exposure time to kill 50% of the test population) 9.2 times greater than nonselected insects. Insects exposed to low O_2 had an LT_{50} 5.2 times greater than nonselected insects. While these insects were able to adapt to extreme atmospheric composition to a moderate extent, the conditions used would not occur naturally.

CA Effects on Insects Under Altered Atmospheric Pressure

Effects of low pressures – Mortality of insects under low pressures is caused mainly by the low partial pressure of O_2 resulting in hypoxia (Navarro and Calderon 1979). The partial pressure of oxygen has a decisive effect on insect mortality, while no significant function could be attributed to the low pressure itself. At 50 mm Hg, partial pressure of O_2 is equivalent to 1.4% O_2, this being similar to the target O_2 concentration under a modified atmosphere obtained by N_2 flushing. Finkelman et al., (2004) showed that less than 3 days under 50 mm Hg at 30°C would control all stages of *Ephestia cautella* (Wlk.), *Plodia interpunctella* (Hbn.), and *T. castaneum*. The times needed to obtain 99% mortality were 45 hours, 49 hours, and 22 hours, respectively. The eggs of all three species were most resistant to low pressure.

Effects of carbon dioxide at high pressures – With CO_2 at high pressures (20 to 40 bar) all types of pests and their life stages can be killed within a short time. Generally, increasing the pressure reduces the lethal exposure time. *Lasioderma serricorne* (F.), *Oryzaephilus surinamensis* (L.), *T. castaneum*, *T. confusum* J. du V., *Trogoderma granarium* Everts, *Corcyra cephalonica* Stainton, *Ephestia elutella* (Hbn.), *E. cautella, P. interpunctella,* and *Sitotroga cerealella* (Oliv.) were exposed at a temperature of 20°C and carbon dioxide at 37 bar for 20 minutes, 30 bar for 1 hour, and 20 bar for 3 hours resulted in 100% mortality of all insects. Survivors of *T. confusum* were found after treatment with 10 bar for 20 hours. The rate of decompression of pressurized storages may also have an adverse impact on insect mortality. The relatively rapid control of pests in all stages of development is based on both the narcotic and acidifying effect induced by the high solubility of carbon dioxide in cell fluid, and on the destruction of the cells following the CO_2 pressure treatment during depressurization.

Effects of CA on Product Quality

Germination of seeds – Seeds below their critical moisture content are not significantly affected at high CO_2 or low O_2 atmospheres. However, with increasing grain moisture contents, CO_2-rich atmospheres could reduce the physiological quality of grain by interfering with the enzymatic activity of glutamine-decarboxylase. The adverse effect of CO_2 on germination of rice, maize, and wheat becomes more pronounced at temperatures higher than 47°C and, from observations carried out so far, this adverse effect may not be detectable at all below 30°C. If preservation of germination is of primary importance, the use of CO_2 free, low O_2 atmospheres is preferred if expected temperatures are significantly above 30°C.

Viability of corn stored under hermetic (148 days storage) and non-hermetic (120 days storage) conditions in the Philippines did not indicate significant changes between the initial and final samples (Navarro and Caliboso 1996; Navarro et al., 1998). In the same trials, viability of grain stored under hermetic conditions did not change significantly. To test viability of wheat stored under hermetic conditions in Israel, two trials were carried out with storage periods of 1,440 and 450 days only under hermetic conditions. Viability of wheat changed slightly from an initial 99% to 97% after 1,440 days, and from 97% to 91% after 450 days, respectively. In both trials, insect populations were successfully controlled and the average CO_2 concentrations ranged between 10% and 15%.

Product quality preservation – Donahaye et al. (2001) reported on quality preservation of 13.4 to 31.9 tonne lots of grain, stacked in flexible enclosures and stored outdoors for 78 to 183 days. The quality of the grain was compared with that of three control stacks (5.3 to 5.6 tonnes capacity) held under tarpaulins in the open for 78 to 117 days. Percent milling recovery and levels of yellowing in the gastight stacks showed no significant change. In a study on quality preservation of stored cocoa beans by bio-generated modified atmospheres, respiration rates of fermented cocoa beans were tested at equilibrium relative humidities of 73% at 26°C in hermetically sealed containers. The O_2 concentration was reduced to <0.3%, and CO_2 concentration increased to 23% within 5.5 days. The free fatty acid (FFA) content of cocoa beans at 7%, 7.5%, and 8% moisture content under hermetic conditions of 30°C remained below or close to 1% after 90 and 160 days of storage (Navarro et al. 2010).

Types of Structures in which CA and MA Have Been Used

Controlled atmospheres have been used in a wide array of grain storage structures. The most important consideration is that they must be airtight for long-term storage or relatively airtight for CO_2 or N_2 fumigation. Acceptable airtightness for CO_2 fumigation is determined by negative pressure testing and should at most hold a negative pressure from 500 to 250 pascals in 10 minutes (Annis and van S. Graver 1990). Attempts have been made to predict gas-tightness relative to leakage areas (Mann et al. 1999; Lukasiewicz et al. 1999). Provisional guidelines based on best estimates from a comparison of variable pressure tests are presented in Table 2 (Navarro 1999). The suggested times given in Table 2 were doubled for empty storages as an approximation to the intergranular airspace.

In-ground storage – Historically, in-ground storage was widely used worldwide to create hermetic storage where CO_2 was produced and O_2 consumed by respiration of grain and microflora. Its use was recorded from Spain to India and China, East Africa, and North America west of the Mississippi River (Sigaut 1988).

Bolted steel bins – Bolted steel bins are not airtight but they can be sealed for partially successful fumigation with CO_2. Alagusundaram et al. (1995) placed dry ice in insulated coolers under a CO_2 impervious plastic sheet above wheat 2.5 m deep in a 5.6 m diameter bin. CO_2 levels were 30% at 0.55 m above the floor where 90% of rusty grain beetles, *Cryptolestes ferrugineus* (Stephens) were killed; CO_2 levels of 15% at 2.0 m above the floor resulted in 30% mortality. A bolted, galvanized-iron silo (21.5 tonnes) was sealed using a polyvinyl resin formula-

Table 2. *Provisional recommended ranges for variable pressure tests carried out in structures destined for gaseous treatments to control storage insects (Navarro 1999).*

Type of gaseous treatment	Structure volume in cubic meters	Variable pressure test decay time 250-125 Pa	
		Empty structure	95% full
		------------- min.	--------------
Fumigants	Up to 500	3	1.5
	500 to 2,000	4	2
	2,000 to 15,000	6	3
CA	Up to 500	6	3
	500 to 2,000	7	4
	2,000 to 15,000	11	6
MA, including airtight storage	Up to 500	10	5
	500 to 2,000	12	6
	2,000 to 15,000	18	9

tion sprayed onto joints from the inside. The silo was loaded with wheat into which cages of insect-infested wheat were introduced, and conditions monitored with thermocouples and gas sampling lines. Oxygen levels were reduced to less than 1% by purging with N_2, and similar levels were then maintained by a slow N_2 bleed for 35 days, after which the silo was emptied. All adult insects were dead but, as expected, some immatures survived. This was because the maintenance period was too short to ensure complete kill at the observed grain temperatures of less than 15°C (Williams et al. 1980).

Sealed steel bins – Airtight, galvanized-steel bins have been manufactured in Australia for the past 30 years and are commercially available (Moylan Silos 2011). Welded steel hopper bins can be modified for CO_2 fumigation for a few hundred dollars. Carbon dioxide from dry ice must be recirculated through the grain and a pressure relief valve installed to the bin. The top and bottom hatches must be gasket sealed. After 10 days at 20°C, 75% of applied CO_2 was retained while 99% of the caged C. *ferrugineus* were killed (Mann et al. 1999).

Concrete grain elevators – Carbon dioxide fumigation of grain has been successful in concrete elevators holding 209 tonnes of wheat. The bottom hopper was sealed and the grain purged with CO_2 for 4 hours (1 metric tonne of CO_2) and additional gas is added as needed. All caged test insects were killed (White and Jayas 2003). A large installation for the application of CO_2-based CA was installed to treat more than 200,000 tonnes of rice annually in flat bins each of 5,000 tonnes capacity in Mianyang, China.

Airtight grain bags – The use of hermetic grain storage in flexible structures is growing throughout the world. Although some structures are not airtight and are easily punctured (Darby and Caddick 2007), new materials offer satisfactory results with high levels of gastightness (Jonfia-Essien et al. 2010; Rickman and Aquino 2004).

One method using airtight bags for 25 kg to 1,000 tonne masses of product is now commercially available as Supergrainbags, Cocoons (Figure 1), MegaCocoon, and TranSafeliners. The bags rapidly produce hermetic storage (Jonfia-Essien et al. 2010, Navarro et al. 2007) and are currently used in 82 countries.

Silobag is another sealed system used for temporary storage of dry grain and oilseeds in South America. Each Silobag can hold approximately 200 tonnes of wheat and is simple to load and unload with available handling equipment (Bartosik 2010).

Figure 1. *Hermetic storage of 150 tonnes of corn in a Cocoon, Rwanda.*

Railcars – Hopper railcars have been treated in-transit with phosphine gas for flour and wheat in Australia and North America (Eco2Fume 2003). Carbon dioxide fumigation requires a much greater level of air tightness than phosphine fumigation. Efforts have been made to seal a railcar containing 90 tonnes of wheat. Even after sealing top hatches with CO_2-impermeable plastic and caulking the bottom hoppers, 118 kg of dry ice produced only 21% CO_2 at 1 day, a level too low for insect control (Mann et al. 1997). If the railcar had been moving, gas loss would have been rapid (Banks et al. 1986).

Commercial Use

Numerous MA and CA systems have been developed over the years to manage insect pests and microflora associated with stored products; however, their general commercial use remains somewhat limited (Adler et al. 2000). Exceptions are for organic products where use of fumigants is not possible because of residues; hermetic storage in plastic structures with application of MA is the preferred choice (Navarro 2006).

Vacuum storage – Vacuum storage or the use of low pressure in flexible PVC chambers has been demonstrated as an effective means for maintaining quality and controlling insect pests in smaller volumes (approximately 50 to 60 tonnes) of peas, beans, wheat, corn, and sunflowers for extended lengths of time (Finkelman et al. 2002; 2003). In these applications, products in bags or totes are placed within the liner, vacuum is applied, and the liner shrinks over the bags. Successful control times have been demonstrated at 55 mm of Hg similar to phosphine (7-day exposure) at temperatures averaging 30°C and humidity averaging 65% RH. Problems can easily be detected using pumps equipped with control panels and sensors, thus, product monitoring becomes unnecessary. These types of treatments are used for high-value commodities because the treatment is nontoxic and relatively quick (highly beneficial in the event of quarantine needs).

Hermetic storage – When placed in sealed airtight storage, commodities and the insects and aerobic microflora that exist within them respire, consuming O_2 and producing CO_2. This modified atmosphere technology has been utilized to a great extent for durables such as grains. Hermetic grain bags (Africa, Argentina, Asia, Australia, North and South America, Middle East) and sealed bunker storage (Australia, U.S., Middle East) have been implemented into commercial application to various extents.

Bunker storage, having designed storage capacities to more than 10,000 tonnes, is established in permanent locations with a prepared base (usually asphalt or compacted soil with a convex profile) and an airtight cover. This type of storage has been used extensively in Australia, Argentina, Israel, and Cyprus (Adler et al. 2000). While low moisture content, high temperature grain supports this type of storage, condensation can remain problematic if the grain is stored with cones or ridges (Navarro et al. 1994). Sealed bunker storage has also been demonstrated as an effective means for utilizing CA or conventional fumigation where the bunker is sealed and flushed with N_2 or CO_2.

A major challenge that South America is facing is to minimize quality and quantity losses, and improve food safety in view of the shortage of permanent storage capacity. As a result, the silobag system for temporary storage of dry grain and oilseeds has been adopted. During the 2008 and 2010 harvest seasons, more than 33 million and 43 million tonnes of grain were stored, respectively, in these plastic bags in Argentina. Commodities included corn, soybean, wheat, sunflower, malting barley, canola, cotton seed, rice, lentils, sorghum, beans, and even fertilizers. The silobag technology is also being adopted in other countries such as the United States, Australia, Bolivia, Brazil, Canada, Chile, Italy, Kazakhstan, Mexico, Paraguay, Russia, South Africa, Sudan, Ukraine, and Uruguay (Bartosik 2011 personal communication).

Controlled atmospheres – Nitrogen and CO_2 have been used as agents for controlled atmospheric storage for many years. Carbon dioxide has been considered to be more efficient than N_2 due to the concentrations necessary for control and the level of gastightness of the structure being used. A CO_2 concentration of about 60% can provide 95% control of most stored-product insect pests at 27°C (Jay 1971), while N_2 use requires interstitial O_2 levels to be reduced to 1% or less. Considerable efforts to improve bin sealing of storage bins have been made (Mann et al. 1999) which in turn facilitates ease in gas application and retention. Mann et al. (1999) demonstrated that CO_2 generated from dry ice and circulated with a vacuum pump at a concentration of 51% caused 100% mortality of *C. ferrugenius* after 10 days at 20°C. Carbon dioxide can also be added to bulk stored products as compressed gas. White and Jayas (1991) demonstrated that by circulating CO_2 released from compressed cylinders, high mortality of several stored-product arthropod pests could be achieved within 14 days. They found that bin sealing was crucial to maintain efficacy especially when commodity temperature fell below 20°C, and that utilizing pressure testing techniques (Banks and Annis 1980) is a useful means of determining a bin's seal.

Nitrogen production has also changed considerably over the years. Pressure-swing absorption systems have proven successful where a 13,660 m^3 bin can be purged to less than 1% O_2 in 7 days. Appropriate sealing allows for accurate calculation for additional gas application required to compensate for gas loss due to sorption, as well as pressure cycling caused by pressure change (Cassels et al. 2000). It also ensures gas concentration can be maintained for appropriate times. Liquid N_2 can be used for topping up the controlled atmosphere, but can cost twice that of other sources. Although CA treatment of grain is an old and proven technology, its applications remained limited. A recent development has been reported by Clamp and Moore (2000), in which N_2 supplied as a bulk liquid under pressure was used to treat 1,800 tonne bins. Since the N_2 treatment was commissioned in 1993, more than 300,000 tonnes were treated in the Newcastle facilities as of 2000 (Clamp and Moore, 2000).

Nitrogen also can be easily generated using molecular membrane generators. These are capable of purging vertical grain storages of 120 tonnes capacity within 3 hours (Timlick et al. 2002). By maintaining a slight positive bin pressure, concentrations within a sealed commercial storage could be maintained (compensation for leakage) and insect mortality was significant after 14 days at 17°C.

In terms of efficacy and efficiency, there is not much difference between using CO_2 over traditional fumigants such as phosphine. Nitrogen has been considered unsuitable for bulk commodity treatment at export position because the length of time required for significant mortality of the pests in question is too long. Effective management procedures can allow for N_2 use when temperatures are appropriate. All require effective sealing and monitoring and efficiency is directly correlated to temperature. While caution is necessary when utilizing any product as an atmospheric control, there are no residues of concern when utilizing MA. Aeration after treatment is of less concern, allowing for outturn of product in export position minimizing concerns for worker safety.

Flexible liners, loading and unloading equipment, nitrogen generators, or pressurized CO_2 (Figure 2) are commercially available. Equipment can be installed, maintained, and replenished with product on site.

Figure 2. *Application of high pressure CO_2 for the dry fruit industry in Turkey.*

Maintenance of sealing of hermetic storage has proven a challenge at times. Large bunkers and grain bags in Australia often have sealing breached by birds pecking holes in the liner. In Canada, deer often break the seals of hermetically stored grain in bags. Consequently, focused research on liner integrity may be of use in these types of situations.

Discovery of breached seals during CA treatments can be difficult to remedy, underlining the necessity of performing pressure testing before application.

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17 Biological Control: Insect Pathogens, Parasitoids, and Predators

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Stored product insects cause millions of dollars per year in losses in stored wheat. Traditionally, stored-product pest management has relied on chemicals to control insects. In some cases, pest management has been improved by applying chemicals only when needed. An increasing effort is being made to reduce or eliminate pesticide residues in the food supply. This trend has increased since the introduction of new food safety standards required under the Food Quality Protection Act (1996), which includes stored raw commodities.

Several stored product insects, such as the lesser grain borer *Rhyzopertha dominica* (F.), are resistant to chemicals applied to stored grain for insect control. The most damaging insects of stored wheat are the lesser grain borer and the rice weevil *Sitophilus oryzae* (L.). Immature stages of these species develop inside the grain kernels, and it is very difficult to remove infested kernels from the grain. If more than 31 insect-damaged kernels are found per 100 grams of wheat, it is classified as sample grade. Biological control is the application of living organisms to control pests. Pathogens, parasitoids (insect parasites), and predators have been investigated in the context of stored product protection.

Since 1992, the addition of parasitoids and predators to stored raw commodities has been allowed under law (Anonymous 1992). The effectiveness has been studied for only a few of the 468 species of natural enemies of one or more of the 1,663 insect species associated with stored products (Hagstrum and Subramanyam 2009). There are many examples for successful biological control. For 19 species of stored product insect pests attacked by 13 species of natural enemies, 163 out of 212 estimates of pest mortality were between 70% and 100% (Hagstrum and Subramanyam 2006). For 87 of these estimates, insect pest mortality was between 90% and 100%.

Advantages of Biological Control

The use of insect parasitoids and predators to control stored product insect pests has many advantages over traditional chemical controls. These natural enemies leave no harmful chemical residues. When released in a storage facility, they continue to reproduce as long as hosts are available and environmental conditions are suitable. Unlike chemicals that need to be applied to a wide area, natural enemies can be released at a single location. They will actively spread, find, and attack pests located deep inside crevices or within a grain mass.

Parasitoids and predators that attack stored product pests are typically very small. They have a short life cycle and high reproductive capacity. They can easily be removed from bulk grain before milling using normal cleaning procedures. In many ways the stored product environment is favorable for biological control. Environmental conditions are generally favorable for natural enemies, and storage structures prevent these beneficial insects from leaving. It is likely that resistance to biological control agents will develop more slowly, or not at all, because the natural enemies are coevolving with their hosts and will tend to overcome host resistance. Insect pathogens are probably compatible with most beneficial insects and may even be spread by the activities of parasitic insects. The application of pathogens is similar to the use of residue-building insecticides. Usually, they can be stored longer than parasitoids.

Disadvantages of Biological Control

The main disadvantage of biological control is that it requires more information and careful timing compared to traditional chemical insecticides. Many beneficial insects are host-specific, which means that the right complex of parasitoids needs to be released to attack the pest insects in a particular bulk of grain. Timing of the release is also critical. For biological control to be practical, releases have to be made early enough in the pest growth cycle so that adult parasitoids outnumber the pests. If parasitoids are released too late, extremely high numbers of parasitoids will need to be released to control the pests. Unlike fumigants, beneficial insects cannot be used successfully if the manager waits until pest numbers have reached damaging levels.

Designing a biological control program for stored product insect pests requires careful planning. Many natural enemies are host-specific, so it is necessary to determine which pest species are causing the problem before releasing the appropriate parasitoid or predator species. Pathogen strains may differ significantly in their effectiveness, and pest resistance toward pathogens also may occur. A well-designed sampling program should indicate which pest species typically exceed economically damaging levels.

Parasitoids and predators can be stored and refrigerated for a short time — typically one week — and must be obtained directly from the producer as needed. In most states, little expertise and infrastructure exists to supply control agents or support the use of biological control of stored product pests. Seven species of parasitoids and predators are commercially available for stored product protection in the United States (Wilson et al. 1994; White and Johnson 2010).

Application Techniques

In stored product protection, generally the pest organisms have a high intrinsic rate of increase, and the pest population buildup has to be prevented. Inundative releases, using mass reared predators or parasitoids, have been used in the majority of cases. Inundative releases require mass-rearing facilities that can produce high-quality natural enemies. The timing of the releases has to be synchronized with the growth of the pest population. Monitoring with traps can help determine the best time to release mass-reared beneficial insects.

Generally, low numbers of insects initially infest commodities. Parasitoids or predators need to be released early before pests reach high numbers. Inundative releases are most effective when there are more parasitoids released than hosts, such as 2:1. If they are released too early, suitable host stages may not be available. Using wheat as an example, the first release of parasitoid insects should be made after about three weeks of storage (assuming the wheat was put into storage in the summer). Sequential releases can add additional insurance, but each additional release will add to the control cost. Sampling the grain at monthly intervals will indicate whether additional parasitoid releases are necessary. Each parasitoid can attack several host larvae each day (Flinn 1991, Smith 1992). For example, *C. waterstoni* can paralyze up to 14 rusty grain beetle larvae per day, and lay 2 to 3 eggs per day. Decision support software and population models can help to design specific release schedules.

Insect Pathogens

Many insect pathogens, including viruses, bacteria, protozoa, and fungi, infect stored product insects (Brower et al. 1996, Moore et al. 2000). Some of these organisms are highly pathogenic and kill the insect by rapid infection. Others, like the protozoa, adversely affect the development or fertility of the insect.

Bacteria

Dipel is a commercial formulation of the spore-forming bacteria, *Bacillus thuringiensis* (*Bt*). It contains an insecticidal protein that kills the insect either directly or by septicemia (blood poisoning) of the insect gut. It can be applied to grain either as a liquid or dust, as the grain is loaded into the bin. It can also be applied to the grain surface and raked into the grain to a depth of 4 inches. Current strains of *Bt* are only effective against moths and not beetles.

Good control was observed in laboratory studies, but moth control was not as consistent in full-sized grain bins (McGaughey 1976). Resistance also has been reported (McGaughey and Beeman 1985).

In most cases, the toxin of *Bt* has little or no side effects on parasitoids. Studying the effect of *Bt*-infected larvae of *E. kuehniella* on the biology of *V. canescens,* Kurstak (1966) found that parasitism was not affected. In addition, *V. canescens* was shown to be a vector for *Bt,* enhancing the spread of the disease in the moth population. Kurstak (1966) and Burkholder (1981) suggested that parasitoids could improve pest control by spreading pathogens.

Viruses

Many viruses have been reported for stored product insect pests. Most of these viruses attack moths, and a few have been reported for beetles. Viruses are generally species-specific. Viruses can only be produced on living hosts or on insect cell cultures. A granulosis virus was found to be effective against the Indianmeal moth. A formulation was patented (Vail et al. 1991) and was registered for control of Indianmeal moth larvae on dried fruit and nuts and for crack and crevice treatments in the United States in 2001. The formulation is not commercially available currently.

Fungi

Several fungi that attack stored product insects have been reported. The most notable is probably *Beauveria bassiana* (Ferron and Robert 1975, Hluchy and Samsinakova 1989). It was previously thought that one of the problems of using fungi for stored product pest control is the requirement of high humidity (greater than 90%) for germination of the infective stage. However, Lord (2005) showed increased mortality of *R. dominica* by *B. bassiana* under dry conditions (45% vs. 75% relative humidity (RH). Currently, there are no fungi registered for use on stored product insects in the United States.

Protozoa

Many species of protozoa naturally infect stored-product insects and often play a major role in regulating population growth. These organisims are usually transmitted orally. In contrast to the often lethal infections caused by viruses and fungi, protozoan infections are often chronic and cause a reduction in fecundity and survivorship. Currently, there are no protozoa registered for control of stored product insect pests in the United States.

Insect Parasitoids and Predators

Insect parasitoids and predators have been used to control pest insects for a long time. In 1911, parasitic wasps were discovered in a flour mill in London, and were reported to greatly suppress the Mediterranean flour moth population. Recently, the Federal Register (Anonymous 1992) published the rule that allows the release of parasitoids and predators into stored grain, stored legumes, and warehouses. The rule makes the use of beneficials subject to regulation by the Federal Insecticide Fungicide and Rodenticide Act (FIFRA) and exempt from the requirement of a tolerance in food products. The Food and Drug Administration (FDA) will continue to use its criteria for enforcement of insect fragments in food, and the Federal Grain Inspection Service (FGIS) is still responsible for inspecting and grading the grain.

Parasitoids are released either as adults from small plastic containers or emerge from pupae stuck to cardboard strips placed in the storage rooms. Shipment of the natural enemies has to be quick, and cooling agents have to be added in summer (Casada et al. 2008).

Moths

For the control of stored product moths, ideally an egg parasitoid should be combined with a larval parasitoid or a predator. The larval parasitoid *Habrobracon hebetor* (Figure 1) complements the egg parasitoids *Trichogramma* spp. because one attacks the larvae, the other the eggs (Grieshop et al. 2006). When *H. hebetor* and *Trichogramma pretiosum* were released in small peanut warehouses infested with Indianmeal moths and almond moths, *Cadra cautella* (Brower and Press 1990), Indianmeal moths were reduced by 37.3% by *T. pretiosum* alone, 66.1% by *H. hebetor* alone, and 84.3% by the combination. Insect feeding damage to the peanuts was reduced to less than 0.4% by the two parasitoids, compared to 15.8% in the untreated checks.

In the United States three different species of *Trichogramma* were evaluated for their potential to suppress *P. interpunctella* in a simulated retail environment (Grieshop et al. 2007). Percentage parasitism of eggs was four times greater for *T. deion* than for *T. ostriniae* or *T. pretiosum*. A central release point for *T. deion* in the shelving units provided the best protection.

In Central Europe, stored product moths are among the most important pests in stored grain, in the retail trade, mills, the food processing industry, and private households. Since 1995, parasitoids were evaluated in Germany in private households and in commercial food-processing facilities. The most important moth species were the Indianmeal moth, *P. interpunctella*, the Mediterranean flour moth, *E. kuehniella*, the warehouse moth, *E. elutella,* and the almond moth, *C. cautella*.

Trichogramma evanescens has been released in facilities ranging from private households to industrial bakeries and the wholesale trade, and combined with *H. hebetor* mostly in commercial facilities. The parasitoids are sold in units of 3,000 *T. evanescens* and 25 *H. hebetor*. The egg parasitoids emerge from the release cards for three weeks. For *T. evanescens*, the host eggs are sterilized before parasitization to prevent the emergence of stored product moths' larvae from unparasitized eggs in the storage environment.

For private households, releasing *T. evanescens* for 9 weeks is recommended. Three *Trichogramma*-cards have to be used per release point during this time. The number of *Trichogramma*-cards required depends on the surface area of the packages that contain products susceptible to attack by the moths. Generally, two *Trichogramma*-cards are necessary for a food cupboard.

A list of studies evaluating the application of parasitoids and predators attacking the Indianmeal moth is listed in Table 1.

Beetles

Beetles cause more damage than moths to stored grain. Although there are several beetle species that attack grain, there are only five species that are the major culprits (lesser grain borer, rusty grain beetle, red flour beetle, rice weevil, and sawtoothed grain beetle). Parasitic wasps that attack stored grain beetles tend to be host specific, but there are several species that will attack more than one beetle species. For example, *Theocolax elegans* (Figure 1) will attack all of the stored grain weevils and the lesser grain borer. This is also true of the parasitic wasps *Anisopteromalus calandre* (Figure 1) and *Lariophagus distinguendus* (Förster). Other wasps — such as *Cephalonomia waterstoni*, which attacks the rusty grain beetle — only attack a single species. These parasitoids are typically small (1 to 2 mm), and do not feed on the grain. They will normally die within 5 to 10 days if no beetles are present in the grain. These parasitoids are found naturally in the grain, which suggests that after they are released they may continue to suppress pests for many years (Arbogast and Mullen 1990). Because the adult wasps are external to the grain, they can be easily removed using normal grain-cleaning processes. Table 2 shows a list of studies evaluating the application of parasitoids that attack stored product beetles.

Anisopteromalus calandrae has been studied for biocontrol (Wen and Brower 1994a, Smith 1992). In simulated warehouse rooms that contained wheat debris with rice weevils, release of 30 to 50 pairs of *A. calandrae* reduced the weevil population by more than 90%, and release of only five pairs reduced the pest population by about 50% (Press et al. 1984). In a similar test with larger quantities of infested grain (18 lbs) and grain in small fabric bags, *A. calandrae* significantly suppressed the weevil population (Cline et al. 1985). Suppression of the rice

***Table** 1. Studies on biological control of the Indianmeal moth Plodia interpunctella.*

Antagonist	Effect	Product	Scale	Reference
Predator *Xylocoris flavipes*	71.4% reduction	Peanuts	Semi-field	Brower and Mullen 1990
Parasitoids *Habrobracon hebetor*	74% reduction of adult moths	Grain	Lab	Press et al. 1974
Trichogramma evanescens	80% reduction of trap captures	Bakery	Field	Prozell and Schöller 1998
Trichogramma evanescens *Habrobracon hebetor* and combinations	37.3% reduction in infestation 66.1% reduction in infestation 84.3% reduction in infestation	In-shell peanuts	Semi-field	Brower and Press 1990 Grieshop, et al. 2006

Table 2. *Studies on biological control of the maize weevil, Sitophilus zeamais, rice weevil; Sitophilus oryzae, rusty grain beetle; Cryptolestes ferrugineus; and the lesser grain borer, Rhyzopertha dominica.*

Species	Antagonist	Effect	Product	Scale	Reference
Maize weevil	Parasitoids *Anisopteromalus calandrae*	For long storage periods multiple releases necessary to suppress build up of weevil population	Maize	Field	Arbogast and Mullen 1990
	Theocolax elegans	Both single and multiple releases suppressed weevil population over 90%.	Maize	Field	Wen and Brower 1994a
		At a parasitoid:host ratio of 8:1 pest population growth was reduced by 50% (semi-field) and 25% (lab)	Maize	Lab. + Semi-field	Williams and Floyd 1971
Rice weevil	Parasitoid *Anisopteromalus calandrae*	Controlled weevils >99% for 4 months	Wheat residues bagged	Semi-field	Press and Mullen 1992
					Cline et al. 1985
Lesser grain borer	Parasitoids *Theocolax elegans*	Reduced populations in bins by 98%	Wheat	Field	Flinn et al. 1996
		Reduced number of insect damaged kernels by 92%, and insect fragments in flour by 89%	Grain	Field	Flinn and Hagstrum 2001
	Anisopteromalus calandrae	Parasitization rate highest at 30°C and lowest at 20°C. 69.5% parasitism at 26°C at a host parasitoid ratio of 10:1	Grain	Lab	Ahmed 1996
Rusty grain beetle	Parasitoid *Cephalonomia waterstoni*	Reduced population in bins by 50%	Wheat	Field	Flinn et al. 1996

Figure 1. *Anisopteromalus calandrae, Theocolax elegans, and Habrobracon hebetor, left middle and right, respectively.*

weevil was 76% in the loose grain, and uninfested grain in fabric bags was almost completely protected. *Lariophagus distinguendus* has been shown to disperse at least 4 m horizontally and vertically in bulk grain (Steidle and Schöller 2001).

There are two species of parasitoid wasps that attack the maize weevil and lesser grain borer (*A. calandrae* and *Theocolax elegans*). These same species will also attack the granary weevil and rice weevil. Because these two species attack the same host stages (fourth instar and early pupa), it probably is not advantageous to release both species. Only one species of wasp, *Cephalonomia waterstoni*, attacks the rusty grain beetle. This species is host-specific and is able to use chemical odors from the cuticle of rusty grain beetle larvae to locate their hosts.

Commercial tests

A study by Flinn et al. (1996) showed that releasing parasitoid wasps into bins of stored wheat reduced populations of the lesser grain borer by more than 95%. Data from this study (Flinn and Hagstrum 2001) also indicates that insect fragments were greatly reduced in grain treated with parasitoid wasps. Most insect fragments in flour probably come from beetle larvae that are developing within the grain kernels. There is also potential for using biological control in the food processing industry in the United States. Moths and beetles cause millions of dollars of losses annually in packaged products. There are several species of parasitic wasps that attack all of the common stored product insect pests. Parasitoid wasps could be released to prevent serious outbreaks. However, releasing live insects into areas where food is prepared for final packaging would probably not be prudent. This is an area in which more research is needed in the United States.

For moth control, industrial applications have to be performed by specialized pest control personnel, because the period of treatment and the timing of the releases as well as the species of parasitoid depend on several factors, including the moth species. Hygiene measures at critical points in the plant have to be combined with the parasitoid release, and the compatibility of other nonbiological control measures has to be checked. For the retail trade in Germany, mainly *Trichogramma evanescens* has been released. In milling areas, bag stacks, and bulk storage, *Habrobracon hebetor* was also used. Again, the number of parasitoids to be released depends on the surface area of the commodities. In addition, data from pheromone-trap catches are used to detect moths. In Germany, *Trichogramma evanescens* were released in grocery stores to protect packaged food from infestation by moths. The moths lay eggs on the outside of packages, where they are susceptible to parasitoid attack. The moth infestation can occur at any step in the production chain. Some products are already infested when they enter grocery stores. Retailers evaluated the the biological control program's success based on the number of customer complaints due to moth infestation and the number of infested packages in the stores.

Usually, the number of parasitoids is high, but the biomass is not. For example, in a factory producing 1.5 tons of bread and breakfast cereals per year, 3 million parasitoids were released per year, with a cumulative dry weight of 6g (Prozell and Schöller 1998). In Germany, parasitoids of stored product pests have been available commercially since 1998. In Germany, Austria, and Switzerland approximately 900 million *T. evanescens* were sold to control stored product moths in 2010. The demand for *Trichogramma* can be expected almost year-round because some populations of stored product moths do not enter diapause. The species of greatest economic importance, *P. interpunctella*, enters diapause, usually from November to April.

Predators

Insect predators are different from insect parasitoids in a number of ways. A predator requires many prey during development; a parasitoid completes development on only one host. Predators also tend to be less host-specific than parasitoids. There are probably many species of predators that attack stored product insects, but most of them remain unstudied, with the exception of the warehouse pirate bug, *Xylocoris flavipes*.

Warehouse pirate bug – The warehouse pirate bug will attack most immature stages of beetles and moths (Jay et al. 1968). The smaller species of beetles appear to be the preferred prey, but eggs and early larvae of most species are utilized as well. The internal grain feeders, such as the weevils and lesser grain borer, are not attacked because they are protected inside the grain kernel.

Red flour beetles were suppressed by warehouse pirate bugs in a simulated warehouse (Press et al. 1975). LeCato et al. (1977) showed that populations of the almond moth and of two beetle species did not increase in a room containing grain debris when warehouse pirate bugs were released in small numbers. All three pest populations increased greatly in the room when no predators were released. Brower and Mullen (1990) released large numbers of the warehouse pirate bug into small peanut warehouses infested with almond moths and Indianmeal moths. Moth populations were suppressed 70% to 80% during the fall storage season, and no moths were present in the biocontrol treatments during the spring.

Integration

There are many integrated pest management (IPM) examples in the literature where the combination of biological and nonbiological control methods is possible. The most promising are sanitation, modified atmospheres, modification of the storage environment (temperature), and the combination of certain species of beneficial insects and some natural insecticides. On the other hand, there are at least as many examples where integration is detrimental. Insecticidal protectants will probably not be compatible with parasitoids because beneficial insects are typically more susceptible to insecticides than their hosts. In some cases, however, parasitoids may be more resistant than their hosts (Baker and Weaver 1993). Protectants are applied at binning, which precludes releasing parasitoids at this time, and they typically last for several months. In stored grain, parasitoids could be released after the protectant had degraded to a low level. In temperate and continental climates, fall aeration would probably work as well or better to suppress pest insect population growth. Releases could be made after fumigation, if sufficient time was allowed for the fumigant to dissipate (1 to 2 weeks). Many species of parasitoids and predators are able to overwinter in the grain (Hansen and Skovgård 2010), and thus, would provide additional protection when the grain warms in the spring. This protection may carry through the marketing system.

Because natural enemies were shown to be most effective at low pest densities (Smith 1994, Zdárková 1996), the development of proper sanitation programs is a prerequisite for the application of beneficial insects. Environmental conditions should also be controlled or altered to promote growth of the beneficial insects (Haines 1984). Figure 2 shows the life cycles for two stored product insect pests and their parasitoids (sawtoothed grain beetle/ *C. tarsalis* and Indianmeal moth/*H. hebetor*). In both of these parasitoid species, the female wasp attacks the larval stage just before pupation. At 30°C, it takes about 15 days for the wasps to complete their life cycle. At 25°C, it would take almost 30 days to complete.

An example of a perfectly compatible physical control method for biological control in wheat is

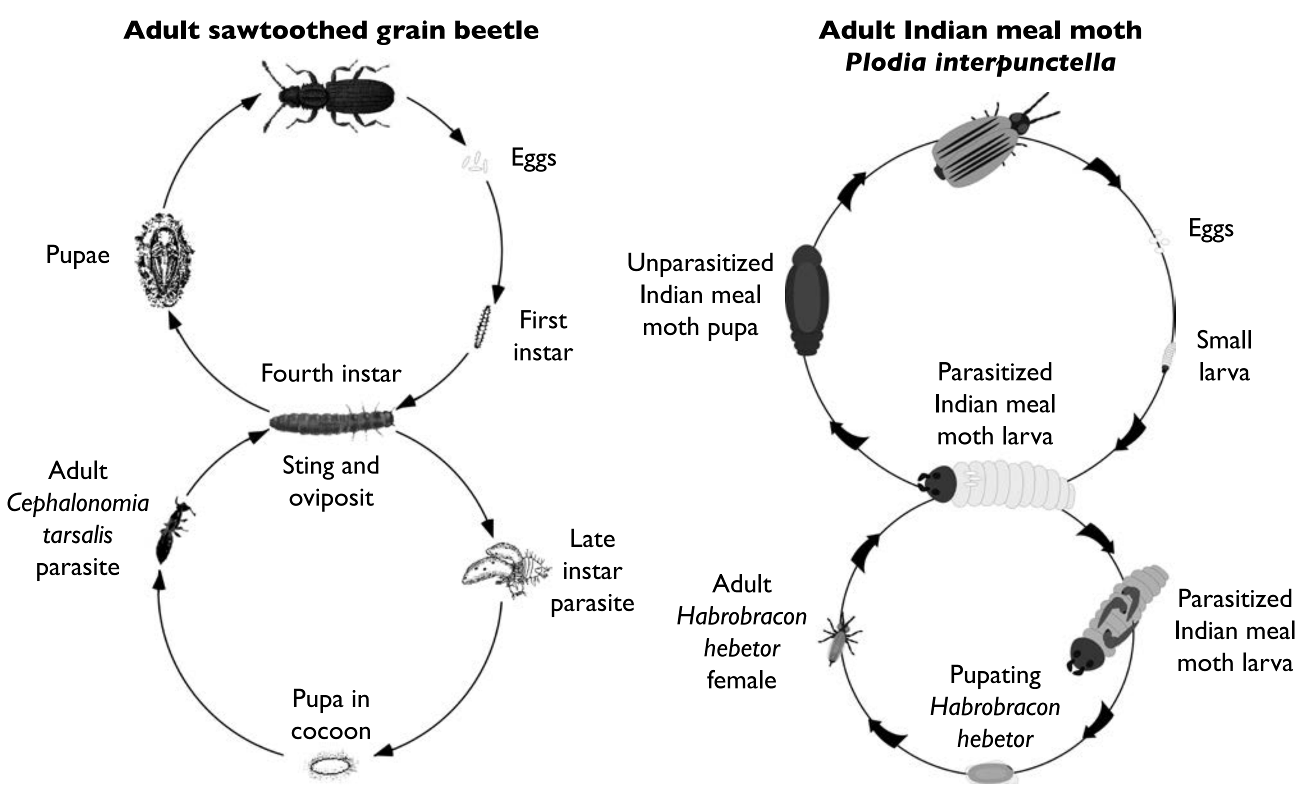

Figure 2. *Life cycle of Cephalonomia tarsalis parasitizing the sawtoothed grain beetle (left) and Habrobracon hebetor parasitizing the Indianmeal moth (right).*

cooling the grain with aeration. Parasitoids should be released in the grain about three weeks after binning. Aeration would start immediately using automatic aeration controllers. Aeration, using electric powered fans, can be used to cool the grain earlier; thus, it suppresses insect population growth sooner in the storage period (Flinn et al. 1997). In the United States, this would cool the wheat from an average of 32°C down to 25°C. The parasitoids would inhibit beetle populations from exceeding economically damaging levels during the warm summer months, until further aeration could be used to cool the grain below 15°C, which would completely inhibit insect population growth. Flinn (1998) conducted studies to assess the effectiveness of *T. elegans* for controlling the lesser grain borer in wheat at 32°C and 25°C. The two temperature regimes were used to simulate an unaerated bin of wheat and a bin with automatic aeration control starting at harvest. Suppression of the lesser grain borer population growth by *T. elegans* was 10 times greater at 25°C than at 32°C. This resulted in a very high level of population suppression; 99% in the cooled grain compared to only 50% in the warm grain.

Economics of biological control

In Germany, the cost for a treatment with *T. evanescens* in households is usually $19.75. In the United States, at least six suppliers have sold *H. hebetor* (Wilson et al. 1994). One release unit containing 50 adults sold for $6.50. In Germany, parasitoids could be released in 3,000 ton grain storage infested with *E. elutella* for $0.14/ton to $0.57, depending on the level of infestation (Schöller 2000). The costs of biological control for bulk-stored grain may be slightly higher than that for traditional chemical controls. Chemical protectants cost about $0.02 per bushel and biological control using predators and parasitoids is about $0.04 bushel (M. Maedgen, Biofac Inc., personal communication). The application of *Lariophagus distinguendus* to prevent infestation of *Sitophilus* sp. and *Rhyzopertha dominica* in bulk grain costs (2010) $0.93/ton in Germany (Schöller, unpublished). Currently in the United States, predators and parasitoids are not commonly used to control insect pests in stored grain. Although parasitoids and predators of stored product insects have been marketed in the United States, there are only a few companies that rear parasitoid species that specifically attack stored grain beetles. Probably the majority of the early adopters of stored product biological control are in the organic foods business. As more grain managers decide to try biological control, the number of companies offering beneficial insects for stored products will probably increase.

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S156 – 17 September 2012

18 Insect Pest Management for Raw Commodities During Storage

David W. Hagstrum
Paul W. Flinn

The tools for making insect pest management decisions have been discussed by Hagstrum and Subramanyam (2000, 2006). These tools include sampling information, cost-benefit analysis, expert systems, consultants, and the predictions of computer simulation models. Sampling to estimate current insect distribution and abundance and using computer simulation models to predict the distribution and abundance of future insect populations can increase the cost-effectiveness of pest management. Sampling methods and computer simulation models have been developed for the primary insect pests of stored wheat: the lesser grain borer, *Rhyzopertha dominica* (F.); the rusty grain beetle, *Cryptoletes ferrugineus* (Stephens); the rice weevil, *Sitophilus oryzae* (L.); the red flour beetle, *Tribolium castaneum* (Herbst) and the sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.).

Decision support systems can be used to find the best pest management solutions. Consultants can optimize the use of simple pest management methods and may be particularly important in using more complex pest management methods. Cost-benefit analysis can minimize both the risk of economic loss and the overall cost of insect pest management.

Pest Management Method

Understanding the general characteristics of some commonly used insect pest management methods can be helpful in deciding which method to use (Hagstrum and Subramanyam 2006). Residual insecticides and insect resistant packaging can provide long-term protection. Biological control, fumigation, and heat treatments can penetrate areas where insects are concealed. Aeration, heat treatments, ionizing radiation, impact mortality, and pest removal may require long-term planning because they require expensive equipment and increase operating costs. By reducing the number of insect hiding places and the level of insect infestation, sanitation and pest exclusion can increase the effectiveness of aeration, biological control, fumigation, heat treatments, insect-resistant packaging, and residual insecticides.

In addition to selecting an appropriate insect pest management method, decisions also need to be made about how the method will be used. For example, maintaining a lethal fumigant concentration is most difficult near the grain surface where insect densities are highest (Figure 1). The difference between grain temperature and outside air temperature can determine the most effective method of applying fumigant (Reed 2006, Flinn et al. 2007b). At elevators, fumigant is typically applied to grain as it is moved from one bin to another. When grain and air temperature are similar, distributing fumigant pellets evenly throughout the full depth of grain is best. When grain is warmer than the outside air temperature, air currents will move fumigant gas generated by pellets located near the bottom of the bin toward the surface. Applying fumigant pellets to the bottom half of grain may be better in this case.

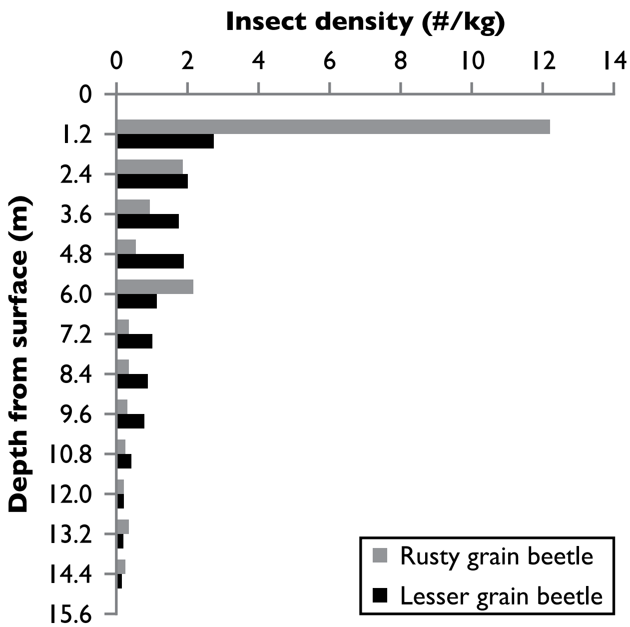

Figure 1. *Depth distribution of insects in grain bins at elevators.*

Sampling

Researchers, consultants, and managers must decide which sampling device to use, the size, location, and number of samples to take, and the time and frequency of sampling (Hagstrum and Subramanyam 2000, 2006). Sampling is used to make inferences about the distribution and abundance of an insect pest population from a small number of representative samples. Sampling is essential to determining whether and where pest management is needed and whether pest management was successful. Cost-benefit analysis can be used to justify the cost of a sampling program by the potential losses likely when the insect pests are not controlled.

Sampling provides information on which insect pests are present as well as their distribution and abundance. This information is important in deciding which insect pest management method to use, because the effectiveness of pest management methods often differs between insect species. Information on insect distribution often differs among insect species and densities. For example, on farms (Hagstrum 1989) and at elevators (Flinn et al. 2004) some bins are heavily infested and need pest management, while others do not. Also, insect densities vary between locations within a bin (Figure 1).

Sampling Device

There are many types of equipment for sampling stored-product insects. The pelican sampler is frequently used to sample moving streams of grain when unloading trucks and when loading railcars, barges, or ships (Parker et al. 1982). The Ellis cup is used to sample grain moving on belts in grain elevators. The grain trier is used to sample nonmoving grain in farm bins and railcars. Grain triers are normally about 5 to 6 feet in length and have an inner cylinder that rotates within an outer cylinder. The trier is pushed into the grain with the inner cylinder twisted so that the compartments are closed. The operator twists the handle to allow the grain to enter the compartments and then closes the compartments again before removing the trier from the grain.

A vacuum probe system can be used to take grain samples in elevator bins as deep as 100 feet in the grain mass (Figure 2). An electric or gasoline powered vacuum pump pulls the grain through sections of metal tubing to a cyclone unit where samples as large as 3 kilograms can be collected. To separate insects from the grain in these samples, it is necessary to use a sieve. An inclined sieve is best for large grain samples. The previous four sampling methods were all absolute sampling methods because insect density can be calculated for a known amount of grain.

Figure 2. *A vacuum probe system can be used to sample grain in elevator bins and an inclined sieve can be used to separate insects from large grain samples.*

Insect traps are sampling devices that can detect low-density populations. Insects move around a lot. Over time, traps catch insects from a large area. Commodity samples, on the other hand, find only the insects present in a sample when the sample is taken. Most traps provide relative estimates of insect densities. Trap catch is influenced by temperature, residual food, air movement, and insect species. It may be helpful to convert trap catch to absolute density estimates when making insect pest management decisions. Converting trap catch to absolute densities has been studied on farm (Hagstrum et al. 1998) and at elevators (Toews et al. 2005). The probe trap (Figure 3) is pushed below the grain surface and left in place for three to five days. The trap is then pulled out of the grain, and insects in the tip of the trap are counted.

Figure 3. *The probe trap is typically used in farm grain bins to detect insects.*

Traps also can be used with pheromone lures to attract insects. The dome trap (Figure 4) is often used to monitor for flour beetles in warehouses and flour mills. A small amount of wheat germ oil can be placed in the bottom of the trap to help attract insects and to keep them in the trap.

Figure 4. *Trap for monitoring insects on mill or warehouse floors.*

Size, Location and Number of Samples

Taking many small samples provides a more representative sample than taking a few large samples and reduces the time required to remove the insects from each sample. Checking traps more frequently reduces the sample size, i.e., trapping for two days provides a larger sample than trapping for one day. Although many statistical analyses assume random sampling, it may be more important to take a representative sample than a random sample. To obtain a representative sample, commodities or facilities must be sampled so that areas that are likely to have different insect densities are sampled in proportion to their prevalence. On farm (Hagstrum 1989) and at elevators (Flinn et al. 2004), insects often infest wheat after it is stored, and their numbers decrease with the distance below the surface (Figure 1). When insect density decreases with depth in the grain, taking samples from each depth can provide a representative sample.

Any one sample is likely to under- or over-estimate average insect density. The number of samples taken should be sufficient to find insects before insect infestations reach economically damaging levels. The number of samples taken will be a compromise between the number providing reliable information on insect density and the number that a manager can afford. Five or 10 kilograms of grain per 1,000 bushels is generally enough to be confident that insect infestations are not above acceptable levels (Tables 1 and 2).

Table 1. *Probability of insect detection in stored wheat.*

Number of 0.5-kg samples	Mean number of insects per kg of wheat					
	0.02	0.06	0.2	0.6	2.0	6.0
1	0.02	0.06	0.19	0.43	0.76	0.95
2	0.04	0.12	0.34	0.67	0.94	1.00
5	0.10	0.28	0.64	0.94	0.99	1.00
10	0.19	0.48	0.87	1.00	1.00	1.00
25	0.42	0.80	0.99	1.00	1.00	1.00
100	0.89	1.00	1.00	1.00	1.00	1.00

Table 2. *Confidence intervals (95%) for estimation of insect density.*

Number of 0.5-kg samples	Mean number of insects per kg of wheat					
	0.02	0.06	0.2	0.6	2.0	6.0
1	±0.07	±0.15	±0.33	±0.67	±1.49	±3.07
2	±0.05	±0.10	±0.23	±0.47	±1.05	±2.17
5	±0.03	±0.07	±0.15	±0.30	±0.66	±1.37
10	±0.02	±0.04	±0.10	±0.21	±0.47	±0.97
25	±0.01	±0.03	±0.07	±0.13	±0.30	±0.61
100	±0.01	±0.01	±0.03	±0.07	±0.15	±0.31

Classifying insect populations as above or below levels causing economic losses generally requires fewer samples than estimating insect density. The number of samples needed to make a decision is greater when the actual insect density is close to threshold levels at which insect pest management is required. After a manager has taken enough sample units to determine that insect densities do not greatly exceed this threshold, the manager should sample again after a month.

Time and Frequency of Sampling

When large amounts of raw commodities are stored, detecting the very low numbers of insects initially infesting the commodity can be difficult. Insects often increase 10-fold each generation (about 30 days at 30°C) and are easier to find a month or two after the commodity is stored. With inaccurate estimates, sampling needs to be done more frequently to ensure that insect populations do not reach unacceptable levels before sampling again. Taking more samples to reduce the risk of not discovering an insect problem may be more efficient than sampling more frequently. The time required to reach and enter a facility with sampling equipment is the same regardless of how many samples are taken. Models predicting insect population growth rate can be used to determine when to sample. Choosing the best time to sample minimizes the number of times that sampling is necessary, the cost of sampling, and the risk of not discovering an insect problem. Automation shifts the cost of sampling from labor to equipment and can provide more accurate and up-to-date information (Hagstrum et al. 1996).

Predictive Models

Insect pest population growth rates are an important consideration in pest management programs. Because stored-product insects can increase 10-fold per generation, pest populations can return to pre-control levels as soon as one generation after 90% control. Grain temperature and moisture content are the most important environmental factors influencing insect pest population growth. Insect development and reproduction are directly related to ambient temperature because they cannot regulate their body temperature. Predictive models can be useful to grain managers because they can be used to determine how soon pest management will be needed.

Predicted population growth is affected greatly by initial grain temperature and moisture (Figure 5).

Optimal grain temperature and moisture allow insects to reproduce and grow at their maximum rates. Even under the same environmental conditions, different species of stored grain insects increase at different rates (Hagstrum and Flinn 1990). In stored wheat in Kansas and Oklahoma, the rusty grain beetle is typically the predominant species, followed by the lesser grain borer, and the red flour beetle. The lesser grain borer increases more slowly than the other species; however, many ecological factors can affect insect populations, such as immigration rate and natural enemies. Many industry practices also affect insect ecology, and Hagstrum et al. (2010) discuss how some of these practices can be beneficial to insect pest management.

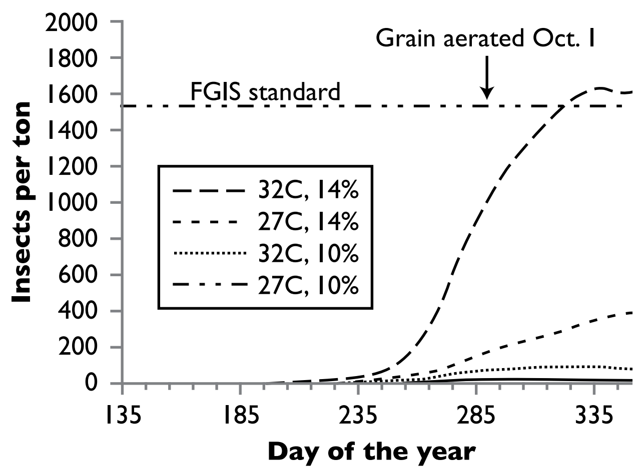

Figure 5. *Predicted population growth of Rhyzopertha dominica at two temperatures and two grain moistures. Source: Flinn and Hagstrum 1990a.*

Models have been used to predict the effects of aeration, fumigation, and grain protectants on five insect species. A one-month delay in harvest due to storing grain later at higher latitudes can reduce insect populations by roughly five- to 25-times. Delaying fumigation reduces the time available for populations to grow before the grain is cooled by aeration or winter temperatures. Populations are five- to 25-times larger for every month that cooling by aeration is delayed. Beneficial insect models have been used to predict when and how many parasitoids to release (Flinn and Hagstrum 1995). Models also have been used to predict the impact of seed resistance, damage caused by insects, insect dispersal, development of pesticide resistance, and seasonal population growth of insect pests as grain moves through the marketing system (Hagstrum and Subramanyam 2006).

Insect pest management programs are likely to be unique for each location in the marketing system, and their cost and appropriateness may need to be reevaluated each time that insect pest management is needed. Decision support software can be used to select the best time and method for insect pest management (Stored Grain Advisor for farms, Flinn and Hagstrum 1990b, and Stored Grain Advisor Pro for elevators, Flinn et al. 2007a, http://ars.usda.gov/npa/gmprc/bru/sga).

Monitoring-Based Pest Management

Pest management methods such as fumigation are generally used on a calendar schedule. When low densities of insects can be tolerated, these pest management methods could be used only when the cost of insect damage is likely to exceed the cost of pest management. Such cost-benefit analysis may be necessary to comply with new regulations and to slow the rate at which insects are becoming resistant to pesticides. This integrated pest management (IPM) approach was developed for field crops when insecticides would no longer control insect pests. Pests were becoming resistant to the insecticides and pest populations were resurging because the insecticides were killing their natural enemies.

Sampling at elevators has shown that usually only a few bins have insect densities that justify fumigation (Table 3). Treating only the bins that require fumigation could reduce the cost of pest management. For example, fumigating all 30 of the bins at an elevator storing 700,000 bushels of wheat could cost $14,000. If the elevator manager knows that only three of these bins have high insect densities, fumigating only these three bins would cost only $1,400 and the cost of pest management would be reduced by $12,600.

Table 3. *Number of bins at each grain elevator in which wheat required fumigation.*

Number out of 100 Bins	Frequency (%)
0-10	71
11-20	12
21-40	13
41-60	4
>60	0

Follow-Up Sampling

Pest management generally does not completely eliminate insect pest populations (Hagstrum and Subramanyam 2006) and follow-up sampling to establish the effectiveness of pest management can be important in determining whether additional pest management is needed. Also, this sampling information may allow insect pest management to be done more effectively the next time.

Expert System and Consultant

In the United States over a two-year period, wheat at 28 elevators was sampled for insect infestations, and an expert system was used to predict which bins needed to be fumigated (Flinn et al. 2003). Data collected with a vacuum probe from the top 40 feet of grain was highly correlated with grain samples taken as the bin was unloaded (r^2=0.79). Also, 96% of the rusty grain beetles and 94% of the lesser grain borers were found in the top 40 feet (Figure 1). Thus, the vacuum probe provided a convenient and reliable method of routinely monitoring grain for insects without having to move the grain.

Out of 533 bins, the need for insect pest management was incorrectly predicted in two cases, and in both cases, insect density was only high at the surface, which suggested recent immigration into the wheat stored in these bins. Treating bins only when insect densities exceed economic thresholds and treating only those bins that need to be treated minimizes the risk of economic losses from unexpected insect problems, the cost of insect pest management, and the use of fumigant.

Fumigations are often not 100 percent effective in eliminating insect populations, and insect populations often recover. Fumigation can be ineffective because insect densities are highest near the surface (Figure 1) where retention of the fumigant is most difficult. Fumigating a few bins early and delaying the fumigation of the other bins may eliminate the need for a second fumigation of those other bins because grain cooling in the fall can prevent insects from recovering after an autumn fumigation. Thus, risk analysis software can improve pest management by predicting when insect pest populations will reach economic injury levels and reducing the frequency of fumigation.

Using this sampling program and decision support software, a private consulting company has provided scouting services to more than 70 elevators in Kansas, Oklahoma, and Nebraska during the past eight years (Flinn et al. 2007a). Scouting may have helped to reduce the average incidence of insect damaged kernels by as much as 24%. The average number of insect damaged kernels was 2.5 per 100 grams of wheat during the first year of scouting and 1.9 per 100 grams of wheat during the second year. Managers have used grain quality information from the scouting reports to better market their grain.

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S156 – 18 September 2012

19 Insect Pest Management Decisions in Food Processing Facilities

James F. Campbell
Joel Perez-Mendoza
Jeff Weier

Pest management in food processing facilities, such as flour mills, rice mills, human and pet food manufacturing facilities, distribution centers, warehouses, and retail stores, requires specific knowlege and skills. To be successful a pest manager should understand food facility structure and operations; taxonomy, behavior, ecology, and biology of pest species; and effective use of monitoring and management tools. Implementation of a pest management program requires cooperation between those who work for the food processing company and those who work for the pest management contractor. The two groups must work together to make decisions about the system as a whole, how to deal with issues before they become major problems, and how to allocate resources effectively.

The food industry has been moving away from structural fumigations and calendar-based chemical pesticide applications toward integrated pest management (IPM). This shift has been driven by the loss of products such as methyl bromide, demand for reduced pesticide usage, and targeted use of reduced risk products. Pest management and food safety practices must withstand increasingly intense scrutiny of external inspections and audits. These trends underscore the need for improvements in the pest management decision-making process in the food industry.

Traditional IPM programs, which are based on the concept of letting pest populations build to a certain point before treatment is economically justified (economic threshold), do not apply in the food industry. IPM programs must focus on prevention, detection, and early elimination of problems. Food industry IPM goals are to prevent insects from entering the facility and to keep populations from increasing or becoming established in the production stream. Where prevention has been unsuccessful, the aim is to suppress insects and monitor the environment. Monitoring is an overarching component because it can be used to evaluate prevention program effectiveness and guide application of suppression tactics.

In most food facilities the goal is zero insect activity. This is seldom possible because insect management is a continuous process of responding to changing conditions and problems. Although an economic or action threshold of one insect for an entire facility is seldom feasible, effective thresholds are needed. Thresholds should be adjustable, targeted, and serve as upper boundaries to indicate a successful program. Management programs should aim to keep insects from reaching threshold levels and triggering a response when limits are exceeded.

Food facilities typically are large, complex structures with many locations vulnerable to insect infestation. They differ from each other in function (food processing, mill, warehouse), commodities (wheat, rice, animal-based materials, spices), product produced (flour, whole grain, human food or pet food products), equipment, structure type (old versus new, construction material), geographic location, surrounding landscape, among other factors. This makes generalizations about pest management difficult. Facility conditions can change over time because of seasonal fluctuations, changes in physical structure and management, and other variables. The pest situation must be characterized for a given location, and an IPM program should be tailored to a specific location and flexible enough to deal with changing conditions. A rigid or standard approach to pest management is rarely successful. Although pest management is part of a food facility's prerequisite program, in many cases it can be implemented more effectively. Specific tools for monitoring and pest suppression have been presented in other chapters. This chapter will focus on the philosophy and strategies for using these tools to make pest management decisions.

Inspection

An inspection should focus on identifying the location and nature of current pest issues and on noting vulnerable areas of the facility with potential to generate pest issues. It is a physical review of a facility, both inside and out, to assess conditions at a given time and their potential to affect the food manufacturing process (AIB International 2010). Inspection also assesses operational methods and personnel practices, equipment maintenance, condition of grounds and structures, and cleaning practices that affect pest management program success. Technical information on the inspection process and types of corrective actions is provided in Chapter 8.

An inspection is the first step in implementing an integrated pest management program. Regular inspections going forward can be used to evaluate program effectiveness. The goal of the initial inspection is to identify the location and nature of current pest problems and pinpoint locations with potential for pest issues. From this, a prioritized list of issues can be developed with both short-term (immediate issue corrected) and long-term (steps to reduce or eliminate the probability of the problem reoccurring) corrective actions (Osterberg 2006, St. Cyr 2006).

Inspection is a fundamental part of a pest management program, but there are limitations. A thorough inspection requires a highly skilled person. It is hard, dirty work and requires access to areas that can disrupt production. Labor and time can limit how frequently and thoroughly inspections can be performed. Quantifying and evaluating trends in insect activity based on inspection reports can be difficult because of variation in how inspections are performed and data recorded, and limited frequency. Inspections function as periodic benchmarks of program success. They identify problems that need correction, but other monitoring methods can be more useful for trend analysis. Inspections, even thorough ones, can miss early stage infestations or those in inaccessible locations. Previous experience with a particular type of facility can help predict where inspections should be focused, but preconceived ideas of where insects are likely to be found can be wrong. Insect distribution within a facility can change over time. Problems can develop in unlikely areas (Campbell et al. 2002, Semeao et al. 2012). It is useful to supplement inspection results with other sources of information.

Exterior inspection

Because the primary goal of a pest management program is prevention, inspection should start outside the building. The goal is to identify locations with insect activity, resources near structures that can attract or be exploited by insects, and potential pest entry routes into a facility. Studies have shown high levels of stored-product insect flight activity outside food-processing and grain-storage facilities, which can represent considerable invasion pressure (Campbell 2006). Many stored-product insects are strong flyers that can easily traverse a food facility site (Campbell and Mullen 2004) and enter buildings (Campbell and Arbogast 2004, Toews et al. 2006). The purpose of exterior pest management is to make a food facility site less attractive and to make it more difficult for insects to enter buildings where food is processed and stored.

The exterior environment can be thought of as two zones — onsite and offsite — with varying potential for contributing to pest problems. Onsite includes the external environment that can be monitored and managed directly. It includes features within the property lines that might support or attract insects. For stored-product insects, these include spills that attract insects or provide reproduction sites, such as bulk storage, trash piles, or containers. The offsite zone includes landscape surrounding the facility that is within pest dispersal distance. Given the mobility of many stored-product insect species, movement from the surrounding area to a facility can occur. Offsite sources within a half mile of a food facility would be well within the dispersal range of many flying stored-product pests, and sources farther away are potential candidates. For example, lesser grain borer adults were captured 1 km (0.6 miles) away from where they were released within one day

(Campbell et al. 2006). Identifying potential offsite sources can help guide outdoor monitoring programs and assess risk level.

When thinking about inspecting the exterior environment and preventing insects from entering a food facility, keep in mind that there are a wide range of insect species occurring outside. They vary in likelihood of entering a food facility and which exterior features are attractive to them. Most species that enter are incidental species rather than stored-product pests because they are not attracted to the food being processed and do not reproduce within the food. To visualize this abundance think of the variety of insects that can be seen around a porch light at night. These species present low risk in terms of product infestation or establishment inside a food facility but are of concern because their presence inside could lead to food contamination and adulteration. Observation of them on inbound or outbound products could lead to shipment rejection or treatment, and they indicate inadequate building sealing.

Understanding features of the environment that favor specific groups of insects can be useful in making management decisions. The type of insects found inside indicate what to look for during external inspection. If incidental species are found around doors and windows, inspection should focus on features that attract them (lights, standing water, vegetation, garbage, food spillage) and the identification of entry routes (lights over doors, interior lighting, gaps around doors and windows, and open doors). Some species are not typically pests of structures or food but enter in the fall in search of overwintering sites, for example, Asian lady beetles and boxelder bugs. These species are likely to respond to building color, shape, and temperature, not necessarily lighting or other factors. Moist environments and decaying organic material near facilities can encourage springtails, sap beetles, fungus beetles, and some fly species that move into buildings.

Stored-product insects are less likely to be attracted to the same features of the landscape as incidentals. They are more likely to respond to food odors associated with external spillage of whole grain or processed materials, bulk stored grain, blown out material, and exhaust vents. Linking the biology of insect species captured indoors with attractive features of the external environment can help to target inspections and prioritize exterior features for improvement.

Food accumulations outside are the most obvious reason for stored-product insect activity. Although grain spillage in elevators has been shown to have a diverse community of stored-product pest species associated with it (Arthur et al. 2006), much less is known about the role of exterior spillage accumulations in maintaining or increasing stored-product insect populations. This role likely depends on how quickly degradation by environmental factors such as rain reduces the quality of the resource.

Even without reproduction occurring in them, spillage accumulations are problematic because they can attract stored-product insects that use them as stepping-stones to move into a facility. They can also attract birds or rodents. Semeao (2011) found that capture of walking stored-product insects outside of food processing facilities was not strongly associated with spillage piles, but in some cases fungal-feeding species were more likely to be associated with these outside spillage accumulations. The fact that these same fungal-feeding species are often captured inside relatively dry environments such as flour mills suggests that accumulations may serve as a source of these types of insects. Although cleaning spillage is important for a variety of reasons, the relative importance of different types of food accumulations as stored-product insect reproduction sites needs further evaluation.

Response to an inspection reporting spillage accumulation might include several steps: 1) take samples of food material and inspect for insect activity or place traps in area to capture walking insects; 2) implement short-term response of cleaning or insecticide treatments (if insect activity warrants); and (3) implement long-term solutions such as regular cleaning, structural modifications to eliminate or reduce accumulations, or modifications such as paving to make spillage easier to clean and less favorable for insect development.

Inspection of the building exterior should focus on features that may be attracting insects and enabling them to enter. These may involve building features (lighting placement, location of doors and windows, wall construction), structural defects (cracks or holes in walls or screens), or employee practices (open doors or windows, materials stored adjacent to building, poor sanitation). The roof is an area that is easy to overlook but needs attention because of numerous entry routes such as passive vents, air intakes, and poor membrane seals. Spillage accumulations can occur on roofs due to location of exhaust points, and insect pests can fly and walk up to these roof areas.

Most stored-product insect species are small enough to move through narrow gaps, so it is not possible to make a building insect proof. Inspectors should evaluate tactics used to prevent entry around identified access points, such as screening, gaskets and seals, air curtains, and door-opening policies. The effectiveness of these tactics can be assessed by monitoring insect activity in these areas. Glue boards or screening coated with the material used in sticky traps and placed around suspected entry routes can be used to determine if the routes are being used by insects (Toews et al. 2006).

Interior inspection

Interior inspection follows the same general principles as external inspection. The initial inspection identifies problems and evaluates the effectiveness of management practices. Regular inspections provide feedback on program success and identify issues as they develop. The components of an inspection program specific to stored-product insect management are the identification of structural features and activities that enable insects to enter a building, those that provide resources that can be exploited, and identification of locations with current insect activity. Inspection programs can reveal a long list of issues that need to be addressed. The challenge becomes how to prioritize issues because time, labor, and money to deal with all issues immediately typically is not available.

The nature of the problem determines priority. Actual signs of insect infestation should be high priority for short-term responses. The species detected, numbers, and developmental stages (adults versus immature stages) and whether activity is in a critical area, should be considered in making decisions on the timing of the response Prioritizing and implementing both short- and long-term solutions to items identified in an inspection program can facilitate an orderly response to pest management.

In evaluating locations where insects might occur, it is important to consider the biology of the important pest species likely to be found in the particular type of facility or those that have been an issue in the past and resources they will exploit. Inspection programs for stored-product insects established within a food facility should focus on bulk or packaged raw ingredients, processing equipment, building structure, and bulk or packaged finished product.

Insect activity in these areas may be connected but vary in product infestation risk and management tools available. For example, some locations are not accessible while the facility is operational, and some insecticides cannot be applied to food handling surfaces or finished product. Areas within a facility can harbor different pest species, and pests can vary in the likelihood of moving from one area to another. For example, species that feed primarily on whole grains may be found near bulk storage areas for raw grain and near grain cleaning areas, but often do not move into food processing areas. Other species may be present within a building structure, but are rarely found associated with the finished product. For example, Indianmeal moth and almond moth can be observed inside mills but are seldom found infesting processing equipment.

Determine Pest Critical Control Points

Hazard Analysis Critical Control Point (HACCP) and other standards are used to identify potential food safety hazards and implement procedures to reduce or eliminate hazards before they occur. As part of this process, critical control points are identified where physical, chemical, or biological hazards to food safety can be targeted in the most effective manner. HACCP is ultimately part of a multicomponent process, which also includes Good Manufacturing Practices (GMP) and Sanitation Standard Operating Procedures (SSOP). While contamination by insects is not considered within HACCP programs, the steps involved in implementing a HACCP program are relevant to developing pest management programs: monitoring, verification, and validation. Monitoring involves making observations or measurements and assessing program needs to determine if problems are under control, and producing accurate records of monitoring results. Verification evaluates whether monitoring tasks are in compliance with the program and is conducted by reviewing records and onsite conditions. Validation determines if the elements of the program are effective at controlling hazards and is assessed either through review of literature or regulations or through actual validation studies.

The HACCP process can be applied to thinking about pest management decisions in food facilities such as where to place monitoring devices and target management tactics. For example, what are the critical areas within a facility where pest activity will cause greater risk of food contamination? What are the critical control points in preventing insects from entering a facility? The emphasis should be on assessing pest risk level in these areas and putting specific procedures in place to respond to pest activity. Responses should be location and pest specific. Monitoring is also used for verification and validation of overall pest management program success.

As with HAACP, verification involves the review of monitoring and pest observation data and inspection of onsite conditions. Because conditions may not be stable and changes can be implemented (for example, changes in structural modifications, sanitation programs, or manufacturing process), critical areas may change, creating a need for regular assessment. Validation means that personnel should keep up to date with advances in pest management and continually assess how well the program is working or if it could be improved. New information such as consumer complaints, increasing numbers of insects, or presence of a new species at a location should be evaluated to see if adjustments to the program are needed.

Each food facility has specific areas that are either more vulnerable to pest activity or where pest activity will have greater negative impacts. Identifying them and developing inspection, monitoring, and management programs that emphasize these areas can improve program effectiveness. Locations where potential for product infestation is greatest such as packaging areas, zones where inbound and outbound product is stored, locations where insects tend to be found the most frequently, and locations with favorable environmental conditions for insect growth such as high levels of spillage or higher temperatures could all potentially be critical control points.

The goal is to place the emphasis of the IPM program in areas where limited resources can be applied with the greatest benefit. Focusing exclusively on these areas can lead to problems because insects can develop in a wide range of areas within a food facility. Without inspection and monitoring in all areas, pest populations can be missed until levels develop to the point where control is more difficult and the insects disperse into critical areas. For example, dispersal of warehouse beetle from a shutdown portion of a food processing plant resulted in high activity levels within the finished product warehouse, where fumigation and aerosol insecticide applications were not effective (Campbell et al. 2002). The idea is not to focus exclusively on these critical areas but to give them greater emphasis and priority. In noncritical areas, less frequent regular inspections and lower densities of traps for monitoring relative to critical areas might be appropriate.

Monitoring Program

Monitoring is the regular surveillance of insect activity over time. A wide range of monitoring tools and tactics are available for monitoring insect activity in bulk grain and in food processing facilities. The type of monitoring program implemented should be aligned with the goal(s) of the IPM program. No single monitoring tactic will supply a complete picture of insect activity at a food facility. Multiple approaches should be used and results integrated. Traps baited with pheromone or food (kairomone) attractants are the most widely used monitoring device for stored-product insects in food facilities with a wide range of commercially available traps and attractants available (Chapter 21). The benefits and limitations of pheromone-baited traps are discussed elsewhere. The focus here is on how to use these types of devices to make management decisions. Results of other types of trapping devices such as light traps and sticky cards can be used in similar ways.

When making decisions from monitoring program data it is useful to keep in mind the differences between direct or indirect sampling methods. In direct sampling, insects are accurately counted and expressed as numbers per unit of measureable physical area or food material. Direct sampling methods include inspection and insect counting in food accumulations within a structure or piece of equipment, sampling food material as it is moving (e.g., counting insects in tailing samples from milled products), and sampling of static materials such as stored grain sampling or product sampling. These measures give a direct assessment of whether a sample of material is infested or what the insect density is in a given amount of material. In food processing facilities, small sample sizes and inability to sample all the locations that can be exploited can reduce the effectiveness of these approaches. Indirect monitoring in a food facility typically involves the use of some type of trap to capture adult insects moving through the facility. Some of the difficulties in interpreting trapping data are discussed in Chapter 21.

Trapping program data is best used by comparing the relative levels of capture among locations and over time. It is difficult to relate captures back to actual insect density or source of the beetles. In food facilities, most of the insect population is hidden in refugia that are difficult if not impossible to sample, and traps primarily capture adults that leave those locations in search of new resources or mates. For example, a large set of data from a variety of laboratory experiments evaluating red flour beetle populations in small amounts of flour indicated that overall the percentage of adults was less than 15% of the total population (Campbell, unpublished data). Considering that only a percentage of these adults are dispersing outside of these hidden refugia at a given time and that there can be a delay while populations build before adults disperse, it becomes obvious that traps can only reflect a small amount of the insect activity in a location. Despite these limitations, trapping programs can provide valuable information if used correctly.

Implementation of monitoring programs

Strategies for using pheromone traps or other types of monitoring devices used in a pest management program fall into two types. The first strategy is to use them as a detective tool for early detection, determining the presence or absence of a problem in a critical control point and to assist in finding foci of infestation to be targeted. The second strategy is analysis of trends over time in either focused problem areas or as a more widespread monitoring program throughout the facility. Overlap between these strategies exists, and they should be integrated.

When traps are used as a detective tool it is typically in response to some sign of insect activity, for example, infested product or spillage, insect tracks in dust, or a hot spot in pheromone trap captures. The objective is to identify the scope and source of the problem, and traps can be used in combination with inspection. Traps can be placed in a grid in the area suspected of insect activity or placed in a transect going out from the suspected problem. This use of pheromone traps is typically in response to an observed problem, although a hot spot in insect captures in a trap, especially if placed at a critical control point, can also be used as a trigger for more intensive follow-up monitoring to prevent problems from growing and spreading.

Because insect hot spots could be due to a localized infestation that can be identified and removed or caused by insects coming in from outside, visual inspection should be part of the program. After an intervention such as sanitation, structural modification, or insecticide treatment, traps can be monitored to determine effectiveness of the response. If the problem is solved, the focused trapping program is removed. This strategy is a dynamic process that is useful for identifying and eliminating established pest problems, but it does not quantify pest activity in a way that can be used to document and evaluate the long-term impacts of management programs. Data from a flour mill shown in Figure 1 can be used to illustrate how traps can be used as a detective tool to aid management decisions, while also being used for trend analysis. On one floor, red flour beetle captures appeared to be centered at a single trap location. Subsequent inspection revealed that the gap between the top of a piece of equipment and the ceiling was an area where flour accumulated and an infestation had become established. Beetles dropped to the floor in this area, and some were captured in the trap. Removal of material and inclusion of the location in a regular sanitation program eliminated the problem.

Another strategy is to use a pheromone trapping program to evaluate pest population trends and the overall success of an IPM program. To implement this approach a standardized monitoring program is needed that generates information that can be accurately compared over time. Maintaining a consistent trapping program, with traps similar in number and position from year to year, enables ongoing, accurate comparisons of capture patterns. Generated data can be used to calculate the average trap capture and to graph trends over time. Trap data can be used to look for pest abundance and distribution differences in specific areas, determine seasonal activity patterns, and look at spatial distribution patterns to identify problems and enable early detection. Through better understanding of the patterns, realistic management goals can be developed and programs can be evaluated. For example, multiple years of red flour beetle pheromone trap monitoring data (Campbell et al.

2010a, b) was used to evaluate the impact of structural fumigations on reduction in captures and how quickly captures rebounded after treatment. This provided baseline information on expected efficacy and whether a new fumigant is giving results in line with previous experience at the mill. Long-term trends can be used to evaluate how an enhanced pest management program affected pest abundance because average capture the year before and the year after making the change could be compared.

Evaluating long-term trends in outside monitoring can provide valuable information in assessing the role of immigration from outside to determine whether increases in activity inside might be related to seasonal patterns in regional abundance of the insects (higher captures overall outside) or are associated with an outside source that is producing more insects (e.g., bulk storage area). For example, in a flour mill Indianmeal moth captures in traps cycled with the season, and fumigations of the structure appeared to have little influence on the captures. This would seem to suggest that the fumigations were not successful, but comparing the trends inside with those outside revealed that inside captures were likely recent immigrants from outside. From this information coupled with little evidence of establishment inside based on inspection, researchers concluded that the fumigations did not appear to impact populations because only actively dispersing individuals were affected and these individuals were quickly replaced after treatment (Campbell and Arbogast 2004).

The potential for outside monitoring to increase insect attraction to the site and to increase attraction into a building if traps are placed near doors is an issue raised by companies and pest management professionals. No data documents that pheromone traps increase attraction to or immigration into structures. It appears unlikely given that food odors from a site are more important in attracting females, which is the sex that will initiate infestations. Most pheromone-baited traps use sex pheromones that only attract males that cannot establish new infestations.

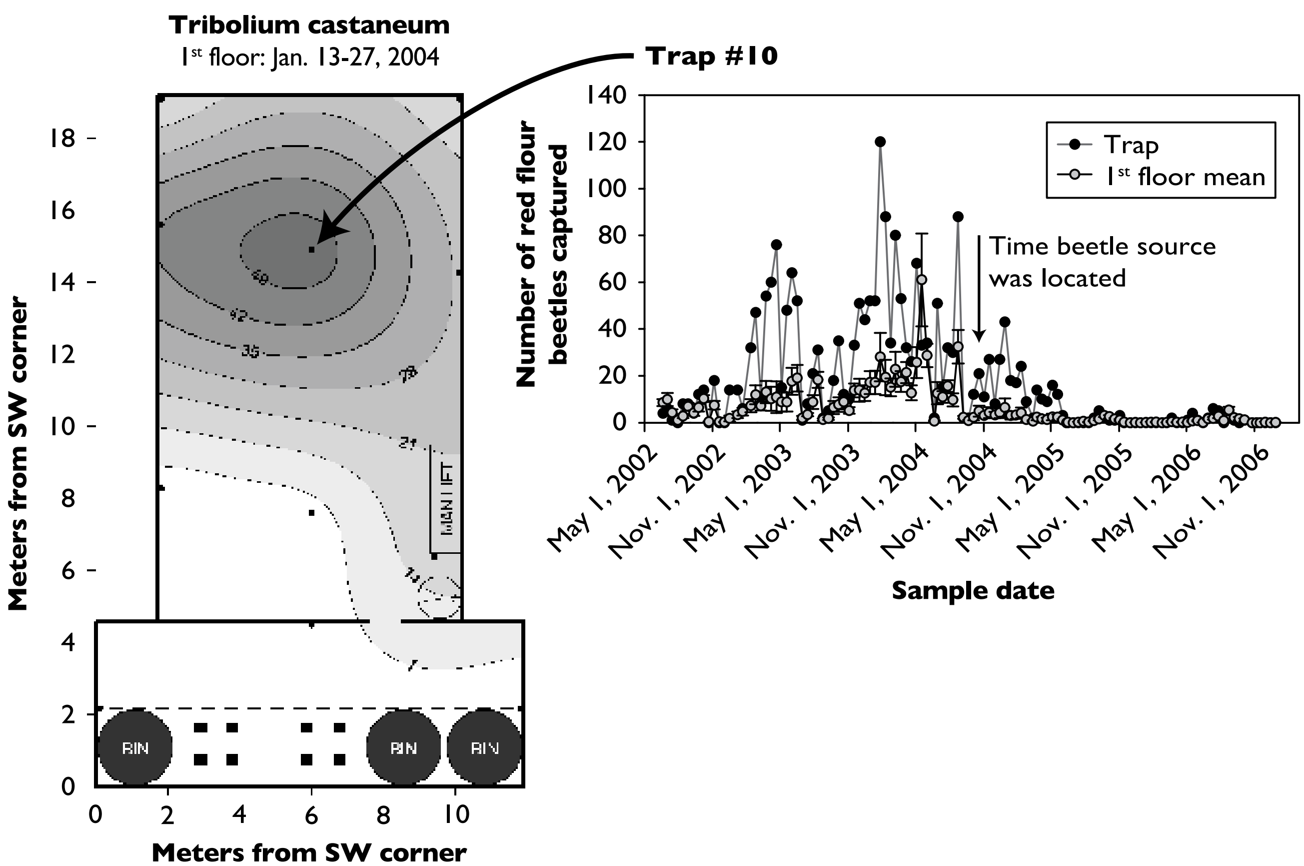

Figure 1. *A hot spot of red flour beetle activity was detected at location of pheromone trap #10, which had consistently greater captures than the average for the floor. Finding and eliminating the source population and including the location in a regular sanitation program consistently reduced captures.*

Captures of stored-product insects outside food facilities or elevators can be high even without pheromones in traps (Dowdy and McGaughey 1998) and the long-range attraction to pheromone is likely to be limited and would attract only insects that are already in the vicinity (Mankin et al. 1999). At a wheat seed warehouse, a wide range of insect species were captured coming in around overhead doors, while only pheromone traps for lesser grain borer were placed inside the facility (Toews et al. 2006). Because in most cases it is not known how many individuals are entering buildings normally, it is hard to determine the size, if any, of an increase due to pheromone use. If as assumed traps do not increase outside activity, then every stored-product insect captured outside is one less that could enter the facility.

As with all monitoring, it is a trade off of cost versus benefit. Is it better to have no measure of insect levels outside a facility and spend either insufficient or excessive amounts of time and money on exclusion, or to eliminate the risk of any increase in immigration that might be associated with outside trapping?

Reporting and interpreting results of monitoring programs

It is becoming increasingly important to have documentation that a monitoring program is in place. As a result, the number of facilities conducting pheromone trapping programs has been increasing over time. In many cases the full benefits of a monitoring program are not being realized. Because pests are not evenly distributed at food facilities, in addition to evaluating overall trends in data over time, there are advantages to evaluating spatial distribution of pests.

As discussed in Chapter 21, a wide range of methods are available for evaluating the spatial distribution of pest species, although there are limitations to where various methods can be applied. Data presented graphically rather than as tables of numbers is a more intuitive way for many people to understand patterns, which is why methods such as contour maps are popular. For example, in Figure 2 contour maps can make it easier to identify areas with greater activity in this warehouse. In this example higher areas of warehouse beetle capture appear to be associated with doors (suggesting an immigration problem due to poor sealing or closing of doors) and near pallet wrapping equipment (perhaps a localized infestation), while for Indianmeal moth it is primarily around the doors.

Accurate contour maps require a relatively large number of traps and good coverage of the area being evaluated, which can limit their application. Care should be taken in interpreting contour maps because they are mapping only the distribution of adult captures in traps, and not the actual distribution of the population, including both males and females along with the different life stages (eggs, larva, and pupae) within the facility. Contour maps also can be vulnerable to distortions when the assumptions behind their calculations are not supported. Contour maps can be used cautiously to guide the targeting of follow-up inspection. Changes in distributions over time can be evaluated by comparing contour maps created at different times or by creating contour maps of the change in capture from one monitoring period to the next.

In situations where a facility consists of multiple floors, separated rooms, or large facilities with low densities of traps, contour mapping becomes more difficult. Many facilities consist of multiple buildings and outside traps that also make the construction of contour maps more difficult. Other approaches such as use of bubble plots can be used in these situations. Figure 2 shows the same data presented as both contour maps and as bubble plots. Bar graphs of numbers captured in individual traps can also be used to visualize patterns in distribution. For example, in Figure 3 captures of predominate species in individual traps is presented as bar graphs. This approach can provide a quick overview of the whole facility as well as help in identifying individual trap locations that have higher captures that might be targets for additional inspection.

Changes in distribution over time can be evaluated by comparing graphs created from different monitoring periods. Sorting and grouping data in different zones also may help with viewing and interpreting the data generated from a monitoring program. In the rice mill example investigators created four zones (two rice storage areas, mill, and outside) and color-coded them in the original graph. These areas tend to have different species present and are managed differently, so they make useful groupings. This approach can be easily customized for a given facility. Averages for the different zones can be calculated and compared over time.

For trend analysis of a food facility as a whole or for specific areas within a facility, line graphs and tables can be useful in consolidating the information generated from a monitoring program. Trend analysis is important for several reasons. Many pests have seasonal activity patterns in traps, and trends upward and downward should be placed within this context before decisions should be made about treatment. Comparing trends in different zones can provide insight into the sources of the insects. For example, as discussed earlier, similar seasonal trends both inside and outside of a food facility suggests that immigration from outside areas may be an important contributor to pest activity in the facility. The converse, trends for populations to increase or cycle independently of outside activity, can indicate an established population within a facility.

Trend analysis can be done for individual species or for functional groups of insects such as whole-grain feeders, stored-product moths, incidental insects, or flies depending on the level of precision needed. Trend analysis enables managers to develop thresholds that trigger responses as discussed below. Trend analysis is important for evaluating the effectiveness of specific treatments or changes in management programs. Seldom can the effectiveness of a treatment such as sanitation, aerosol insecticide application, or structural modification be determined based on a single monitoring period. To determine impact, long-term trends should be evaluated or compared to trends in previous years. For example, cleaning programs can disturb insects and increase the capture in traps for a period of time after intervention. Increasing sanitation or the frequency of aerosol insecticide applications will have a gradual impact on reducing pest populations, which can take months to years to fully evaluate. For example, in a rice mill the trending data on red flour beetle captures over the period of two years could be used to help assess whether the implementation of an aerosol insecticide program is suppressing pest populations (Figure 4). This is a useful approach, but care needs to be taken because pest activity can change over time for reasons other than the change in treatment. In this example, there is evidence to suggest that change in the program is keeping pest levels below a threshold value that could be used to trigger additional pest management

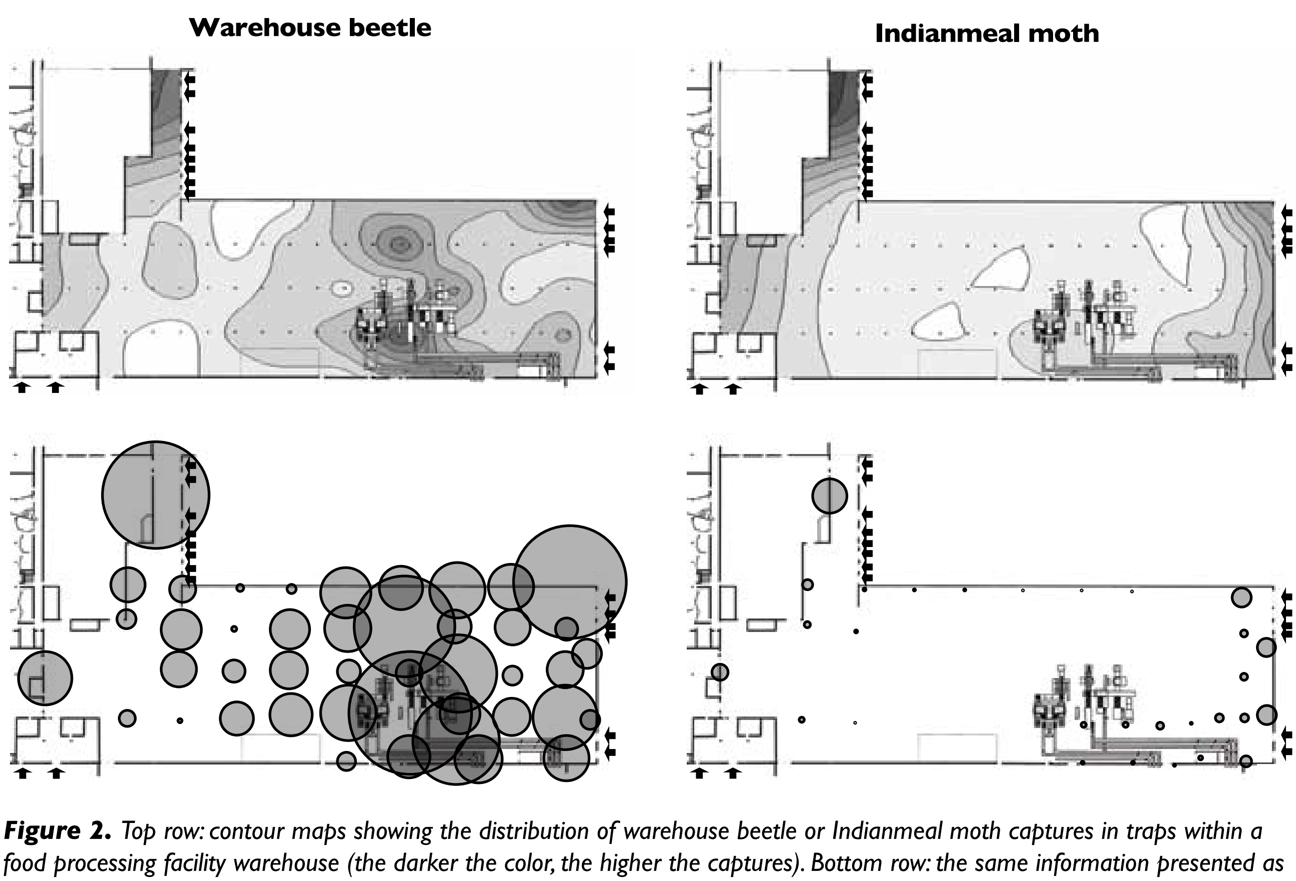

Figure 2. *Top row: contour maps showing the distribution of warehouse beetle or Indianmeal moth captures in traps within a food processing facility warehouse (the darker the color, the higher the captures). Bottom row: the same information presented as bubble plots with the diameter of the circle proportional to the number of insects caught. Arrows indicate doors to the outside.*

interventions. Information should be confirmed by evaluating multiple years and using other measures of pest activity such as inspection.

Establish Action Thresholds and Responses

In manufacturing, production is monitored to ensure tolerances are being met. This is a critical component of quality control programs. This process involves establishing thresholds for what is considered a quality product, conducting regular measurements, and evaluating trends and implementing a specific set of responses if threshold values are exceeded. Ideally, this same process should be applied to pest populations in food facilities and the assessment of the quality of a pest management program. Levels of pest activity detected should trigger specific responses, either additional monitoring and inspection to identify the foci of the problem or application of additional management tactics to solve the problem in both the short and long term.

Collecting monitoring data and storing it in a folder to document that a program is in place is not sufficient. The challenge for developing thresholds in the food industry is that relating measures such as number captured in traps to an economic impact usually is not possible, so developing economic thresholds as used in field and orchard situations is not possible. Even action thresholds are somewhat different because in a food plant a baseline level of tactics is already in place, i.e., sanitation, residual insecticide application, and structural modification. This is because programs are focused on prevention. Thresholds must be developed to determine if there is breakdown in prerequisite programs. Levels below this threshold can indicate a successful program and meeting quality standards. Exceeding the threshold level should trigger additional responses because it would indicate some sort of problem in the program.

Unfortunately, limited scientific data and analysis exist on what trap capture levels mean and how best to respond to specific levels. Levels are also likely to vary considerably with type and facility location. Some companies have adopted thresholds of insect capture that trigger specific actions based on historical trends in the data such as the average level captured in previous year capture levels that were associated with product infestation. In other situations these initial threshold levels may be relatively arbitrary and can be considered as starting points or goals and these can be refined as needed over time. For example, one approach might be to use the average number of a certain insect pest species trapped from last year as a target for the current year, with goal of keeping levels below this average in the current year. This will result in a new, lower average that can then be a new target. Levels can be adjusted to specific areas or buildings because capture levels that indicate a failure in the program and trigger an additional response may be lower in critical control points than in less critical areas. These action thresholds can be as low as one insect captured in certain situations. Action thresholds could also be triggered based on outside monitoring because as outside activity increases, invasion pressure also increases. Exclusion programs may need to be stepped up and personnel reminded about keeping doors and windows closed or screened.

Thresholds should be easy to calculate and to understand; measures such as individual trap captures above a certain level or mean trap capture for a facility or zone within a facility are reasonable measures to use. These values should be adjusted to a standard trapping interval, because sometimes traps are in place for different periods of time. Not adjusting the numbers can lead to over or underestimating pest levels and makes comparisons difficult. Action thresholds based on single traps should focus on determining the location and extent of the pest infestation and implementing a precision IPM program that will be targeted at that location to prevent the spread of the pest to the whole facility. Measures based on the whole mill will in turn give an assessment of the overall program success, with targeted response depending on identifying the specific trap locations that are out of line with the overall pest level. Proportion of traps with captures also can be used as a measure of how widespread a pest population is within a facility, and thus provides different information than mean capture data.

Campbell et al. (2010b) developed a risk threshold for red flour beetle in flour mills based on the likelihood of a large increase in average capture in the next monitoring period. This approach was based on the assumption that large increases in average number of beetles captured from one monitoring period to the next are likely to be associated with greater risk than when the average trap capture is unchanged

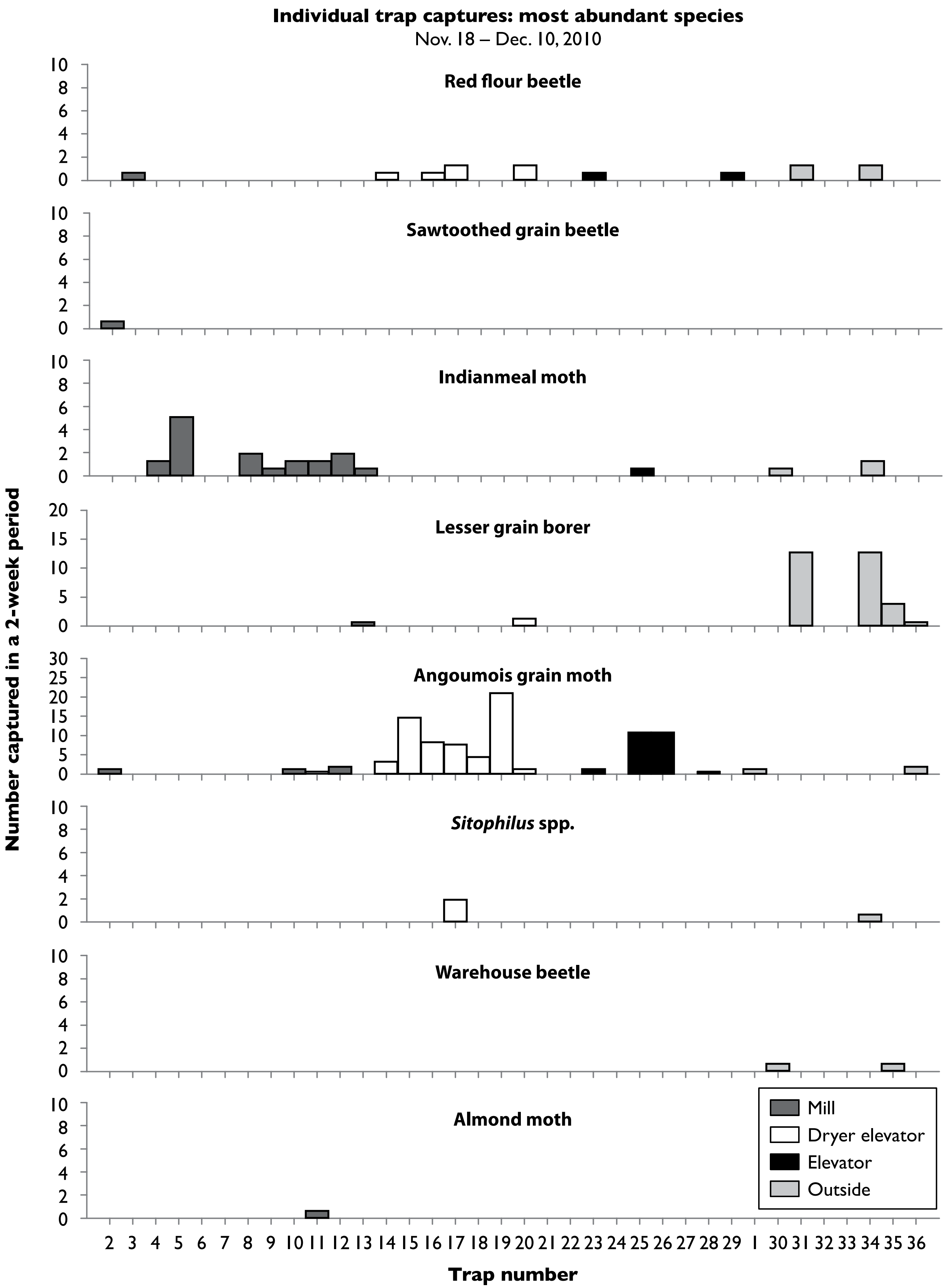

Figure 3. *Captures of stored-product insects at a rice mill represented in a bar graph of individual trap captures and the trap locations sorted into different zones.*

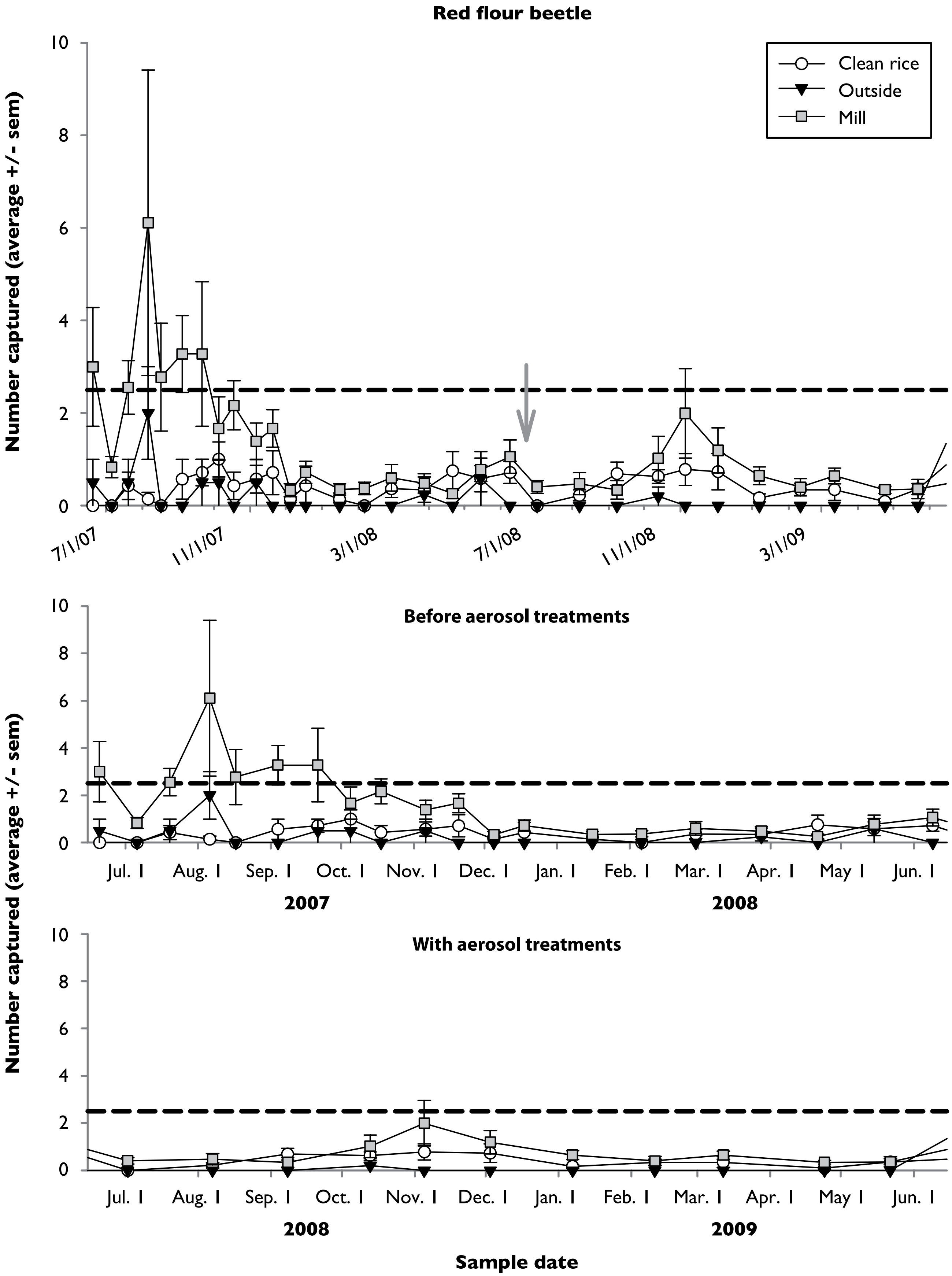

Figure 4. *Trend analysis of average capture of red flour beetle adults in three different zones of a rice mill before and after the implementation of an aerosol insecticide program involving regular applications of pyrethrins and methoprene insecticide. Dashed line indicates a potential management threshold value and the arrow indicates date mill was fumigated.*

or has a small increase. Large increases in captures from one monitoring period to the next may be related to a problem that is more difficult to control, increased insect dispersal associated with increased captures in traps could lead to greater infestation of products, and higher insect captures can reduce effectiveness of treatments (greater captures prior to fumigation resulted in greater numbers captured after treatment).

Analyzing a large data set from two commercial mills it was determined that 2.5 red flour beetles per trap per standardized two-week monitoring period was a reasonable threshold. Below this value trap captures tended to be stable from one monitoring period to the next, and above it they tended to increase. Preliminary analysis at other types of facilities suggests that this threshold relationship holds in other types of food facilities for red flour beetle, but further evaluation is needed into whether this approach can be applied to other insect species. It was determined that when red flour beetle captures in traps at a flour mill were above this threshold, the average number of beetles in the product samples was significantly greater than when trap captures were below the threshold. There may be a relationship between this easy-to-measure metric of insect activity and the potential for product infestation.

The risk threshold value described above may be useful as a starting point for red flour beetle management because it is the first value based on some documented potential risk. Although this level of capture may be too high as a practical action threshold and a given mill may choose a lower threshold as a management target, these values could still have practical benefit in serving as an upper limit threshold. Indeed, it might be desirable to use multiple threshold levels that trigger different levels or intensity of response. In Figure 4, the dashed line indicating the 2.5 beetles per trap per monitoring period threshold is used to show when beetle captures in traps exceeded this level.

Pest Management in Response to Monitoring Information

Although the number of chemical tools available for pest management is limited and may be decreasing, a wide range of chemical and nonchemical tools are available for managing pest populations, especially when the focus is on prevention rather than trying to eliminate populations after they have become established. Specific tactics to avoid the establishment of pests, reduce or eliminate pest populations and movement of individuals, include sanitation and structural modifications (Chapter 8); aerosol, surface and crack and crevice insecticide applications (Chapter 9); structural and commodity fumigations (Chapter 14); heat treatments of structures or equipment (Chapter 15); and resistant packaging (Chapter 12), among other tactics. There is not a single management tool that can be applied to every situation. Even structural fumigations, which are often thought to completely eliminate pest problems, seldom appear to result in pest-free structures due to either survival or rapid recolonization. Using fumigations as a last resort, and relying instead on targeted treatments of localized problems identified early using a monitoring and inspection program to prevent them from increasing and spreading should result in both a more effective and ultimately more economical strategy.

When evaluating what tactic(s) to include in a pest management program and which specific tactics are warranted in response to a problem, the decision process must emphasize which tactic will be the most effective, safest, most economical, most targeted, and least disruptive. Using monitoring and inspection tools to find the source of the problem and to define its scope can assist with the process of deciding on a management tactic. Permanent solutions such as sealing and structural modification often will be the most effective responses. Simply finding an area with pest activity and spraying insecticides often is ineffective, especially if the insecticide is not getting directly to the hidden refugia the insects are exploiting.

Part of implementing a pest management tactic is to evaluate its impact. It may be necessary to evaluate impact over a long time to fully determine treatment consequences. In most cases there is an immediate impact, and then there is the time it takes for the problem or the pest abundance to reoccur. The rebound or recovery of pests after treatment is a process that can be managed through tools such as sanitation, temperature manipulation, and residual insecticides.

Care should be taken in evaluating effectiveness of treatments, especially pesticides, because the observed response may not accurately reflect the true impact on the pest population. Adults can make up a small percentage of an insect population, even though this may be the most visible developmental stage. In experimental warehouses it has been shown that insecticide applications can result in large numbers of dead adults being observed and reductions in beetle captures in traps, but no corresponding decrease in the total pest population within hidden refugia (Toews et al. 2009). Relying only on adult activity and the perception of mortality levels based on observing dead adults can be misleading. This finding also highlights how multiple sources of information on pest activity are needed to evaluate impact of treatments.

Conclusions

A wide range of monitoring and management tools are available for stored-product pest management in the food industry. The difficulty is how to best integrate various tools into a coherent and effective program within the constraints imposed by maintaining the operation of a food production and storage facility and the production and maintenance of a quality food product. Effective programs should be knowledge-based, flexible, and developed for specific features of a given location. In this chapter, we have reviewed tools and approaches that can be used in the development of effective IPM programs.

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20 Organic Approaches and Regulations for Stored Product Pest Management

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The management of pests in organic systems, Organic Pest Management (OPM), has received an increasing amount of attention over the past decade. Similar to Integrated Pest Management (IPM), OPM stresses the use of sampling and thresholds to know when to treat. It calls for integration of multiple pest management tactics and the use of less disruptive pest management tactics such as sanitation, aeration, and biological control before appplying chemicals. The primary difference between these two management approaches are the types of tools available to the manager. In the case of IPM in the United States, managers are allowed to use pest management products labeled by the U.S. Environmental Protection Agency (EPA) for a particular crop, pest, and situation. In OPM, products and approaches also must meet the more stringent standards of the USDA National Organic Program (NOP).

The Organic Materials Review Institute (OMRI) is a private nongovernmental organization that provides third-party certification to organic inputs. Products that OMRI finds to be in compliance with the NOP carry the OMRI seal and typically are allowed in organic production or handling situations. Organic certifiers — accredited organic certifying agents or USDA-approved state organic programs — determine whether a particular product is allowed. They should be contacted before using any new pest management product. A list of OMRI certified compounds is maintained at www.omri.org.

In agricultural production systems, OPM is typically based upon the development of a healthy soil and agroecosystem and the use of insect- or disease-resistant cultivars. Stored products represent a special case for OPM because there is limited potential for plant regrowth. The same regulatory standards that apply to agricultural production also apply to products as they move further through the food system.

The national organic rules were fully implemented on Oct. 21, 2002. Since then, producers and handlers must be certified by a USDA accredited organic certifying agent or a USDA-approved state organic program to sell, label, or represent their products as "100 percent organic," "organic," or "made with organic (specified ingredients or food group(s))." The certification agency used by a particular producer or handler need not be in the same state, although state governments may require that the certifier be licensed by the state department of agriculture. The organic rules (7 CFR Part 205) are easily accessed at the National Organic Program website: http://www.ams.usda.gov/nop/.

Before October 2002, there were no national standards for organic claims. A few states had requirements for certification and standards for food labeled as organic, and private organizations. For example, California Certified Organic (CCOF) or Oregon Tilth certified products to their own standards or to a particular customer's standards. The USDA Agricultural Marketing Service (AMS) administers the national standards, but there is no federal inspection or certification. The National Organic Program uses accredited private certifiers or approved state organic programs. State authorities may also act as accredited certifiers using the national standards. The national organic rules undergo regular review to ensure compatibility with normal operations of organic producers and handlers as well as consumer expectations of the organic label.

Definitions and Procedures

A handler, in the national organic rules, is an inclusive term for anyone who stores, processes or otherwise handles organic products or ingredients, except for final retailers. Retailers are exempt from the certification requirements unless they are processing organic products. Those handling organic products or providing pest management services for a handler of organic products will need to establish a clear, strong, professional relationship with the USDA Accredited Organic Certifying Agent (USDA-AOCA) or the USDA Approved State Organic Program (USDA-ASOP).

The USDA Agricultural Marketing Service National Organic Program has promulgated the final rules and implemented the program. The AMS Administrator and the NOP are the primary interpreters of the rules. The National Organic Standards Board (NOSB) is an advisory committee that functions in accordance with the Federal Advisory Committee Act (5 U.S.C. app. 2 et seq.). The board has specific responsibilities when it comes to the approval of substances to be used in organic production and handling operations as regulated by that part of the rules referred to as the National List. However, the NOSB is also called on by the NOP for advice on a wide variety of issues related to the rules and the program.

Those who work on pest management in an organic handling operation and find difficulties complying with the rules, or if there is a particular input that is thought to be compatible with organic handling, should discuss these issues with the NOP staff and with the NOSB. A process is specified in the national organic rules (§ 205.607 Amending the National List) to petition the NOSB to review new inputs to appear on the National List. These inputs would be approved synthetic materials or classified as a natural (nonsynthetic) substance unless specifically prohibited on the National List. NOSB meetings, as required by the Federal Advisory Committee Act, are public meetings. Opportunities for public comment are always part of meeting agendas.

When working with products that are to be ingredients in organic foods or with organic foods it is wise to be familiar with the entire organic regulation 7 CFR Part 205, but sections of the rule most directly applicable to pest management in organic handling operations are discussed.

- 205.103 Recordkeeping by certified operations.
- 205.201 Organic production and handling system plan.
- 205.271 Facility pest management practice standard.
- 205.272 Commingling and contact with prohibited substance prevention practice standard.

And from the National List:

- 205.601 Synthetic substances allowed for use in organic crop production.
- 205.602 Nonsynthetic substances prohibited for use in organic crop production.
- 205.605 Nonagricultural (nonorganic) substances allowed as ingredients in or on processed products labeled as “organic” or “made with organic (specified ingredients or food group(s)).”

Other sections of the rule may need to be consulted, but these provide a basic understanding of pest management activities that are or are not approved and and how to document them.

Section 205.103 – Recordkeeping by certified operators

Records addressed under this section include transactional records that are not dealt with by pest managers. Records of pest management inputs used — whether baits and traps or pesticides — are required. Transactions for lease or contracting for heating or chilling equipment are other examples of non-chemical records required that might support and verify the organic handling plan.

Section 205.201 – Organic production and handling system plan

This section lists the regulatory requirements of an organic plan. The purpose of an organic plan is to describe the details of an organic system, and could be extensive for large facilities or simple for small operators. Plans must be agreed to by both the organic handler and the USDA Accredited Organic Certifying Agent or Approved State Organic Program, which emphasizes the importance of the relationship with those programs. The organic plan must reflect all practices and procedures used for pest management, plus a list of all inputs that may be used including sources, composition, and locations where used. The plan would also include descriptions of the monitoring practices instituted in the handling facility and the frequency with which they will be performed. Monitoring refers to pest monitoring and also refers to the process of monitoring for compliance with the plan.

Recordkeeping practices must also be covered and include requirements described in section 205.103. Practices ensuring that no organic product comes in contact with prohibited substances must also be addressed in the organic plan. In working with the USDA certifying agent and state organic program, additional information may be required in the plan for a particular facility.

Section 205.271 – Facility pest management practice standard

The facility pest management practice standard as expressed in section 205.271 is based on intensive preventative management. Hermetic sealing to generate a low-oxygen condition, vacuum sealing to generate a low oxygen condition, chilling practices, and heat treatments are acceptable. The use of carbon dioxide or nitrogen to generate a low-oxygen atmosphere is also acceptable practice. Carbon dioxide is registered as a fumigant and is listed in section 205.605(b). Nitrogen, oil free grade, is listed in 205.605(a) as an allowed nonsynthetic in this form in processed products as a processing aid. Ozone is another gas of interest to organic handlers but is only registered as an antimicrobial (disinfectant) and could not currently be used as a fumigant regardless of any organic status.

The rule specifies preventive management as a first line of defense, followed by mechanical or physical control methods. These methods are briefly described in more detail later in the chapter, and many are described in detail in other chapters of this volume. Mechanical or physical methods include traps, light, and sound. They also include lures and repellents using natural or synthetic substances consistent with the National List. Physical or mechanical methodologies other than those listed in the standard also may be acceptable. In accordance with the Organic Hierarchy of Pest Management — Section-205.206, the use of a pesticide consistent with the National list is available for use only after preventative management, mechanical controls, or physical control methods have proved ineffective.

Section 205.272 – Commingling and contact with prohibited substance prevention practice standard

Section 205.272 paragraph (a) is a simple statement prohibiting the commingling of organic and nonorganic products. Additionally, any contact of organic products with prohibited substances is not allowed and requires that any handler have in place measures to prevent any such occurrence. Paragraph (b) contains a pair of specific prohibitions directly required by the Organic Food Production Act of 1990. The first specific prohibition in subparagraph (b)(1) denies the use of any packaging materials and storage containers, including bins, that contain a synthetic fungicide, preservative, or fumigant. The second prohibition in subparagraph (b)(2) is intended to prevent the inadvertent contact of organic products with a prohibited substance that might be in any bag or container used or reused for the storage or packaging of organic products or ingredients.

The National List (Sections 205.601 - 205.606 – The List)

This list is derived from an interpretation of the language in the Organic Food Production Act of 1990, which is the statutory basis for the NOP rules. In approaching the list, the first consideration is that any natural (nonsynthetic) substance is considered approved for use in organic production or handling unless it is specifically prohibited on the list. Any natural substance that is registered with EPA for use on stored grains, other raw agricultural commodities, or in food storage facilities or food processing plants is by definition approved for use in organic handling operations. Likewise, all synthetic substances are prohibited for use in organic handling operations unless they appear on the list.

Pesticide Formulations and Their Relationship to The List

Section 205.601 – Synthetic substances allowed for use in organic crop production

This section covers the synthetic substances that are active and inert ingredients in any pesticide formulation used for pest control in stored products. Any such substance must be labeled and registered for such use by the U.S. Environmental Protection Agency (EPA). In section 205.601(m)(1), synthetic inert pesticide ingredients used in formulations of pesticides in organic production and handling operations are limited only to those registered inert ingredients classified by EPA as List 4 – Inerts of Minimal Concern. Unfortunately List 4 is no longer used by EPA; it exists as an obsolete artifact and has not been used to classify inerts for several years. More information about this appears later in this chapter. This places any pest manager in a difficult and uncertain situation because inert ingredients do not appear on pesticide labels and are not generally published. These inert ingredients often are considered proprietary and are covered by confidential business information regulations where the contents cannot be revealed even by regulators.

OMRI provides independent and confidential review of input formulations. OMRI listing does not guarantee that a particular pesticide is certified for use in organic systems. The final decision on any input remains in the hands of the certifier (USDA-AOCA or ASOP) although many certifiers will list accepted commonly used inputs, and typically they do allow the use of OMRI listed products.

The EPA is also proceeding to review all new inerts and inerts for which there was not enough data to make safety decisions. The result of these reviews is that those with adequate safety data are classified as not needing any tolerance in foods (no tolerance required). Neither the National Organic Program nor the National Organic Standards Board have developed an inerts policy that reflects the EPA process. The board is also intent on reviewing some of the more critical inert ingredients not appearing on the out-of-date List 4 and then placing them on the National List if they are deemed appropriate for use in pesticide formulations used in organic production and handling operations.

The pest manager has to be circumspect in making choices among pesticide formulations, even those with natural or allowed synthetic active ingredients. This is another reason to establish a strong professional relationship with federal and state certifying officials. What follows is a list of the pesticide active ingredients and methodologies that appear to be acceptable for use as pest control agents or techniques in pest management systems in facilities handling organic labeled ingredients or finished products. This list is rendered from a reading of the regulations appearing as 7 CFR Part 205. The previous discussion of inert ingredients is a necessary preface to this list.

Over the years, some products will be removed from the National List (205.601- 205.606) and other products will be added, so this list cannot be projected as accurate beyond a few months to a year after the publication date of this chapter. It does illustrate the extent of the pest management tools available to the pest manager faced with the responsibility of management in a facility handling organic products. Any product used as a pesticide must have EPA pesticide registrations and labels for the specific use intended.

Nonsynthetic substances such as pyrethrum, neem, diatomaceous earth (DE), or spinosad (recently reviewed by the NOSB) are designated as nonsynthetic substances and not prohibited from use in organic production and handling. Registered and labeled products containing these ingredients for use in storage and processing applications may be used in or around organic products or commodities so long as they have OMRI or certifier approval. Pyganic (MGK) has recently received such a label and may be used in organic systems. Dow Agrosciences is in the late stages of gaining a stored product use label for Entrust, its OMRI approved formulation of spinosyn. The common synergist piperonyl butoxide, a derivative of a plant extract, was classified as a synthetic substance and by definition prohibited in organic production and handling. As a result, any substance containing piperonyl butoxide is prohibited.

Insecticides Approved for Organic Use But Not Currently Labeled for Stored Products

Neem – The active ingredient in neem, azadirachtin, is a terpenoid derived from the Indian neem tree, *Azadirachta indica*. It produces direct toxicological effects on larvae and adult insects, and its effects are similar to insect growth regulators on the immature stages (Immaraju 1998). Extensive tests have been conducted with neem against agricultural pests. Reviews have been published during the last 10 to 15 years (Trisyono and Whalen 1999), but very little published research has been reported for insect pests of stored grains or food warehouses.

One recent report (Makanjuola 1989) describes laboratory and field tests with neem from seed and leaf extracts for control of stored-product beetles. More research data are needed to determine the effectiveness and practicality of neem for postharvest markets. Currently, the production of azadirachtin is labor-intensive and expensive compared to synthetic insecticides, and may be restricted to high-value markets (Immaraju 1998). Although there are several registrations in the United States for neem (Immaraju 1998), at this time there are no commercial products labeled for use on stored commodities or as surface or aerosol treatments in food warehouses. Pest managers must keep current on such neem labeling as changes occur.

Spinosad – This is a broad-spectrum biological pesticide that has been evaluated against a variety of insect orders, and is labeled for more than 100 crops in the United States (Thompson et al. 2000, Hertlien et al. 2011). It is highly effective at low label rates against insect pests in stored grains (Fang et al. 2002). In May 2002, spinosad received an experimental use permit (EUP) for direct application to wheat. Additional trials have been conducted on stored grain with great success against both beetles and moths (Toews et al. 2003, Flinn et al. 2004, Huang et al. 2004, Getchall et al. 2008, Huang and Subramanyam 2007, Subramanyam et al. 2007). The registrant (DowAgrosciences) has also tested spinosad for use in processing, structural, and stored product applications. Entrust was found to be highly toxic to many stored product pest natural enemies (Toews and Subramanyan 2004). Spinosad received a label by the US-EPA in 2005 for application to stored grains and also received allowable international residue tolerances. Spinosad has not been marketed in the United States because some countries will not allow spinosad residues on imported wheat. This matter had not been resolved as of press time. A registration of Entrust, Dow's organic formulation of spinosad on stored products is expected sometime in the near future.

Insecticides Approved for Organic Use and Currently Labeled for Stored Products

Boric acid – This dust is one of the oldest registered insecticides. It is strictly limited to structural pest control, and is not labeled for direct contact with organic food or crops. It is used for void treatments in dry areas against insects that may use these sites as harborages.

Pyrethrins – Pure pyrethrum and mixtures without any synergist are approved for use, but without a synergist, the pyrethrum is less effective. Pyrethrins without a synergist may not give sufficient control at economical application rates when used in pest management programs for stored products. Pyganic was not found to be effective at managing psocids in wheat, rice, or corn (Guedes et al. 2008, Athanassiou et al. 2009), but little work has been published regarding its effect on major internal and external feeding stored product beetles or moths.

Diatomaceous earth – This is an inert dust composed of fossilized skeletons from microscopic single-celled plants called diatoms. It kills insects through interference with the lipid layer in the exocuticle and through dessication (Glenn et al. 1999). Commercial diatomaceous earth formulations can be manufactured from marine or freshwater sources, and there are many products currently available in the United States and throughout the world for direct application to grains and for structural applications inside mills, warehouses, and processing plants (Quarles and Winn 1994, Subramanyam and Roesli 2000). The physical characteristics of the individual particles, origin of the deposits, and presence of added material can all affect insecticidal efficacy of commercial diatomaceous earth formulations (Korunic 1997, Fields and Korunic 2000). Insect species also vary in their response to diatomaceous earth. Small mobile beetles and immature stages are particularly vulnerable (Mewis and Ulrichs 2001), while less-mobile species and larger beetles are often more tolerant in comparison (Arthur 2001, 2002). Most diatomaceous earth formulations tend to lose effectiveness with increases in grain moisture content or relative humidity (Golob 1997, Korunic 1998, Arthur 2000, Athanassiou et al. 2005). Some formulations contain added ingredients such as food attractants, silica, and other products to enhance toxicity. It is essential that the use of a particular diatomaceous earth formulation be discussed in advance as part of the management plan and be approved for use by federal and state certifying officials.

Physical Control Treatments for Organic Use

Bulk grains

Hermetic sealing – Hermetic sealing to create low-oxygen conditions for pest control has been used for more than 2,500 years (Adler et al. 2000). The time required for oxygen depletion depends on many factors, including the specific commodity, moisture content, temperature, volume, and storage structure (Hill et al. 1983). Most of the research conducted in this area has been with underground bunker-type storage of raw grains in low-moisture environments, particularly in the middle East and in Australia (Adler et al. 2000). Little current research in the United States exists on hermetic sealing for insect control in bulk grains. The use of carbon dioxide or nitrogen to generate a low-oxygen atmosphere is also acceptable practice. Carbon dioxide is registered as a fumigant and is listed in section 205.605(b). Nitrogen, oil-free grade is listed in 205.605(a) as an allowed nonsynthetic in this form in processed products as a processing aid. Ozone is another gas of interest to organic handlers but is only registered as an antimicrobial (disinfectant) and could not currently be used as a fumigant regardless of any organic status.

Vacuum sealing – Over the past several years a system of low pressure application, or vacuum sealing has been developed which circumvents some of the obvious problems of vacuum sealing of stored products, both bulk and packaged. The system can be applied to bulk product in bags or to packaged products in packages that will withstand the external pressures from vacuum sealing of the products. The system utilizes large heavy gauge flexible polyvinyl chloride (PVC) bags, known commercially as "cocoons," which can be used to create a container for bagged or otherwise packaged products. These "cocoons" are sealed and evacuated with a vacuum pump creating a low pressure environment with an atmosphere very low in oxygen. Oxygen levels of 1 to 2% prove insecticidal to all live stages of major stored product insect pests when applied at common room temperatures for 1 to 4 days. (Mbata et al., 2001, 2004, 2005; Phillips 2006, Phillips et al. 2007). Commercial scale vacuum treatment will take longer than traditional fumigation (e.g., 4 hours for methyl bromide), but it can be done in buildings while workers are present and poses no risk because there is no chemical input, simply removal of air from the cocoon.

Aeration for cooling bulk grains – Aeration is the practice of using low-volume ambient air to cool bulk grains. It is an important component of grain management in temperate climates throughout the world (Armitage et al. 1994, Mason et al. 1997, Arthur et al. 1998, 2001, Arthur and Casada 2005, 2010). This process utilizes fans that either draw air into the bottom of the grain bins and forces a cooling front upward in the bin, or air can be brought into the bin from the top to force the front downward through the grain mass. The purpose of aeration is not to kill insects, but instead to cool the grain below levels that support insect population growth and development. Growth and reproduction of most stored-product insects ceases at 60°F (15°C) (Howe 1965, Fields 1992), so this temperature is commonly used as an initial threshold in management plans (Arthur et al. 2001, Arthur and Flinn 2000). Airflow rates are usually specified in the United States as 0.1 to 0.5 cubic feet per minute (cfm) per bushel, or 0.0013 to 0.0065 $m^3/s/m^3$. It is important to differentiate aeration from grain drying, which often utilizes rates of much greater magnitude to dry grain immediately after harvest, and also can involve specialized heating equipment (Reed and Arthur 2000).

Grain chilling – Chilling treatments in stored raw commodities are accomplished using commercial refrigerating equipment designed to quickly cool large bulk bins and elevator silos (Mason et al. 1997, Maier et al. 1997). Commodities are usually cooled to 10 to 15°C, so there is very little mortality of insect pests even when using chilling technology (Burks et al. 2000). If commodities are held for long periods of time, chilling could eventually eliminate pests. Initial costs for chilling equipment are high, but long-term costs when amortized over time can be compatible with other pest management strategies such as fumigation or aeration with ambient air (Mason et al. 1997, Roulon et al. 1999).

Heat treatments – Heating systems for bulk grains have been devised using fluidized beds, radiation, or microwave technology (Burks et al. 2000). Although high temperatures can kill insects, the costs of older equipment and technology used for heating whole grains often were prohibitive compared to other methods. The ability of insects to acclimate to lethal temperatures or the difficulties involved in heating a bulk grain mass must also be considered when discussing heat as a control method for bulk grains. Grains can crack, harden, and become brittle if heating is introduced too quickly or if excessive temperatures occur during the process (Burks et al. 2000), and the germ could also be damaged by extreme heat. In addition, milling characteristics and baking quality can also be affected by extreme temperatures (Lupano and Anon 1986, 1987, Guerrieri and Cerletti 1996). Although new equipment and technologies may reduce the costs of heating for disinfestation of bulk grains, the concerns regarding effects on product quality may limit the use of heat to kill insects in bulk grain.

Mills, processing plants and warehouses

Cold treatments – Cold treatments have been tried as a whole-plant disinfestation strategy in flour mills in western Canada (Worden 1987). In one case, the mill was opened during the winter, and the outside air was used to lower the temperature to levels that would be lethal to insects. This method is not very practical, given the ability of insects to acclimate to cold temperatures, the effects of extreme temperatures on milling and processing equipment, and the processes required to distribute these temperatures equally throughout the mill (Burks et al. 2000). Also, the plant may need to be shut down for several days while the cold temperatures are maintained, causing losses in production and income. Cold treatments are more likely to be used as chamber treatments to disinfest bagged or packaged commodities. Even when used in this manner, the time required to bring the core temperature in the center of the room to the desired level could be several days (Mullen and Arbogast 1979). The same difficulties will occur when chilling bulk commodities in chambers.

Heat treatments – The use of heat to kill insects dates back to the early 20th century (Dean 1911, 1913). New technologies and advances in heating equipment and design are contributing to renewed interest in using heat for insect control (Dowdy and Fields 2002, Wright et al. 2002). Thermal requirements for mortality are known for most of the economically important stored product insects (Howe 1965, Fields 1992), and several private companies are actively using heat as a part of their management strategies. Treatments of heat combined with diatomaceous earth appear to be effective and can reduce lethal temperatures or time intervals required for complete kill of exposed insects (Dowdy 1999, Dowdy and Fields 1992). Heat treatments also can be used in small-scale chamber or vacuum fumigations. The procedures, difficulties in transferring heat, and the ability of insects to partially acclimate would be similar to challenges for using cold treatments in small chambers.

Additional Control Measures

Section 205.271(d) allows for a situation in which all the previously discussed approaches have failed. In that situation, use of any registered pesticide (this would include fumigants and rodenticides) might be used; however, *contact of these prohibited substances with organic ingredients or products must be prevented.* Such a treatment must be agreed on by the handler and the USDA-Accredited Organic Certifying Agent or Approved State Organic Program, and methods of application and measures to prevent contact with organic products must be included in the agreement. Paragraph (f) makes a similar allowance for treatment required by federal, state or local authorities, with the same stipulation about contact with organic products. While these allowances provide for emergency treatment of infested facilities, they would not allow the treatment of organic products that were themselves infested. In that situation, the products or their approval for the organic label would be sacrificed. Any application of a nonsynthetic or synthetic substance to control or prevent pest infestations would require an update of the facility's organic plan. The update would have to include the substance used, method of application, and measures to assure that contact with organic products or ingredients was prevented (Section 205.271(e)). Organic stored product management includes rules requiring strict segregation of organic ingredients and products from commingling with nonorganic ingredients or products. A repetition of the requirement of prevention of contact of any organic ingredient or product with prohibited substances is stated in Section 205.272 .

Commingling and Contact with Prohibited Substance Prevention Practice Standard

Details are not included here because they are only marginally relevant to organic stored product pest management. Stored product managers in general may be interested in this section of the rule.

Conclusion

The rules for handling organic products, particularly pest management in storage and processing facilities, are unquestionably challenging. Many tools are available to help the modern pest manager meet the requirements specified for handling organic products. Intensive integrated pest management techniques can eliminate much of the need for pesticides. The rules (7 CFR Part 205) emphasize an intensive approach to pest management. Personnel with high levels of management skill and training will be needed to successfully carry out such approaches.

To deliver pest management for organic stored products, either for a company or a client, the regulations as described and explained in this chapter must be followed. It is most important to establish a strong professional relationship with the USDA Accredited Organic Certifying Agent or the state authority certifying under a USDA-approved state organic program. This relationship will be immensely important in solving problems before they arise. Vigilance and circumspection from those responsible for pest management decisions will be required not only in managing the system but in the changing regulatory environment as new pesticides and approved inert ingredients become part of the equation. *When in doubt about the use of a pesticide, whether synthetic or nonsynthetic, do not use it until clarification is received from the USDA-Accredited Organic Certifying Agent or USDA-Approved State Organic Program.*

As national organic standards evolve, participate in discussions among the National Organic Program, National Organic Standards Board, USDA-AOCA or USDA-ASOP, and the public. Involvement will will help the practical evolution of the program and regulatory framework.

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S156 – 20 September 2012

21 Trapping and Interpreting Captures of Stored Grain Insects

Michael D. Toews
Christian Nansen

This chapter provides an overview of insect trapping and interpretation of trap captures for stored-product protection in bulk grain, food processing, and retail environments. The use of traps for detection, monitoring, and population estimation requires considerable knowledge of insect biology and appropriate trap use. Trap use is essential for development of meaningful integrated pest management programs. Concepts and ideas presented are based on insect ecology and behavior rather than formulas for number of traps and fumigation triggers. No universal recommendations exist for insect trap use.

Practical, economic, and ecological considerations require experimentation before pest managers can decide how to implement a trapping program in a given facility. Pest managers should understand appropriate use and operation of trapping programs and be aware of common problems in commercial facilities. This chapter covers traps, attractants, and factors that influence captures. It offers practical tips for managing a trapping program and concludes with a discussion of how to interpret and use data.

Why use traps?

The objectives of insect trapping programs in stored product protection are to document presence or absence of a particular insect species, monitor changes in species composition, and estimate changes in insect density over time or space. Data from trapping programs are used to justify changes in pest management practices or to investigate the efficacy of a particular treatment. Trapping data should be used to complement ongoing pest management inspections, not to replace them.

While visual inspections of warehouses and stored products are important, they do not provide numerical data for decision support. Visual inspections alone may not provide sufficient information about emerging insect pest problems. Pest management professionals conduct visual inspections with the expectation that a particular insect pest species will be observed, if present. Technicians should also look for dead insects and evidence of insect activity such as trails in flour or damaged food products.

Stored product insects often are sedentary during the day and active at night when they search for food, mates, and shelter (Toews et al. 2003). Campbell and Hagstrum (2002b) showed that only 6% of red flour beetles were moving at any given time. Continuous trapping of insects (beetles, moths, and psocids) or arachnids (spiders, mites, and predatory mites) during a two-week period provides more information about insects present than an estimate based on visual inspection. Traps also can show the absence of insect activity, precluding the need for pesticide application or fumigation.

Trap use and interpretation of insect captures provide the foundation for integrated pest management programs and may be considered a method of sampling the insect population. Sampling can be categorized in two ways. Direct sampling is defined as enumeration of insects present per defined unit of space or volume of a particular commodity — for example, counting the number of Indianmeal moth larvae in a single box of breakfast cereal or the number of beetles in a grain sample. Although direct sampling methods provide the most reliable estimates of insect density, it is unrealistic to use them with finished goods because products cannot be sold with adulterated packaging. Direct sampling for insects that accumulate in cracks and crevices is not feasible, nor is it likely that a manager could identify every insect harborage. Indirect sampling is any method of capturing insects or estimating damage that is not directly tied to a unit of area, volume, or weight. Trapping is considered indirect sampling because it is not known from how far away insects were drawn into the trap. Insect trapping programs can be operated in all types of commercial storage, processing, warehousing, and retail establishments without jeopardizing product appearance or customer confidence.

Adoption of a trapping program may present challenges that require personnel training and education. For example, traps are frequently swept up, damaged, and discarded by custodial crews. Workers sometimes view traps as garbage that prevents them from maintaining a high level of sanitation within the facility. Trapping devices may be tampered with — for example, the removal of glue boards — because personnel are concerned that third-party auditors will use trap captures as part of their assessment. Similarly, some insecticide applicators view traps as unimportant, mistakenly believing that spraying a residual insecticide precludes the need for follow-up assessment.

Pest managers and employees must continuously improve their interpretation of trap captures and insect identification skills. Even when insects are correctly identified and reported, client reaction to new knowledge of insects present can be difficult to manage. While managers are usually aware of the most economically important insect species, they may have less knowledge about predators, parasitoids, and fungus-feeding species. Traps will inevitably show presence of these and other species that are not economically important, such as antlike flower beetles or ground beetles. Some clients may feel that presence of any insect at any density justifies intervention. They may need to be educated about economically important species, economic thresholds, and economic injury levels.

Ironically, trap use can make it difficult for pest management professionals to justify their efforts because contracts are often based on insecticide application frequency and linear feet of insecticide applied. Some clients may not perceive they are getting the same level of service if the pest management professional spends more time servicing traps than spraying insecticides. In these cases it is important to articulate a shift, from calendar-based spraying without regard for insect presence to monitoring followed by targeted interventions at an appropriate time and place. A contract between a food facility client and a pest management professional should specify that insect infestations will be suppressed, even though the technician may not need to spray every visit. Insect pest management should not be based soley on insecticide treatments but also on prevention (for example, reducing the likelihood of pests entering the food facility), sanitation, monitoring, evaluation, and client education.

Types of Traps

Commercial traps for capturing stored product insects in grain storage and food-processing facilities are widely available. New trap designs are continuously being introduced. Traps intended for stored-product insects generally fit into four categories: light traps, aerial traps, surface traps, and bulk grain traps. Pest managers should understand uses and constraints of each type of trap to select a model that is appropriate for the species of interest. To provide usable data, traps must be durable, easy to service, and adapted to the environmental conditions where the trap will be deployed (Barak et al. 1990). In most cases, price influences the decision on which trap to use. It is important to have as many trapping stations as is feasible.

Light traps are wall-mounted, corner-mounted, or ceiling-suspended traps that utilize ultraviolet light (315 to 400 nm wavelength) as the insect attractant. The principle of operation is that flying insects are attracted to the light and are captured or killed when they enter the trap. Traps typically have a low current immobilizing electrical pulse or an electrocuting grid around the light source to kill insects and replaceable sticky cards to hold the insects (Figure 1). Located above the line of sight, they are commonly used for fly control in food preparation and pharmaceutical production facilities. Some models look like normal lights and can be mounted discretely in canteen, office, and reception areas where presence of flying insects is a sensitive issue.

Light traps attract a wide variety of adult flying insects, including stored-product insects, but are limited in ability to detect and monitor key stored-product insect species. Nualvatna et al. (2003) found that light traps were useful for capturing Angoumois grain moths, lesser grain borers, maize weevils, and red flour beetles in rice mills and paddy seed stores. Hagstrum et al. (1977) found that the rate of female almond moth captures increased when a black light was included on the trap compared to separating the lamp from the trap; no differences were observed for male almond moth captures. Care should be taken when mounting traps. Traps placed near doors could attract nuisance insects into the facility. Broce (1993) warned that traps should not be located above production lines where insect parts or debris could fall into the product. For proper performance, light traps should be cleaned frequently, and light bulbs replaced every 6 to 12 months.

Figure 1. *Example of an electrocuting light trap.*

Aerial traps are intended to capture flying insects attracted by a pheromone lure or food that then become entangled in a sticky coating or are collected in an escape-proof chamber. Rather than being placed on a flat surface, traps are suspended in the air from poles, conduit, structures, or equipment. This category includes bucket traps, funnel traps, and any of the sticky traps made of laminated cardboard coated with a sticky material (Figure 2). Aerial traps are intended for capturing adults of economically important species. Hagstrum et al. (1994) used aerial traps for early detection of insect activity in bin headspaces. When properly baited with a pheromone lure, aerial traps are effective in capturing adult moths such as Indianmeal moth, Mediterranean flour moth, raisin moth, tobacco moth, and almond moth, and beetles such as the warehouse beetle, cigarette beetle, and lesser grain borer. Bucket and funnel traps are much more durable, but they are larger and require an insecticide impregnated strip in the collection reservoir or a liquid to prevent escapes. Funnel traps are excellent for outdoor monitoring of the lesser grain borer. Aerial traps are sometimes deployed resting on the ground such as under shelves or packing equipment in retail and warehouse establishments. Manufacturers offer many versions of these traps with small openings that reduce excess dust accumulation, which is important because dust decreases trapping efficiency. Sticky traps can be scraped cleaned with a putty knife and redeployed multiple times following a fresh application of Tanglefoot Tangle-Trap Insect Trap Coating (Contech Enterprises, Victoria, British Columbia) or a similar trapping adhesive.

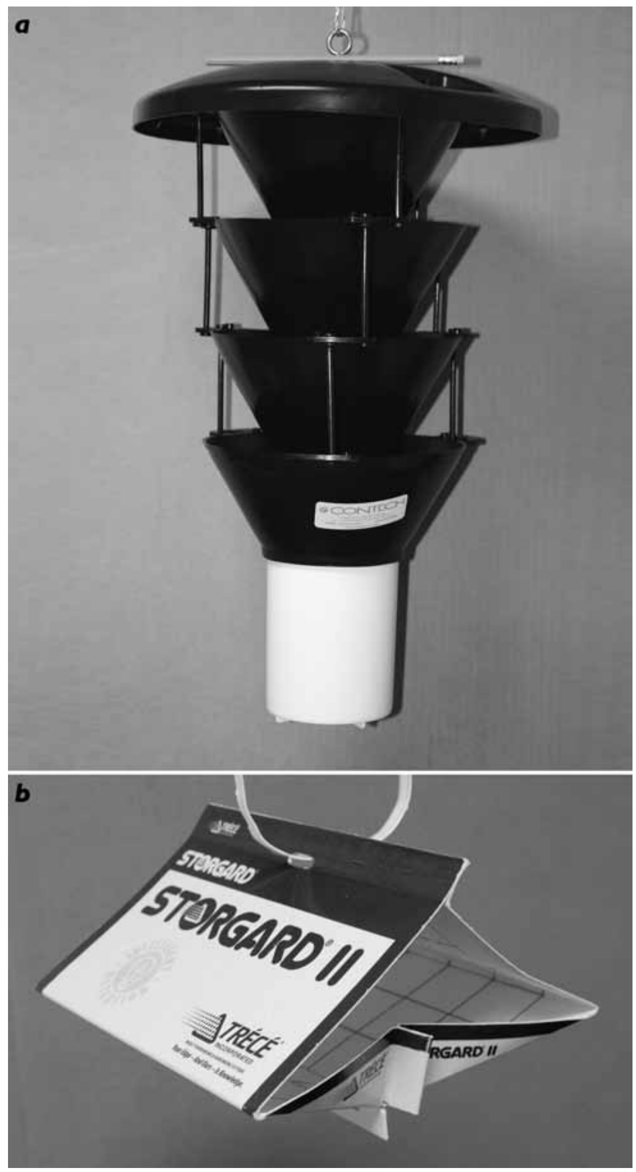

Figure 2. *Common aerial traps including a funnel trap (a) and sticky trap (b).*

Surface traps are small, low profile traps intended to rest on horizontal surfaces to capture crawling insects such as stored-product beetles. Surface traps will capture adults of a wide variety of insect species and occasionally wandering immatures. Surface traps vary greatly in appearance but are typically constructed to take advantage of an insect's preference for seeking shelter and hiding in dark crevices (Figure 3). Traps that contain corrugated cardboard are particularly effective at attracting wandering moth larvae. Mullen (1992) developed an early pitfall trap for capturing red flour beetles with a pheromone lure. Plastic pitfall traps are molded in the shape of a cone with a hollow center where attractants can be attached and insects can accumulate. These traps usually include a dust cover. Pitfall traps are unique because they are baited with both pheromone lures and food attractants. This combination is important because some insect species are more attracted to pheromone plus food odors than either component alone. Food odors may attract immatures such as warehouse beetle larvae. Multiple studies have shown that there are many more immatures compared with adults in a stable insect population (Perez-Mendoza et al. 2004, Toews et al. 2005b). Although several species may be present in the trap, pheromone baiting tends to bias the capture frequency toward the insect for which the pheromone lure is intended.

Figure 3. *A pitfall trap, a type of specialized surface trap for capturing stored-product beetles.*

Bulk grain traps are specialized pitfall traps for use in grain stored in facilities such as concrete silos, steel bins, and flat storages. These traps are constructed of a perforated cylinder with a collection vial attached on the bottom (Figure 4). The trap is inserted just below the top surface of a grain mass and left in place for several days. Insects wander into the traps and fall into the collection tip where they cannot escape. Loschiavo and Atkinson (1967) first described a grain probe trap based on the idea that it would exclude grain kernels but permit insect entry. Pheromone lures are not recommended for use in probe traps, but research in this area is lacking. White et al. (1990) provided a comprehensive review of probe trap development, construction, and factors that affect usage. Bulk grain traps are placed near the surface because research shows that there are more insects in this portion of the grain mass (Flinn et al. 2010). Multiple authors have examined using probe traps to estimate population density (Cuperus et al. 1990, Reed et al. 2001, Toews et al. 2005c). An interesting advance in this area is the Insector Insect Detection System (OPI Systems, Calgary, Alberta), which includes a trap integrated with electronics to enable automated counting, insect size determination (for identification purposes), grain temperature, and a time stamp for each capture (Flinn et al. 2009). This additional information can be helpful when interpreting insect capture data.

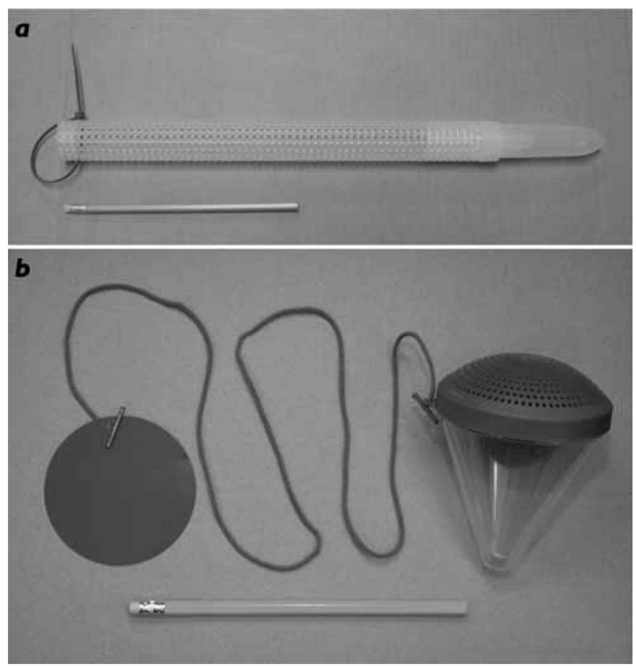

Figure 4. *Bulk grain traps including the WB probe II (a) and the PC trap (b).*

Attractants

The most common type of attractant for capturing a wide range of stored product beetles is a food odor attractant or kairomone. Commercially available formulations of food-based attractants vary from solid food attractants to a liquid blend of edible oils and stabilizers. Doud (1999) tested many different oils and found that walnut oil was a good attractant for red flour beetles. Several oils, including walnut oil, are attractive to Indianmeal moths (Nansen and Phillips 2004). Food based attractants are commonly used to capture sawtoothed grain beetles, merchant grain beetles, rice weevils, granary weevils, and rusty grain beetles. Traps designed for use with solid food attractants generally have a sticky surface inside the trap to hold the captured insects. The kairomone oil both attracts the insect and kills it by suffocation after the insect falls into the trap. Food based oils used as attractants will eventually go rancid and lose their attractant qualities with time, so it is important to change the oil every four to eight weeks. Food attractants, such as freshly kibbled grain, can also be used for monitoring species that do not have a commercially available pheromone lure. The "attractiveness" of food baits such as kibbled grain obviously depends on how much food is available in the given food facility. That is, all food baits used in traps are essentially competing with attractive odors from other food sources within the food facility.

Pheromone lures are important attractants for capture of important stored product beetle and moth adults. Lures that attract most of the common economically important species are widely available from commercial sources. Managers should be aware that pheromone lures are specific to recruiting a single species or a few closely related species. Presence of the lure will strongly bias the captures toward that species. This can be a tremendous advantage since the technician will not have to sift through hundreds of non-economically important species as would be attracted to a light source. There are exceptions to this rule. For example, commercially available pheromone lures for Indianmeal moth also attract four closely related moth species: Mediterranean flour moth, raisin moth, tobacco moth, and almond moth. The commercially available pheromone lures for red flour beetle also attract the closely related confused flour beetle. In addition, some companies market a single lure impregnated with a multi-pheromone formula. For example, they may provide a combined lure for warehouse and cigarette beetles. Pheromone components also may be impregnated into the glue in sticky traps. Although these traps have not been evaluated in controlled scientific studies, they eliminate the need to transfer lures from one trap to the next.

It is important to distinguish between sex pheromones and aggregation pheromones. Sex pheromones are very powerful attractants, but they only attract one sex (Mankin et al. 1983, Mankin and Hagstrum 1995). For example, the female Indianmeal moth produces a sex pheromone when she is ready to mate to attract conspecific male moths. Baiting a trap with the commercially produced Indianmeal moth lure will only recruit the male moths of a few closely related species. Conversely, aggregation pheromones attract both males and females to the trap. In the field, male lesser grain borers naturally produce aggregation pheromones when feeding that will attract male and female beetles to exploit the food source.

The effectiveness of combining single or multiple lures with pheromones and kairomones in the same trap is a common question. Studies show that with some beetle species, the combination of food attractant oil and pheromone is more effective than either component alone (Faustini et al. 1990). The data are much less clear about how combinations of multiple pheromones and attractant oils in the same trap influence capture efficiency (Dowdy and Mullen 1998). For example, pest management professionals commonly deploy Indianmeal moth and warehouse beetle lures in the same sticky trap; the lures need only be located in the center of the trap to maximize the opportunity for a responding insect to contact the sticky adhesive. While combining multiple species of lures in the same trap will reduce the number of traps that need to be serviced, this practice increases the probability that the trap will become saturated with insects and could require more frequent service intervals. In pitfall traps, common lure combinations include the cigarette beetle, red flour beetle, and warehouse beetle. Because the amount of pheromone in a given lure varies with manufacturer, it is important not to change lure manufacturers in the middle of a trapping program. Likewise, efforts should be made to ensure that spare lures are stored in unopened foil packages in a household freezer to prevent premature degradation.

As an alternative to pheromone lures as attractant for moths in food facilities, water by itself (Chow et al., 1977; Ryne et al., 2002; Nansen et al 2009) or water in conjunction with food and antifreeze (Ni et al., 2008) have been proposed. An important advantage of using water as attractant is that it is equally attractive to male and female moths. Water as a moth attractant does not perform well in environments where water is available. It should only be considered a possible attractant for use in stored grain silos/warehouses and or dry food processing facilities with high ambient temperature and low relative humidity. Recommendations about shape and size of holes in water bottles are available in Nansen et al (2009). Water-baited traps for moths also may be considered as part of evaluating the performance of mating disruption programs.

Factors That Affect Trap Capture Rate

The premise of insect monitoring programs is that the number of insect captures fluctuates in response to changes in insect population density or changes in the environment. Data from many environments with numerous insect species show that this premise is valid. IPM practitioners often struggle with the idea that factors other than pest population density can affect captures. Toews et al. (2006b) showed that pheromone lure age and trap replacement interval affected captures of lesser grain borers in outdoor funnel traps. In some cases these factors can be mitigated with careful planning and routine trap maintenance. Because pest management professionals will not be able to control all of the factors, understanding their potential impact on trapping programs is critical. Professionals should study long-term trends in data sets at each facility to make educated decisions about why the number of captures changed. Unusual changes in capture rates should trigger additional investigation to identify and address problem areas.

Environmental conditions of the facility and general sanitation level around the trap will have a profound effect on the number of insects that can be trapped. For example, dust accumulation in both sticky traps and surface traps is a common problem in facilities that move or process grain. In these facilities, traps that have small openings are preferred because a smaller opening permits less dust accumulation, but stored product insects can easily find their way into the traps. Additionally, managers should conscientiously select rooms that will not rapidly become covered with dust as this could occlude dispersal of the attractants, while rendering a sticky trap surface completely useless. General sanitation level influences how far an insect must travel to meet its biological needs. Ecologically speaking, warehouses are temporally and spatially fragmented landscapes; the degree of spatial fragmentation determines how far the insect will need to travel to find food, shelter, and mates. Increased travel distance is correlated with increased potential for encountering a trap. For example, Roesli et al. (2003) showed that the number of weevils captured in pitfall traps located in pet specialty stores increased by more than 50% immediately after vacuuming, sweeping spilled food, and removal of severely infested products. Nansen et al. (2004e) showed that surface trap captures of beetles in pet stores increased immediately after sanitation but resumed to lower levels after a few weeks. In these cases the increase in trap captures was interpreted as beetle populations being "disturbed" rather than actually controlled by the sanitation procedures.

Trap position will affect capture rate. Research shows that traps positioned under refugia, in corners, along walls, and near food sources capture more insects. Managers should consider the condition of concrete floors and walls in warehouses when interpreting captures. Old floors that are cracked and have product accumulation in the cracks will harbor insect populations that would have to range over much larger areas if the surface was clean and contiguous. Similarly, cracks near the junction between the floor and wall will permit insects to infest wall voids. They provide a conduit to wall voids and to the ceiling, where flour accumulates and is difficult to clean.

Indoor conditions such as air temperature, air movement, light, and photoperiod (light and dark cycles) affect insect captures in traps. Biology students learn that arthropods are poikilothermic; that is, their body temperature and metabolism rate are governed by the ambient temperature. A mobile insect, such as a red flour beetle adult, is more active and likely to be captured when the inside air temperatures are between 90°F and 100°F (32°C to 38°C) compared with an inside temperature in the 65°F to 75°F range (18°C to 24°C). Toews and Phillips (2002) investigated capture of rusty grain beetles in stored wheat and observed a quadratic increase in captures between 20°C and 40°C. Regardless of species, few insects will be captured indoors or outdoors when the air temperature is less than 60°F (15.5°C). Air currents carry pheromone plumes and food odors to areas where insects are likely to detect these chemical cues. Hence, traps are visited by more insects if positioned near doors and windows, in rooms with air handling units, or near moving machinery. Light and photoperiod can be especially important when sampling moth populations as they tend to have the highest flight activity immediately after the lights are turned off.

The intrinsic mobility of a given insect species will determine how often they are captured in traps. For example, stored grain pests like rice weevils and lesser grain borers move very little in grain bulks compared to rusty grain beetles. For this reason, the presence of a single weevil or lesser grain beetle in a probe trap may be cause for concern, but the capture of several thousand rusty grain beetles can be tolerated until the grain is sold. In warehouse and retail environments, strong fliers like the Indianmeal moth and warehouse beetle will be detected much farther from the food source compared to insects like the red flour beetle or merchant grain beetle. This can be exploited by the pest management professional, because capture of more than one or two merchant grain beetles in the same trap strongly suggests that the source of the infestation is in proximity of the trap.

Pest management professionals may utilize concurrent application of residual insecticides and insect monitoring using traps. Ironically, recent research showed that the use of residual insecticides (for example: Conquer, Suspend SC, Talstar P, or Tempo SC Ultra) resulted in fewer red flour beetles being captured in traps and measurable increases in dead adults observed on the floor, but no change in the population density of the flour beetles in the food patches (Toews et al. 2009). These observations strongly suggest that managers relying on trap captures in insecticide treated structures could easily be deceived into believing that the insecticide was suppressing insect population growth when, in fact, the population was constant or even increasing. Dead insects on the floor should be considered a useful indicator of a continuing infestation rather than evidence that the insecticide program is successful.

Developing and Managing a Trapping Program

Books and other extension publications provide specific recommendations for operating a trapping program. Research and practical experience strongly suggest that grain storage, food processing, warehousing, and retail facilities are far too diverse to expect a single set of recommendations to be adequate. The purpose of this section is to help practitioners address six fundamental questions when developing a trapping program:

- What type of trap should be used?
- Should pheromone lures and oil attractants be utilized?
- How many traps are necessary?
- Where should traps be located?
- How often should traps be serviced and lures replaced?
- Is every insect species captured economically important?

In addressing these questions, pest management professionals should realize that some level of experimentation will occur in operating a trap-based sampling program. Many of the following examples are based on studies of the Indianmeal moth in food processing facilities, but the case studies are relevant for other moth pests such as almond moth, raisin moth, and Mediterranean flour moth. Similarly, studies with red flour beetle, warehouse beetle, rusty grain beetle, and the lesser grain borer are highlighted below, and those examples are similar to other beetle pests.

What type of trap should be used?

The answer requires careful assessment of the pest community in the given food facility and an attempt to identify the most economically important species that will be targeted. Information about the most likely pests for a given combination of food products and geographical region can be readily obtained through university Extension programming, reputable pest control operators, distributors of trapping devices, and industry peers. After establishing which pests to target, the next step is to evaluate available traps. Traps vary in price, size, durability, placement restrictions, and potential for using different attractants, such as food attractants or pheromone lures. Research comparing insect captures among traps is available. For example, Campbell et al. (2002a) conducted an experiment to compare warehouse beetle captures in hanging Pherocon II sticky traps with FLITe-TRAK pitfall traps placed on the floor immediately below the aerial trap. The two types of traps were placed in the same horizontal distribution pattern with 37 traps of each trap. Trapping was conducted for nine consecutive weeks. Because of their placement on the ground, almost one-third of the FLITe-TRAK traps were lost because of warehouse operating procedures. Mean captures in the FLITe-TRAK traps were almost twice of those with Pherocon II traps. In other words, either the trap itself or the vertical placement greatly influenced captures of warehouse beetles. The number of "zero captures" (empty traps) was 96 with Pherocon II traps, but only 30 with FLITe-TRAK traps. This example illustrates that trapping of the warehouse beetle appears to be most effective when traps are placed on the ground; however, traps on the ground are more vulnerable to getting lost or damaged.

As part of the selection process, carefully review the existing literature and consult with vendors of insect trapping supplies or extension services to reduce the list to the two to three most likely trap candidates. One recommendation is to purchase a few traps and conduct in a simple comparative study in two to three separate rooms or portions of a food facility. Consider a situation where you have identified three potential traps: T1, T2, and T3. Next, identify a stored product facility with three distinct trapping spaces (rooms or floors) with insect infestation: R1, R2, and R3. Conduct weekly trapping for nine consecutive weeks following a pattern with weekly rotation of traps (Table 1).

By operating all three traps in all three rooms in different weekly intervals, after nine weeks it is possible to rank the captures with each trap and see if one trap is consistently trapping more insects than the others. For example, hypothetical trap captures are shown in Table 1. From the last three columns note that weekly captures varied and captures were higher in rooms 1 and 2 compared to room 3. Despite the variation, note that trap 1 caught 13 of the 34 insects trapped in room 1, 17 of 35 in room 2, and 5 of 12 in room 3. Thus, it caught considerably more than 33% of the trap captures and therefore seemed to perform better than the other two traps. A similar comparative approach can be used to examine different placement options of traps and for comparison of trap lures. Other important considerations regarding choice of trap type include proportion of traps lost, how easy the traps are to service, and whether trap captures tend to show trends over time or indicate meaningful spatial distribution patterns (see section on trap data interpretation).

Should pheromone lures and oil attractants be used?

The purpose of using an attractant (pheromone lures and oil attractants) is to increase the capture rate. Apart from probe traps inserted into unprocessed food products, unbaited traps typically capture very few insects. There are few studies showing that trap color, color contracts, and trap shape are important for effective trapping of stored product moths (Levinson and Hoppe. 1983, Nansen et al 2004d). Most stored grain insects show highest level of flight

Table 1. *Suggested trap rotation among three rooms and example insect captures to evaluate how performance of three trap types can be assessed during nine weeks of trapping.*

	Room in Facility				Example Number of Captures		
Week	Room 1 (R1)	Room 2 (R2)	Room 3 (R3)		Room 1 (R1)	Room 2 (R2)	Room 3 (R3)
1	T1	T2	T3		6	3	0
2	T3	T1	T2		3	6	0
3	T2	T3	T1		4	3	2
4	T1	T2	T3		5	2	1
5	T3	T1	T2		4	7	2
6	T2	T3	T1		4	4	1
7	T1	T2	T3		2	3	2
8	T3	T1	T2		3	4	2
9	T2	T3	T1		3	3	2
				Total	34	35	12

active around dusk and dawn, so they respond much less to bright colored traps (like yellow traps placed in gardens) than, for instance, flies, mosquitoes, gnats. Pheromone lures and food-based oils are the most important attractants used in traps for monitoring of stored grain insects. The question of which lure or attractant to use can be studied based on a simple comparison of lures (as outlined in the study of trap types in Table 1).

A couple of important additional concerns regarding effective use of trap lures need to be addressed. Suppose a highly attractive lure was available that attracted insect individuals within a range of 50 to 100 m of the trapping station. Such a lure will obviously enable high insect captures, but how should those captures be interpreted if insects were attracted over such long distances? It seems reasonable to argue that a lure with much shorter trap catch range (distance or range of attractiveness) may be more appropriate for meaningful interpretation, especially if the objective is to interpret the spatial distribution pattern of insect pests and to locate "hot spots" with high pest incidence. Mark and recapture studies with Indianmeal moths have demonstrated that these moths migrate among floors in flour mills and can migrate as far as 137 m within food processing facilities (Campbell et al. 2002a). Nansen et al. (2006b) released groups of 30 Indianmeal moth males from a single known location in an otherwise empty space with 30 pheromone-baited trapping stations arranged in a 3 m by 3 m grid. With the release point (supposedly the position of high insect densities) known, the question was how well pheromone-based trap captures could identify that area. Figure 5 below shows results from three of the male moth releases; the release point is indicated with a cross and increasing magnitude of captures is depicted by increasing bubble diameter. Interestingly, the results from that study suggested only a modest correlation between trap captures and distance from release point. In other words, it was not possible to accurately pinpoint the release point (or theoretical infestation) based on trap captures.

An important characteristic of trap lures is that they may be more attractive to a specific proportion of the insect pest population, which means that the trap captures may not be representative of the entire insect pest population. For instance, sex pheromone lures for trapping of moths are only attractive to males. Several careful experimental studies have shown that age and mating status of the individuals caught in traps may not be representative of the pest population at large. Also, the life stages captured may not be the ones actually damaging food products. This is clearly the case with stored product moths; adults are exclusively captured in the traps but the damage is caused by larvae.

How many traps are necessary?

This question is important for several reasons: more traps increase costs and labor needed to maintain the trapping program, so it is important not to deploy more trapping stations than necessary; stored product insects may vary greatly in response to commercial attractants; and stored food products vary in value depending on processing level and overall market price (crop seeds are much more valuable than regular unprocessed grain). Typically, there is a positive correlation between food product value and number of trapping stations deployed. The choice of how many trapping stations to deploy depends on the overall objective of the trapping program. If the main purpose is to monitor changes in insect trap captures over time, then continuous service of 10 to 20 stations may be sufficient for a given facility. Considerations such as facility size, number of floors, complexity of trapping environment, and varying temperature conditions are all good reasons to increase the number of traps.

One way to evaluate the number of trapping stations necessary is to select a high number of trapping stations initially and reduce the number of traps deployed during consecutive weeks. Set the largest number of traps deployed equal to 100% and then conduct trapping with random sequences of trap numbers representing 50% to 90% of that total during subsequent weeks. Based on weekly captures, calculate the average number of insects per trap and determine at what trap density captures appear to stabilize. For instance, imagine that the following captures are obtained during a 12-week experimental trapping period (Figure 6). The theoretical example illustrated in Figure 6 shows that average captures varied greatly when 10 to 12 trapping stations were used, while they were much more consistent when more than 20 trapping stations were used. This simple exclusion study can be used to determine the appropriate number of trapping stations in a given stored-product facility, but the complexity of the facility is important in deciding how many traps to deploy (Campbell et al. 2002a).

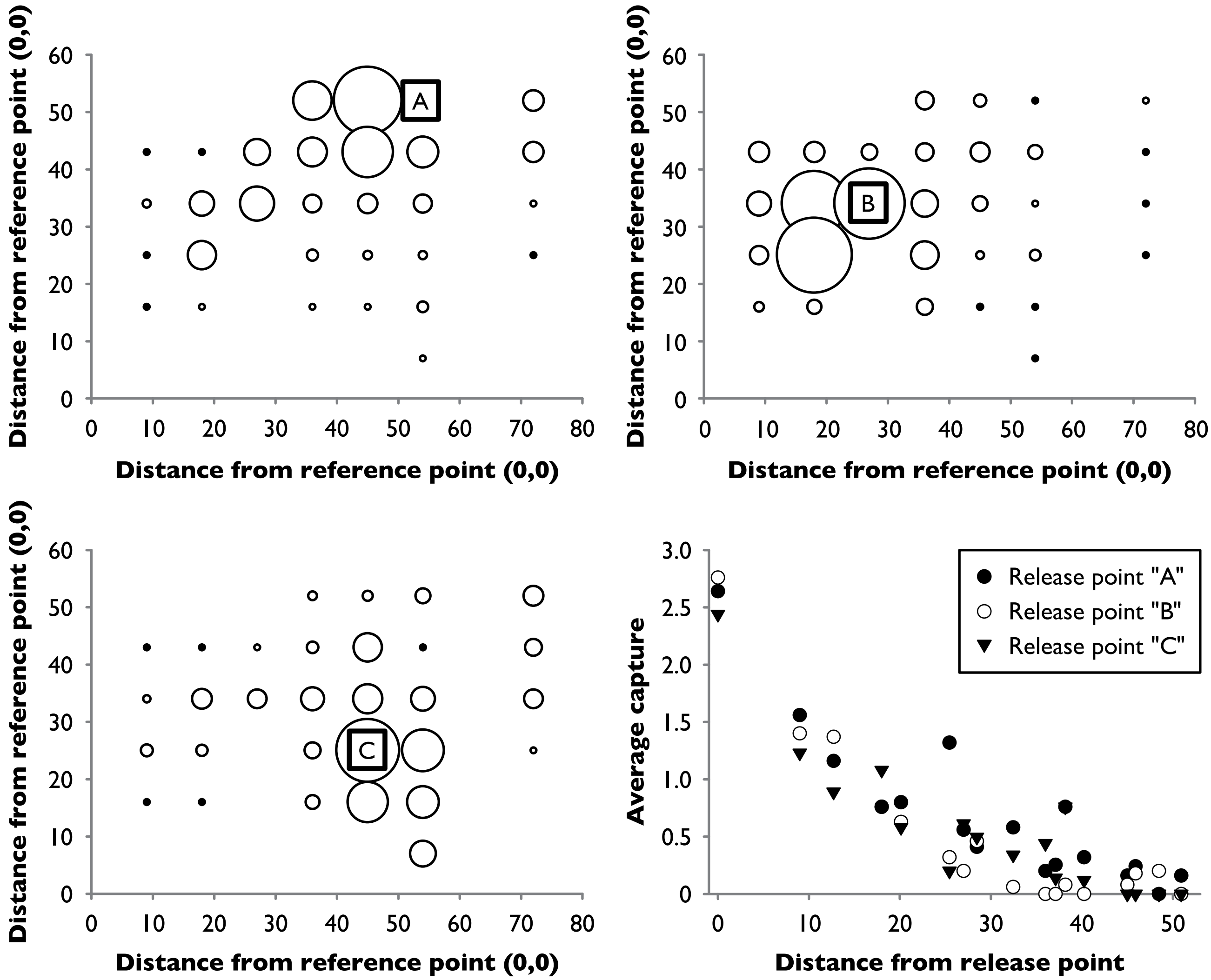

Figure 5. *Bubble plot of moth captures in relation to the release point of the moths in an empty warehouse. X's mark the release point while circles with proportionately larger diameters indicate increasingly larger numbers of captured insects at that location.*

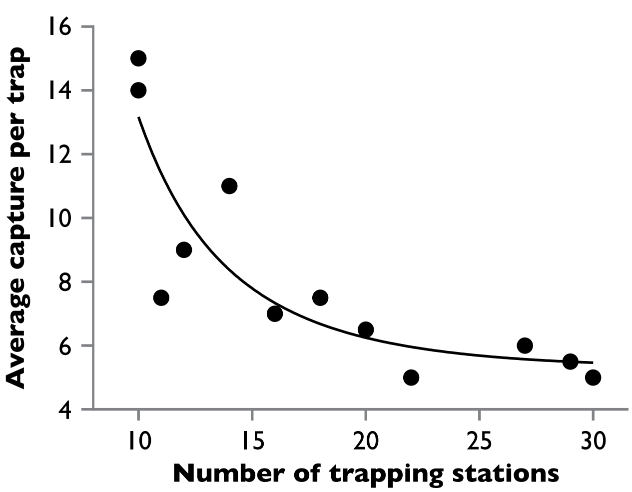

Figure 6. *Relationship between number of trapping stations and average moth captures.*

Where should traps be located?

One of the key aspects of trap placement is to know the "attractive range," or from how far target insects will be attracted. No scientific studies address how far apart pheromone baited traps should be placed under commercial conditions. With so many variables it may not be feasible to address this issue. The only scientific evidence, conducted under experimental still air conditions, suggests that sex pheromone lures are attractive to moths at distances of about 4 m (Mankin et al. 1999). This should be considered the minimum trap distance when commercial lures are used. No controlled studies were found in the literature on trap catch range with food-oil based lures.

Most researchers place trapping stations 20 to 50 m apart in food processing facilities. In large facilities, this distance is highly influenced by costs and positioning of pillars or similar structures that are convenient for trap placement. Ventilation systems, open doors, and machinery producing heat and air currents will affect the shape and size of attractive plumes being emitted from the trap. A lure may have a much wider trap catch range if a ventilation fan generates an air current that passes through the trap and increases pheromone dispersal. One must also consider that the concentration of attractant in the plume decreases with distance from the lure. Insects attracted to a pheromone-baited trap move upwind towards higher pheromone concentration, so the size, shape, and consistency (level of turbulence) of a pheromone plume can greatly influence the likelihood of an insect being able to locate and be captured in a given trap. Constant changes in air currents occur inside food processing facilities because of moving objects and ventilation systems. A practitioner of insect trapping must realize that the complex nature of the stored product facility can influence trap captures.

Another aspect of trap placement is vertical positioning. Food processing facilities and warehouses are comprised of large buildings with multiple floors and rooms sometimes reaching 5 to 10 m in height. The question of how high aerial traps should be positioned off the ground has received little attention. In one of the few studies specifically addressing this aspect of trapping programs, Nansen et al. (2004d) used freely suspended pheromone baited Pherocon II aerial traps on a vertical string at different heights above the floor (Figure 7). When traps were away from the walls, more moths were captured closer to the floor and near the ceiling. Captures were similar at all heights when a landing platform was added or the traps were placed near a wall (Figure 7).

Several conclusions can be drawn from this study and studies of pyralid moth mating behavior. Phelan and Baker (1990) provided drawings of pyralid moth courtship behavior and demonstrated how males fly toward the calling females but walk the last part of the way before encountering the female. It appears that male moths responding to the synthetic pheromone are more likely to enter the Pherocon II trap when there is an adjacent surface (floor, ceiling, or landing platform). In commercial settings, diamond-shaped pheromone baited traps are often suspended freely from pipes or other structures.

Data presented here clearly demonstrate that traps may perform quite differently simply because of their vertical position and/or proximity to surfaces. Trap capture efficiency may be increased by placing traps on the floor. Similar results were obtained in a trapping study of the warehouse beetle (Campbell et al. 2002a). Unfortunately, traps placed on the floor are also more likely to be lost or damaged so careful marking and consideration of trap site is critical.

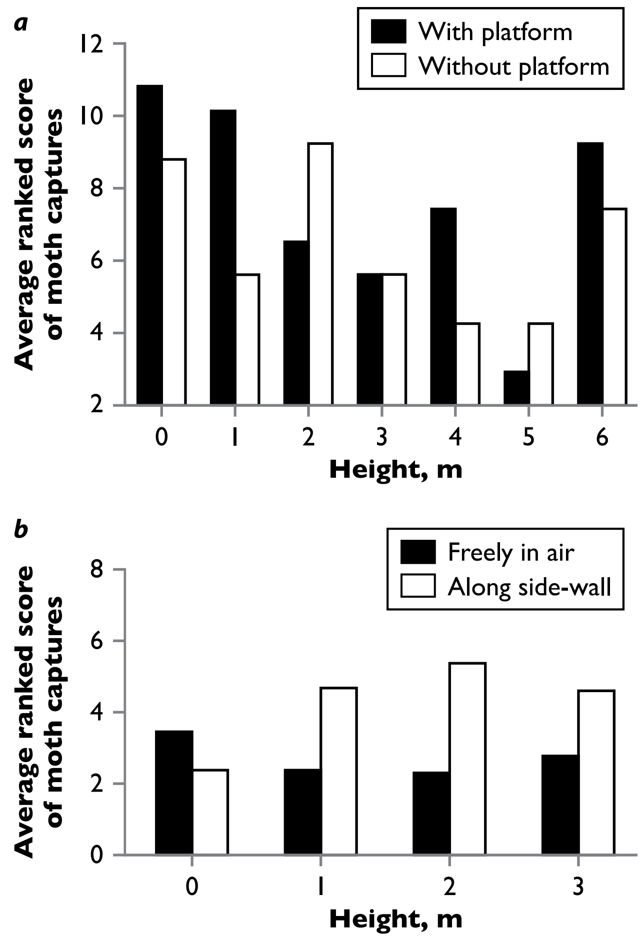

Figure 7. *Trap captures of moths along vertical gradients with/without a platform attached the pheromone baited sticky trap (a) and (b), or when traps are placed freely suspended or alongside wall (c).*

How often should traps be serviced and the lures replaced?

The service interval, defined as the amount of time between checking traps, is important. Stored grain insects complete their life cycle within 21 to 35 days, so a monthly service interval means that only one data point is obtained per generation. Risks of monthly service include changes in food availability (turnover of food products); changes in weather patterns and insect mobility, including flight; and environmental changes due to sanitation or other operational procedures. Each of these factors can cause marked changes in insect mobility and therefore increases in trap captures even though pest populations are unchanged. Monthly trap service will increase the risk of substantial insect damage before a problem is detected. Generally speaking, traps should be serviced on a 7- or 14-day schedule. Make sure trapping stations are serviced the same day and that all lures are replaced to enable direct comparisons of captures among traps. The question about how often to replace lures depends on the lure. Some synthetic sex pheromones for stored product moths remain attractive for many months, while the aggregation pheromone for lesser grain borers loses attractiveness in one week. Generally, lures for red flour beetle, warehouse beetle, and Indianmeal moths should be changed every four to six weeks.

Is every insect species captured economically important?

Species composition of the captured insects is also critically important. In bulk grain storage, there is seldom an economic incentive to fumigate in response to the presence of external infesting insect species, even at relatively high population densities. Examples of commonly encountered external infesting species in bulk grain bins include the Indianmeal moth, sawtoothed grain beetle, red flour beetle, hairy fungus beetle, flat grain beetle, and rusty grain beetle. Conversely, internal infesting species such as Angoumois grain moth, rice weevil, granary weevil, maize weevil, lesser grain borer, bean weevils, and khapra beetle are serious and economically important pests of stored commodities. The khapra beetle is arguably the most serious pest of stored products worldwide and is under strict quarantine from the United States. Population development by internal infesting species should initiate conversations about the intended use of the raw commodity, how much longer the commodity will be stored, ability to manage temperature and moisture content, and potential for effective fumigation.

Insect species composition is an equally important consideration in the food processing, warehousing, and retail segments of industry. Because consumers will not tolerate visibly contaminated foodstuffs, the same externally infesting stored product insect species that are not an economic problem in bulk stored grain are indeed a problem in this arena. Additional species of common economic concern include the warehouse beetle, cigarette beetle, drugstore beetle, merchant grain beetle, Mediterranean flour moth, rice moth, and almond moth. Facilities that use animal proteins may develop larder beetle and red legged ham beetle infestations. These animal feed products become particularly susceptible to infestations if the feed products become moist, which may happen if machinery is creating steam or roofs or walls are leaking water. Managers should realize that not all insect species captured in traps infest grain or processed foods. Research shows that general predators and fungus feeders persist in many structures. Ground beetles, fungus beetles, click beetles, and antlike flower beetles are all large families of beetles that fit this category and have been captured in stored product insect traps.

Data Interpretation

Considerable differences exist in the number of traps required for various purposes. Characterization of seasonal changes in pest population dynamics over time can be conducted successfully with 10 to 20 trapping stations. Long-term trapping data are valuable for interpreting the impact of changes in operating procedures, fumigations, or other management tactics. They can also show how seasonal differences affect pest populations. Conversely, spatial analyses such as contour mapping and use of spatial statistics generally require more data points. In fact, some authors provide empirical data suggesting that insect counts from traps may not be the best candidates for predictive spatial pattern analyses (Nansen et al. 2003, 2006a).

Environmental effects on trap capture interpretation

A given set of trapping data is highly dependent on the environmental conditions in the sampling universe (the trapping space). For example, a capture of 10 moths is not necessarily twice as concerning as capturing five moths, because so many interacting factors can be responsible for an increase in trap captures. Toews et al. (2005a) trapped red flour beetles in experimental arenas with different levels of environmental heterogeneity and complexity. Under experimental conditions, they showed that beetles were predominantly captured in the corners of the room and underneath structure like shelves. They also showed that there was a stronger correlation between known insect density and number of insect captures when food was absent, which means that sanitation practices can greatly impact trapping captures. In a study of beetle captures in commercial pet stores, Nansen et al. (2004e) showed that captures of several beetle species increased markedly immediately after implementation of sanitation practices but later resumed to pre-sanitation levels. Similarly, changes or fluctuations in ambient temperatures, light conditions (Bell 1981), and movement of food products can greatly impact trap captures. The presence of food material in the environment around a trap can influence insect captures in traps and this is likely to vary over time and among trap locations. A lack of food due to increased sanitation will cause insects to search larger areas, which will increase trap captures (Nansen et al. 2004e). Managers should also collect environmental data including temperature, humidity, and information about sanitation procedures, movement and turnover of food products. This information can be of critical importance when trying to interpret trapping data in both spatial and seasonal contexts.

What does the number of caught insects actually mean?

There are many studies suggesting that there is not always a tight correlation between captures of stored product insects and insect population densities (Vela-Coiffier et al. 1997, Hagstrum et al. 1998, Campbell et al. 2002a, Nansen et al. 2004c, Toews et al. 2005b, 2005c, 2009). As a possible solution to this problem, Nansen et al. (2008) proposed a binomial approach to trap capture interpretation, in which they focused on the proportion of empty traps. Instead of counting how many insects were captured or examining average counts per trap, they based their interpretation on how many traps did not capture any insects. Two major advantages to this approach are that it is much easier and faster to determine the proportion of empty traps than to count how many insects were caught in each trap; and working with proportional data (empty traps / total number of traps) eliminates data outliers. Nansen et al. (2008) showed that a wide range of data sets followed a similar frequency distribution. A baseline trapping data set may suggest that action against a given insect pest should be taken when the proportion of empty traps falls below 0.40 or 0.20.

Toews et al. (2006a) approached the problem of trap capture interpretation by focusing on both the quantity and distribution of captures in space. The researchers suggested concurrent plotting, by species, of the proportion of traps with at least one capture, overlaid with the capture mean and standard error of only the traps containing captures (Figure 8). Using this method, a consultant can easily assess an increasing insect population by the presence of an increasing proportion of traps, with at least one capture (January 1 to August 15 on Figure 8). Little change in the proportion of traps with at least one insect, coupled with a disproportionate increase in the standard error (or no standard error) (November 20 on Figure 8), indicates a localized problem that should be handled with direct interventions. Examples include improved exclusion, screen repairs, repair of door sweeps, improved sanitation, or targeted application of residual insecticides. The absence of an increasing proportion of traps with at least one capture, coupled with a significant increase in the mean number of captures with a proportionate increased standard error, would indicate that the population is increasing in a relatively small area. Obviously, both increasing means and proportion of traps with captures indicates a more serious problem; depending on the situation and time of year this could be used to justify a global intervention such as fumigation.

Advanced spatial interpretation

Spatial analyses are used to characterize the relationships among sample data points and then interpolate values between points. Spatial mapping of insect counts has been used to show changes in stored product insect density in grain storage (Arbogast et al. 1998), in food processing plants (Campbell et al. 2002a), and in outdoor habitats (Nansen et al. 2002). This type of analysis is typically used to identify specific areas for enhanced control or suppression efforts. In contrast to conventional statistical approaches that assume each sample point is completely independent, the general premise of spatial analysis is that sample points that are closer together are more correlated than sample points that are farther apart. The usefulness of these maps is directly proportional to the number of sample points used to construct them. In other words, the tradeoff to using fewer traps is less precise predictability. There are many methods used to interpolate the areas between the sample points, each with important theoreti-

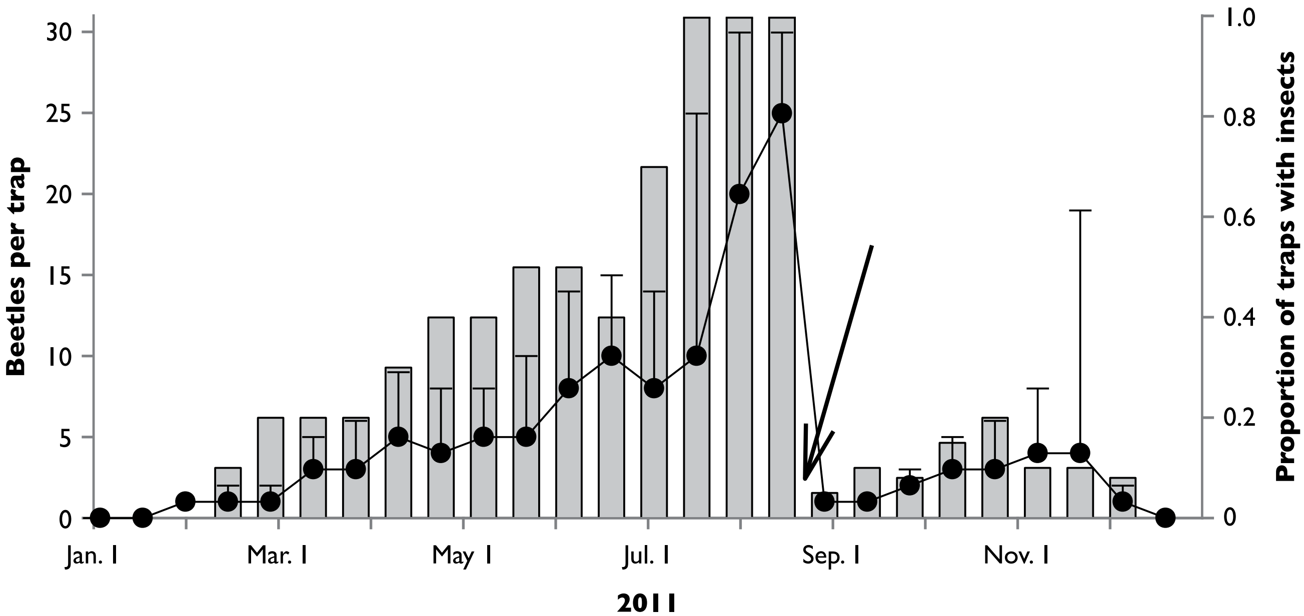

Figure 8. *Illustration of red flour beetle captures in pitfall traps. Vertical bars (right axis) indicate proportion of traps containing at least one insect. Means and standard errors (left axis) represent captures in traps containing at least one insect (no zeros included in mean and standard error calculations). The arrow shows when a fumigation was conducted.*

cal and statistical considerations that are beyond the scope of this publication. While algorithms and computations are complex, the process of generating a contour map using a software program is relatively easy. Each trap location in the data set must be associated with x and y coordinates that accurately represent the location of that particular trap in space. In a spreadsheet, list x-coordinate, y-coordinate, and number of captures in three successive columns, and then import those data into a software program such as Surfer 10 (Golden Software, Golden, Colo.). Brenner et al. (1998) provide suitable background information for creating spatial maps for spatially targeting insects in structures.

Another approach to spatial interpretation is to use simple "bubble plots." The investigator creates scaled maps in which increasing bubble diameters indicated trap locations where larger numbers of insects were captured. Nansen et al. (2009) used this technique to interpret moth captures in specially designed water bottles that were suspended in a 3 m by 3 m grid in commercial peanut warehouses. This study showed gradual increases in moth populations over four weeks, but weekly patterns of trap captures indicated clearly distinct zones either with or without moth captures (Figure 9). Thus, even though trapping stations were only a few meters apart, it was possible to detect zones with hot spots and zones without moths.

Impact of outside conditions

The importance of pest immigration into grain and food processing facilities is readily apparent in long-term data sets (Toews et al. 2006a, Campbell et al. 2010a, 2010b). Monitoring outdoor pest insect populations can often explain why indoor pest populations change (Campbell and Arbogast 2004). This is true because stored-product insects are well adapted to survival and reproduction in a variety of natural and manmade habitats. Newly emerged adults will find and exploit patchy habitats, and it is extremely difficult to completely exclude insect pests from stored-product facilities. Studies of the lesser grain borer and its close relative, the larger grain borer, revealed that these pests are abundant in natural habitats and are able to complete their life cycle on tree nuts (Nansen et al. 2004c; Edde et al. 2005; Edde and Phillips 2006, Jia et al. 2008). Toews et al. (2006b) compared lesser grain borer captures in outdoor traps and traps suspended from the ceiling inside a modern bagged grain storage facility; those data showed highly significant correlations between these locations. Campbell and Mullen (2004) captured warehouse beetles and Indianmeal moths inside and outside food processing and storage facilities. There seemed to be considerable movement of stored product insects both migrating out of and immigrating into stored product facilities. Finally, Toews et al. (2006b) monitored stored product insect pests on unbaited rodent glue boards placed around overhead doors and documented seven species with distinct seasonal population trends. These compelling data showcase how indoor captures can be predicted with outdoor captures. They could also be used to explain why indoor insect captures continue immediately after fumigation (Campbell and Arbogast 2004, Toews et al. 2006a, Campbell et al. 2010b).

The potential value of outside trapping is further supported by a considerable body of research demonstrating that weather variables can be used to characterize seasonal fluctuations in stored grain insect captures (Nansen et al. 2001; 2004a; Edde et al. 2006; Toews et al. 2006b). Changes in insect captures can be attributed to a wide range of circumstances (change in temperature, barometric pressure, humidity, food availability, and disturbance) without actually representing a change in pest population density. Concurrent logging of temperature and relative humidity can help with interpretation. Campbell et al. (2010b) showed that there was a direct relationship between indoor temperature in an operating mill and outdoor temperature. The trap data management spreadsheet or digital storage system should allow the practitioner to enter climate data and data concerning food availability, sanitation, operating machinery, insecticide applications (including fumigations), heat treatments, and other control tactics (Roesli et al. 2003).

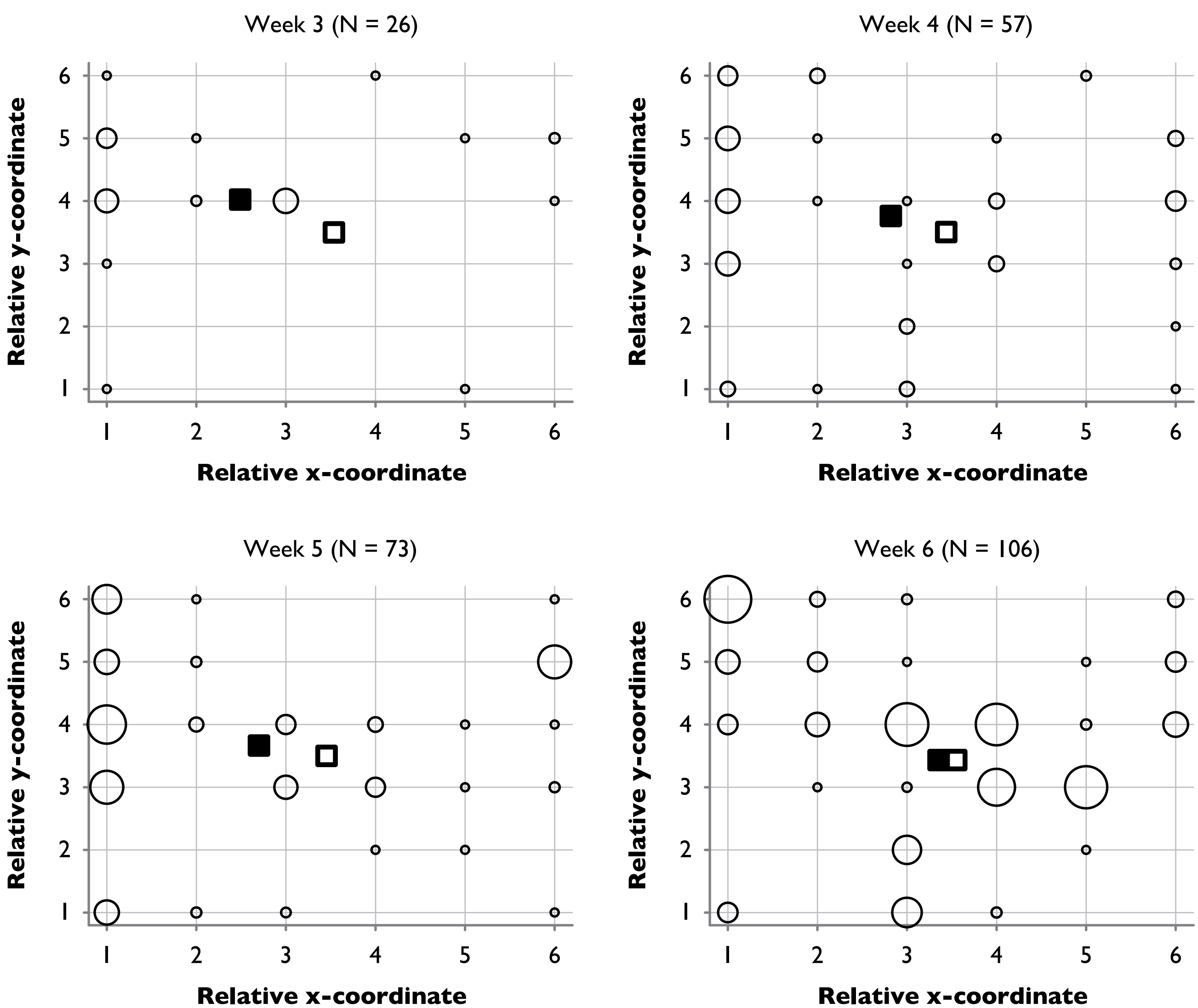

Figure 9. *Bubble plots of insect captures by week in a commercial peanut plant with size of circles depicting the magnitude of captures. Total weekly captures varied between 26 and 106 moths. Empty squares represent the sampling centroid and filled squares trap capture centroids.*

It seems reasonable to propose that practitioners of trapping in commercial stored product facilities and applied researchers collaborate on development of weather-based risk warning systems, which could serve to alert food facility managers about when high levels of insect flight activity (and therefore risk of infestation) should be expected. Such weather-based risk warning systems would involve careful analysis of how weather variables affect insect flight activity (Nansen et al. 2004b). In Figure 10, the bold line represents a seasonal baseline, which may have been developed on the basis of how weather variables influence insect flight activity, and it may require several years of initial trapping before such a seasonal baseline can be developed. The seasonal baseline clearly indicates that the given insect has higher flight activity in the summer months than during other parts of the year. The dots represent trap captures obtained after the seasonal baseline was developed, and the idea behind this interpretation approach is that trap captures should be of concern if they exceed those depicted by the baseline with a certain margin. In other words, a trap capture of five moths in July would not be considered alarming, because that is during the time with high level of flight activity. Conversely, five moths per trap would be alarming from December through February.

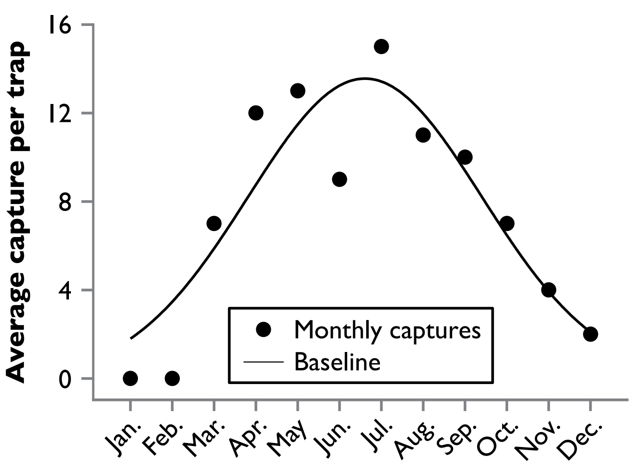

Figure 10. *Illustration of how a trapping baseline can be used to interpret seasonal trap captures.*

Conclusion

The use of traps and subsequent interpretation of insect captures for monitoring and population estimation are the most efficient and cost effective tools available. Practical, economic, and ecological considerations require pest management professionals to conduct some level of experimentation each time a new trapping program is initiated. Data generated using traps and interpretation provides the best pest management decision support.

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Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement.

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S156 – 21 September 2012

22 Acoustic Monitoring of Insects

Richard Mankin
David W. Hagstrum

Farmers, grain elevator managers, and food processors often sample grain for insect-damaged kernels and numbers of live adult insects (Yigezu et al. 2010), but these easily obtained measurements of insect levels do not provide reliable estimates of the typically much larger populations of immature insects feeding internally (Perez-Mendoza et al. 2004). If stored products were transparent, sampling of this much larger immature population could enable better estimates of total population levels, earlier detection of internal insect infestations, and improved forecasting of when to aerate, fumigate, or sell for optimum profitability (Adam et al. 2010). Retail store managers could better focus on where and when to conduct sanitation efforts and remove infested stock or spillage (Arbogast et al. 2000). Breeders could screen more quickly for different varieties of grain that were resistant to larvae of different pest species (Devereau et al. 2003).

Used carefully, acoustic devices provide a measure of "transparency" and enhance inspection of many stored products that otherwise could not be monitored inexpensively without destructive sampling. In addition, acoustic methods can be adapted for automated, continuous monitoring, increasing the likelihood of detecting infestations before they cause economic damage. Such capability can be of benefit to pest managers, regulators, and researchers. New acoustic devices and signal processing methods have been developed in the last few years that greatly increase the reliability and efficacy of insect pest detection (Mankin et al. 2011, Leblanc et al. 2011).

Equipment

Microphones are ubiquitous in cell phones and recorders, particularly the inexpensive, compact electret microphones, but piezoelectric sensors that are in direct contact with the grain or stored product containing the insects are better choices for many stored product insect detection applications. Piezoelectric sensors reduce the losses caused by attenuation when acoustic signals cross from one transmission medium to another. Commercially available guitar pickups, geophones, and accelerometers (see Figure 1) contain piezoelectric sensors that use different kinds of amplifiers to increase signal amplitudes sufficiently for data analysis and interpretation. All of these sensors have been used successfully to detect insects in stored products. Table 1 lists many of the stored product insects that have been monitored by acoustic sensors of different types.

Because small insects, particularly young larvae, are weak emitters of sound, researchers have developed and tested various procedures to minimize or filter out interfering background and electrical noise. Electrical noise often can be reduced by placing amplifiers as close to the sensor as possible. Calibrated, low-noise amplifiers are typically the most costly part of a detection system, but when many sensors are employed in a detection project, the costs can be reduced by multiplexing many sensors to one amplifier. Several soundproofing and vibration-reduction methods have been described for sampling stored grain (Vick et al. 1988a, Hagstrum and Flinn 1993, Mankin et al. 1997b), and are applicable for detection of insects in packaged goods as well.

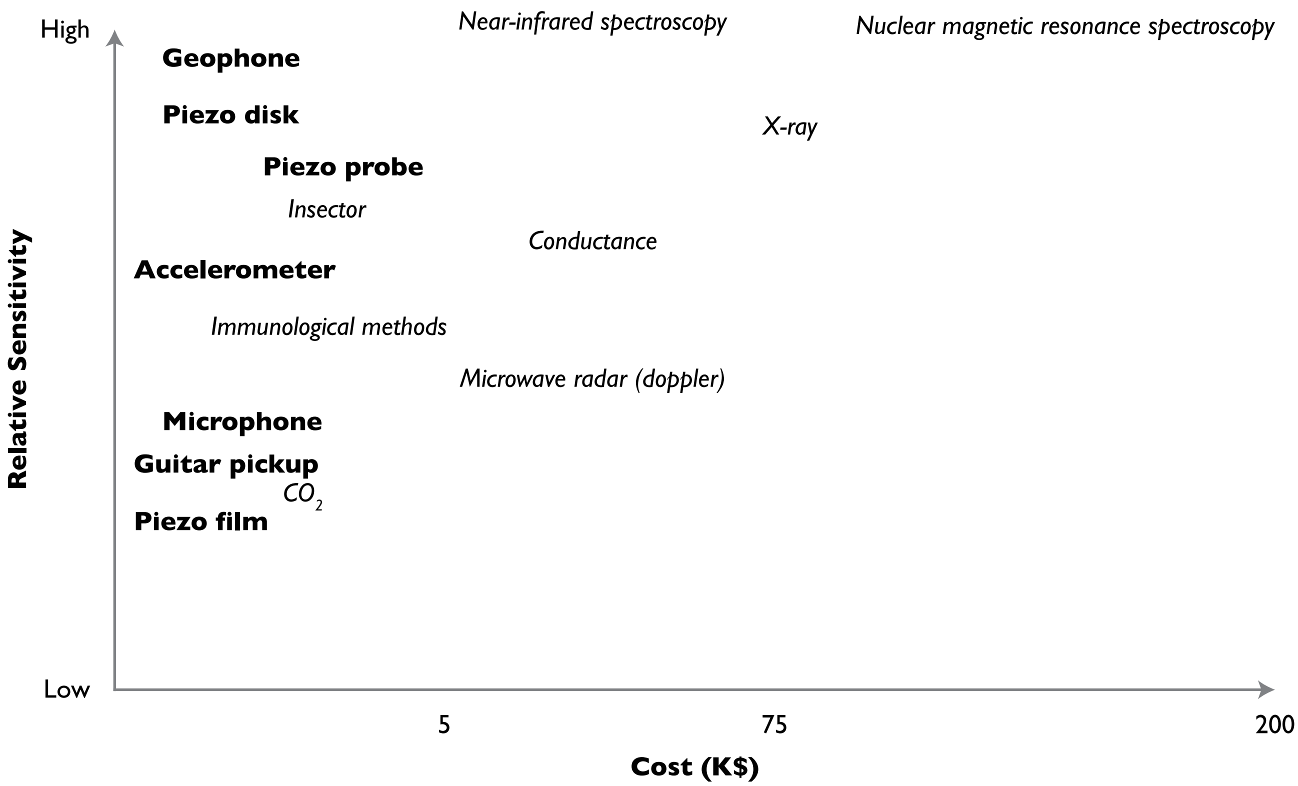

Figure 1. *Comparisons of the sensitivities and costs of different acoustic sensors (bold) in relation to other detection methods (italics): piezo film, probes, and disks, ultrasonic sensors, accelerometers, and geophones typically use piezoelectric technology, and cover a range from low to high sensitivities. Other detection methods, including CO_2 emission, immunological methods, the Insector (Flinn et al. 2006, Opit et al. 2009), microwave radar, X-ray, infrared spectroscopy, and nuclear magnetic resonance, can have high sensitivity relative to acoustic methods, but also may be considerably higher in cost (Chambers et al. 1984, Neethirajan et al. 2007, Pearson et al. 2007).*

Ultrasonic sensors that detect signals between 20 and 200 kHz can be useful for detecting nearby insects in moderate to high levels of background noise. The benefit is that background noise usually is low at ultrasonic frequencies. Unfortunately, the signals attenuate rapidly over short distances in stored grain (Shade et al. 1990). One solution to this problem in sampling stored grain is to place the sample inside a long, narrow metal cylinder so that no individual grain is more than 2 to 3 cm from the edge. This also enables the approximate location of each infested kernel to be identified, and the infestation density can then be estimated as the number of separate infested locations (Shuman et al. 1993, 1997).

When background noises cannot be filtered out entirely, it is possible to filter out frequencies above and below the peak energies of signals typically produced by the target insect. Modern amplifier systems often enable this capability, and much of the interference from background noise can be eliminated by filtering out signals below 200 Hz.

Insect Sound-Production Variability

Adult and immature stages of stored product insect pests vary considerably in size and in the amplitudes and rates of sounds they produce (Arnett 1968, Mankin et al. 1997a). Relatively large *Sitophilus oryzae* (L.) and *Tribolium castaneum* (Herbst) adults, for example, are more readily detected than intermediate-sized *Rhyzopertha dominica* (F.), while the smaller *Cryptolestes ferrugineus* (Stephens) and *Oryzaephilus surinamensis* L. are less readily detected (Hagstrum and Flinn 1993). Some insects become quiet when they are disturbed, and the time needed for them to return to normal activity after a disturbance must be taken into account when they are monitored (Arnett 1968, Mankin et al. 2011). The rate of sound production also is affected by external factors such as temperature and disturbance levels. Vick et al. (1988a) determined that *S. oryzae* larvae in grain can be detected from distances up to 10 to

15 cm. *Tribolium castaneum* adults were detected up to 18.5 cm (Hagstrum et al. 1991). On average the sound production rate of immature stored product insects tends to increase with instar, as was found for *S. oryzae* larvae in grain (Pittendrigh et al. 1997, Hickling et al. 2000) and *Callosobruchus maculatus* (F.) larvae in cowpeas, *Vigna unguiculata* (L.) Walp., (Shade et al. 1990). Also, externally moving adults often produce sounds at considerably higher rates than internally feeding larvae, up to 37 times higher for *R. dominica* (Hagstrum et al. 1990), and 80 times higher for *T. castaneum* (Hagstrum et al. 1991). It should be noted, however, that because sound levels attenuate with increasing distances from a sensor, a small larva in a nearby grain kernel might be detected at the same time that signals from a much larger adult outside the 15 to 20 cm active space might fall below background noise levels. In addition, a small adult insect like *C. ferrugineus* will move through the interstices between grains easily and produce fewer sounds than larger adults such as *R. dominica*.

Disturbance can enhance or reduce detectability of stored product insect pests, depending on the species, and increases in temperature usually result in increased rates of sound production until temperatures exceed 30 to 40°C. Stirring of grain containing 4^{th}-instar *S. oryzae*, for example, reduced sound production for periods of up to 20 minutes (Mankin et al. 1999). Adult *T. castaneum* sound production increased between 10 and 40°C (Hagstrum and Flinn 1993), while *C. maculatus* larvae decreased their rates of sounds above 38°C in cowpeas (Shade et al. 1990). Sound production of *S. oryzae* adults in grain decreased above 30 to 35°C, and *R. dominica* adult sound production rates plateaued above 30°C (Hagstrum and Flinn 1993).

Rapid heating has been tested to increase the detectability of adults and internally feeding larvae in stored grain initially at low temperatures below 20 °C. The use of radiant or convective heat, to raise the temperature rapidly above 29°C, increased the rate of sounds from internally feeding *S. oryzae* larvae by a factor of 2 to 5 (Mankin et al. 1999). A patent was issued in France for heating grain to increase insect sound production (Mihaly 1973).

Under conditions of low disturbance and optimal temperatures, monitoring times of 180 seconds are adequate to reliably detect many stored product insects. The minimum monitoring interval depends on the fraction of time the insects are active. Vick et al. (1988b) found that *R. dominica* produce feeding sounds in grain in 61% of 5-minute intervals recorded over a 7-day period, *Sitotroga cerealella* (Olivier), 71%, and *S. oryzae*, 90%, and that quiescent periods occurred primarily during molting.

Acoustic Signatures and Temporal Patterns of Insect-Produced Signals

Problems in distinguishing sounds produced by target species from background noise and sounds from other insects have hindered usage of acoustic devices, but new devices and signal processing methods have greatly increased detection reliability. One new method considers spectral and temporal pattern features that prominently appear in insect sounds but not in background noise, and vice versa. Insect chewing and movement sounds usually have acoustic signatures (high-frequency components containing few harmonics) and they occur in bursts of short, 3 to 10 millisecond impulses (Potamitis et al. 2009, Mankin et al. 2010, Mankin and Moore 2010). Listeners or scouts can readily identify many distinguishing characteristics in the sounds produced by a target species after about an hour of training (Mankin and Moore 2010). Better understanding of these signal characteristics has led to improved capabilities for automated insect detection and monitoring (Mankin et al. 2010, 2011).

Efficacy and Reliability of Acoustic Detection Devices

The efficacy of acoustic devices depends on many factors, including sensor type and frequency range, substrate structure, interface between sensor and substrate, assessment duration, size and behavior of the insect, and the distance between the insects and the sensors. Larvae and/or adults of 18 species of stored product insect pests have been detected in grain or packaged goods using one or more of six types of acoustic sensors (Table 1). Considerable success has been achieved in protection against false positives (predicting the presence of a target insect when none is present) and some with false negatives (predicting the absence of insects when one is present) in detecting grain insect pests. For example,

Table 1. *Stored product insect pests of different stages detected with different types of acoustic sensor (adapted from Mankin et al. 2011).*

Species (Order[a]: Family)	Stage[b]	Sensor[c]
Achroia grisella (F.) (Lepidoptera: Pyralidae)	L	p_u
Acanthoscelides obtectus (Say) (Bruchidae)	(A)	p
Alphitobius diaperinus (Panzer) (Tenebrionidae)	L, (A)	p
Anobium punctatum (DeGeer) (Anobiidae)	L	p
Callosobruchus chinensis (L.) (Bruchidae)	L	m
Callosobruchus maculatus (F.) (Bruchidae)	A, L	p, p_u
Cylas formicarius elegantulus (Summers) (Curculionidae)	L	m_c
Cryptolestes ferrugineus (Stephens) (Laemophoelidae)	A	p
Oryzaephilus surinamensis (L.) (Silvanidae)	A	p
Plodia interpunctella (Hübner) (Lepidoptera: Pyralidae)	L	p
Rhyzopertha dominica (F.) (Bostrichidae)	A, L	m_c, p
Sitophilus granarius (L.) (Curculionidae)	A, L	p
Sitophilus oryzae (L.) (Curculionidae)	A, L	m, m_c, m_e, p, p_f, p_u
Sitotroga cerealella (Olivier) (Lepidoptera: Gelechiidae)	L	m_c, p, p_u
Stegobium paniceum (L.) (Anobiidae)	A	m_e, p_f
Tribolium castaneum (Herbst) (Tenebrionidae)	A	m_e, p, p_f
Tribolium confusum Jacquelin du Val (Tenebrionidae)	A, L	p
Zabrotes subfasciatus (Boheman) (Bruchidae)	L	p_u

[a]Species order is Coleoptera if not specified.
[b]A, adult; L, larva
[c]m = microphone (unknown type), m_c = capacitance (condenser) microphone, m_e = electret microphone, p = contact pickup using PZT (Lead zirconate titanate) piezoelectric transducer, p_f = PVDF piezoelectric film transducer, p_u = PZT ultrasonic transducer (20-200 kHz).

Shuman et al. (1993) found that 6% of grain samples infested with *S. oryzae* larvae were falsely rated positive for infestation and 34% were falsely negative. Adult *R. dominica* were identified successfully in continuous monitoring in 73% of tests, *T. confusum* 72%, *S. granarius* 63%, and *O. surinamensis* 61% (Schwab and Degoul 2005). Larvae were identified with somewhat less success (73% for *S. granarius*, 58% for *S. cerealella*, 57% for *R. dominica,* and 52% for *T. confusum*).

In grain stored in on-farm (65 to 191 metric ton) bins, an insect detection threshold of approximately eight intervals per day with sounds resulted in 11.5% false positives, 15 to 40% false negatives for more heavily infested bins and 52 to 86% false negatives for some of the more lightly infested bins (Hagstrum et al. 1996). The false positives are most often caused by electrical noise because grain is a good sound insulator. The false negatives are probably the result of insects being inactive when a sensor is checked, thus the number of false negatives may be reduced by checking a sensor more often.

Successful Applications of Acoustic Technology for Stored Product Pest Detection

Acoustic methods have been applied successfully for grain inspection (Vick et al. 1988a, b, Pittendrigh et al. 1997, Shuman et al. 1993, 1997), estimations of population density (Hagstrum et al. 1988, 1990, 1991, 1996), and mappings of stored product insect pest distributions (Hagstrum et al. 1996). Data collected by acoustic sensors from grain infested with a single species and stage typically provides sampling statistics similar to those estimated from grain samples for *R. dominica* larvae (Hagstrum et al. 1988) and *T. castaneum* adults (Hagstrum et al. 1991).

Acoustic devices of various kinds have been marketed for field use, and instrumented sample containers in sound-insulated chambers have been developed for commodity inspection. A sample container in a sound insulated chamber has been marketed for laboratory use (Sito Detect, Fleurat-Lessard 1988). Other sample containers with acoustic sensors (Pest-bin detector and EWDLab, Systelia Technologies, Carqueiranne, France) are discussed by Mankin et al. (2011). Probes for field use may be pushed directly into a commodity, i.e., Larva Sound Detector (Bad Vibel, Germany, Weinard 1998) and EWD Portable (Gobernado et al. 2005, Schwab and Degoul 2005, Fleurat-Lessard et al. 2006) or may be attached to a waveguide that is inserted into the substrate or commodity, e.g., the Pest probe detector (Sound Technologies, Alva OK, Betts 1991).

Another successful acoustic detection device, reported by Kennedy and Devereau (1994), was a microphone system that monitored insect population levels in bag stacks in Zimbabwe. An automated system combining microphones, light-emitting diodes, and vibration sensors successfully distinguished *S. oryzae* from *T. castaneum* and *Stegobium paniceum* (L.) (Mankin et al. 2010).

Continuous monitoring with automated acoustic systems has considerable potential for enabling early detection of small populations of stored product pests. For example, Hagstrum et al. (1996) found that automatic continuous monitoring detected insects in grain bins 3 to 28 days earlier than taking grain samples. Insect infestation levels were estimated from the number of 10-second intervals with insect sounds over a range of 0 to 17 insects per kilogram. Automatic continuous monitoring with sensors in grain is advantageous partly because adult grain pests often are very mobile, and many will eventually move close enough to a sensor to be detected. In the on-farm grain bin study of Hagstrum et al. (1996), insects initially were most abundant in the top center of the grain bin. Subsequently, they dispersed in all directions and were found at 16 additional locations after 85 days of storage. This dispersal might improve overwinter survival because grain at locations deeper in the grain mass will remain warm longer.

Finally, networking opportunities provided by modern communication systems could assist in agricultural sourcing and tracing initiatives (Elliot et al. 1998) and permit tracking of insect infestations in grain and other commodities as they move through the marketing system. The capability of acoustic sensor systems to interface directly with intelligent computer networks enables reductions in the labor costs and risks of collecting such information. As reliability and ease of use increase and costs decrease, acoustic devices have considerable future promise as insect detection and monitoring tools.

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23 Temperature Monitoring

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Grain moisture content and temperature are the two most critical factors for maintaining grain quality during storage. Under unsafe grain temperatures and moisture content, cereal grains and oilseeds deteriorate and produce heat, water, and carbon dioxide (CO_2). Most, if not all, processes by which stored crops deteriorate are exothermic. Measuring increase in grain temperature, moisture content, and CO_2 are effective for detecting incipient deterioration. Studies have shown that measuring CO_2 concentrations in the intergranular air can faciliate early detection of spoilage in storage grain bulk (Muir et al. 1980, 1985, Singh et al. 1983, Sinha et al. 1986a, b, c). Using CO_2 sensors to monitor grain quality is still under investigation (Maier et al. 2010). Researchers are developing an inexpensive, highly accurate CO_2 sensor (Neethirajan et al. 2009, 2010). A device to measure grain moisture content in-situ is not commercially available.

Compared to CO_2 and moisture content, continuous temperature monitoring within grain masses is relatively easy and inexpensive using thermocouples. The accuracy of temperature sensors sold on the market is about 0.5°C. Measured temperature and relative humidity (RH) can be used to predict grain moisture content based on equilibrium moisture content (EMC) equations. The predicted EMC can differ by more than 0.25 percentage points with grain moisture contents (dry basis) measured using the oven method (Uddin et al. 2006).

Although measuring grain temperature has limitations and drawbacks, it is an effective, commercially practicable, reliable, common, and traditional method of detecting incipient grain deterioration and monitoring grain quality. One important advantage of temperature monitoring is that it provides information on a wide range of grain quality parameters when measured grain temperatures are correctly interpreted. For example, grain temperature and moisture content can be used to estimate storage life of grains and oilseeds.

Heat Produced by Living Organisms

All living organisms in a grain bulk respire including grain, insects, mites, and microorganisms. During respiration carbohydrates, fats, or proteins in the grain or living organisms are oxidized. The general respiration process is described approximately by the formula:

$$C_6H_{12}O_6 + 6\ O_2 = 6\ CO_2 + 6\ H_2O + 2870\ kJ$$

Applying this formula, 15.7 kJ of heat is produced for each gram of $C_6H_{12}O_6$ broken down (Zhang et al. 1992). The amount of heat released is 3946 kJ per gram of lipids and 15.7 kJ per gram of glucose (Multon 1988). Glucose fermentation usually occurs when oxygen is limited or absent, under airtight conditions, for example. The heat released under fermentation conditions is about one-tenth of that released under aerobic conditions (Multon 1988). The total respiration of the living organisms increases with temperature, grain moisture content, infestation level, and degree of fungal spoilage (White et al. 1982 a, b).

The heat produced by grain normally is not an important factor in the grain storage ecosystem because, under safe storage conditions, grain has negligible respiration rate (Hummel et al. 1954). There is no evidence that respiration of the seeds themselves is a major factor in total respiration, heating, or other deteriorative processes in stored grain. The heat produced by the dry cereal grain itself may be about 0.01 W/t (Zhang et al. 1992). Respiration rates of molds and bacteria are usually much higher than that of the dry grain except when moisture content rises rapidly and germination occurs (Sauer et al. 1992). Consumption of dry matter by respiration and heat produced by the grain itself under safe storage conditions usually can be ignored.

The peak rate of heat production by molds and moist grain at 45°C and 27% moisture content is 150 mW/kg of wheat (Zhang et al. 1992). The average rate of heat production (mW/kg) over the initial storage period until 0.1% dry matter loss has occurred in wheat is 2 for 20°C and 17% moisture content; 7 for 30°C and 17%; and 36 for 30°C and 25% (White et al. 1982 a, b).

When moisture is high, it is difficult to separate the respiration between grain and mold. Actually, mold is the more important contributor of the heat produced in damp or wet grain (about 85 to 95%). For example, wheat stored at 24% moisture content can rapidly deplete oxygen to 0% in 2 to 3 days, while CO_2 continually increases. At 17% moisture content, it takes 70 days for the oxygen to drop to near 0%. At 14% moisture and 15°C there is less than 2% reduction of oxygen in 18 months (Bell and Armitage 1992).

The rate of heat production by adult rusty grain beetle is 4 to 20μW per insect (Cofie-Agblor et al. 1996) and 66 to 81 μW per insect by granary weevils (Cofie-Agblor et al. 1995). Heat production (or rate of respiration) increases with temperature and moisture content of the wheat and changes only slightly with age and population density. Grain stored at safe moisture content and in otherwise safe storage condition, except for the presence of insects, can develop hot spots. This heating, which can only be attributed to heat released by the insects, is termed dry grain heating.

Postharvest maturation of grain may affect respiration and the amount of heat produced. Grain, such as wheat, might follow a complex series of biological and chemical changes immediately after harvest (Sinha 1973). Seed germination at the beginning of this period is low and increases over several weeks. Moisture content of the grain and temperature can influence the length of this period. This may explain why freshly harvested grain passes through a sweating period when grain temperature rises, and spoilage may occur (Muir 1999).

Water and heat produced during respiration increases moisture content and product temperature. Such increases may increase the growth rate and respiration of pests and microorganisms. A succession of organisms can occur. For example, insects in dry grain can produce sufficient moisture that fungi can begin to grow. This results in grain deterioration within hot spots, while grain outside the hot spot is still at safe storage moisture content. The heat produced and the increased grain temperature are the reason grain temperatures should be measured to detect deterioration.

Temperature monitoring cannot detect all of the mold and insect infestations even though the temperature cables are located at the infestation locations. In wheat and corn at 14.0 to 14.5% moisture and 10 to 25°C, *Aspergillus restrictus* grows so slowly that it causes no detectable rise in temperature (Sauer et al. 1992). Blue-eye of corn is produced by spore masses of fungi without a temperature rise in the grain. Insects at low density will produce a certain amount of heat, which is undetectable using temperature sensors currently on the market.

Heat Transfer and Temperature Gradients in Stored Grain Bulks

Inside the mass of stored grain, heat can be transferred by conduction, convection, and radiation. During storage without aeration, the grain temperature is mainly influenced by conduction (Smith and Sokhansanj 1990, Jayas 1995, Jian et al. 2005). The thermal properties (such as thermal conductivity and thermal diffusivity) of the stored grain influence heat transfer. Thermal conductivity is used to calculate the rate at which heat moves through a material. Thermal diffusivity is used to calculate the rate at which the grain will change temperature. The faster heat is conducted through a material, the more rapidly its temperature will change. The more the heat required to change the temperature of a given volume of material, the slower the temperature will change. Grain with low thermal diffusivity will change temperature slowly. Although glass wool (a common insulation material of buildings) has a lower thermal conductivity than wheat, the temperature of a bin of glass wool changes about 22 times faster than that of a bin of wheat because wheat has a higher density and specific heat than glass wool, which results in lower thermal diffusivity. But glass wool is a better insulator because it transfers heat at about one-third the rate for wheat. Compared with wheat, rapeseed (canola) has a low thermal diffusivity mainly due to its low thermal conductivity. Wheat cools faster in fall and warms faster in spring. This is one of several reasons it can be more difficult to safely store canola than wheat. Low thermal conductivity and diffusivity of the grain are the main reasons heat produced inside a hot spot is prevented from dissipating.

Freshly harvested grain loaded into an unaerated bin in the fall will cool by conduction toward the bin's periphery. Grain temperatures near the walls (within 15 cm) are mainly influenced by seasonal weather temperatures (Figure 1). Solar radiation causes the temperatures at the south and west walls to be higher than at other locations from August to March in the Northern hemisphere. Bin wall and grain temperature is also influenced by bin surroundings. For example, if the bin is under the shadow of a structure, the bin under the shadow will not receive solar radiation. Jian et al. (2009) found that temperatures at the north wall of the tested bin were not the lowest temperatures during winter, and temperatures at the east wall were the highest temperatures from the March to August. They suspected that the dyke to the east and the identical silo north of their test silo might have influenced wind speeds and directions that cause the temperatures on the east wall to have the largest fluctuations. Montross et al. (2002) also found that pilot bins were more heavily influenced by wind than conventional-sized bins.

There are different temperature gradients at different sides of bins due to the differences of wind speed, solar radiation, and surroundings of the bins. The temperature gradients in uninfested steel bins of farm-stored wheat or barley (39 to 217 t) in the autumn and winter range from 1.2 to 15.3°C/m and from 3.1 to 20°C/m, respectively, in infested steel bins 1 m below the top of the grain bulk in Manitoba, Canada (calculated from the data of Loschiavo 1985). In the United States, temperature gradients in farm-stored wheat often reach 7 to 10°C/m in the

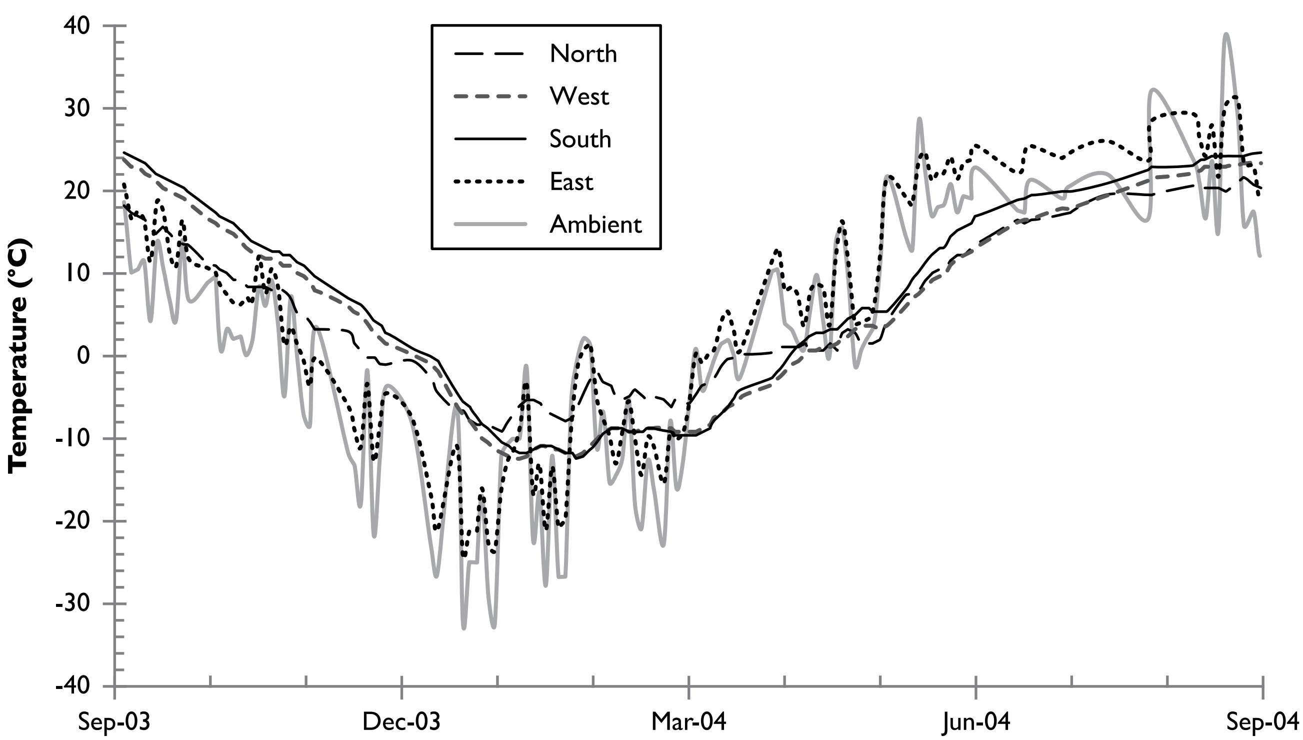

Figure 1. *Hard red spring wheat temperatures at 15 cm away from the walls and 1.0 m depth in a flat-bottom steel bin (3.7 m diameter, 5.7 m high) near Winnipeg, Manitoba, Canada (49°54'N, 97°14'W).*

autumn and winter months (Hagstrum 1987). In a galvanized steel silo located near Winnipeg, Manitoba, Canada, the highest temperature gradient was 32.4°C/m, and it was located at 0.0 to 0.90 m from the center. At this location, the average temperature gradient was 10.8°C/m during the 15-month experimental period (Jian et al. 2009).

The directions of the temperature gradients also vary depending on location and time. During summer, the wall temperature might be higher than at other locations, while in winter it will be lower. Temperatures of the grain at the top and bottom of flat bottom silos are mainly influenced by the headspace and soil temperatures, respectively. This causes the complex distribution of temperature gradients inside silos. The following factors also influence grain temperatures and temperature gradient distribution: initial grain temperature, grain moisture contents, bin wall materials, bin structures (shapes and bottom configurations), bin diameters, grain and bin heights, geographical locations, grain types, storage times, and operations (such as grain turning and aeration). The interpretation of temperature data should be based on temperature distribution patterns and heat transfer theories.

Methods of Temperature Measurement

Temperature measurement methods can range from persons feeling stored-crop temperatures with their hands, to using a computer to control temperature measurement and fans automatically. For example, if devices for measuring temperature are not available, a metal rod can be used to estimate the grain heating and spoilage using following procedure:
1) Insert a metal rod at least 1 m into the grain mass;
2) Leave the rod for approximately 30 min;
3) Remove the rod and, with the palm of the hand, test it for warmth and wetness at various points of the rod. Any section of the rod that feels warm or wet to the touch is an indication of heating and grain spoilage.

Harner (1985) described temperature monitoring systems that were commercially available before 1985. Temperature measurement devices commercially available now include temperature probes, temperature cables with handheld monitors, personal computer (PC)-based temperature monitoring systems, and computer control systems.

Temperature Probe

A temperature probe is made of a 1- to 4-meter steel rod with one to three sensors. If the probe has only one sensor, it will be located at the tip. Manufacturers also make probes longer than 4 meters and more than four sensors along one metal rod, if asked. The thermocouples, thermistors, or digital temperature sensors inside the rod can be connected to a digital handheld reader at any time. This handheld reader can be a single probe or up to several probes (multisensors) connected to a monitor with LCD display. Models made by some companies can store the temperature data for a year or more and graphically display the history of the measured grain temperatures.

A temperature probe usually is not permanently installed in a grain silo. It is carried around, pushed into the grain mass and left for at least a half hour to measure temperature. During grain loading and unloading, temperature probe(s) should be taken out of the silos. The data stored inside the handheld monitor can be transferred into a PC so temperatures can be displayed. Probes also can be directly connected to a PC. This connection is similar to PC-based temperature monitoring system.

PC-Based Temperature Monitoring System

Even though different manufacturers have different PC-based temperature monitoring systems and use different terms, the system usually consists of hardware (suspension, anchor, and accessories), temperature cables, connector (lead wire), RTU (remote terminal unit) box (central reading station, remote scanner), power supply, wire (communication cable), converter, and PC (Figure 2). The communication cable can be replaced by one pair of radios.

The temperature cable may comprise an inner sensing element and outer cable jacket. The sensing element (sensors and conductors) is housed inside a protective cable jacket, which can be a tube or a layer of coating over the sensing element. The tube or cable jacket is fastened to the roof and floor of the silo. For ease of maintenance and repair, the sens-

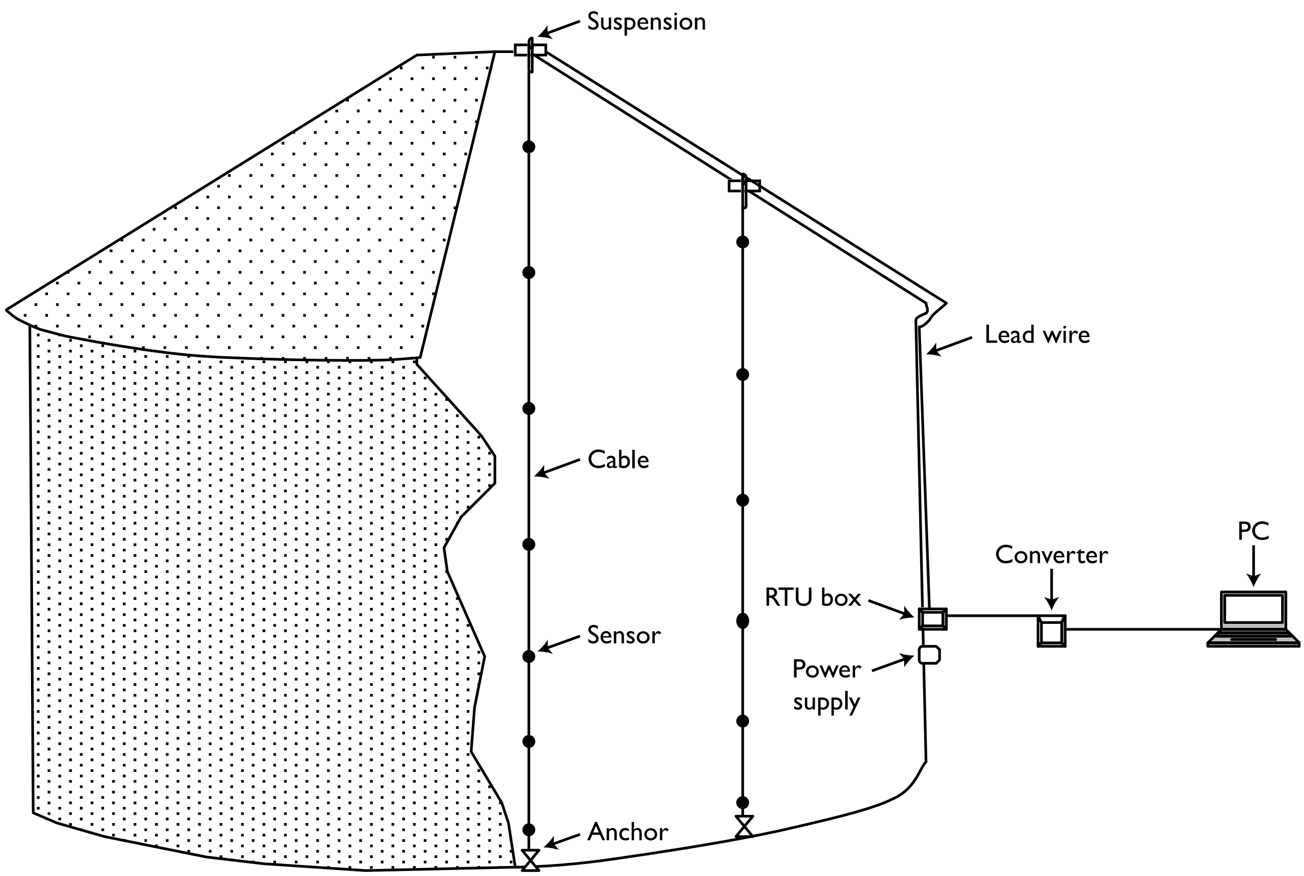

Figure 2. *Schematic presentation of a PC-based temperature monitoring system.*

ing element can be removed from the tube. (This is called a retractable cable). Companies try to make small cables because a smaller diameter cable jacket reduces the pulling force on the cable during grain unloading. To reinforce the retractable cable, which bears the pulling force, the tube is coated and lined with high-strength steel wire. Retractable cables allow the sensors to be changed without removing the cable tube, even if the silo is full of grain.

Because the temperature in the grain mass varies, the sensors must be adequately distributed throughout the stored mass. The number of sensors in a cable mainly depends on cable length and distance between sensors. Companies usually recommend that the maximum length between sensors is 5 meters. The best result is achieved if the distance between the sensors is kept around 1.2 to 1.8 meters or less. The temperature cable can be installed permanently or temporarily. From an economic and practical viewpoint, the cable should be installed permanently.

The sensing element can be a T-type thermocouple, high-impedance thermistor, or digital temperature sensor. The digital temperature sensor provides the highest accuracy reading. Multiple sensors per cable and multiple cables per bin can be interconnected inside the RTU box to form one simple two-wire connection (the communication wire). If the cable does not contain digital sensors, addressing sensors and converting analog signal to digital signal will be completed in the center reading station (remote scanner). The signal transmitted via the communication wire or the pair of radios is read by the software installed in the PC.

The PC-based software of the temperature monitoring system usually provides the following basic functions: field input and site configuration, site and structure navigation, and statistics of the measured grain temperatures. Field input and site configuration let the user enter information about the structure, such as grain type, moisture content of the grain, and grain loading date. Site and structure navigation let the user find the right cables and sensors to view the measured grain temperatures.

Temperatures can be reviewed using graphs or tables. The graph or table can show the history of the grain temperature in time scale or current temperatures inside the entire structure. The views of grain temperatures provide statistical information associated with the measured grain temperatures, such as the average, maximum, minimum grain temperatures at one cable location or inside the entire structure.

Some companies also incorporate several advanced functions such as level, reports, printing, and alarm. The level function estimates the grain depth at each cable location. Based on the estimated grain depths, the total volume of the grain inside the silo is estimated. Report and printing functions help the user document the measured grain temperatures. Based on the user setting, such as the high limit temperature and the rate of rise in grain temperature, the system can generate alarms. Alarm output can be on-screen and on-site (audible or visual) or delivered via text messaging and email if the system is connected to the Internet.

Computer Control Systems

The computer control system connects the PC-based temperature monitoring system with fans and other measurement and control devices. For example, the Intergris pro developed by OPIsystems (Calgary, Canada) connects the temperature-monitoring system with temperature cables, Insectors, moisture cables, fans, heaters, and roof ventilation fans. The system measures temperatures, relative humidities, pressures inside silos (including grain mass, plenum, and headspace), and the ambient air. The measured temperatures and relative humidities are used to calculate grain moisture content. The Insector system classifies captured insects into species groups and estimates the insect densities at each Insector location. Based on this data and user setting such as aeration, natural air drying, and drying with heater, the software can do calculations and make decisions. The PC sends control signals to field devices to prompt starting and stopping of aeration fans and roof ventilation fans, for example. This system is fully modular and can adapt to any storage configuration and still allow for expansion. Computer control systems make automatic multiple silo control possible.

Location of Temperature Sensors

To detect spoilage spots in the early stages, the ideal distance between two temperature sensors and between two cables must be within about 0.5 m (1.64 ft) (Singh et al. 1983) and temperature must be measured on a closely spaced grid. This distance might be impractical because too many cables would increase cost, roof loading, and increase the difficulty of grain loading and unloading. To measure temperature economically, measurements should be taken at locations where spoilage is expected, rather than on a grid of measurement points. For example, cable should be installed at locations where dust and dockage (broken kernels, weed seeds, etc.) accumulate. At least some sensors should be located at the center of the silo because the largest moisture accumulation in non-aerated grain storage usually is at the top center of grain bulk. The center of a grain silo without aeration usually can maintain high temperatures that allow insects to survive and multiply. Insects enter the silo from the top and gradually move down into the grain. Warmer temperature in the headspace will help insects multiply at the top center of the silo. Also multiplication of insects at the top of the grain mass might also initiate hot spots there.

Cables are installed before grain loading and will be used for several years. The grain silo might store various grain types at different depths. This increases the difficulty of predicting spoilage locations. Usually, cables are installed with equal distance between them. Some companies consider possible spoilage locations when making recommendations.

Temperature Measurement Frequency

Measurements should be taken consistently and frequently because temperature change is more significant than the temperature itself at any given time. During spring in Manitoba, temperatures of a fungus-induced hot spot rose from 20 to 65°C, and then cooled back down to 30°C within about 2 weeks. If the interval between readings is more than 2 weeks, such a hot spot may not be detected by temperature measurement. With PC prices decreasing and CPU processing ability increasing, temperature measurement in less than a half hour over the entire storage period is possible. In some measurement situations, the larger distance between sensors might be remedied by increasing measurement frequency.

Even though well-designed software can expedite the process, monitoring temperature consistently and frequently takes time. The amount of time should be based on grain storage and weather conditions. For example, temperature should be checked more frequently during hot weather. If grain moisture content is higher than recommended for safe storage, temperature measurement and review frequency should be increased. The common practice is that if grain is not under safe storage condition (because of warmer temperature, damp grain, and possible insect infestation), temperature should be measured at least every 3 hours, and reviewed every 1 to 2 days. If grain is under safe storage condition, measurements can be taken daily and reviewed biweekly.

Interpretation of Temperature Readings

Temperature measurement is not only used to detect active deterioration but also to indicate, along with moisture content and infestation information, potential for deterioration (or safe storage time). Each spoilage process has temperature ranges in which the rates of deterioration are rapid, slow, or prevented. For example, optimum development of the granary weevil (*Sitophilus granarius* L.) occurs at 26 to 30°C; for the saw-toothed grain beetle (*Oryzaephilus surinamensis* L.) it occurs at 31 to 34°C (Loschiavo 1984). Magnitudes of measured temperatures, temperature differences among locations in the stored bulk, temperature gradients, and changes in temperatures over time must be correctly interpreted. Correct interpretation requires a general knowledge of storage ecosystems and experience with specific types of grain, grain bins, and climate. Grain physical properties (such as thermal conductivity and thermal diffusivity) and heat and mass transfer theory should be used to interpret temperature readings. For example, wheat and canola stored inside the same structure and at the same geographic location would have different temperature gradients. Compared with canola, wheat cools faster in fall. It also warms faster in spring because wheat has higher thermal diffusivity than canola. Hot spots might be more difficult to detect in canola than in wheat.

To correctly interpret the temperature reading, the more information that is collected the better. Information should include history of the temperature reading, pattern of temperature distribution, temperature difference between sensors, and temperature rise rate at a particular location, grain infestation and insect species, grain moisture content and distribution, structure and surrounding of the silo, weather data, and history of the operation inside the silo. For example, fungi can grow at temperatures as low as -5°C, and mites can continue reproducing at 5°C. A low-level infestation or infection undetectable by temperature measurement can do considerable damage over a long storage time. Also, such a situation can rapidly develop into a major problem when conditions in the bulk move into optimum ranges for the pests. This information should be used to detect major problems as early as possible.

Temperature Patterns of Stored Grain Without Aeration

In Canada, wheat is normally harvested in late summer or early fall when the outside air temperature is decreasing. The newly harvested wheat usually has a higher temperature than the outside ambient temperature due to the solar radiation on the heads of the grain swath. On sunny days the temperatures of wheat heads on the top of the swath and in standing crop are about 7°C above the ambient air temperature (Williamson 1964, Prasad et al. 1978). The grain kernels maintain this increased temperature as they move through the combine to the truck and into the storage bin.

At all North American latitudes in an unventilated bin, wheat begins to cool at the bin's periphery. A few days after grain loading, temperature gradients develop from the bin center to the periphery of the bin. From the beginning of the grain loading until the ambient weather temperature begins to rise in spring, the warmer grain in a bin will be at or near its center.

In spring and summer, the bin warms along with the ambient temperature. Temperatures of the grain near the walls rise above the temperatures of the grain at the center. Grain near the walls and the headspace will be warmer than in other places.

Bin diameter and grain depth are two main factors that influence the temperature pattern inside the bin. As bin diameter increases, center temperature changes more slowly. Small bins cool most rapidly in the fall and warm most rapidly in the spring. Increasing bin diameter will decrease the difference between maximum and minimum temperatures. Grain loading time and initial temperature and storage time also influence the temperature pattern in bins (Jayas et al. 1994).

Monitor Grain Temperature in Bins Without Aeration

For economic reasons, there are usually no cables at or near the walls. This increases the difficulty of identifying the temperature distribution pattern. Daily average of the ambient temperature (or weather station data) could be used to approximate the grain temperatures within 15 cm away from the walls. Grain temperature distribution pattern and temperature fluctuation should be monitored at least biweekly.

During spring and summer, grain temperature at the center of silos is cooler than the ambient temperature. If fan ducts located at the bottom of the silo are not properly sealed, the dense air at the center of the silo will leak out through the unsealed fan ducts. This moving air will drive warmer air inside the headspace down to the grain mass. Daily monitoring of grain temperature and rate of temperature increase at the locations close to the headspace can detect this problem.

Temperature Patterns of Grain Bulks with Hot Spots

Hot spots refer to small patches or pockets of grain that are warmer than surrounding grain in the bin of sound grain (Sinha and Wallace 1965). Insects and mold can initiate hot spots. After a hot spot is initiated, heat and moisture produced by biological respiration will speed the rate of grain temperature increase because the heat-insulating properties of the grain prevent heat from dissipating. For example, the temperature in a developing hot spot in a wheat granary increased 10°C from 0°C in three weeks, and then increased a further 54°C to a maximum temperature of about 64°C in only 10 more days (Sinha and Wallace 1965). When active spoilage is localized in a bulk, a sharp temperature gradient can develop. For example, the temperature only 45 cm from the 64°C grain was still at the normal grain temperature of 10 to 15°C (Sinha and Wallace 1965).

The size of hot spots depends on the amount of moist grain and moisture content around the hot spot. It can be as small as 50 cm in diameter. Small spoilage pockets may die out as the heat produced causes convection currents and moisture diffusion that dry out the moist spoiling grain. It is not clear when and how the small spoilage pocket dies out. A large hot spot may continue to increase its size with accompanying increases in temperature, moisture content, and deterioration of the grain. When the grain temperature reaches above 60°C, biological respiration of the grain might cease and chemical oxidation may continue. Grain temperature can reach 380 to 400°C after oxidation (Muir 1999), and this high temperature can cause the entire bin to catch fire if enough oxygen is available.

Hot Spot Detection

When there are hot spots inside the grain mass, determination of the temperature distribution pattern (including seasonal pattern and the temperature distribution pattern around the hot spot) and rate of temperature increase at a given location are important. For example, a temperature at the center of a bulk that is higher than the ambient temperature can mean either the grain is spoiling or the grain has not cooled from its initial storage temperature. Yaciuk et al. (1975) reported that the temperature at the center of an unaerated, 8-m diameter bin of sound wheat stored at 25°C at harvest time in Canada can still be at 25°C on January 1, four months after harvest, when the ambient temperature is below –20°C. Without the history of measured grain temperature at the center location, it can be mistaken as a hot spot.

Because of the low thermal diffusivity of grain, hot spots affect the temperature of the grain only a short distance from the center of the hot spot. Detection of a small hot spot requires temperature measurements in less than 1 week and at intervals of less than 50 cm apart. The distance between cables is usually larger than this recommended distance. If measurement intervals are less than one day, tem-

Table 1. *Locating hot spots in a 140-foot (43 m) diameter flat-bottom bin with corn 70 feet (21 m) deep in the U.S. Midwest, using 36 cable Integris[Pro] system developed by OPIsystems Inc., Calgary, Canada.*

Grain	Selected Cables									
depth (ft)	C1	C2	C3	C5	C6	C9	C10	C23	C28	C33
80	48.0	89.4	53.8							
76	53.3	57.7	56.9	51.0	53.4					
72	61.1	55.9	55.8	49.8	55.0	49.8	51.3			
68	71.2	57.0	54.3	49.3	54.9	45.5	51.6	50.2		
64	73.1	56.0	54.3	51.0	54.3	41.3	51.1	47.3	19.1	45
60	69.4	52.0	53.1	52.9	52.2	41.5	49.6	42.5	9.0	36.6
56	52.5	41.6	52.5	53.8	48.6	41.9	45.0	39.6	0.8	29.3
52	54.6	35.1	53.1	52.9	45.8	40.3	38.9	33.1	-2.9	21.9
48	54.1	24.1	55.2	52.3	43.0	38.9	31.9	31.7	-2.9	14.6
44	53.9	16.7	54.5	50.2	38.1	36.7	24.2	26.1	-1.5	4.9
40	52.2	8.5	53.1	49.2	34.9	33.6	15.6	19.1	2.8	1.3
36	51.5	4.9	53.0	47.9	34.0	30.6	4.5	9.2	13.9	1.9
32	50.4	5.6	51.6	45.7	27.4	26.5	0.8	3.0	31.0	4.3
28	47.1	12.8	50.5	41.3	20.1	24.5	2.7	1.7	31.8	9.0
24	31.1	28.7	46.6	40.1	11.7	22.9	9.1	2.8	25.5	18.0
20	19.9	31.0	43.8	36.7	3.1	21.5	28.2	21.1	23.9	28.7
16	29.6	27.7	25.6	34.4	4.0	24.2	32.2	28.3	26.9	29.5
12	25.1	30.8	6.7	41.4	20.9	19.3	26.1	29.2	28.3	26.4
8	20.6	26.5	6.2	46.0	33.4	16.2	26.5	28.9	27.2	28.3
4	19.3	24.3	31.9	17.5	26.2	31.4	27.8	27.9	27.3	25.6
0	18.8	19.7	26.3	12.9	27.9	32.3	17.9	27.5	27.4	24.1

peratures associated with larger than 50 cm distance might be used to detect some hot spots (if not all).

Based on the temperature distribution pattern and temperature increase rate, at least two hot spots could be identified in a flat bottom bin located in the U.S. Midwest (Table 1). One hot spot is located at the center of the bin and 8 feet down from the surface of the grain mass (C1 in Table 1). The size of the hot spot might be 16 feet in diameter. The second hot spot is located at the C2 and at the surface of the grain mass. There might be other hot spots at the surface of the grain mass and at the locations C3, C5, C6, C9, C10, and C23. The hot spots might connect with each other. After sampling and further monitoring, it was confirmed that there were at least two hot spots at the center location. The hot spots at C3, C5, C6, C9, C10, and C23 were a thin layer (less than 1 ft), and the grain in this layer spoiled and sprouted because of water dripped on grain from condensation on the bin ceiling.

Temperature cables also can be used to monitor aeration and drying (see chapters 10 and 11). Drying fronts can be located because of evaporative cooling during drying.

Prediction by Temperature Models

Grain temperatures and moisture contents inside grain silos can be predicted by published mathematical models (Jayas 1995). Even though the mathematical simulation is less accurate than actual tests, calibrating and validating models can verify and improve their accuracy. Mathematical models are used by some companies for customer consulting, management strategy planning, fan selection, and storage structure design. Using a mathematical model to control grain aeration (without measurement of grain temperatures) is marketed and practiced by one Australian company (Aeration Control Australia, Joondalup WA).

If a mathematical model is combined with a PC-based temperature monitoring system, the predicted temperatures can be checked and corrected frequently by the measured grain temperatures. The advantage of this combination is that the model can show the right pattern and possible trend of the temperature distribution. Also, the model can warn users of impending storage problems. By comparing the pattern predicted by the model with that of measured temperatures, hot spots can be easily detected at the early stage. For example, when the fungus-induced hot spot was at 3°C, the temperature of the hot spot began to rise above the temperature of the control bin, indicating active spoilage (Sinha and Wallace 1965). But this temperature rise due to biological deterioration would not be readily apparent if a control bin was not available for comparison.

Future Research and Application

Even though temperature monitoring can be conducted by using inexpensive and simple methods, new technology will be developed and the measurement technique will be continuously updated. There might be an opportunity to increase the temperature sensor accuracy because the sensor accuracy on the market is about 0.5°C. Reducing the distance between cables and sensors is one of the methods for an early detection of grain spoilage. Decreasing cable diameter without losing load-bearing capacity might help make this possible. Mathematical models with a high accuracy will play a role in grain temperature monitoring and storage management. To decrease the costs of grain temperature monitoring, mathematical simulation without temperature measurement might make grain storage management possible.

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24 Monitoring for Spoilage and Mycotoxins

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Ideally, grain placed in storage should be high quality, without disease or structural damage. Grain entering the storage facility usually has some damage due to preharvest diseases. Damage and breakage also occur during harvest, drying, and grain transfer. Keeping grain moisture content below the level required by fungi (mold) to grow (Chapter 6) will minimize spoilage. Poor quality grain is more likely to spoil, especially during the warmer months. Managers should monitor grain diligently. When mycotoxins become an issue, managers should have a plan for testing grain to assure mycotoxins are below levels acceptable for marketing or safely feeding livestock.

Grain Odor

All grain has odor. Distinguishing good quality grain from grain spoiled because of fungal growth is easy. Grain odor comes from volatile metabolites (chemicals) naturally produced by the grain. They are a mixture of numerous classes of small molecules including short chain hydrocarbons, terpenes, aldehydes, and alcohols (Buśko et al. 2010). Grain spoiled by fungal growth has an off-odor that can be described as musty, sour, earthy, or even putrid. Each of these odors is caused by one or more volatile fungal metabolites. The molecules often responsible for grain with musty and earthy odor have been identified as geosmin (a terpene) and 2-methylisoborneol (structure similar to camphor) (Jelenä et al. 2003). The human olfactory threshold for these metabolites is low, and the average person can detect concentrations that are in the part-per-trillion range (Polak and Provasi 1992). Facility managers should monitor the headspace of grain storage units for these easy to smell off-odors

Research on electronic nose technologies suggests that equipment that can provide early warning of grain spoilage and mycotoxin production will be available in the future (Campagnoli et al. 2009, 2011). Some sensors include small semiconductors coated with materials that interact with volatile compounds. Computer programs are needed to recognize the signature of the targeted odor molecules. Research shows that fungal metabolites can be detected, but it is not possible to establish the relationship between a measured amount of metabolite and the level of fungal growth or spoilage. Producing equipment to withstand the rough conditions of the grain facility is also a challenge.

Off-odor is pervasive. When off-odor grain is mixed with good quality grain, the good grain will not mask the off-odor. Eliminating odor can be difficult. Extensive aeration can reduce the off-odor if damage is not severe (see Chapter 11). Treating grain with ozone (O_3) can remove off-odor. Ozone is a strong oxidizing gas that can be produced by electrical corona discharge in air (Hosselet 1973). Ozone can destroy off-odor volatiles, but the treatment also will reduce or change the other molecules that give grain its particular smell. When the treatment is done correctly, the off-odor will be removed and the grain will smell like good quality grain. The treatment will not affect the quality of the grain for its end-product usage (Mendez et al. 2003).

Other Methods of Monitoring Fungi

Chapter 23 describes the production of carbon dioxide (CO_2) and heat by fungi and insects during the formation of hot spots of spoilage in a grain mass. Temperature monitoring by a sensor within the grain is unlikely to detect a hot spot early unless it is located within inches. CO_2 detection appears to have great potential as a means of monitoring for spoilage (Ileleji et al. 2006). Sensors placed in the headspace of a grain storage unit or at fan exhausts can monitor normal CO_2 levels and detect significant increases due to fungal or insect activity.

Routine monitoring of the average moisture and temperature during grain storage can alert managers to changes that may lead to spoilage. Chapter 6, Table 1 provides equilibrium moisture content for corn and wheat. Maintaining low relative humidity (65%) between grain kernels will assure that spoilage by fungi will not be an issue. See Chapter 11 for a discussion about using aeration to maintain proper temperature and moisture conditions.

Mycotoxin Contamination

Numerous mycotoxins have been identified in grain, including citrinin, cyclopyazonic acid, moniliformin, patulin, sterigmatocystin, trichothecenes, zearalenone, fumonisins, ochratoxins, and aflatoxins. Only a few of these occur often enough to warrant routine screening. Chapter 6 describes the major mycotoxins — aflatoxin, fumonisin, zearalenone, and deoxnivalenol — produced by fungi that cause preharvest diseases of corn and wheat.

Monitoring grain in disease-affected areas at harvest is necessary to prevent contaminated grain from entering the food and feed supply chains. Aflatoxin and ochratoxin are also found in hot-spot formations within stored grain. It is impossible to determine if grain is contaminated with mycotoxins by looking at it with the naked eye. Aflatoxin-producing fungi (*Aspergillus flavus* and *Aspergillus parasiticus*) can be detected on corn by examining kernels with a black light (long-wave ultraviolet) to indicate potential contamination. If kernals show a bright green-yellow fluorescence (BGYF) aflatoxin is indicated, and grain should be tested. The greater the percentage of kernels that show BGYF, the higher the probability that aflatoxin is at significant levels. This test is prone to false positives and negatives, and it does not indicate aflatoxin concentration. The only way to determine if grain is contaminated is to have it analyzed for mycotoxins.

Sampling grain for mycotoxin analysis

Once the decision has been made to test grain for mycotoxins, the most important step is to obtain a sample that is representative of the entire grain mass. Mycotoxin-contaminated grain will not be uniformly distributed. Some areas will be highly contaminated, and other areas will have little or no contamination. Individual kernels will vary greatly in the amount of mycotoxin they contain. As a result, it is impossible to obtain an accurate assessment from just a handful of grain.

Most of the error in the mycotoxin analysis will be attributable to sampling error. An online reference, *Grain Inspection Handbook*, that describes various sampling methods for grain structures, trucks, and railcars is available from the USDA Grain Inspection, Packers, and Stockyards Administration (GIPSA). The handbook includes several chapters on grain sampling. It recommends taking multiple samples — usually 10 but no fewer than three — from different locations and depths in the grain mass and periodically collecting samples from the moving stream of grain during loading or unloading. Samples should be combined and mixed well to form a composite sample that is ground and tested for mycotoxin. GIPSA recommends a sample size of 10 pounds (4.5 kg) for corn. Taking fewer samples or collecting less grain will increase the probability for error in determining mycotoxin level.

Mycotoxin analysis

Locating a laboratory that provides mycotoxin testing of grain samples can be difficult. Check with the local extension service or grain association for a list of laboratories that offer testing services. Most university veterinary schools have a toxicology laboratory that provides mycotoxin analysis. Also many of the grain certification offices perform mycotoxin testing. Drawbacks to sending grain out for testing are high cost and time required to receive the results, which can be several days. The alternative is to use a commercial rapid test kit. Some of the best known companies include Romer Labs, Vicam, Charm, and

Neogen. All the commercial test kits use some form of immunoassays. This technology takes advantage of antibodies that are specific to one mycotoxin. Antibodies can bind to a particular mycotoxin in a mixture of grain extract, making detection and quantification possible.

Analysis of mycotoxins by chromatography

Traditional mycotoxin analysis methods are based on some form of chemical chromatography. These technologies — which include thin-layer chromatography (TLC), high-performance liquid chromatography (HPLC), and gas chromatography (GC) — separate mycotoxins by their chemical interaction with silica-based, solid-phase materials. Silica, which is primarily silicon dioxide, is what makes up sand at the beach.

Thin-layer chromatography (TLC) – TLC is the least sophisticated of the chromatography methods for mycotoxin analysis (Betina 1985). Extracts from grain samples are spotted onto a plate of glass (also metal or plastic) that is coated on one side with a thin layer of silica gel. Depending on the size of the plate, multiple samples can be placed in a line near the bottom of a plate. Once the samples are spotted, the plate is placed on edge into a tank containing a shallow level of organic solvent(s). The solvent moves up the plate by capillary action, carrying the mycotoxin.

Separation is achieved by the relative solubility of the mycotoxin in the solvent mixture and its interaction with the silica gel. The mycotoxin will migrate to a specific distance from its spotted origin. This is measured as the R_f, which is relative to the solvent front. Mycotoxins are visualized on the plate several ways, including examination under UV, as with aflatoxin, and by spraying the plate with a reagent followed by heating in an oven, as with fumonisins. Running mycotoxin standards of known quantity on the TLC plate allows for either quantitative or semi-quantitative measurements.

High-performance liquid chromatography (HPLC) – An HPLC is a fairly expensive machine, which in its basic form consists of one or two pumps, a separation column, and a detector. Higher end machines include add-on devices such as auto-sample-injectors. The silica material used in HPLC is packed into a small steel column that can withstand high pressure. Reverse-phase columns often are used for mycotoxin analysis. A molecule such as a C18 alkyl chain is attached to the silica, creating a hydrophobic layer. Extracts from grain samples are injected into the solvent stream that is flowing through the column. Movement of the mycotoxin molecules is slowed by their interaction with the column material, and by the time they reach the end of the column, separation from other metabolites in the sample has been achieved. Once the mycotoxin leaves the column, the solvent carries it to some type of detector. The most common detectors measure UV absorbance or fluorescence. Identification of the mycotoxin is based on the retention time on the column, which is compared to a standard. A mass spectrometer also can be used as detector. Regardless of which detector is used, mycotoxin quantity is determined by comparison with a concentration curve obtained from known mycotoxin standards.

Gas chromatography (GC) – A GC machine is commonly used for analysis of the trichothecene mycotoxins such as deoxynivalenol and T-2 toxin (Kientz and Verwej 1986). This machine, which is also quite expensive, consists of a high temperature oven, a separation column, and a detector. GC columns are long coils of tubing that are often lined with fused silica coated with various silicon derivatives, which give columns specific separation properties. For GC analysis, the mycotoxin must be volatile, because the carrier through the column is an inert gas, such as helium. Mycotoxins are not volatile compounds, so extracts from grain must be treated with trimethylsilane (or other reagents) that bind to the mycotoxin making the mixture volatile when heated to the operating temperature of the GC (above 200°C). A grain sample is injected into the gas flow that is running through the GC column. Separation is achieved by the interaction of the mycotoxin with the column material, which slows movement of the mycotoxin. From the column, the mycotoxin flows into a detector, which can be a mass spectrometer, a flame ionization detector (FID) or an infrared spectrometer (FTIR). As with HPLC, identification of the mycotoxin is based on the retention time on the column, and quantification is determined by comparison with a concentration curve made with mycotoxin standards.

Analysis of mycotoxins by rapid-test kits

There are two main formats used in commercial rapid-test kits sold for mycotoxin analysis: enzyme linked immunosorbent assay (ELISA) and lateral flow strips (Figure 1). Both are based on competition for binding to specific antibodies, which are fused to the bottom of the ELISA assay cup and at a location on the lateral flow strips. Mycotoxins in a grain sample compete with a known amount of standard mycotoxin that is mixed with the grain sample extract. Depending on the type of test, the standard mycotoxin is conjugated to a molecule which facilitates the optical reporting of the mycotoxin level (Zheng et al. 2006). Thus, more mycotoxin in the grain sample results in less binding of the standard mycotoxin conjugate to the antibodies in the assay.

In the ELISA assay, samples with more mycotoxin will have less color (Figure 1A). For the lateral flow assays, more mycotoxin results in a toxin line that is absent or one with much less intensity (Figure 1C). These tests kits are sold as a quick-screen, semi-quantitative or quantitative. The quick-screen kits test for a threshold level of mycotoxin. These tell the user whether a sample has more than the threshold level, such as 20 ppb aflatoxin. Kits are convenient for testing feed are often used at grain elevators to test incoming grain. ELISA kits can be quantitative, and the lateral-flow assays can be semi-quantitative. Measurements will require the user to purchase a device from the kit provider that is specific to the kit manufacturer. Readers currently cost around $2,000. Companies that sell these kits also provide or sell materials needed for sample extraction, cleanup, and running the tests.

Immunoaffinity columns (IAC) are also commercially available and widely used for sample cleanup and mycotoxin analysis (Scott and Trucksess 1997; Zheng et al. 2006). The IAC contains antibodies that are immobilized onto a solid support, such as agarose gel in phosphate buffer contained in a small plastic cartridge. The sample extract is applied to an IAC containing specific antibodies to a certain mycotoxin. Then the mycotoxin binds to the antibody, and water is passed through the column to remove any impurities. Finally, by passing a solvent through the column, the captured mycotoxin is removed from the antibody and eluted from the column. The mycotoxin is then further developed by addition of a chemical substance to either enhance fluorescence or render

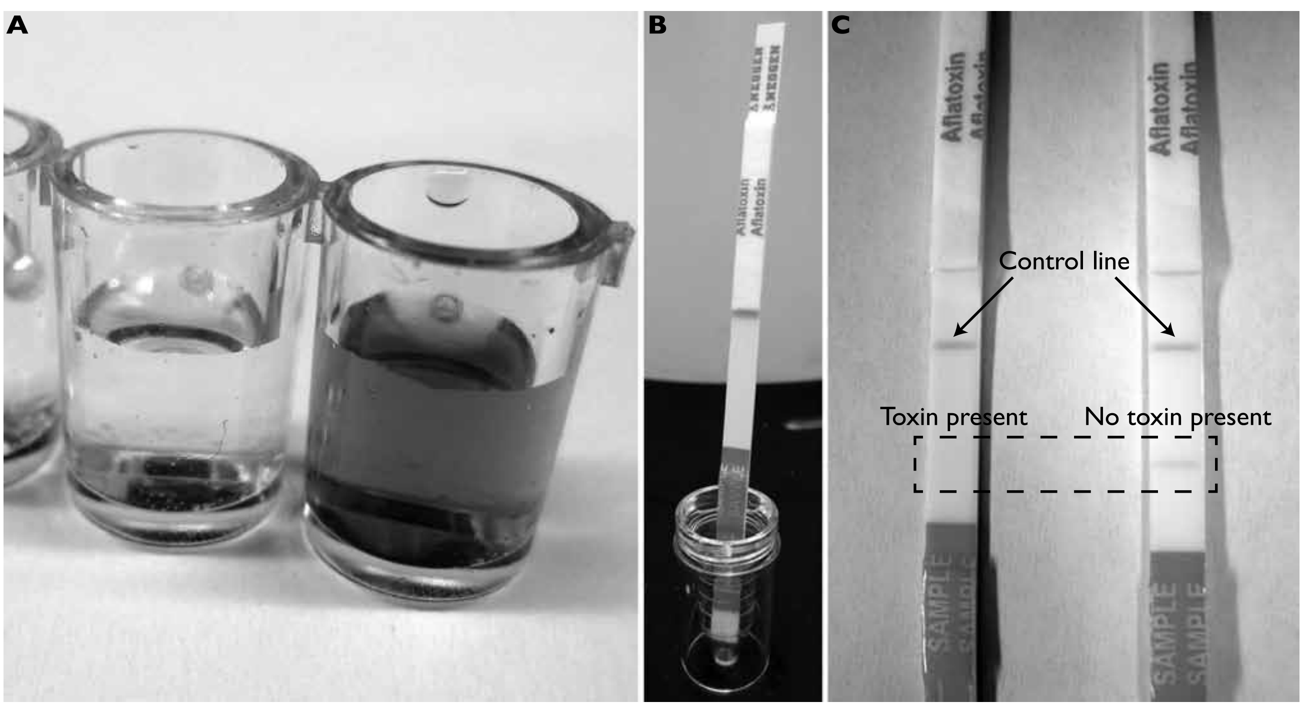

Figure 1. *A) ELISA results showing the difference between a grain sample containing mycotoxin (left) and one without mycotoxin (right). B) Lateral flow strip placed into a cup containing extract from a grain sample. C) Lateral flow strip results showing the difference between a grain sample containing mycotoxin (left) and one without mycotoxin (right).*

the mycotoxin fluorescent before measuring in a fluorometer.

Future assays

Research continues to apply new technologies to the task of measuring mycotoxins. One of these new technologies is called fluorescence polarization immunoassay (FPI) (Maragos and Plattner 2002; Zheng et al. 2006). As with technologies already discussed, mycotoxin-specific antibodies are used to bind mycotoxins in the grain sample extract. In the FPI system, this binding prevents the subsequent binding of a tracer molecule, which allows it to freely rotate, exhibiting nonpolarized fluorescence. The more mycotoxin in the sample, the less polarized fluorescence is measured (Zheng et al. 2006).

Research is also being conducted on evanescent wave technologies such as surface plasmon resonance biosensors (Zheng et al., 2006). The principle of surface plasmon resonance is based on the detection of a change of the refractive index of the medium when an analyte binds to an immobilized partner molecule (antibody). The number of analyte molecules bonded by antibodies to a thin metal layer correlates with the changing of the resonance angle. This application has several advantages such as small sample volumes, reusable metal chips, and the potential for measuring several different mycotoxins simultaneously.

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Kansas State University Agricultural Experiment Station and Cooperative Extension Service

S156 – 24 September 2012

25 Role of Extension Educators and Consultants

David W. Hagstrum
Bhadriraju Subramanyam

Many university extension entomologists have extension and research responsibilities, and conduct demonstration projects to solve known or emerging insect problems. Traditionally, extension agents have provided research-based education and training on stored product protection. Over the last three decades the number of extension agents and scientists who spend a portion of their time in this area has decreased, as institutions focus on discipline-related rather than commodity-related positions. Lack of funding for extension and research positions and losses due to positions that were not refilled have contributed to falling numbers. This void in stored-product entomology extension has been filled by a few university and USDA researchers who now provide the bulk of information needed by the grain, food, and pest management industries. A few university scientists have also served as consultants to solve specific insect problems faced by grain and food industry stakeholders. More recently, insect diagnostic laboratories and websites have become an important source of information on stored-product insects (Ascerno 1981).

Fewer chemicals now are available for use in stored-product protection, and more state and federal regulations (FQPA, Montreal Protocol, fumigation management plans) have been implemented to restrict their use. At the same time, consumer demand grows for food free of pesticide residues. Needs in stored-product protection are greater than several decades ago, yet the task of generating and disseminating established and new information cannot be fulfilled by the decreasing number of existing scientists and extension educators. Private consultants specializing in stored-product protection are urgently needed to facilitate the use and proper adoption of monitoring-based pest management and alternative, nonchemical-based IPM programs.

Private consultants who provide research-based education and training in addition to scouting services have been critical to the implementation of IPM programs in field and orchard crops (Lambur et al. 1989). Consultants can provide advice on the optimal use of simple insect pest management methods and provide the expertise needed to use more complex methods. With a greater awareness and adoption of IPM, many exterminators previously referred to as pest control operators are now called pest management professionals. They are correctly called pest management professionals because they use a variety of pest management methods and depend less on chemical pesticides (Bruesch and Mason 2005). At present, few consultants specialize in the area of stored-product protection, and many offer services primarily to the food industry and not throughout the postharvest supply chain. Additionally, confidentiality agreements consultants have with the companies that hire them preclude valuable scientific exchange of the information to the public.

Extension Programs

Extension programs have included bulletins, fact sheets, demonstration projects, and training programs. Printed extension bulletins have been supplemented by online extension bulletins (Hagstrum and

Subramanyam 2009a) that can be updated more easily (VanDyk 2000). For example, in Kansas, the value of probe traps for monitoring insect populations in stored wheat and deciding whether pest management intervention is needed was first demonstrated with cooperating producers (Lippert and Hagstrum 1987). Harein and Clarke (1995) provided a list of training programs that have been offered consistently in the "train-the-trainer" format for university extension entomologists and state Department of Agriculture representatives responsible for stored-product protection.

The online extension bulletins and fact sheets typically provide information on insect biology and management with emphasis on insecticides currently registered for use. This creates an opportunity for consultants to replace researchers and extension educators, working closely with producers, grain elevator managers, food industry sanitarians, and pest management professionals to provide customized management solutions.

The earmarked funding for extension programs of several decades ago is no longer available, and extension effort has now become part of integrated projects supported by federal agencies on a competitive basis. Competitive grants now are required to be multi-authored, multi-institutional, and multi-year projects with outcomes that are widely applicable and implementable. The lack of people working in this area makes it difficult to get consistent funding for federal projects that require large working groups. Consultants have a great potential to enter the stored-product protection arena and to collaborate with university and USDA scientists on funding opportunities, in addition to filling the void created by the loss of extension personnel and services.

Scouting Programs

International trade has increased the likelihood of uncommon insect species being found (Hagstrum and Subramanyam 2009b). More than 1,663 insect species have been associated with stored products, making identification difficult. Monitoring and treating only when insects are detected can eliminate unnecessary sprays or fumigations (Mabbett 1995).

Timing of pest management is critical and requires insect monitoring (Subramanyam 2007). Understanding the problem often involves detective work. Selection of an optimal pest management method may depend on which insect species are present.

During World War II, when Canada could not ship grain, a scouting program was developed to monitor long-term flat storages (Smallman 1944). In Kentucky, a pilot grain-scouting program for insect and moisture problems was started with 15 producers in one county in 1978, and then expanded to six counties (Skinner 1982). Producers paid from 1 to 5 cents per bushel for the scouting service. As a result a number of serious problems were prevented. This was an extension initiative, but this program was unable to be sustained beyond the time limits of the research program. These scouting programs require trained staff and timely help, which consultants can provide. Generally, extension educators and county extension staff are responsible for several areas of expertise other than stored product protection. Many states do not have an extension specialist in the area of stored product entomology. Questions are deferred to researchers working in stored product entomology or pest management professionals.

Diagnostic Laboratories

Identification of insects to species is the first step in effective pest management (Hagstrum and Subramanyam 2006). Species identification is necessary if published information on biology, ecology, and behavior is to be used in designing a pest management program. Also, the type and amount of damage the insects cause varies among species. The methods used for monitoring various species and the developmental stage most vulnerable to pest management programs also differ among insect species. For a broad-spectrum chemical pesticide, the susceptibility of insects to the pesticide and the choice of the best application method are likely to vary with species as well. Diagnostic laboratories in at least 11 states have dealt extensively with stored product insects (Table 1). In most cases, identification services are primarily for state residents, but at least four states will identify insects for nonresidents. These diagnostic laboratories are supported by tax dollars or have a mechanism for cost recovery through fees for services.

In Minnesota, from 1976 to 1979, the sawtoothed grain beetle was the third to fifth most frequent problem in homes handled by the diagnostic laboratory (Ascerno 1981). The number of inquiries about the sawtoothed grain beetle increased through the

***Table 1.** Diagnostic laboratories that provide stored-product insect identification services[a].*

http://edis.ifas.ufl.edu/sr010 Lyle Buss Bldg. 970, Natural Area Dr. PO BOX 110620 University of Florida Gainesville, FL 32611-0620 Phone: 352-273-3933 Fax: 352-392-5660 ufinsectid@ifas.ufl.edu	http://ppdc.osu.edu/ The C. Wayne Ellett Plant and Pest Diagnostic Clinic The Ohio State University 110 Kottman Hall 2021 Coffey Road Columbus, OH 43210-1087 Phone: 614-292-5006 Fax: 614-292-4455 ppdc@postoffice.ag.ohio-state.edu
http://www.ppdl.purdue.edu/ppdl/services.html Plant and Pest Diagnostic Laboratory LSPS-Room 101 Purdue University 915 W. State Street West Lafayette IN 47907-2054 Phone: 765-494-7071 Fax: 765-494-3958 ppdl-info@purdue.edu	http://www.clemson.edu/plantclinic Clemson University Plant Problem Clinic 511 Westinghouse Road Pendleton, SC 29670 Phone: 864-646-2133 Fax: 864-646-2178 ppclnc@clemson.edu
http://www.entomology.ksu.edu/DesktopDefault.aspx?tabid=49 Holly Davis gotbugs@ksu.edu Department of Entomology 123 West Waters Hall Manhattan, KS 66506 Phone: 785-532-4739	http://utahpests.usu.edu/uppdl/ Utah Plant Pest Diagnostic Lab Dept. of Biology Utah State University 5305 Old Main Hill Logan, UT 84322-5305 Phone: 435-797-2435 Fax: 435-797-8197
http://pmo.umext.maine.edu/ipddl/ipddl.htm Clay Kirby, Insect Diagnostician University of Maine Cooperative Extension Pest Management Office 491 College Avenue Orono, ME 04473-129 1-800-287-0279 in Maine or 207-581-2963 Fax: 207-581-3881 ckirby@umext.maine.edu	http://www.idlab.ento.vt.edu/ Eric R. Day, Manager Insect Identification Laboratory Department of Entomology Virginia Tech Blacksburg, VA 24061
http://www.entomology.cornell.edu/cals/entomology/extension/idl/index.cfm Insect Diagnostic Laboratory Dept. of Entomology 4140 Comstock Hall Ithaca, NY 14853-2601 diagnosticLab@frontier.com	http://anr.ext.wvu.edu/pests/identification Pest Identification Laboratory West Virginia Department of Agriculture 1900 Kanawha Blvd. East Charleston, WV 25305-0191 Phone: 304-558-2212
http://www.entomology.wisc.edu/research-staff-profile-phil-pellitteri Insect Diagnostic Lab 240 Russell Labs 1630 Linden Drive Madison, WI 53706	

[a] Labs in Florida, Indiana, Ohio, and South Carolina identify insects for nonresidents.

summer and then declined, perhaps as a result of cooler fall and winter temperatures (Figure 1). A private diagnostic laboratory in Kansas (www.alteca.com) sells insects to food-processing companies in specially designed cards to be placed throughout the facility to monitor effectiveness of fogging, fumigation, or heat treatment. They also provide technical training on insect identification and other micro-analytical entomology services such as identification of insect fragments in grain and processed food. Diagnostic laboratories will continue to be important as consultants become active in the postharvest area.

Research Programs

Researchers often conduct applied research and transfer this technology directly to the end-users. For example, a cowpea warehouse manager in Florida could stand in the doorway of her warehouse in the spring and hear cowpea weevils moving around inside the paper bags in which the cowpeas had been stored the previous fall after being harvested and dried. She wanted to know how the cowpea weevils got into the bags. By sampling cowpeas as they were harvested, researchers found that small numbers of cowpea weevils were infesting the cowpeas in the fields and reproducing in the bags. Offspring slowly developed through the cool winters and emerged from the cowpeas in large numbers in the spring (Hagstrum 1985). Johnson and Valero (2003) determined that organic garbanzo beans needed to be in a freezer for only 14 days to eliminate cowpea weevil infestation.

Reed and Harner (1998) demonstrated to farmers the value of aeration controllers in protecting stored grain. Both the farmers and extension agents were made an integral part of this learning experience. After the demonstration project ended, farmers continued to use the aeration controllers.

Curtis (1984) showed that navel orangeworms laid eggs on almonds remaining in the trees after harvest, but did not lay eggs on almonds that had fallen to the ground. Johnson et al. (2002) showed that combining an initial disinfestation treatment with one of three protective treatments — cold storage (10°C), controlled atmosphere (5% oxygen) storage, or application of the Indianmeal moth granulosis virus — was an effective alternative to chemical fumigation of almonds and raisins for suppression of Indianmeal moth and navel orangeworm populations. Soderstrom et al. (1987), using a sex pheromone that

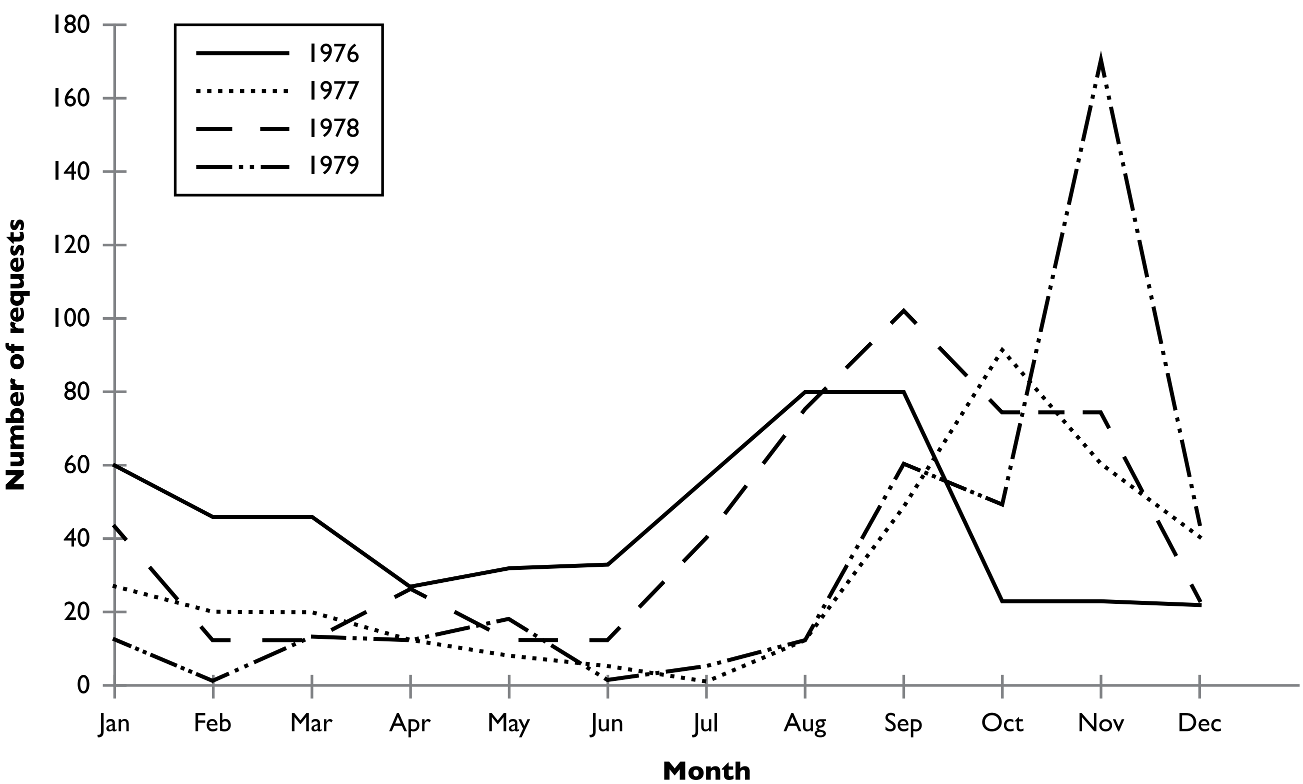

Figure 1. *Sawtoothed grain beetle infestation inquiries (redrawn and used with permission from Ascerno 1981).*

attracts five species of stored product moths, showed the species captured differed among raisin packing plants in the United States, shipping containers, and European warehouses.

Locating and eliminating source populations can be one of the least expensive and most productive components of an IPM program. Vick et al. (1986) used pheromone traps to show the moth problems in grocery distribution warehouses were associated with birdseed and chicken feed. Platt et al. (1998) found stored-product insects most frequently in the flour and pet food aisles of grocery stores. Bowditch and Madden (1996) found that moths were abundant in only 3 of 35 rooms of a confectionary factory. These rooms were used for chocolate refining and nut roasting, and high captures were near infested machinery or a result of insects being attracted to water that was present.

At Kansas State University, a total of six heat treatment workshops were held to train food industry staff about the use of elevated temperatures (50 to 60°C for 24 to 36 hours) for disinfesting food-processing facilities. A total of 350 participants from the U.S. and other parts of the world attended these workshops. During the workshops, the pilot flour and feed mills at Kansas State University were heat-treated with gas and electric heaters, so that participants were part of practical heat treatments, from the beginning to the end.

Research by Kansas State University scientists on the maximum time required to kill adults and the heat-tolerant young larvae of the red flour beetle (Mahroof et al. 2003) showed that these two insect stages were killed 12 hours into the heat treatment. Based on these data, a breakfast cereal manufacturer reduced total heat treatment time to 24 hours, resulting in an annual cost savings of $25,000 (Subramanyam 2010). The cost-effectiveness prompted this company to use heat treatments in their other processing facilities to replace fumigations, which would require sealing the facility and stopping production until the air is safe for workers to continue work.

Consultants

Consultants are routinely used in the grain and food-processing industry as a second, unbiased, pair of eyes and a means of keeping up with new pest management methods and regulations (Gerberg 1991). These consultants often are active faculty members at a university, or retired government, food industry, and university personnel. In some cases, companies hire consultants to provide services as expert witnesses in legal cases. Consultants are valuable because they have knowledge and access to scientific and popular literature (Hagstrum and Subramanyam 2009a) plus relevant practical experiences.

A private consulting company, Precision Grain Management (http://www.grainstoragescience.com), founded and run by an emeritus university faculty member, now provides scouting services. As the only one doing this type of work, the company advised more than 70 elevators in Kansas, Oklahoma and Nebraska from 2003 to 2010 (Hagstrum et al. 2010). The sampling program has improved insect pest management by ensuring that fumigation is done when it is most cost-effective. For example, Precision Grain Management personnel sampled insect populations in 25 flat storages of corn or wheat at elevators in Kansas 116 times between 2003 and 2009, by taking a total of 16,549 grain samples (Hagstrum et al. 2010). The samples were often taken after aeration and fumigation to assure elevator managers that pest management efforts had been effective. Insects were not found in 20 of the flat storages. Insect populations in the grain in the other five flat storages generally did not reach densities that would result in an infested designation on the grain-grading certificate.

Adoption of New Methods

Extension educators and consultants can encourage adoption of new technologies. Automation of monitoring for insects in grain using acoustical methods, methods of converting trap catch to absolute estimates, models predicting insect population growth rates, and more accurate economic thresholds and cost/benefit analysis can improve pest management. Attracticide (lure-and-kill), mass-trapping, and biological control may be useful in some situations. These methods have potential and are being more widely tested and adopted by the grain and food industry. The use of biological control is reviewed in Chapter 17 of this book.

Acoustical methods are commercially available for automatic continuous, non-destructive, remote monitoring of insect populations in stored grain (Mankin et al. 2010 and Chapter 22 of this book), but they are not widely used. Probe traps for automatic, continuous, non-destructive, remote monitoring insects in grain also are being marketed (Flinn et al. 2009), but are not widely used. Methods have been developed for converting these trap catches (Flinn et al. 2009) and those for sticky traps to absolute insect densities (Savoldelli 2006). Many of the tools and techniques have not been adopted because of lack of understanding and risk-averse behavior to newer technologies that deviate from traditional methods.

The decision tools developed for IPM in field and orchard crops have not been widely adopted for the protection of stored products. Sampling-based decision-making is being emphasized, but few economic thresholds have been developed for stored-product pests. The economic threshold is specific for a given species, and is the insect density at which pest management must be applied to prevent economic losses, but below which pest management is not economical (Onstad 1987). The thresholds depend on cost of the pest management method and market value of the commodity being protected. Multiple thresholds need to be considered if more than one pest management method is available, and the threshold must be adjusted as cost of pest management methods or the market values of the stored commodities change. Also, insect population growth models can be useful in predicting future insect densities, preventable commodity damage, and economic losses. The population growth models that have been developed for stored-product insects are listed in Table 7.3 in Hagstrum and Subramanyam (2006). The models can be used to determine when the economic threshold will be reached.

Pheromones and food attractants have been investigated as means of increasing the effectiveness of spot insecticide treatments for the Indianmeal moth (Nansen and Phillips 2004) and navel orangeworm (Phelan and Baker 1987). A Hawaii company (Food Protection Services) has conducted long-term studies on the use of mass trapping to find source populations and reduce cigarette beetle and moth populations in food storage warehouses and bakeries (Pierce 1994,1999). Similar studies were done successfully in a flour mill in Italy (Trematerra and Gentile 2010).

Follow-Up Monitoring

Monitoring is critical to determining whether the instituted pest management was effective. Roesli et al. (2003) used traps for stored-product beetles and moths to gauge the effectiveness of heat treatment in a feed mill. Some species — such as the cigarette beetle, Indianmeal moth, and almond moth — were completely controlled by the heat treatment, and very few insects were captured during the post-heat treatment period, whereas populations of the red flour beetle were captured within two to four weeks. Pest management professionals offering IPM services should monitor insect populations to show clients the degree and duration of insect management obtained due to an IPM intervention.

Mason (2005) suggested that the use of follow-up insect monitoring is an important consideration in selecting a fumigator. Using 15 published studies, Hagstrum and Subramayam (2006, see Table 8.1) showed that pest management was often ineffective. The ineffectiveness of pest management in the studies was a result of the breakdown of insecticides over time, inadequate sealing of facilities before fumigation, insects becoming resistant to pesticides, damage to insect-resistant packaging, diapause, and refuges in which insects could avoid being removed or killed. These studies covered many locations in the marketing system, ranging from the farm to the retail store. Pest management methods included the use of insecticides as protectants, fumigation, fogging with aerosols, sanitation, and insect-resistant packaging. Effectiveness can be influenced by the age structure of the pest population, insect species composition, environmental conditions, improper selection and incorrect implementation of pest management, including the absence of quantitative insect-monitoring methods.

The landscape of stored-product protection in the 21st century is changing and will continue to evolve, with IPM shifting from chemical methods to methods that are environmentally benign. The shrinking number of stored-product protection centers worldwide, and the decreasing number of researchers and educators offers great opportunities for consultants to embrace this area, as they have with field crops, and to develop and implement customized programs for the grain and food industry stakeholders. The new knowledge that the consultants can generate in stored-product protection and the role they can play to meet the needs of the end-users for the foreseeable future is immense.

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26 Quarantine

Scott W. Myers
David W. Hagstrum

The term quarantine originated from the Italian word *quarantina* (meaning 40 days) when the Black Death arrived in Europe in 1347 (Ebbels 2003). The incubation period from infection to symptoms was nearly 40 days, so 40 days was the quarantine period for ships suspected of carrying infection. Today, quarantine insects are those of economic importance that may or may not be present in an importing country but are not widely distributed in that country. The terms plant quarantine or plant health in Europe and plant protection in North America cover legislation and regulation designed to minimize the introduction and spread of harmful organisms using inspection, survey, risk assessment, treatment, post-entry quarantine, containment campaigns, and eradication.

International Programs

Worldwide invasive species cost billions of dollars annually in loss of commodities, reduced agricultural productivity and control measures. All countries have a vested interest in preventing the introduction and spread of invasive insect species. Legislative control can be effective in regulating the introduction and establishment of alien insect pests in a country and limiting their spread within that country. Most countries have some legislation restricting the importation of infested commodities. Information on international legislation is available at the International Plant Protection Convention website (https://www.ippc.int/).

Internationally, the International Plant Protection Convention (IPPC) was written in 1951 and revised in 1997 as part of Food and Agriculture Organization (FAO) efforts to help standardize the phytosanitary certification by different countries (Anon. 2001, Tyler and Hodges 2002). A model phytosanitary certificate was developed by FAO (Figure 1).

The World Trade Organization (WTO) enforces Agreement on Application of Sanitary and Phytosanitary Measures, also known as the SPS Agreement, which establishes food safety and animal and plant health standards for international trade. Although SPS allows individual countries to establish their own phytosanitary requirements, it encourages the use of international standards and a science-based approach to develop treatment regulations.

Within Africa, national legislation and regulations are based on Inter-African Plant Phytosanitary and Quarantine Regulations of 1988. Regional enforcement is coordinated by the following groups: Inter-African Phytosanitary Council (IAPSC), Asia and Pacific Plant Protection Commission (APPPC), Caribbean Plant Protection Commission (CPPC), Comunidad Andina (CA), Comité Regional de Sanidad Vegetal del Cono Sur (COSAVE), European and Mediterranean Plant Protection Organization (OEPP), North American Plant Protection Organization (NAPPO), Organismo Internacional Regional de Sanidad Agropecuaria (OIRSA), and Pacific Plant Protection Organization (PPPO).

Two hundred and thirteen contracting parties and their territories have National Plant Protection Organizations (IPPC 2010). The International Plant Protection Convention (IPPC) requires contracting parties to establish, update, and make available lists of regulated pests (Anon. 2003). In the United States these lists are available through the PExD database maintained by United States Department of Agriculture (USDA). They are available to federal and state regulatory personnel as well as exporters in industry to learn requirements of individual countries to allow the import of specific commodities.

United States Programs

The USDA, Animal and Plant Health Inspection Service (APHIS) is the agency responsible for preventing the introduction of invasive exotic species with the potential to cause harm to U.S. agriculture or natural resources (http://www.aphis.usda.gov/). USDA-APHIS provides guidelines, instructions, and procedures for performing inspections of imported commodities, international mail, and passengers arriving in the United States. These are carried out by U.S. Customs and Border Patrol (CBP) personnel stationed at airports, maritime ports, and land points of entry. Cooperative state and federal programs are established to restrict interstate movement of invasive species when domestic quarantines are established.

On inspection, when insects are found to be nonregulated species, the inspector can release the shipment to the importer (Caresche 1969). If the identification of insects is uncertain, the decision may be deferred. If the insect is a regulated pest species, the inspector can have the commodity treated to kill the pest, quarantine the shipment, return the shipment to sender, or have the commodity destroyed. A variety of training programs and materials are available for inspection personnel. Plant Protection and Quarantine (PPQ) unit within APHIS provides treatment descriptions, guidelines, and certification programs for imports and domestic movement in the PPQ Treatment Manual (USDA 2011a) and has developed a curriculum that several universities are now using (USDA 2011b). Similarly, a training manual developed in Africa has an appendix covering inspection of commodities for stored-product insects (Caresche et al. 1969).

To help reduce the burden on port inspectors and the overall number of interceptions at U.S. ports, the USDA-APHIS has established preclearance programs in a number of exporting countries that include inspection, treatment, and other measures to reduce the risk of accidentally introducing pest species. Preclearance programs can be beneficial to both trading partners as they allow commodities to move to market without interruption; however, they are expensive and can be cost prohibitive because most or all of the cost is the responsibility of the exporting country. These programs are conducted under supervision of USDA-APHIS employees and are typically developed in partnership between APHIS and the exporting country (USDA 2003).

Regulated Insect Pests

The first step for a new import is to develop a pest risk analysis for the pests of the commodity. Some insects are of greater regulatory significance than others, so species lists can be divided into quarantine pests and regulated non-quarantine pests. Regulated non-quarantine pests are those that are of economic importance but are already widespread in a country. The overall number of regulated stored-product insects can vary considerably by country and world region. New Zealand, for example, regulates 110 species of stored-product pests (Table 1), while China lists 18 species, and the European Union lists just a single species (*Alucita sacchari*). The economic consequences of the establishment of these pests have been severe both in terms of costs associated with contamination, yield loss, and the cost of control measures. Additional costs are incurred from trade restrictions that may occur when nonnative insects are established.

Relatively few stored-product insects are quarantine pests because so many already have been distributed worldwide by commerce. Many important stored-product pests in North America are nonnative and have long been established in the United States. These include Indianmeal moth, *Plodia interpunctella* (Europe/Asia); lesser grain borer, *Rhyzopertha dominica* (India/Tropics); confused flour beetle, *Tribolium confusum* (Africa); Mediterranean flour moth, *Ephestia kuehniella* (Europe); European grain moth, *Nemapogon granella* as well as others.

Presently, khapra beetle, *Trogoderma granarium* Everts (Figures 2 and 3) is the main actionable species associated with stored products imported into the United States (Stibick 2007). *Trogoderma granarium* is a serious pest to stored foods, grains, cereals, and spices throughout the world and has been found infesting 96 commodities (Hagstrum and

Model Phytosanitary Certificate

No. ________

Plant Protection Organization of ______________________________

TO: Plant Protection Organization(s) of ______________________________

I. Description of Consignment

Name and address of exporter: ______________________________

Declared name and address of consignee: ______________________________

Number and description of packages: ______________________________

Distinguishing marks: ______________________________

Place of origin: ______________________________

Declared means of conveyance: ______________________________

Declared point of entry: ______________________________

Name of produce and quantity declared: ______________________________

Botanical name of plants: ______________________________

This is to certify that the plants, plant products or other regulated articles described herein have been inspected and/or tested according to appropriate official procedures and are considered to be free from the quarantine pests specified by the importing contracting party and to conform with the current phytosanitary requirements of the importing contracting party, including those for regulated non-quarantine pests.

They are deemed to be practically free from other pests.*

II. Additional Declaration

III. Disinfestation and/or Disinfection Treatment

Date ________ Treatment ___________ Chemical (active ingredient) _______________

Duration and temperature ______________________________

Concentration ______________________________

Additional information ______________________________

____

Place of issue ______________________________

(Stamp of Organization) Name of authorized officer _______________

Date _______________ (Signature) ______________________________

No financial liability with respect to this certificate shall attach to (name of Plant Protection Organization) or to any of its officers or representatives.*

* Optional clause

Figure 1. *FAO model phytosanitary certificate.*

Table 1. *Regulated stored-product insect pests in New Zealand including species that do not breed in storage but can occur in large enough numbers to require pest management[a].*

Acanthoscelides argillaceus	*Carpophilus freemani*	*Lophocateres pusillus*
Acanthoscelides armitagei	*Carpophilus fumatus*	*Lyctus africanus*
Acanthoscelides obvelatus	*Carpophilus lugubris*	*Maruca vitrata**
Acanthoscelides zeteki	*Carpophilus maculatus*	*Mezium americanum*
Anthrenus pimpinellae isabellinus	*Carpophilus mutabilis*	*Necrobia violacea*
Apate monachus	*Carpophilus mutilatus*	*Niptus hololeucus*
Apomyelois ceratoniae	*Carpophilus obsoletus*	*Opogona sacchari**
Attagenus fasciatus	*Caulophilus oryzae*	*Palorus ratzeburgi*
Attagenus jucundus	*Conopomorpha cramerella**	*Palorus subdepressus*
Attagenus unicolor	*Corcyra cephalonica*	*Pectinophora gossypiella**
Bruchidius incarnatus	*Cryptolestes turcicus*	*Pharaxonotha kirschii*
Bruchus affinis	*Curculio caryae*	*Phradonoma nobile*
Bruchus atomarius	*Curculio sayi*	*Phthorimaea operculella* strain
Bruchus dentipes	*Cydia caryana*	*Prostephanus truncatus*
Bruchus emarginatus	*Cydia nigricana*	*Ptinus villiger*
Bruchus ervi	*Cylas brunneus*	*Pyralis maihotalis*
Bruchus laticollis	*Cylas formicarius elegantulus*	*Scrobipalposis solanivora*
Bruchus lentis	*Cylas puncticollis*	*Sitophilus linearis*
Bruchus luteicornis	*Dinoderus bifoveolatus*	*Stelidota geminata*
Bruchus pisorum	*Dinoderus distinctus*	*Thaumatotibia leucotreta**
Bruchus rufimanus	*Etiella zinckenella*	*Tinea fictrix*
Bruchus rufipes	*Euscepes postfasciatus**	*Tribolium audax*
Bruchus signaticornis	*Gibbium psylloides*	*Tribolium brevicornis*
Bruchus tristiculus	*Glischrochilus fasciatus*	*Tribolium destructor*
Bruchus tristis	*Glischrochilus quadrisignatus*	*Tribolium freemani*
Cadra calidella	*Gnathocerus maxillosus*	*Tribolium madens*
Cadra figulilella	*Hypothenemus areccae*	*Trogoderma anthrenoides*
Callosobruchus analis	*Hypothenemus eruditus*	*Trogoderma glabrum*
Callosobruchus chinensis	*Hypothenemus liberiensis*	*Trogoderma granarium**
Callosobruchus maculatus	*Hypothenemus obscurus*	*Trogoderma grassmani*
Callosobruchus phaseoli	*Latheticus oryzae*	*Trogoderma inclusum*
Callosobruchus rhodesianus	*Leguminivora ptychora*	*Trogoderma ornatum*
Callosobruchus serratus	*Liposcelis decolor*	*Trogoderma simplex*
Callosobruchus subinnotatus	*Liposcelis entomophila*	*Trogoderma sternale*
Carpophilus binotatus	*Liposcelis paetus*	*Trogoderma variabile*
Carpophilus bisignatus	*Liposcelis rufus*	*Zabrotes subfasciatus*
Carpophilus foveicollis	*Liposcelis terricolis*	

[a] Species followed by asterisks are also regulated pests in the United States. In the United States, *Curculio nacum*, *Hypothenemus hampei* and *Cydia splendania* are also regulated pests that can occur in large enough numbers to require pest management during storage.

Subramanyam 2009). The high potential for spread of *T. granarium* through international trade makes this species a continued threat. If *T. granarium* were to become established in the United States it would create market accessibility problems for a number of commodities. Several studies have predicted the risk of establishment of *T. granarium* in different climates (Howe and Lindgren 1957, Banks 1977, Viljoen 1990).

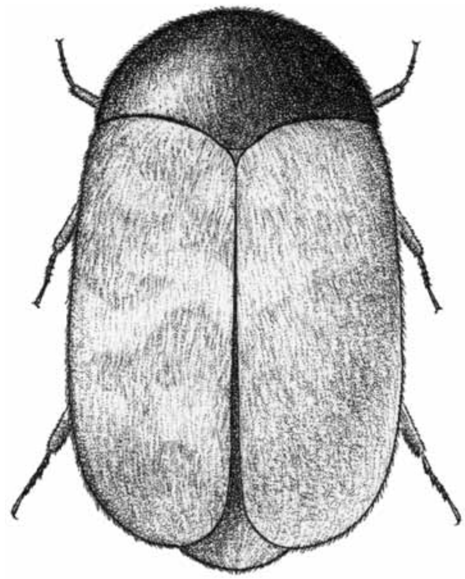

Figure 2. *Khapra beetle adult, Trogoderma granarium, 1.7 to 3 mm long (from Gorham 1991).*

Figure 3. *Khapra beetle, Trogoderma granarium larvae on wheat. Photo modified from Stibick 2007.*

Permits are required to import commodities known to harbor *T. granarium* into the United States. This includes grains, seeds, nuts, dried milk, fish meal, meat and bonemeal, dried animal hides, and other products. Phytosanitary certificates are required for restricted commodities from countries that maintain inspection programs.

The Pest Identification (PestID) database, a subsystem of the Agricultural Quarantine Activity Systems (AQAS) database maintained by USDA-APHIS, reported that from 1985 through 2010 *Trogoderma* spp. were intercepted at U.S. ports of entry 666 times, and 559 were identified as *T. granarium*. Of these, 50.8% were found in passenger baggage, 30.4% were general cargo, and the remainder split among mail, ship holds and stores, and other cargo. The introductions came from 43 countries (Table 2), with the overwhelming majority coming from North Africa, South Asia, and the Middle East. In 2011 a total of 162 interceptions of *T. granarium* were made over the first 9 months of the year, prompting APHIS to restrict rice imports to permitted commercial shipments only in order to reduce the number of introductions.

Khapra beetle larvae can easily penetrate packaging and infest stored goods, pet food, and food packets after they get into a home or storage site. Once in a product, they can reproduce and move to cross-infest previously clean materials. Khapra beetle larvae can easily infest, contaminate, and render various processed foods unfit for human consumption. Khapra beetle can enter a quiescent stage where it may hide for many months in convenient cracks, crevices, or other hiding spots. It can then emerge when food becomes available, such as when a stored product comes into contact with a wall in an infested warehouse or grain storage. A sign of infestation may be tracks of wandering larvae in dust on floors or surfaces as larvae scavenger for protein. *Trogoderma* spp. can survive long periods without food, and are able to retrogressively molt when food is not present (Beck 1971a). The larvae may resume growth and molting to maturity, but subsequent molt and regrowth cycles result in lower fecundity food sources (Beck 1971b).

Eliminating infestations is generally achieved through a combination of sanitation and pesticide applications. Large scale infestations, such as storage facilities or warehouses, may require fumigation or heat treatment to eliminate an established popula-

Table 2. *Countries of origin for interceptions of T. granarium at U.S. ports of entry from 1984 through 2010 (Unknown 6%)[a].*

Asia (45%)	Middle East and North Africa (43%)	Sub-Saharan Africa (4%)
China	Bahrain	Mali
India	Egypt	Nigeria
Indonesia	Ethiopia	Senegal
Japan	Iran	Sudan
Laos	Israel	Tanzania
Malaysia	Iraq	Zamibia
Pakistan	Jordan	
Philippines	Kuwait	**Europe (1%)**
Singapore	Lebanon	Cyprus
Thailand	Qatar	Denmark
	Saudi Arabia	England
Oceania (<1%)	Sri Lanka	Germany
Australia	Syria	Spain
	Tunisia	Ukraine
Central America (1%)	Turkey	
El Salvador	United Arab Emirates	**North America (<1%)**
Guatemala	Yemen	Canada

[a]US Dept of Agriculture, AQAS-PestID database

tion. Khapra beetle may enter a status of quiescence, often referred to as facultative diapause, where metabolism is low and development is retarded. Under these conditions, *T. granarium* larvae are tolerant of methyl bromide fumigation and require high doses to achieve effective control (USDA 2011a).

Several tools are available for trapping and monitoring populations. Floor-placed dome traps use wheat germ oil to attract larvae and a pheromone lure to capture adult males adults (Trece Inc., Adair, OK). A vertical wall-mounted trap developed by USDA (Barak 1989) uses the same lure combination and has the advantage that it is stationary and can be positioned at any height. Aerial traps using the *T. variabile* (warehouse beetle) pheromone lure are often included in *T. granarium* survey efforts because they help to minimize the number of *T. variabile* captures in the *T. granarium* traps. This helps to ease identification of potential *T. granarium* captures.

Interceptions of *T. granarium* in commodities imported into England between 1957 and 1973 ranged from 46 to 131 per year (six to 18 per 1,000 inspections); *T. granarium* was intercepted mostly in rice and peanuts from Burma, India, Nigeria, and Sudan (Freeman 1974).

Eradication of established populations

There have been numerous occurrences where *T. granarium* has been able to establish populations in the United States and other foreign locations. Eradication of these populations is often difficult and expensive. *Trogoderma granarium* was introduced in California before 1946 but incorrectly identified as *Attagenus piceus* and spread to 16 counties in California, five in Arizona, and three in New Mexico before being correctly identified in 1953 (Armitage 1956, 1958). By 1958, 51,000 premises in 27 states had been inspected, and the pest was eradicated in the United States by 1966. The cost of eradications was $8.4 million spent by federal government and an additional $6.5 million spent by property owners (Klassen 1959). From 1978 to 1983, it was again established in the United States, and 25 infestations in California, Maryland, Michigan, New Jersey, New York, Pennsylvania, and Texas were discovered and eradicated (Kennedy et al. 1991). More recently, a khapra beetle infestation was discovered in a Connecticut residence in 2006. It was determined to be an isolated infestation, and the population was eliminated through sanitation, reinspection, and insecticide applications.

Khapra beetle infestations reported in Baja California in December 1954 were apparently from infested products originating in the United States. In Mexico total of 25 million cubic feet of storage space at 92 properties infested by khapra beetle were successfully fumigated with methyl bromide by September 1961. Additional introductions and eradications of khapra beetle have occurred in Australia (Emery et al. 2008), Japan (Sonda 1968), South Africa (Banks 1977), and Tanzania (Banks 1977).

Other quarantine stored-product insect pests

Within the United States, legislation restricts the movement of commodities infested with sweet potato weevil, *Cylas formicarius*, into some states in which it is not yet established. This species is an actionable species in Asia, and there have been eradication programs for sweet potato weevil and West Indian sweet potato weevil, *Euscepes postfasciatus* in Japan (Moriya and Miyatake 2001). In Asia, potato tuber moth, *Phthorimaea operculella*, is also an actionable species. In Africa, legislation restricts movement of larger grain borer, *Prostephanus truncatus*, between countries (Tyler and Hodges 2002). *Prostephanus truncatus* has been introduced into Israel (Calderon and Donahaye 1962) and Iraq (Al-Sousi et al. 1970) with maize imported from the United States. It was not detected for several months. Malawi has restrictions on the importation of tobacco and tobacco products infested with cigarette beetle, *Lasioderma serricorne*, and tobacco moth, *Ephestia elutella*.

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S156 – 26 September 2012

27 Economics of Commodity Storage

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For agricultural commodities there is a mismatch in the timing of consumption and production. Consumers want to eat bread every day, but there are only a couple wheat harvests per year. The function of storage is to smooth consumption of a commodity over time, both within and between crop years. The supply of a commodity is equal to production in a given year, plus carryover of stored product from the previous year. Carryover stocks serve two important functions. They meet pipeline needs while buyers are waiting for the following harvest and guard against poor yields the following year.

Individual Incentives to Store

Farmers, grain elevators, and processors store commodities for several reasons. The first is to make a profit because they anticipate higher prices in the future. Inventory may be stored unpriced, speculating that prices will be higher in the future. Alternatively, the stored commodity may be priced for delivery in a future period, where higher future prices have been established.

Another reason to store commodities is to assure future supply. For example, processors such as wheat millers want to be sure they have the year-round supply necessary to operate at full capacity. Livestock producers may store corn, silage, or forage to assure the needed year-round supply of feed. Both of these groups store commodities to avoid the catastrophic consequences of running out of the commodity. Increased operational efficiency is another reason to store commodities. Most processors have at least 3 to 7 days of commodity storage at their facility to ensure a constant flow for processing. One of the primary motivations for on-farm storage is to increase harvest efficiency. During harvest, there is often a long wait to deliver commodities to local buyers, which can create bottlenecks.

Alternative Storage Technologies

Bulk commodities are stored in a wide range of storage structures. Commodities are stored on farm and at commercial facilities at various points in the marketing channel, in raw form and after one or more stages of processing. The following is not intended as an exhaustive discussion of storage technologies for bulk agricultural commodities. Instead, it is focused on major commodities and those with particularly notable storage structure issues.

Grain is one of the major commodities stored in the United States, with almost 10 billion bushels of off-farm storage capacity and an addition 12 billion bushels of on-farm capacity. These statistics reflect the storage of corn, wheat, grain sorghum, barley, soybeans, oats, rye, millet, canola, flaxseed, mustard seed, safflower, sunflower, rapeseed, Austrian winter peas, dry edible peas, lentils, chickpeas/garbanzo beans, and other minor grains. Other bulk commodities including rice, peanuts, storage of oilseeds at crushing facilities, warehouses storing tobacco, seed and other types of dry edible beans are not reflected in U.S. grain storage capacity statistics.

Major types of grain storage structures include concrete silos, steel bins, and flat (rectangular) storage warehouses. Many early grain storage structures were constructed of framed or cribbed wood, but this construction has been virtually abandoned due to fire hazards and other issues. Concrete silos are upright cylinders made of reinforced concrete that can be designed much taller than steel silos. Additionally, concrete silos can be designed in clusters to take advantage of adjacent walls and utilize the area between the silos (interstice area) for additional storage. Concrete silos maximize the storage in a limited space, which becomes important in a plant addition or where land cost is a premium. Concrete silos have a longer useful life expectancy than steel bins. Concrete silos require periodic inspection and maintenance (sealing or caulking) to prevent water penetration to the embedded rebar.

Concrete silos are filled by elevating the grain to the top of the silo by an elevator leg (often called a bucket elevator). The grain is then gravity fed directly into the silo or to a structure located at the top of the silo, known as a headhouse, where it is moved by a belt or drag conveyor to the desired silo. As it leaves the elevator leg the grain may pass through a variety of devices such as scales, samplers, cleaners, or other machines that are necessary for a particular product. The grain is removed from the silo from the bottom; most commonly onto a belt located in the tunnel (basement).

Many concrete grain facilities in the United States were constructed before 1950 using a construction process known as slip form. Slip form construction involves a continuous pour with concrete and rebar added around the clock until the structure reached design height, a process often requiring 7 to 10 days. Early slip form technology limited the diameter of the bins to 20 feet or less, which resulted in storage structures with a number of separate silos. This design provides opportunities to segregate different grain types or quality levels.

Grain is not directly inspected in these small diameter silos but is sampled as it is moved (turned) from one silo to another. The grain from several silos may be blended as it is turned or as it withdrawn from storage. Historically, insect control treatments were also applied as the grain was turned. Some concrete structures have been retrofitted with recirculation systems that allow one or more silos to be fumigated without moving the grain.

Larger diameter (up to 90 feet) concrete silos can now be constructed. Many larger diameter silos are constructed using a process called jump form. Jump form construction involves a number of separate pours, with the form lifted between each pour and a cold joint installed between each section. Grain in large diameter silos is managed similar to that in steel bins and is not moved during the storage cycle. Pest control is accomplished by fumigating the entire silo of grain.

Steel bins are constructed of horizontally corrugated curved sheets of galvanized steel bolted together. Bins can be constructed from a variety of materials, from carbon steel to stainless steel, and technologies include bolted and welded smooth wall designs. Most steel bins have vertical columns (stiffiners) that may be mounted on either the inside or outside of the bin. Steel bins can be constructed in a wide range of sizes, from a few thousand bushels to hundreds of thousands of bushels. Steel bins cost less to construct than concrete bins, particularly for smaller capacities. As the capacity and height of the structure increases, scale economies make concrete construction more competitive. Like concrete silos, steel bins require periodic inspection and more frequent maintenance such as painting. Improper filling and discharge are the primary causes for premature failure of steel silos.

Steel bins are filled by gravity flowing grain from an auger or elevator leg. When multiple bins are constructed in a complex, they may be fed from gravity chutes connected to a distributor at the top of the elevator leg or by a drag conveyor fed by the elevator leg. Discharge can be either flat bottom or hopper bottom design. Large bins have a flat bottom design and include automatic augers (sweeps) that rotate slowly on the floor of an almost empty bin to ensure that the bin can be emptied as completely as possible without a worker having to enter.

Unlike small diameter concrete storage structures, grain in steel bins is not moved from the bin until it is removed for storage. Steel bins are constructed with access hatches at the top that facilitate inspection of the grain or commodity. Pest-management treatments are performed by sealing and fumigating the bin.

Flat grain storage structures range in shape from arch-roof types to slant- and straight-wall rectangular units. Grain unloading can be partially mechanized. On a capacity basis, flat storages can be constructed for less than steel bins or concrete silos. Operating costs can be higher because they are more difficult to load and can only be partially unloaded with mechanical conveyors. Achieving uniform air movement for proper aeration of a flat storage structure can be difficult. Flat storage structures are useful for materials that do not flow and cannot be moved with augers or stored in conventional bins where gravity flow is required. For example, the inconsistency and unpredictability in handling characteristics of by-product feed ingredients makes flat storage appropriate for these commodities.

Outside grain storage

In many years producers and commercial operators pile grain and other products (for example, whole cottonseed) in outdoor piles when harvest volume exceeds storage capacity and/or freight logistics make it impossible to move the commodity into the marketing channel. If the commodity is sufficiently dry, often it can be stored in piles during the cooler fall and winter weather without being covered and aerated. Longer-term storage requires tarp covers and provisions for aeration. Outside storage involves higher levels of shrinkage and quality deterioration than storage in a structure. Proper site selection, aeration, tarping, and monitoring are factors in minimizing losses.

Filling and unloading of temporary storage is accomplished with a portable auger or other inclined conveyor. The conveyor is shifted to shape the pile. The grain is reclaimed using a front-end loader or pneumatic vacuum conveyor. The reclamation process may necessitate further grain conditioning via aeration, drying, or blending. Spoiled grain can become comingled with sound grain, contaminating the entire amount with damaged kernels and commercially objectionable odors.

Specialty warehouse configurations

Various agricultural products are stored in specially configured warehouses. Farmers store peanuts in flat storage structures. Although similar to flat grain storage structures, the elevator leg and horizontal belt must be designed to minimize mechanical damage to the peanuts. Spouting must be at a 45-degree angle to ensure adequate flow. Structures known as "deadheads" must be installed at the end of the spout to reduce velocity to prevent damage. The design of the aeration and headspace ventilation system is also an important factor in minimizing quality losses during peanut storage. Pest management systems for peanut storage include both fumigation and timer-released insecticide application.

Each bale of cotton ginned in the United States creates more than 800 pounds of cottonseed that must be placed in temporary or long term storage. Cottonseed is hydroscopic, meaning that it absorbs or gives up moisture to the surrounding air. Cottonseed has a high angle of repose (45 degrees). After the seed has settled, the angle of repose may increase to 90 degrees allowing the seed to "bridge" or remain upright in columns. Cottonseed is handled most efficiently by pneumatic conveyors although it can be handled with belts and screw conveyors.

Cottonseed is stored in clear span metal buildings engineered for the lateral forces exerted by the cottonseed as it is loaded and unloaded. Warehouses are typically lined with ¾-inch plywood to increase wall strength and facilitate cleanout. Long-term storage of cottonseed requires aeration, with 10 cubic feet per ton airflow considered standard. Because cottonseed is hydroscopic, aeration fans in cottonseed warehouses should not be operated when it is humid, foggy, or raining.

Storage Ownership Options

Producers of grain and other bulk agricultural commodities have several storage options. They can invest in on-farm storage structures, store products at commercial storage facilities (by renting storage space and management services), invest in condominium storage and become a part owner of a large-scale facility, or rent on-farm storage from another producer. On-farm storage facilitates harvest by reducing transportation of grain to the elevator and eliminating the time waiting to unload. It also allows the producer to separate and preserve the identity of a commodity. The producer is not locked into marketing the commodity through a particular facility but instead can merchandise the commodity through the most attractive outlet. The variable costs of on-farm storage facilities are less than commercial storage.

Major disadvantages of building on-farm storage include the initial investment, which may or may not be recouped through the lower variable cost of storage. The producer is responsible for monitoring grain throughout the storage period and absorbing shrinkage and quality loss costs. The investment in on-farm storage is also a sunk cost in an asset that may not be matched with future farming decisions or market conditions. The producer is directly involved in merchandising the commodity and arranging transportation.

Condominium storage involves purchasing or entering into a long-term lease for storage space at a commercial facility. Condominium storage options also occur when a group of producers go together to purchase or construct a large-scale storage facility. Generally, the producer makes an initial investment to reserve the right to use a fixed volume of storage. The storage interest can generally be sold at a later date with approval of the condominium entity. Storage is managed by the facility manager and the entity guarantees grade and quality factors. A service fee based on the volume stored is charged to cover management and the variable costs of storage.

Condominium storage allows producers to take advantage of the economies of scale of larger structures. It also provides another storage option for producers with a large amount of rented land who do not want to invest in on-farm storage without a long-term crop lease. In most cases a producer investing in condominium storage can use it for two or more grains in any proportion (for example, corn or soybeans), which gives greater flexibility than on-farm storage, where bins must be dedicated to a specific crop. Disadvantages of condominium storage include the fact that the commodity is comingled, eliminating marketing opportunities for an identity preserved product. Marketing flexibility also is limited as is the case with commercial storage. The future market and value of condominium storage or storage interest is difficult to predict.

The Storage Decision

The decision whether to store a commodity, how much to store, and how long to store will depend on the individual decision maker's return to storage, which is determined by the price today relative to the price at some future date minus the cost of storage. For existing storage capacity, each individual will balance the expected returns to storage with the variable costs of storage. If the individual does not have storage, then the variable cost of storage will be determined by the commercial rate of storage. If the individual is considering whether to invest in additional storage capacity, then the individual will focus on multiyear returns to storage relative to the fixed costs of building storage. Each of these returns and costs will be discussed in detail.

Expected Returns to Storage

The return to storage is the difference between the cash price today and the price for delivery on some future date, called either the future price or the forward price. If the contemporaneous future price is higher than the current price, this positive price difference represents the return to storage. Decision makers also undertake storage to capture speculative returns, which is the difference between the current cash price and the expected future price. In the case of speculative storage, while the realized returns to storage depend on the realized price on the future delivery date relative to the current price, the decision is made based on the expected future price.

Typical price patterns

The overall returns to storage depend on the level of stocks for a particular commodity (Working 1949). If grain inventories for a particular commodity are large, then the relationship between prices for delivery on two different dates will reflect the "cost of carry", i.e., the variable costs of storing the grain. In contrast, if grain inventories are tight for a particular commodity, the carry in the market tends to be small because competition between firms offering storage services will drive down the price of storage. There tend to be positive returns to storage in years with large inventories, which means that prices increase through the storage period. For years with tight stocks, the highest prices may be offered at harvest with little price appreciation through the storage period, resulting in minimal return to storage.

Space, or the distance to market, also plays a role in the return to storage. Several studies have shown that the returns to storage increase as the distance to market increases (Wright and Williams 1989; Benirschka and Binkley 1995; Brennan, Williams and Wright 1997). For example, the returns to storage will be negligible or small in New Orleans, La., which is the largest export market, while the returns to storage will be positive and likely cover the full cost of carry in Fargo, N.D., which is far from terminal markets.

Storage hedges and futures market transactions

Hedging in the futures market can be used to "lock in" a positive return to storage (Wisner and Hurt 1996). Storage hedges are used by grain elevators and processors to protect themselves from fluctuations in the value of their inventory. Farmers use storage hedges to capture a return to storage and establish a higher price for their crop. The concept of hedging is best illustrated with an example, but first we need to introduce the concept of basis. Basis is the difference between the local cash price and the futures price, i.e., local cash price – futures price = basis. The futures price is established each day during trading on the commodity futures exchanges, while the basis is established by the local buyer.

Example 1 presents a storage hedge that might have been implemented by a farmer in 2009. For the 2009 crop, the futures market is a carry market, i.e., the futures prices for later delivery are higher than the prices for the nearby contract. On October 9, the farmer has a cash bid from the local elevator at $3.32 per bushel, or $0.30 under the December 2009 futures, which are trading at $3.62. On the same day, the May futures price is $3.83. The expected basis for early May delivery is $0.10 under May futures, so the expected May hedge price is $3.73 ($3.83 - $0.10 = $3.73). Thus, the expected gross storage return is $0.41 per bushel, calculated as the expected $3.73 May hedging price less the $3.32 harvest price.

The farmer establishes the storage hedge by selling the May futures at $3.83 on October 9. With the hedge, the farmer's market position is long (owns) 20,000 bushels of corn in storage and short (sold) 20,000 bushels of May futures. The hedge is converted to a cash sale on May 3 and the basis on that date is $0.05 over the May futures.

The pricing summary illustrates how to arrive at the farmer's net final price. The farmer sells the cash corn on May 3 for $3.65. On the same day, the farmer lifts the hedge to realize the gains or losses in the futures market. The farmer had sold May futures in October at $3.83 and subsequently buys back May futures at $3.60, for a gain of $0.23.

As shown in the gross returns to storage summary, the gross return to hedged storage (before deducting storage costs) is $0.56 per bushel. The storage hedge locked in the $0.21 December to May carrying charge (also called the spread) by selling the May futures. In addition, the basis appreciated from $0.30 under at harvest to $0.05 over in May for a gain of $0.35. The gross storage return of $0.56 is the sum of the $0.21 spread and the $0.35 basis appreciation. The $0.56 gross storage return in this example is before hedging costs, which would be roughly $0.02 to $0.03 per bushel. To determine if storage is profitable, the farmer must compute the net storage return, which is the gross storage return with hedging and the cost of storing corn from October 9 to May 3 subtracted.

Example 1. *Storage hedge by farmer.*

Date	Cash	Futures	Basis
October 9, 2009	Cash bid for current delivery is $3.32	December 2009 corn futures is $3.62	Basis for current harvest delivery is $0.30 under December 2009 futures
October 9, 2009	Expected net price is $3.73 for early May 2010	Sell 20,000 bushels of May futures at $3.83	Expected early May basis is $0.10 under May futures
May 3, 2010	Sell 20,000 bushels of cash corn at $3.65	Buy 20,000 bushels of May futures at $3.60	Basis is $0.05 over May futures

Pricing summary:	Gross storage return summary:	
The farmer delivered cash corn on May 3 at $3.65.	December to May Futures spread:	$0.21
The farmer lifted the futures hedge, gaining $0.23	December to May basis gain:	$0.35
($3.83-$3.60), for a net price received of $3.88.	Gross return to storage:	$0.56

While the expected basis appreciation in October was $0.20, the actual basis gain was $0.35. This additional basis gain illustrates that with a storage hedge, as with any hedge, changes in local basis impact the final net price and the gross storage return. For further reading on hedging see Wisner and Hurt (1996).

Speculative storage

In contrast to using storage hedges, other market participants store inventory unpriced, i.e., without using hedges. These decision makers are anticipating that prices will be higher later in the storage season. Although the typical price pattern is for prices to increase during the storage season, anticipated higher prices do not always materialize. Speculative storage is risky; in some years there may be very large returns to speculative storage and in other years there may be losses. For example, consider a soybean farmer who delivers soybeans on May 1. Figures 1 and 2 illustrate the May 2006 and May 2007 Chicago Board of Trade soybean contracts, respectively.

Now look at the speculative returns for this farmer comparing the May soybean futures prices on the business day closest to October 1 and May 1. In 2006, the May soybean futures were trading at $6.04 per bushel on October 3, 2005 and at $5.93 on May 1, 2006, a loss of $0.11 per bushel before considering the variable costs of storage. In contrast, in 2007 the May soybean futures were trading at $5.81 on October 2, 2006, and at $7.34 on May 1, 2007, a gain of $1.53 before considering costs. Clearly, speculative storage in 2007 would have been very profitable, while it would have led to a loss in 2006. This example illustrates both the risks and the potential rewards of speculative storage.

Figure 1. *May 2006 Chicago Board of Trade soybean futures contract.*

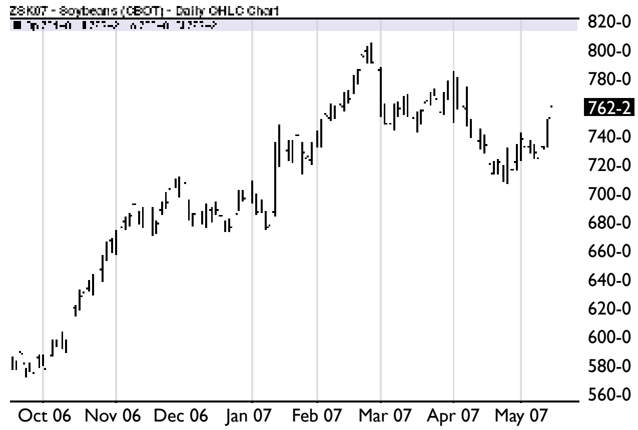

Figure 2. *May 2007 Chicago Board of Trade soybean futures contract.*

Variable Costs of Storage

The variable costs of storage include the costs that are only incurred if grain is stored. These costs will also be a function of the quantity of stored grain and the length of the storage period.

Interest on inventory

Typically, the largest variable cost associated with storage is the interest cost. This cost represents the foregone interest that would have been earned if the commodity had been sold, or the interest charges that would have been avoided if debt was paid off. The magnitude of interest cost depends on the length of the storage period, the interest rate, and the harvest price of the grain. The following example presented in Table 1 shows how the interest cost increases if corn is stored on farm for 6 months versus 4 months. For this example, the interest rate is the average operating loan interest rate during the third quarter of 2010 (Federal Reserve Bank of Chicago 2010). The corn harvest price is for central Indiana in October 2010 (Chris Hurt, personal communication). As shown in Table 1, the interest cost of storage increases with the storage period and in the example of corn stored in central Indiana in 2010, the interest cost is 9.6 cents per bushel for four months of storage and increases to 16 cents per bushel for 6 months.

Table 1. *Interest cost of storing corn.*

	4 months of storage	6 months of storage
Corn harvest price, Central Indiana 2010	$5.30	$5.30
Interest rate	6.04%	6.04%
Months of storage/ 12 months per year	0.3	0.5
Interest cost	$0.096	$0.16

Utilities

The variable costs include the cost of utilities for drying, aeration, and conveyance (i.e., augers to move grain). For grain to be stored for any length of time, it needs to be dried to a safe storage moisture level. The variable costs associated with drying include fuel for heating the grain and electricity to run the fans. The drying cost will depend on the starting and final moisture levels of the grain, the type of dryer and the drying air temperature, the airflow rate and the outside weather conditions (Uhrig and Maier 1992). When storing grain for long periods of time aeration is often used to both cool the grain in the winter to inhibit insect development and to equalize moisture differences in the grain mass. The variable cost of aeration is the electricity to run the fans. This cost will depend on the length of the storage period. Finally, conveyance costs are associated with moving grain from the dryer into the bins and loading out of the bins into the truck. Augers used for conveyance may be powered by tractors using diesel or may use electricity.

Handling

For farmers who choose to store grain in bins on their farm, there will be an additional handling cost when the grain is sold.

Monitoring costs

Grain that is stored for long periods of time needs to be monitored for any changes in quality. Experts recommend that grain is monitored for temperature, moisture, insects, and molds every 1 to 2 weeks during warm months and every 3 to 4 weeks during cold months (Mason and Woloshuk 2010). Monitoring costs include the labor and equipment used to sample the grain. The balance of these costs will depend on the equipment. For example, if a farmer has a temperature-monitoring system in the storage bin, the cost of monitoring will be primarily the depreciation on the monitoring equipment because checking temperature would take minimal time. In contrast, if the farmer does not have a temperature monitoring system, he would need to climb into the bin with a thermometer to test the temperature of the grain, which requires more time but the equipment cost would be substantially lower.

Pest management costs

There are two categories of costs associated with managing pests: preventive and curative. There are several common steps associated with prevention of insect damage. Before the storage structure is filled with grain, the structure needs to be sanitized. The sanitation process starts with cleaning the structure and removing any spilled grain that could harbor insects. Often an insecticide is also sprayed on the walls and floor of the structure. After the storage structure is filled with grain, the grain will be monitored for insects. The lowest cost way to prevent insect growth, which is only financially feasible when the ambient temperature is low, is to use aeration to chill the grain. At low temperatures, the insects remain dormant or can even be killed. Other prevention strategies include using diatomeous earth as a protectant on the grain surface. If monitoring finds that insect populations are high, then the grain will need to be fumigated, which is a curative measure. The grain can be fumigated with an insecticide or a chemical such as ozone. Fumigation tends to be expensive because the storage structure needs to be completely sealed before the fumigant is introduced.

Shrinkage

As grain loses moisture, it loses weight. This weight loss is called shrink. Because grain is sold based on weight, and grain continues to lose moisture during the storage period, shrinkage must be considered one of the storage costs. A common rule of thumb for handling shrinkage is to assume 0.5% shrinkage for "in and out" and an additional 0.25% shrinkage every time the grain is turned. A bin of grain that is turned one time would be expected to have 0.75% total shrink by the time it is removed from storage. Moisture shrinkage is calculated by the formula:

$$\frac{Mi\% - Mf\%}{100 - Mf\%} \times 100 = \%\ moisture\ shrink$$

Where *Mi* is the initial moisture content and *Mf* is the final moisture content. Moisture shrinkage from drying from 15% moisture to 10% moisture would be:

$$\frac{15 - 10}{100 - 10} \times 100 = 5.56\%$$

Quality deterioration

As the length of time in storage increases, grain quality tends to deteriorate (Mason and Woloshuk 2010). Lower quality grain may receive a discounted price, depending on the delivered quality and the buyer's discount schedule. Any discounts applied to the grain due to this lower quality are a cost of storage. A decision tool developed by Oklahoma State University (Grain Handling Cost Template) estimates the fixed and variable costs of handling and storing grain based on the grain type and price, storage type, handling equipment, interest rate, and electricity rates and other inputs (Kenkel 2010).

Storage Returns Over Variable Costs

From an economics perspective, in the long run the average costs of storage should be equal to the returns to storage. Storage returns in any individual year will vary, so the producer will decide whether to store grain, and how much to store depending on whether the storage returns cover the variable costs. If the producer has existing on-farm storage facilities, he will compare the storage returns to the on-farm storage variable costs. If the producer does not have on-farm storage, then he will compare the storage returns to the commercial storage variable costs.

Decision to Invest in Storage Facilities

When deciding to invest in storage facilities, the decision maker needs to consider the fixed costs associated with the storage investment relative to the expected annual returns to storage. At a minimum, the annual returns over variable costs need to cover the annualized fixed costs of storage.

Fixed costs of storage

The fixed costs of storage are incurred whether or not grain is stored in the facilities. Total annual fixed costs depend on the size of the investment in storage facilities, which includes the storage structure, monitoring equipment, conveyance equipment, aeration, site preparation, concrete pad, and construction. These annual fixed costs of storage facilities include interest, depreciation, taxes, insurance, and maintenance. The interest fixed cost is the interest payment on the loan for the storage facility investment. Depreciation is the investment divided by its useful life, also called straight-line depreciation.

Returns on investment in storage structures

The return on investing in storage structures will depend on the return to storage from holding grain in the storage structure and the cost of the investment in the storage structure. The most basic way to calculate return on investment for storage structures is to use the following calculation:

ROI = Return to Storage – Cost of Investment/ Cost of Investment.

The primary return to storing grain comes from price increases in the futures and basis between harvest and later in the storage season. Some producers also factor in the benefit of capturing price differences between buyers, seasonal premiums, the ability to identity preserve grains, and additional harvest efficiencies. The annual return to storage is the difference between the gain from the price increases minus the variable costs. The lifetime return on investment in the storage structure will include the discounted annual return to storage for the life of the structure and the cost of the investment, which is the fixed cost of building the structure.

Economies of scale in storage structures

As shown by Dhuyvetter et al. (2010), there are significant economies of scale in on-farm storage bins. They estimate the costs associated with site preparation, concrete, and construction and show that as the bin size increases, the required investment decreases on a per bushel basis, but at a decreasing rate. They find that in 2010 in Kansas the investment cost for a 10,000 bushel bin was $2.31 per bushel compared to

$1.49 and $1.24 per bushel for 50,000 and 100,000 bushel bins, respectively.

A decision tool developed by Oklahoma State University calculates the predicted cost for various sizes and types of commercial grain bins (Kenkel 2011). Results also indicate that the per bushel cost declines as bin sizes increase (Figure 3). At large capacities the per-bushel cost actually increases (diseconomies of scale) due to the cost of the aeration equipment. The relationship between aeration horsepower and bin capacity is not linear, and aeration horsepower can increase dramatically for very large bins.

Identity preserved storage costs and benefits

With the introduction of genetically modified crops, much of the food-grade supply chain has implemented identity preserved (IP) programs and most of these programs start at the level of the first handler (Anderson 2004; Stevenson 2004; Voigt 2004; Hurburgh 1994). For instance, National Starch has implemented the TrueTrace™ program and Cargill has implemented the Innovasure™ program, to name just a few of the IP programs for food-grade corn. Any IP program that guarantees quality and segregation will require additional handling efforts, and thus create additional costs. For farmers interested in participating in an IP program that offers premiums, on-farm storage capacity is almost always a prerequisite.

Most of the literature on IP grains has focused on the additional costs associated with an IP program and assumed that these programs would only succeed if the final market was willing to pay a premium sufficient to compensate for these additional costs. Many studies have focused on the additional costs faced by grain elevators or the entire grain-handling supply chain. Hurburgh (1994) estimated the additional physical costs of segregating soybeans at country elevators based on protein and oil content and found that the additional costs of testing and segregation were two to three cents per bushel. Lin, Williams, and Harwood (2000) estimated that the cost of segregating non-GM grains and oilseeds along the marketing chain from country elevator to export elevator could add about $0.22 per bushel, not including any premiums to the farmer. Kalaitzan-

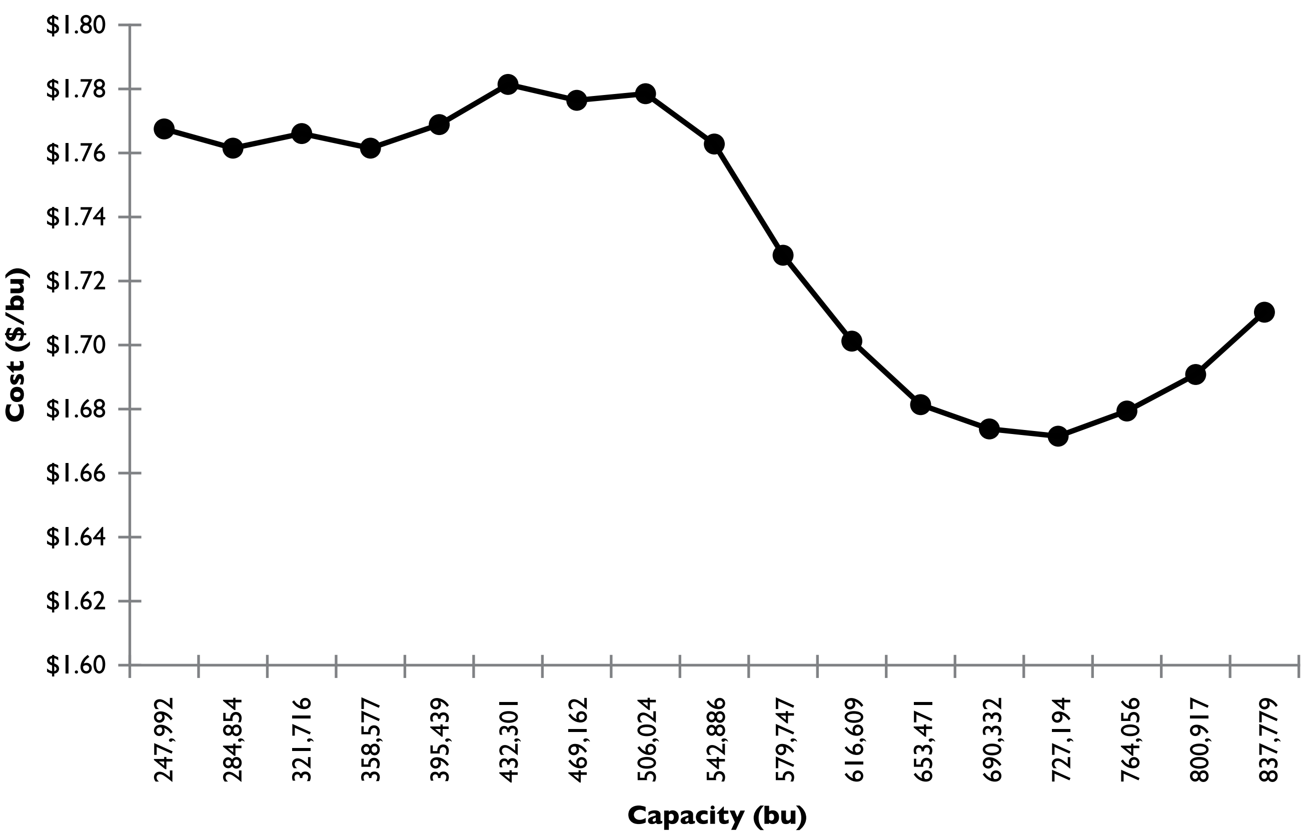

Figure 3. *Predicted cost of steel bin construction at various capacities.*

donakes, Maltsbarger, and Barnes (2001) estimated the costs of IP high oil corn at the 5% purity level for three elevators with multiple scenarios of bin filling schedules, crop-to-bin assignments, incoming volumes, and other key parameters and found an additional average IP cost of $0.35 per bushel. They also highlighted the importance of hidden or opportunity costs (e.g., grind margin loss, losses from underutilization of capacity) that can occur from adapting current commodity operations to IP.

Wilson and Dahl (2005) used a stochastic optimization model to examine the supply chain-level costs of a dual marketing system of GM and IP non-GM wheat relative to a non-GM system for a vertically-integrated export supply chain. They model the costs and risks of adventitious commingling at every stage of the supply chain, incorporating testing accuracy and whether growers truthfully report the GM content of the grain. They estimate the total costs of a dual marketing system relative to a non-GM-only system range from $0.0145 per bushel at a 5% tolerance level to $0.0425 per bushel at a 0.05% tolerance level.

Other studies have also examined on-farm IP costs. Huygen, Veeman, and Lerohl (2004) estimated the IP costs at the farm level, primary elevator level, and export elevator level for three supply-chain systems designed to IP non-GM wheat where the GM tolerance levels ranged from 5% to 0.1%. Based on data from 14 seed growers, they estimated that farm-level IP production costs range from $0.029 per bushel at the 5% tolerance level to $0.18 per bushel at the 0.1% tolerance level. Their IP cost estimate included only direct production costs such as isolating the crop, controlling volunteer plants, and cleaning of the seeder, combine, truck, bin, dryer, and auger.

Karaca, Alexander, and Maier (2007) conducted a cost-benefit analysis of using an on-farm quality assurance process to deliver IP food-grade non-GM corn. They found that on average, the additional labor costs associated with the on-farm quality assurance (QA) program ranged from $0.0053 to $0.0212 per bushel depending on the equipment management strategy and farm size. Depending on the improvement in the grain quality due to the adoption of the QA program, the producer could gain up to $0.0842 per bushel from avoided discounts.

Yigezu et al. (2011) use a stochastic dynamic programming model for an Indiana on-farm IP corn storage case study to examine the returns to an integrated pest (both insects and molds) management strategy. They demonstrate that using a monitoring-based IPM strategy that includes both aeration and timing of sales as control variable, is profitable when delivering food-grade IP corn. For farmers who plan to store commodity corn that will be delivered by March when warmer temperatures increase the chance of insect and mold problems, the additional costs associated with monitoring and a more intensive aeration strategy are not justified.

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S156 – 27 September 2012

28 Economics of IPM Decisions

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Corinne Alexander

Two aspects of consumer preferences for food conflict with one another. On one hand, consumers demand wholesome products free of insects, molds, other pests, and toxins. On the other, they are increasingly concerned about insecticide and herbicide residues on their food (Senauer et al. 1991; Magnusson and Cranfield 2005).

Because of food safety as well as worker safety and environmental concerns, many of the pesticides used to control pests in stored products and food processing facilities are being significantly restricted by regulations or phased out. Also, to reduce the potential for residues on their food products, some food manufacturers severely limit the amount of pesticides that can be applied to ingredients they purchase (Phillips et al., 2002). Moreover, insects are developing resistance to some of the pesticides currently used (Zettler and Cuperus 1990).

Integrated Pest Management

The reduced arsenal of pesticides combined with increased demands for wholesome and pest-free food poses a challenge for managers of grain storage and food processing facilities. Some authors have proposed Integrated Pest Management (IPM) as a solution. IPM is information based and is a balanced use of biological, chemical, and cultural control tactics. While conventional pest management typically uses regular pesticide applications, IPM programs treat for insect pests only when necessary to prevent economic losses. Stored products are sampled for insect pests to determine how many and what kinds of insects are present and the risk of economic losses. Less risky and nonchemical methods are used first, and additional pest control methods, including chemical pesticides, are employed only when these are insufficient.

Choosing from among grain storage management alternatives requires careful consideration of the costs and benefits of each. With no treatment, damage costs can be high. Treating grain can reduce damage costs, but as treatment costs increase, the benefits of reduced damage costs decrease. The following paragraphs highlight major factors managers should consider when evaluating these tradeoffs. This section compares IPM and non-IPM approaches to storing wheat in Oklahoma and discusses the economics of managing mold.

IPM vs. Non-IPM Approaches to Storage Management

Calendar-based fumigation is a typical non-IPM approach that elevator managers use to control insects. Phosphine fumigation is conducted at one or more predetermined times of the year, based on experience, without sampling for insects. Fumigating too early allows insect populations to rebound before the time of grain sale; fumigating too late allows insect populations to cause irreversible damage before they are killed. In contrast, a sampling-based IPM approach uses insect density estimates to determine when pest management is needed (Flinn et al. 2007). Treatment may or may not include chemical application such as phosphine fumigation.

If in an IPM approach, sampling indicates that further treatment is not necessary, those treatment costs are avoided. But sampling itself adds cost even when treatment is not necessary. When treatment is necessary, both treatment and sampling costs are incurred. IPM thus requires more management skill and labor. Some managers may not follow recommended IPM practices for maximum effectiveness, resulting in higher insect numbers than if conventional practices were followed. For example, sampling too infrequently, either to save money or because workers were working on other projects, may not detect insects that calendar-based fumigation would have killed.

Non-IPM fumigation approaches have their own concerns. Because insect population growth is determined by temperature, moisture content, and time, differences in weather from year to year may result in calendar-based phosphine fumigation being done too early or too late for effective control.

For both IPM and non-IPM, conventional phosphine fumigations are typically poorly managed due to leaky storage facilities, improper application methods, incorrect dosages, and incorrect timing (Noyes 2002). Poor fumigations result in insect resistance to phosphine. Also, some insect stages are more susceptible to fumigant than others.

Mold Damage

Stored-product mold damage, like insect damage, also can be managed with IPM strategies. Any management strategy that includes monitoring for molds can be considered an IPM strategy. One key difference when managing molds is that to date there are no proven treatment options. Because mold damage, like insect damage, cannot be reversed, the management goal is to prevent the formation of molds by putting the grain into storage at a safe moisture content and using aeration to prevent the formation of hotspots or to further dry the grain. If mold damage develops, the producer's only option to halt mold damage is to sell the grain immediately. The primary value of using an IPM strategy to manage molds is to have a monitoring protocol that identifies mold development in its early stages so that the crop can be sold before mold damage reduces quality significantly. The non-IPM mold strategy would be to put grain into storage at a safe moisture and then ignore it.

Balancing Costs of Control and Costs Due to Insects and Molds

The goal of both IPM and non-IPM approaches is to manage insect population and mold damage in a storage structure most cost effectively. Insect population growth in a grain storage structure depends on grain temperature and moisture, and immigration rate of grain-damaging insects into the stored grain. Immigration into elevators and stored grain depends on environmental conditions such as wind and temperature, as well as cleanliness and structural integrity of the facility. The effectiveness of insect control treatments also depends on these factors. The cost of loading and unloading grain is an important storage cost, but it is not considered here because it is assumed to be the same for both calendar-based and sampling-based approaches.

Insect control must be done thoroughly and carefully to prevent large discount penalties for insect contamination and damage. The cost of this damage must be balanced against the cost of treatments to control insect populations. The treatments that could be used as part of any approach to insect control include fumigation, use of grain protectants, turning grain (either separately or with fumigation), aeration, sampling, sanitation, and bin sealing. For mold, turning or aerating the grain help to minimize hot spots and prevent mold growth. The cost of these treatments can be estimated by considering costs of activities and materials needed for these treatments including equipment, labor, chemicals, materials, electricity, grain weight lost, and safety training.

Table 1 summarizes the cost components of each of these treatments. Cost components of fumigation include chemicals, labor, training (including safety training and certification), and equipment such as fumigant monitoring devices. In concrete facilities, turning is usually required for effective fumigation; grain is emptied from one silo (bin) and transported on a moving belt to another silo within the facility. Fumigation is conducted by adding aluminum phosphide tablets into the moving grain as the bin is filled. Closed-loop circulation of fumigant typically

Table 1. *Cost components of alternative treatment approaches for stored grain.*

	Sampling	Fumigation	Aeration	Turning	Fumigation with turning	Sanitation	Bin sealing
Equipment	X	X	X		X		
Labor	X	X		X	X	X	X
Chemicals		X			X		
Materials							X
Electricity			X	X	X		
Grain weight lost				X	X		
Safety training		X			X		

requires one-third less fumigant to achieve the same level of effectiveness. It does not require turning of the grain, but it does require an investment in equipment. Bin sealing is important for fumigation-based and IPM approaches. Carefully sealing holes, even very small ones, reduces insect entry into the bin (immigration) and increases fumigation effectiveness by limiting the escape of the gas. There are some material costs for this, but the biggest cost is labor.

Turning also may be done as part of other management practices such as blending for particular quality characteristics, to break up sections of "fines" or "hot spots" to prevent grain infestation or spoilage, or simply to cool the grain. Cost components for turning grain are electricity to run the belts, labor, and shrink, which is a loss of grain weight that occurs while turning, typically 0.25% to 1% by weight.

Cost components of using grain protectants (not shown in the table) include the cost of the chemicals, labor (including safety training and certification to apply the chemical), equipment needed to apply the chemicals, and loss of revenue due to disruption or slowdown of grain handling.

Aeration costs are made up primarily of electricity costs, although some weight loss of grain may occur. Aerating immediately upon receipt of grain is more costly than aerating after outside temperatures drop because electricity cost is higher for the same amount of cooling. Early aeration is more likely to reduce insect damage and avoid fumigation. Savings can be achieved if aeration fans are shut off when outside temperatures are higher than the grain temperature, and turned on only when outside temperatures are lower than grain temperature. This can be done manually, but perhaps more economically and effectively using aeration fan controllers. Aeration can be an effective component of an IPM, but most concrete facilities do not have aeration capability.

Sampling costs incurred with IPM are primarily the cost of sampling equipment and trained labor needed to conduct sampling and analysis. Sampling may indicate that fumigation is not needed or that only some bins need fumigation. Although sampling is an added cost, it may actually reduce treatment cost by reducing the cost of fumigation.

Sanitation is also an important part of IPM. Its biggest cost is labor. Sanitation includes cleaning out empty bins, elevator legs and boots, and areas surrounding bins. For additional information on sanitation costs for on-farm bins see Alexander et al. (2008).

Application to Wheat Storage in Oklahoma

This section compares the cost of treatment and the cost of insect damage for both sampling-based IPM and conventional calendar-based fumigation for stored wheat in Oklahoma. To provide a baseline for evaluating the IPM and non-IPM approaches, the example shows the results if the manager did nothing to protect the grain. The cost of treatment is estimated using economic engineering methods in a partial-budgeting approach. The cost of insect damage is estimated by simulating insect growth under various environmental conditions and treatments. Adding these two sets of costs provides an estimate of the total cost of using each insect control approach.

Cost of Insect Damage

Cost of insect damage is made up of three parts: discount due to infestation, discount due to insect-damaged kernels (IDK), and a sample-grade discount when the number of IDK reaches 32 in a 100-gram sample. Insect damage may slightly reduce grain weight, but compared to the loss from discounts, cost of the quantity loss is relatively small.

Insect population can increase rapidly in warm or moist grain, a common situation in Oklahoma. Lesser grain borers (*Rhyzopertha dominica*), in particular, cause damged kernels in wheat. The larvae feed inside the kernel until they mature into adults and burrow out of the kernel, which results in an IDK. The life cycle of the lesser grain borer is approximately 5 weeks at 32°C, so there is approximately a 5-week lag between immigration of an adult insect until appearance of new adults.

Also, if two or more live insects injurious to grain are detected in a 1-kilogram grain sample at time of sale, the U.S. Department of Agriculture (USDA) does not permit the grain to be sold for human consumption. This prohibition can be overcome by fumigating to kill live insects, but the discount charged by buyers is commonly somewhat larger than the cost of fumigating. Often in practice, this discount is imposed by commercial firms if only one live grain-damaging insect is detected in a 1-kilogram sample.

An insect population growth model developed by Flinn et al. (2007) was used to predict the number of live insects on any given day within a grain structure. This, in turn, was used to predict the amount of insect damage.

Cost of Treatment

Cost components shown in Table 1 were estimated using economic engineering and partial budgeting methods. For illustration purposes, a grain elevator with a group of 10 concrete bins, each 24 feet (7.28 meters) in diameter and 80 feet (24.4 meters) deep, holding 25,000 bushels (680 tonnes) of wheat, is assumed. Table 2 shows component costs of sampling and Table 3 shows component costs of fumigation with turning. The cost of sampling includes the amortized cost of an investment in a PowerVac sampling machine, labor used to set up and take down the sampling equipment, and labor used in sampling. The cost of sampling is $0.011/bushel ($0.404/tonne), including amortized equipment costs of $0.0084/bushel ($0.309/tonne), and variable costs of $0.009/bushel ($0.33/tonne), including labor required to separate and count insects.

The cost of fumigation includes amortized equipment cost, insurance and training, labor, chemical costs, electricity used to turn grain, and value of grain lost in turning. Fumigation, with turning, costs $0.033/bushel ($1.20 tonne). The component of fumigation that costs the most is the value of grain lost in turning. Assuming a wheat loss of 0.25% based on Kenkel (2008), and a wheat price of $6.50/bushel ($239/tonne), that cost is $0.016/bushel, or $0.588/tonne. Thus, wheat lost in turning makes up nearly one half of the cost of fumigation. Turning may have an added benefit, not quantified in these calculations, of cooling grain.

Simulation Procedures

Adam et al. (2010) compared the cost of a calendar-based fumigation (non-IPM approach) in which fumigation is conducted the same time every year (for example, December 20), with the cost of a sampling-based fumigation (IPM approach). In sampling-based fumigation, the manager samples December 20, and if the sampling detects an average density of 0.5 or more adult lesser grain borers per kilogram sample, then he fumigates.

Because insect growth depends heavily on temperature and moisture, the insect growth model was simulated using weather data observed in four locations in Oklahoma and Kansas: Oklahoma City, Oklahoma, and Wichita, Topeka, and Dodge City, Kansas. The only difference across these locations that affected the simulation was the weather, so these locations were conceptualized as representing four sets of weather conditions. Results are presented on page 324.

Table 2. *Component costs of sampling.*

Sampling Cost Components	Rate	$/bu
Fixed		
PowerVac ($8,000 amortized over useful life of 10 years) + insurance + maintenance	$2,102/year	$0.0084/bu
Setup/takedown labor		
3 people, 3 hours each, @$16/hour	$144/fumigation	$0.0006/bu
Sampling labor		
3 people @$16/hour, 0.08 hours/sample, 10 samples/bin	$384/fumigation	$0.0015/bu
Average Cost (10 bins each 25,000 bu)		$0.011/bu

Table 3. *Component costs of fumigation with turning.*

Fumigation Cost Components	Rate	$/bu
Fixed		
Liability insurance	$200/year	$0.0008/bu
Fumigation training (training hours/employee x number of employees x labor cost + training fee)	$434/year	$0.0017/bu
Fumigation equipment ($3,800 amortized at 10% over 10 years + insurance + maintenance)	$998/year	$0.004/bu
Labor		
2 people, 3 hours per bin, @$16/hour	$960/fumigation	$0.0038/bu
Fumigant		
120 tablets/(1,000 bu) x $0.04286/tablet	$5.14/1,000 bu	$0.0051/bu
Grain lost in turning (shrink)		
0.25% x grain price ($6.50/bu)		$0.0163/bu
Turning Electricity		
$0.10/kwh x 250 kwh/bin (3 hours x 83 kwh)	$25/bin	$0.001/bu
Average Cost (10 bins each 25,000 bu)		$0.033/bu

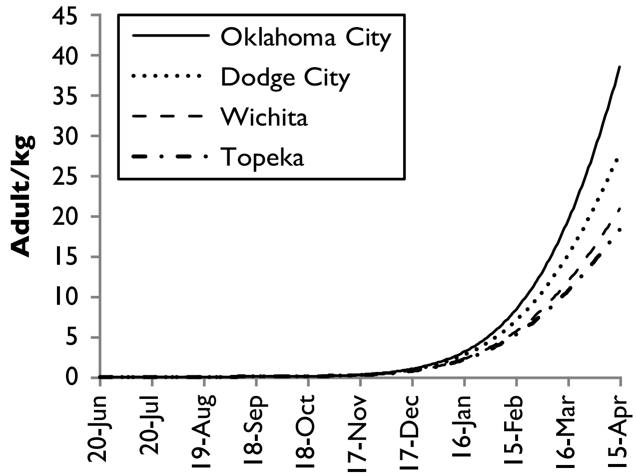

Figure 1. *Population of adult lesser grain borer in four locations (adult/kg), medium immigration rate, no treatment.*

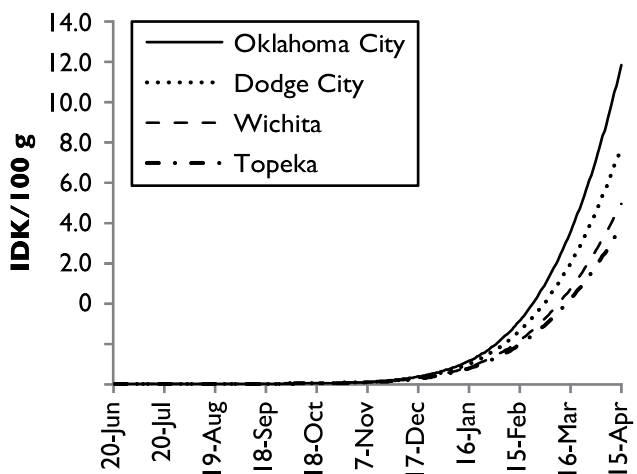

Figure 2. *Insect-damaged kernels (IDK) in four locations (IDK/100g), medium immigration rate, no treatment.*

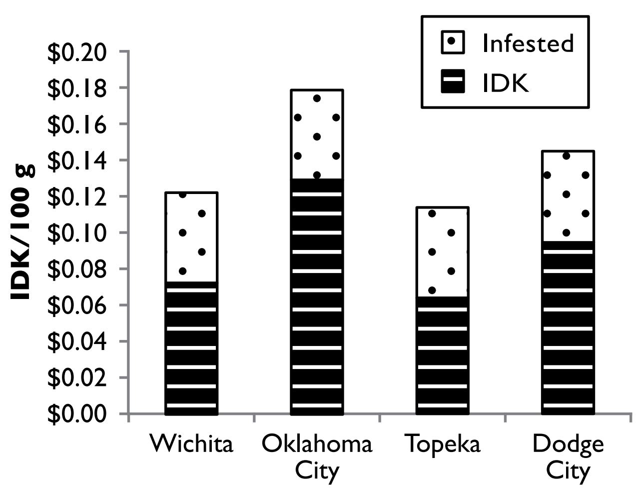

Figure 3. *Costs of doing nothing (discount in $/bu).*

Results

No treatment: Total costs (treatment cost plus insect damage cost) – Figure 1 shows insect population at each of the four locations if insects were to grow unchecked from the time the wheat is binned at harvest. Figure 2 shows the insect-damaged kernels (IDK) that result from these insect populations. If the manager were to hold this grain for sale until mid-April, there would be discounts for live insects and IDK. As shown in Figure 3, these costs range from $0.12/bushel in Wichita and Topeka to $0.18/bushel in Oklahoma City. The problem is worse, and the discounts higher, in locations with warmer, moister weather conditions. Selling earlier (by mid-January, for example) would substantially reduce discounts due to IDK, but there would probably still be an “infested” discount. There are no treatment costs.

Calendar-based fumigation: Total costs (treatment cost plus insect damage cost) – Figures 4 and 5 show the adult lesser grain borer numbers and resulting IDK with calendar-based fumigation on December 20. Insect numbers begin to increase rapidly in November, even though outside temperatures cool considerably, because the grain mass stays warm and favorable to insect growth without aeration until fumigation on December 20. After fumigation, few new adult insects emerge, and IDK increases are halted. In March, the insects surviving fumigation renew population growth, but not enough to cause a problem before mid-April, when it is assumed the grain is sold. There are no discounts due to insect damage, so the total cost is a fumigation cost of $0.033/bushel ($1.21/t).

Sampling-based fumigation (IPM): Total costs (treatment cost plus insect damage cost) – Under this approach, sampling every year on December 20 results in a sampling cost of $0.011/bushel. Depending on weather conditions, the rate at which insects immigrate into bins from the outside, and other factors, if sampling indicates that fumigation is necessary, a fumigation cost of $0.033/bushel is also incurred. Thus, treatment cost may be $0.011/bushel or $0.044/bushel. There are no insect damage costs. For the weather conditions simulated here, there were no locations in which fumigation was not necessary, so sampling simply adds unnecessary costs compared to a calendar-based fumigation approach.

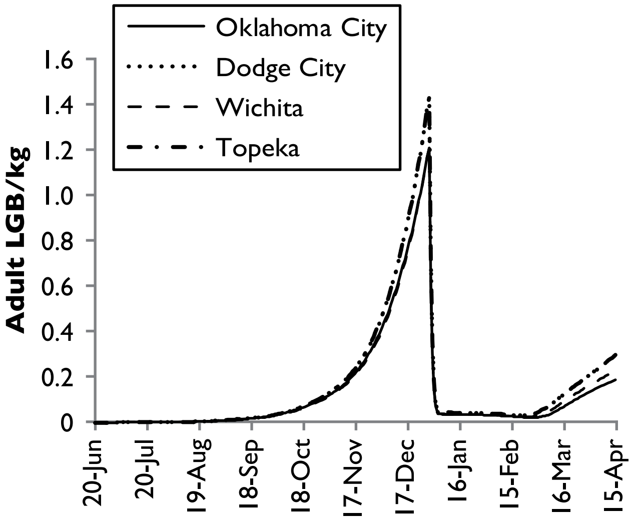

Figure 4. *Population of adult lesser grain borer in four locations (adult/kg), medium immigration rate, fumigation on December 20.*

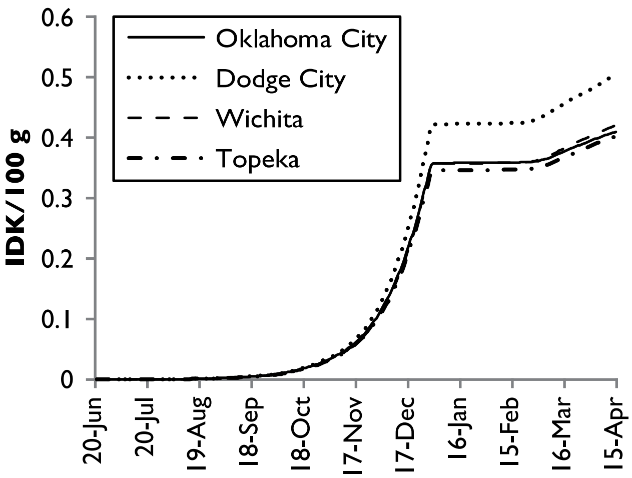

Figure 5. *Insect-damaged kernels (IDK) in four locations (IDK/100 g), medium immigration rate, fumigation on December 20.*

That result changes significantly if the rate at which insects immigrate into bins from the outside can be reduced. Sanitation around the bins and bin sealing, for example, can substantially reduce the rate at which adult insects enter a bin. Similarly, cleaning the inside of a bin thoroughly after it is emptied can reduce insect problems when the bin is filled again. Complicating this, within an elevator, some bins may have normal insect immigration rates, and some may have lower immigration rates. Bin sealing and sanitation also add expense, but that cost is much less on a per bushel basis than either sampling or fumigation.

With a reduced immigration rate, the simulation indicates that cooler, dryer weather may make fumigation unnecessary, while warmer, more humid weather may still require fumigation. Even in warmer weather, fumigation may be avoided by selling the grain earlier. Sampling can help distinguish between those situations. Also, expert-system computer software such as SGAPro (see Flinn et al. 2007), used together with sampling, can use weather information to help determine whether fumigation is necessary.

Given the relative costs of sampling and fumigation with turning, results reported by Adam et al. (2010) indicate that if an elevator has at least four out of 10 bins that do not require fumigation, a sampling-based approach achieves the lowest combined total treatment cost plus insect damage cost. If more than six out of 10 bins require fumigation, a calendar-based fumigation approach is lowest cost.

Elevator managers can increase the probability that sampling-based fumigation would be economical by reducing the insect immigration rate (by better sanitation practices or by sealing holes in grain bins), or by storing the grain a shorter amount of time. Sampling would help them assess the success of these efforts.

Figure 6, page 326, illustrates these factors and their effects on total cost (insect damage cost plus treatment cost). Clearly, doing nothing (perhaps because of failing to notice a problem) or improperly fumigating can be expensive, as in the first bar. Although there is no treatment cost, cost due to insect damage is high. In the second bar, when sampling is conducted and fumigation is always required (because of weather or because insect immigration rate cannot be reduced), there is no insect damage cost, but treatment cost is relatively high. In the third bar, doing no sampling but conducting a calendar-based fumigation every year reduces treatment cost slightly compared with sampling and fumigating. In the fourth bar, if the elevator can use a sampling-based fumigation IPM approach in which an average of 60% of its bins must be fumigated in any year, the treatment cost is just as low. In the fifth bar, if an elevator uses a sampling-based fumigation IPM approach in which only 40% of the bins must be fumigated in any given year, the treatment cost would be reduced even further.

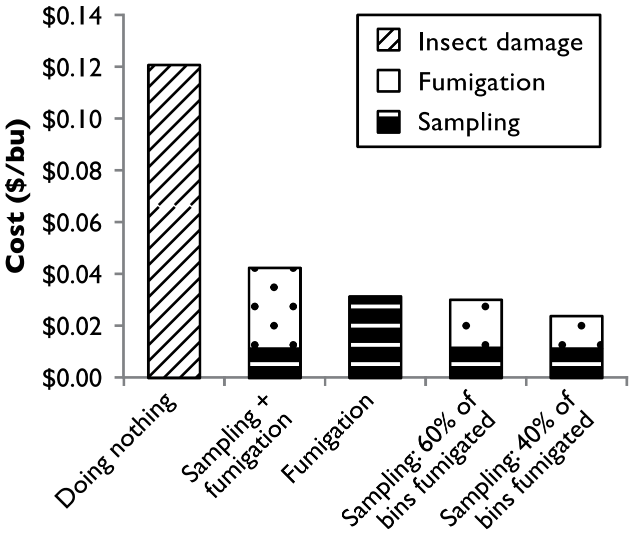

Figure 6. *Cost of alternative approaches to insect control.*

Finally, elevator managers may wish to consider investing in closed-loop fumigation systems (which significantly reduce chemical costs and increase fumigation effectiveness). Such an investment would likely pay for itself in about three years (Jones and Adam unpublished data). They may also wish to consider installing automatic (conditional) aeration capabilities, retrofitting concrete facilities that do not have them. Use of conditional aeration, which aerates only when outside temperature is cooler than grain temperature, would reduce the need for fumigation and potentially increase the profitability of sampling-based IPM. Work in progress is evaluating the payoff from such an investment.

IPM strategies for mold

One of the major challenges in managing mold growth is that the worst mold and mycotoxin problems occur in the field and are beyond the control of the farmer. Johnson, Wilson, and Diersen (1995) conducted one of the few economic studies measuring the impacts of a severe vomitoxin infestation in 1993 and 1994 in spring planted crops. If vomitoxin (or any other mold-produced toxin) is present, the grain handling system can respond by either destroying the grain or blending the infested grain with clean grain to meet the regulatory limits established by the FDA. When weather-induced mold outbreaks occur, the entire grain supply chain faces economic losses. The Johnson, Wilson, and Diersen study found that the 1993 vomitoxin infestation reduced the value of wheat production in North Dakota by $86 million.

Producers, processors, and grain elevators that are storing grain are also concerned about mold growth during the storage period. The three major storage conditions that favor mold growth and are necessary for mycotoxin formation in stored grain are warm temperatures, high grain moisture content, and high humidity (Shanahan et al. 2003). When these storage conditions are present, molds can grow rapidly, leading to grain spoilage (Sweets 1996). Growth of mold populations is generally low at temperatures below 50°F (10°C), but slow growth will occur even at low temperatures when the moisture conditions are favorable. Moisture levels below 12% will prevent mold formation (Shanahan et al. 2003).

Two other factors may affect mold growth in stored grain. Friday et al. (1989) suggest that mold damage levels depend on the grain hybrid being stored. Several studies have found that the extent of grain kernel mechanical damage is also important in determining the level of mold damage (Wilcke et al. 2001; Gupta et al. 1999). Farmers can mitigate both of the factors by choice of hybrid and care taken to reduce mechanical damage during the harvesting and handling of the grain.

Because molds are difficult to manage, monitoring becomes even more important. An IPM strategy based on regular monitoring is effective at controlling molds. Several scientists suggest that the best strategy for controlling molds is to control the storage environment (Wilcke et al. 2001, Pitt 1993, Northolt and Bullerman 1982). IPM-based strategies of monitoring and aeration have been found to be very effective in controlling the atmospheric conditions in on-farm storage (Ileleji et al. 2007, Maier et al. 1996, Arthur et al. 1998, Thompson 1972).

To date, there has been only one economic study of integrated pest management related to molds. Yigezu et al. (2008) examined the case of IPM for molds for corn stored on-farm in Indiana. They used a stochastic dynamic programming model to compare the profitability of a monitoring-based IPM strategy where farmers use aeration and sales to manage mold damage, to the traditional non-IPM strategy of keeping the grain cold during the winter with minimal monitoring and delivering the corn before March. One of the contributions of Yigezu et al. (2008) was to explicitly recognize the decision to sell grain as a strategy to halt the economic losses due to further mold damage. Overall, they found that the monitoring-based IPM mold program is profitable for farmers who are delivering food-grade corn, especially if they have a contract to store the corn into the warmer summer months. Yigezu et al. (2008) also identified management rules of thumb, such as, if the level of mold-damaged kernels is approaching the limit set by the food-grade corn buyer, the farmer should sell the grain immediately.

Conclusion

Integrated pest management has been shown to be potentially profitable in the case of managing both insects and molds. For producers, processors, and elevator managers interested in adopting IPM principles, the primary change from non-IPM to IPM management is the introduction of regular grain sampling. This practice offers decision makers information with which to make storage management decisions, and it will be profitable as long as the benefit of more informed decisions exceeds the cost of sampling.

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S156 – 28 September 2012

29 Economics of Commodity Grading and Segregation

Phil Kenkel
Brian D. Adam

The quality of grains and other commodities can be measured in various ways. To some extent "quality" depends on the needs of the end user. The quality properties of a grain are affected by genetic traits, growing period, harvest timing, grain harvesting and handling equipment, drying system, storage management practices, and transportation procedures. In general, measures of the quality of grains can be separated into physical, sanitary, and intrinsic traits.

Physical traits relate to the physical appearance or characteristic of the kernel. Examples of physical traits include test weight, kernel size, moisture content, damaged kernels, and other properties of the grain that can be determined by physical inspection or mechanical separations. Sanitary traits relate to the cleanliness of the grain. Sanitary traits include the presence of dockage and foreign material, as well as other undesirable materials such as fungi and mycotoxin, insects and insect fragments, rodent excrements, toxic seeds, pesticide residue, or commercially objectionable odors. Intrinsic traits are often critical to the functionality of the grain but usually can only be determined by analytical tests. Traits such as protein, ash and gluten content, milling yield, oil content, starch content, hardness, germination percentage, and feed value are all examples of intrinsic traits which could affect the value of a grain for a particular use.

In addition to these measures of quality, there are market-based quality measures. An obvious example would be the designation of organic. While it is difficult to distinguish organic grain based on physical appearance, cleanliness, or analytical tests, the property may have value to particular end users and thus result in a difference in value. Market-based traits are usually reflected by premiums or discounts. The importance of these traits also often varies across markets. For example, the absence of genetically modified varieties might be important in one market and have no value in another.

Grain Grading System

A system of grades and standards improves the efficiency of the marketing system by communicating to buyers and sellers the properties of the commodity being marketed. Grades provide a common trading language, or common reference, so buyers and sellers can more easily determine the quality (and value) of commodities. Grade and standards improve price discovery, the process by which buyers and sellers arrive at the transaction price for a given quantity and quality of grain at a given time and place. Uniform grades and standards are essential in order for electronic commodity markets and futures markets to function. Grades and standards also communicate what commodity characteristics are or are not permissible.

An efficient grading system must have a number of characteristics. It must measure characteristics that are important to users and that can be accurately and uniformly measured. It must be easily applied and not slow the process of handling and transportation. It must measure quality characteristics that are available in significant volume and important to a significant number of users to justify the costs of measuring the characteristic and segregating the grain. Ideally, a set of grain standards should measure the difference in the value of the grain to the end user. Achieving this ideal is complicated by the fact that some traits cannot be efficiently measured and by the fact that different end users have different standards as to what traits are important.

Commodity Inspection and Grading

The system for inspecting and grading grains in the United States is based primarily on physical inspection. Grain is inspected for quality characteristics, damage, foreign material, and dockage. The Federal Grain Inspection Service (FGIS) operates under the oversight of the Grain Inspection, Packers and Stockyards Administration (GIPSA). The USDA oversees federal grain inspection and weighing programs. These programs were established by the U.S. Grain Standards Act (USGSA) of 1976. Standards exist for 12 grains (listed from largest to smallest volume inspected): corn, wheat, soybeans, sorghum, barley, oats, rye, flaxseed, sunflower seed, triticale, mixed grain, and canola. Many grains have several classes. For example wheat is divided into hard red winter, hard red spring, durum, soft red spring, hard white wheat and soft white wheat. Commodities such as rice, pulses, and hops have similar standards for grade and factors. In contrast to the system used in some other countries, grain grades and standards in the U.S. are not adjusted for year-to-year differences in crop quality.

Grain can be inspected numerous times as it moves through the marketing chain between the producer and final end user. Grain can be inspected and graded by both private individuals who are licensed to grade grain and by FGIS employees. The only mandatory inspection and grading is for grain that is exported from the U.S. (with exemptions for some grain exported to Canada and Mexico). Grain delivered to a state or federally licensed warehouse is also required to be inspected, graded, and weighed by a licensed inspector.

Grain may be officially or unofficially graded. Unofficial graded grain is graded by state or federally licensed graders that are not under the direct supervision of FGIS. Guidelines are provided by FGIS for collecting samples for officially graded grain samples but a license is not required for the person collecting the samples. The person weighing and grading the grain must be federally or state licensed. Grain delivered to the first handler (country elevator) is typically unofficially inspected by licensed graders at the facility. The first handler often sells the grain to a regional elevator, export elevator or end user on the basis of an official grade. The first handler therefore bears the risk of grading inaccuracy.

Official grades are determined by graders trained, licensed, and periodically tested by the Federal Grain Inspection Service. Inspectors may be employees of FGIS/USDA, a private company, states with a cooperative agreement with GIPSA or employees of the Canadian Grain Commission with GIPSA oversight. The person obtaining the sample and the person grading official graded grain must be licensed by the FGIS.

U.S. grain grades are based on a number of factors, which are based on visual observation and physical measurement. The grain grading system includes numerical grades for each grain as well as special grades and non-grain information, which is officially measured and included on the grade sheet. In order to achieve a numerical grade the grain must meet or exceed the minimum level for each characteristic that is specified for that grade. For example, grades on wheat are based on test weight, shrunken and broken kernels, foreign material, damage, heat damage, and total damage. Any one or a combination of those factors could be the binding grade factor that determines the grade of a sample of wheat. Other factors may be officially measured and indicated on the grade sheet but do not influence the numerical grade. In wheat, moisture, dockage, and protein are factors that can be officially measured but are not grade factors. Insect infestation is a special grade factor that is also listed on the grade sheet but does not change the numerical grade. All of the factors, both grade and non-grade, as well as other characteristics such as milling and baking test or feed value, may be specified in grain contracts and affect the value of the grain.

Segregation

Segregation involves testing and separating grain with specific characteristics so that it can be comingled only with grain with similar characteristics. Segregation often occurs at the farm and first handler level. Many grain facilities are not well suited for segregation because they are designed for bulk storage and rapid handling. Grain generally becomes more commingled as it progresses through the marketing system.

Segregation can generate value by creating a more uniform product. It also can add value by aggregating lots of grain with properties that have value to a particular user. For example, a flour miller might be willing to pay a premium for a certain variety of wheat that they believed had superior milling characteristics. In some cases the value that is created by segregation is through minimizing the reduction of value from grain with undesirable traits. Grain with high moisture might be segregated so that it can be dried or conditioned. Corn with a high level of aflatoxin might be segregated so that it can be marketed to an end user with less stringent standards for aflatoxin levels. This segregation might be preferable to comingling the affected corn with higher quality corn, reducing the value of the entire bin or elevator.

Blending

Blending grain can also increase value. In this case segregation is performed as a vehicle to separate categories of grains with different characteristics so that they can be combined in a manner that maximizes the total value of the grain to the end users. A simple example would be three lots of grain which each received a No. 2 grade for a different binding grade factor but with levels of the other grade factors above the required minimums. In theory the three lots of No. 2 grain could be combined into one lot of No. 1 grain.

Blending can also occur as part of a storage strategy. Grain in concrete storage structures may be turned from one bin to keep it cool or to treat it to control insects. When multiple bins are simultaneously turned, the grain is often intentionally blended. Grain in all types of storages can also be blended during unloading. Because the fine material in the grain tends to move to the outside of the bin as the bin is loaded, the last portion of a bin will have a disproportionate amount of undesirable material. Blending the last portion of one bin with initial grain from one or more other bins can help to maintain shipments within the contract specifications.

As mentioned previously, grain is also unintentionally blended (comingled) as it passes through the handling and storage systems. Bulk handling and storage systems, by their very nature, commingle grain from multiple loads. Many conveying systems are not completely self-cleaning and commingle some grain after the destination bin is changed. A more important source of unintended or structural blending occurs due to the mismatch between storage units and efficient transportation units. For example, the most efficient rail shipment, a unit train, requires more than 300,000 bushels. Grain from multiple bins is typically commingled as the unit train is loaded.

Identity Preservation

The concept of identity preservation is to produce grains with a particular trait and keep them segregated such that they are only commingled with grains of the same trait throughout the marketing chain. Almost all grains are identity preserved with respect to some trait. Corn separated from soybeans is identity preserved with respect to type of grain. Hard red winter wheat separated from hard white wheat is identity preserved with respect to class. As commonly used, the term identity preserved grain refers to separation of grain with or without specific traits such as genetic modified traits (GMO), high oil corn or high oleic oil soybeans, specific production practices such as variety or organic production. The most stringent form of identity preservation would separate the grain from an individual producer through the marketing process.

Identity preservation results in additional costs in the storage and marketing system. A greater number of bins may be needed to maintain more categories of grain. Large bins may be underutilized if there is insufficient grain of a particular category to fill the bin. The opportunity to create value through blending is obviously eliminated. It may not be possible to use the bulk transportation system. More costly shipping methods such as shipping containers may be required. Any link in the storage system where a significant amount of grain can remain after cleanout is potential problem with identity-preserved storage. Poorly designed augers, dump pits, and other transfer points are common causes of commingled grain. When designing a grain-handling system for identity-preserved grain, transfer points can minimized by installing clean-out panels to allow easy access. Special handling equipment such as dedicated bucket elevators and conveyors may help minimize cross contamination of ordinary grain with high value grain, but they also require proper cleaning procedures.

Grading, Segregation, and Blending Implications for Storage Management

An understanding of the role of grading, segregation, blending, and identity preservation highlights some of the structural challenges to the management of stored grain and other commodities. Grain is marketed on the basis of grade standards and additional contract specifications, which often are more stringent. While it is obvious that quality deterioration during handling and storage can decrease grain value, the exact mechanism is difficult to describe and model. For example, consider the implication of stored grain insects. The presence of live insects in a sample would result in the special grade of "infested" and would likely trigger market discounts. Insects could be present in the grain but not detected in the sample. Insects could create insect damaged kernels (IDK). IDK is both a special grade factor and a component of the measure of total damaged kernels. If the number of insect damaged kernels is below the special grade threshold, then the implication of the damage depends on whether it resulted in a change in numerical grade. Market-based discounts for IDK that are included in contract specifications could have additional consequences for grain shipped to particular buyers.

The strategies of segregation and blending also have implications for stored grain management. If storage management were the only criteria, high risk grain would be moved out of storage at the first marketing opportunity. But because of the value of the grain in the future blending process – for example, high protein – the elevator manager may dictate that it remain in storage. Blending, both intentional and unintentional has the effect of spreading insects and storage damage throughout the facility.

Identity preservation also creates unique storage issues. In addition to bin size, bin utilization, and handling systems implications, the penalties for storage damage in identity-preserved systems are often higher. Identity-preserved grain is typically sold to a smaller set of buyers, often on a contract basis. Contract specifications for damage and insect presence are usually much stricter than those for commodity grain. In some cases such as organic grains, the contract may restrict the use of chemical controls.

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S156 – 29 September 2012

30 Food Safety Requirements

Pamela Peckman
Tim Pettitt

Knowledge of basic food safety requirements is important for those involved in stored product protection. Laws and regulations govern nearly every aspect of food from genetic design to consumption. At the federal level, laws, which are often called Acts, are promulgated by Congress and found in the U.S. Code. Over time, laws may be amended to reflect the need for change. Congress authorizes specific federal agencies to put those laws into effect by creating and enforcing regulations. Regulations are focused on implementation. Federal agencies are responsible for interpreting the law and often delegate implementation to state agencies that create and enforce specific regulations. State regulations can be more restrictive than federal, but not less restrictive. Both laws and regulations are requirements.

Food laws and regulations exist to protect consumers. It is easy to point to a few catastrophic failures and ignore the day-to-day vigilance of most companies to keep food safe. Unfortunately, the failures provide lessons. Failure in food safety systems often results in greater scrutiny and root-cause analysis that may lead to increased regulatory requirements.

Although food companies strive to be self-regulating, history shows that some level of governance is necessary. Some companies choose to operate with a higher tolerance for risk or are simply uninformed with respect to food safety. Science and experience demonstrate that foods can be unsafe and can cause serious injury and death in the absence of appropriate design and controls. Food regulations provide necessary boundaries. With the wide array of scientific discovery and emerging issues, regulations help food companies more effectively understand and manage risks, thereby improving consumer protection. Regulations also exist to ensure that consumers are furnished with enough information to select appropriate foods for health and nutrition and to ensure that the labeling accurately represents package contents.

Everyone who handles food is expected to be informed, trained, self-regulating, and to put in place all necessary controls for wholesome and safe food. Controls for safe food begin with agriculture or extraction and extend into storage, product development, processing, packaging, distribution, food preparation, and food service.

Two important sources for learning more about food and pest management industry requirements are Statues at Large and Code of Federal Regulations.

Statutes at Large (Stat.) – The official source for laws passed by U.S. Congress. Because these statutes are published chronologically and span many areas of interest, they are reorganized into United States Code (U.S. Code or U.S.C.), which contains 50 titles. Titles most relevant to food and pest management include Title 7 – Agriculture and Title 21 – Food and Drug.

Code of Federal Regulations (CFR) – CFR includes regulations adopted by executive agencies such as federal EPA, FDA, or USDA. These regulations are initially published chronologically in the Federal Register (FR) and reorganized by subject in the CFR. The CFR is the official record of all regulations created by the federal government and is divided into 50 titles by topic. The following titles are of interest to the food and pest management industry, Title 21 – Food and Drugs, Title 29 – Labor, Title 40 – Protection of Environment, and Title 49 – Transportation. The FR is the source for notices on recently proposed rules, request for comments, or printed final rules.

Listed below are a few helpful websites that provide quick access to written requirements.

- **U.S. Government Printing Office (*www.gpoaccess.gov*) –** to access government documents such as FR, CFR, Stat., guidance documents.
- **eRulemaking Program (*www.regulations.gov*) –** to access and participate in developing regulations, submit comments on proposed rules.
- **National Pesticide Information Network (NPIN) (*http://npic.orst.edu/*) –** technical and regulatory information on pesticides, links to state lead pesticide agencies for easy access to state pesticide requirements.
- **EPA Residue Chemistry Test Guidelines OPPTS 860.1460 Food Handling (*http://fedbbs.access.gpo.gov/library/epa_860/860-1460.pdf*) –** lists definitions of terms used on pesticide labels for use in food-handling establishments.

Many other regulations affect the food supply chain, but space does not permit a full review in this chapter. Readers should be familiar with requirements that apply to their industry. Any individual or enterprise associated with food must know the regulations. Ignorance is no excuse for noncompliance.

Basic Food Safety Requirements

In the United States, there are two primary federal food regulatory agencies: the Food and Drug Administration (FDA) and the U.S. Department of Agriculture (USDA). In Canada, the primary food regulatory agency is the Canada Food Inspection Agency (CFIA).

The three primary food laws in the United States are the Federal Food Drug and Cosmetic Act (FD&C Act or FFDCA); the Federal Meat Inspection Act; and the Federal Poultry Inspection Act. The primary food laws in Canada are the Food and Drugs Act and the Canada Agricultural Products Act.

The FDA is primarily responsible for administering the FD&C Act and ensuring the safety of food that moves in interstate commerce. The USDA is responsible for administering the Meat Inspection Act and the Poultry Inspection Act. There are also other federal, as well as state and municipal, laws governing food safety. Many countries have similar regulating bodies and their own sets of food regulations.

Among the most basic of regulations is the definition of adulteration, which is found in the FD&C Act, Section 402. In part, it states that, "A food shall be deemed to be adulterated if it meets the following criteria:

> (a)(3) it consists, in whole or in part, of any filthy, putrid, or decomposed substance, or if it is otherwise unfit for food; or
>
> (a)(4) it has been prepared, packed or held under insanitary conditions whereby it may have become contaminated with filth, or whereby it may have been rendered injurious to health."

Actual contamination of food is not required to meet the definition of "adulteration." Section 402(a)(4) includes the statement "may have," meaning that if it is likely that the food may become adulterated, it can be considered adulterated.

Any person found in violation of the prohibited acts as specified in the FD&C Act may be enjoined and subject to fines and other penalties, and products can be subject to seizure. With the passing of the Food Safety Modernization Act (FSMA) in 2010, FDA has been given broader authority to review food plant manufacturing records and mandate food recalls, if necessary. The intent of the FSMA is to reduce food-borne illnesses by requiring companies to develop and maintain food safety plans. Although not specifically called out in FSMA, Hazard Analysis and Critical Control Points (HACCP) has long been the food industry approach to the assessment and control of biological, chemical, and physical hazards throughout the food supply chain.

CFR Title 21, Part 110 is entitled Current Good Manufacturing Practice in Manufacturing, Packing, or Holding Human Food (GMPs). GMP regulations go far beyond requirements related to personal hygiene and provide requirements related to buildings and facilities, sanitary operations, equipment, production and process controls, and defect action levels for natural and unavoidable defects in food. A thorough understanding of GMPs is a must for individuals who work with food.

Subpart G of the GMPs provides requirements for Defect Action Levels (DALs) in human food. DALs are often misunderstood. The DALs regulate the maximum levels of "natural and unavoidable" defects in food. The FDA sets these action levels because it is economically impractical to grow, harvest, or process raw products that are totally free of nonhazardous, naturally occurring, unavoidable defects (FDA Defect Levels Handbook).

Basic Pesticide Safety Requirements

Because pesticides are sometimes used to protect food, it is important to understand the regulatory requirements related to their use in food handling establishments.

The Environmental Protection Agency (EPA) was established in 1970 to serve as "the public's advocate for a livable environment" (Mosley and Thomas 2010). The agency is made up of several different offices that oversee different areas such as water, air, pesticides, solid waste, and emergency planning, research, and enforcement. In addition, there are 10 regional offices that cover specific states to assist in local programs throughout the United States.

EPA has been given authority by Congress to regulate pesticides under two federal statutes.

Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) – This structure contains provisions for pesticide product registration, labeling, disposal, emergency exemptions, and cancellations, label violations, applicator certification, and more.

FD&C Act – The primary law for food safety that authorizes EPA to set food additive tolerances in or on foods or animal feed, while FDA inspects and enforces those requirements. Before 1970, USDA's Pesticide Regulation Division was responsible for implementation of FIFRA requirements, and FDA for FD&C Act food tolerances requirements.

FIFRA 2(u) defines the term pesticide as any substance or mixture intended for preventing, destroying, repelling, or mitigating any pest. The definition also includes plant regulators, defoliants, desiccants, and any nitrogen stabilizer. This is a rather broad definition for pesticides and helps explain why some products may not make pesticidal claims on their product labels. If the manufacturer did claim to destroy or even repel pests, they would then be subject to a rigorous and expensive pesticide registration process.

In 1972, significant changes were made to FIFRA when it was amended by the Federal Environmental Pesticide Control Act (FEPCA). Changes important to the food industry included the following:

- Addition of label statement that use of a pesticide inconsistent with its label was prohibited and deliberate violations are subject to fines/imprisonment.
- Classification of General Use and Restricted Use pesticides (RUPs).
- Certification requirements for private and commercial pesticide applicators.

Labeling

Pesticide applicators are often taught that "the label is the law." Failure to follow the label is a federal violation. It is important to read and know what is on the label before using a pesticide. The pesticide label is more than the label printed on the container. It also includes supplemental labeling such as booklets that are often attached or shipped with the product. Although it is true that the label is the law, requirements and interpretations of the label make it clear that the label may not contain all of the information that is needed. It is important to know state and local requirements that apply to pesticide usage and might not be mentioned on the federal label. Some labels are fairly short one- to two-page documents, while others such as RUP fumigants, can be more than 40 pages.

FIFRA exceptions

FIFRA 2 (ee) defines exceptions for using a pesticide in a manner inconsistent with its labeling. Not all states recognize FIFRA 2ee, and some have specific exemption requirements. Applicators should check with the state lead pesticide agency if there is a need for an exception. In certain cases, these exemptions allow a pesticide to be used at less than label rates unless specifically prohibited on the label or for use on a target pest not listed, as long as the use site is listed and there are no specific label restrictions.

Restricted use pesticides

Products restricted by EPA for use only by a certified applicator, or in some cases, by persons under their direct supervision or "trained" individuals are known as restricted use pesticides (RUP). For example, current RUP phosphine labels allow trained individuals to receive railcars that have been fumigated in-transit; however, the "trained" individual must undergo specific annual training. Once again, not all states allow trained individuals, even though the federal label language does.

Direct supervision currently is defined in FIFRA 2(e)(4) as follows, "Unless otherwise prescribed by its labeling, a pesticide shall be considered to be applied under the direct supervision of a certified applicator if it is applied by a competent person acting under the instructions and control of a certified applicator who is available if and when needed, even though such certified applicator is not physically present at the time and place the pesticide is applied." State pesticide lead agencies often have more restrictive definitions of direct supervision and may require the certified applicator to be physically present and within sight.

Certified applicators

40 CFR 171 defines a certified applicator as "any individual who is certified to use or supervise the use of any restricted use pesticides covered by his certification. In general, certified applicators are defined as private or commercial.

Private: One who uses or supervises the use of restricted use pesticides for the purpose of producing an agricultural commodity. This activity may occur on property owned or rented by the applicator or the applicator's employer or on the property of another person.

Commercial: One who uses or supervises the use of any pesticide that is classified for restricted use for any purpose or on any property other than provided by the definition of "private applicator."

In addition, EPA provides 10 different application categories: 1) Agricultural, 2) Forest, 3) Ornamental and Turf, 4) Seed Treatment, 5) Aquatic, 6) Right-of-Way, 7) Industrial, Institutional, Structural and Health Related, 8) Public Health, 9) Regulatory, and 10) Demonstration and Research Pest Control. The applicator must be certified in the right category before purchasing and using an RUP. The state lead agency often modifies categories, so it is important to verify with the state which category of licensing is appropriate for the type of application that will be necessary.

Food additive tolerances

40 CFR 180 provides information on tolerances and exemptions from tolerances for pesticide chemicals in food. EPA sets food additive tolerances while the FDA enforces them.

Pesticide use in food handling establishments

When selecting pesticides for use in food handling establishments, it is important to verify that they are labeled for use in the area of intended application. Label language will specify if the product can be used in food areas, nonfood areas, or both, and in some cases the product may be labeled for exterior use only. It is important for food handling facilities to develop a list of pre-approved chemicals, including pesticides, to ensure that the label language is consistent with the intended use.

The Cost of Noncompliance

Compliance with food regulations can be expensive, but failure to comply can be catastrophic. A recent and notable food safety failure was the lack of diligence on the part of the Peanut Corporation of America (PCA) of Lynchburg, Va. PCA manufactured about 2.5% of the nation's processed peanuts and released to the trade peanut products that had tested positive for the presence of Salmonella. In late 2008 and early 2009, nine people died and at least 691 people in 46 states fell ill due to food poisoning from eating products containing peanuts. The Center for Disease Control, through epidemiological analysis and laboratory testing, confirmed the cause of the illness as *Salmonella typhimurium* and confirmed the source as peanut products produced at PCA. The infection triggered the most extensive food recall in U.S. history. On Feb. 13, 2009, PCA filed for bankruptcy liquidation. A dozen lawsuits have been filed against PCA and financial losses to the U.S. peanut industry have been estimated at $1 billion (Wikipedia 2011).

Failure to properly use pesticides can also result in tragedy and the creation of additional labeling restrictions, as was the case following the death of two young children in Utah in February 2010. A state investigation revealed that the certified applicator operated in a negligent manner by misapplying a fumigant when treating exterior rodent burrows. The misapplication included failure to read the entire label, improper dosage rate, application within the 15-foot buffer zone (including near the front stairs of the house), and lack of a fumigation management plan as required by the label. The misapplication led to swift action on the part of both federal and state agencies to impose additional restrictions and the cancellation of the use pattern, residential burrow treatments. Although this was a residential case, its implications to the food industry are that misuse of pesticides can lead to cancelled uses.

Because of the ever-changing regulatory climate, food industry personnel must stay current with requirements. Communication with regulatory and peer contacts, trade associations, suppliers, contractors, manufacturers, and others can help to monitor changes.

Regulations cannot assure good food safety programs, they cannot provide automatic and continu-

Table 1. *History of significant food and pesticide safety laws (Ware, G.W. and D. Whitacre 2004).*

1906	Passage of the Federal Food, Drug, and Cosmetic Act (Pure Food Law).
1910	Passage of Federal Insecticide Act.
1938	Amendment to Pure Food Law (1906), preventing contamination of food.
1947	The Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) becomes law.
1954	Miller Amendment to FDC&A (1906) set tolerances for pesticides on raw food and feed products.
1959	FIFRA (1947) amended to include all economic poisons, e.g., desiccants, nematicides.
1969	Publication of the Mrak Report, which laid groundwork for concerted environmental protection, resulting in Environmental Protection Agency.
1970	Formation of Environmental Protection Agency (EPA), which becomes responsible for registration of pesticides (instead of USDA).
1972	Passage of Federal Environmental Pesticide Control Act (FEPCA or FIFRA amended).
1978	Certification training completed for applicators to use restricted use pesticides. First list of restricted-use pesticides issued by EPA.
1980	Through new legislation Congress assumes responsibility for EPA oversight.
1981	Passage of the Comprehensive Environmental Response Compensation and Liability Act (CERCLA or “Superfund”) for cleanup of toxic wastes, spills, and dumps. The Delaney Clause is reexamined. Any regulatory action on pesticides by EPA must be preceded by a risk and benefit analysis.
1985	Congress reauthorizes the Federal Endangered Species Act, originally passed in 1973 and amended in 1978, 1979, and 1982. Superfund is amended by Congress to include Title III, The Emergency Planning and Community Right-to-Know Act.
1995	HACCP-Fish and Fishery Products final rule.
1996	Meat and Poultry HACCP final rule.
1996	Food Quality Protection Act (FQPA) signed into law.
2000	Push for USDA established standards to allow organic food labeling.
2002	Juice HACCP final rule.
2002	Organic foods must comply with new USDA regulations in October.
2010	Food Safety Modernization Act.

ous compliance, and they cannot replace the intelligent interpretation of food safety risks. In spite of all the regulations, food producers and handlers must continue to exercise diligence in the training and application of food safety principles. Anything less than that puts the producer, the food handler, and the consumer at risk. The job of the food industry is to maintain the integrity of foods. If this is done consistently, minimum regulatory attention should be expected. An unsafe food does not meet any acceptable standard.

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31 Liability Basics and the Importance of Risk Management

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It is important for agricultural professionals to have a proper understanding of the legal environment in which they operate. Financial losses resulting from fines and court verdicts can be avoided with a basic knowledge of the law and proper risk management.

Federal law regulating pest management can be found in several acts of Congress, most notably the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). FIFRA outlines the manner in which individuals will be allowed to use and apply pesticides. FIFRA also regulates what type of information and directions will be listed on the pesticide label, and to some extent, regulates pesticide control devices. Another important federal law on pesticides for agricultural professionals is the Food Quality Protection Act (FQPA), which amended FIFRA's process for establishing tolerances (maximum allowable pesticide residue limits) for pesticide residues in food and feed. The FQPA established a new safety standard that reduced tolerances to a level where there is a reasonable certainty that no injury would result from total, prolonged exposure to regulated pesticides. The FQPA also amended the Food, Drug, and Cosmetic Act (FDCA), and required the Environmental Protection Agency (EPA) to ensure that tolerance levels for residues in food are safe for infants and children.

State law typically fills in gaps and supplements federal law. In many instances, state law standards are far stricter than federal standards. Consequently, although compliance with state law *may* ensure compliance with federal laws, the reverse is not necessarily true. Because state and federal laws often have different purposes, specific regulations may vary. An example might be where the federal government is regulating pesticides to protect consumers, while the state is regulating pesticides to protect farm workers. Both statutes regulate pesticides, but for different reasons. Compliance with state regulations is not always sufficient to ensure compliance with federal regulations.

Local regulations may be stricter still. Counties and cities throughout the United States are becoming increasingly aware of the dangers posed by the mismanagement of wastes and are concerned about having to share a disproportionate share of the costs of such mismanagement. Pest control professionals should contact county and city commissions about details relating to local regulation. It should be noted that local regulations can be preempted by state law, just as state law can be preempted by federal law, if the particular state has a preemption statute. (*See Wisconsin Public Intervenor v. Mortier*, 501 U.S. 597 (1991). Not every state has a pesticide preemption statute, but most states do preempt local regulations. (*See, e.g.*, Or. Rev. Stat. §634.057 (2003) *and* Mich. Comp. Laws §324.8328 (2007).

Legal Basics

The American legal system is divided into two broad categories: statutory law and common law. These two approaches are employed together to create a framework by which laws are implemented, evenly applied and enforced, and by which punishments for violation of the law may be fairly applied.

Statutory law

Statutory law is passed by either the federal or state legislature. Formally, a statute may be understood as an act of the legislature that declares, commands, or prohibits something. The legislative body at issue (state or federal) outlines basic goals and general procedures to accomplish these goals. Although statutes often provide fairly specific directions or prohibitions, the actual implementation requirements are frequently too detailed for the legislature. Therefore, the legislature delegates this regulatory responsibility to administrative agencies. The legislature has delegated a portion of its lawmaking authority to these agencies (such as the EPA) in the name of efficiency. Otherwise, legislative bodies would be bogged down in hopeless minutia and would never be able to address the broad range of issues that arise in modern society. For example, the legislature might decide to regulate the use of certain pesticides or pest control devices and measures. It might pass a statute that broadly outlines acceptable practices or prohibitions. Then, an agency, in this case the EPA or appropriate state agency, would make rules carrying out the intent of the legislature. An administrative agency typically enforces its rules by requiring permits or licenses. They can enforce their rules through both criminal and civil penalties.

State law is similar to federal law in its implementation, execution, and enforcement. It is important to emphasize the relationship between federal and state laws if both are applied to the same issue. If there is a federal law on an issue, that law sets up a minimum standard that always applies. State and even local law may be stricter than federal law, and those standards must also be met. However, compliance with a state statute or local ordinance that has a lower compliance threshold than the federal standard will not protect an activity from federal regulation. Simply, federal law reigns supreme, and may not be preempted or diluted in influence by a state or local law.

A good example for understanding the relationship between agencies, federal law, and state law is found in FIFRA, since both the federal and state governments play a role in pesticide regulation. The federal FIFRA statute established a guideline for pesticide regulation, which is the registration process that determines the safety level of pesticides, but the EPA has the delegated authority to create rules and procedures for making sure pesticides are actually acceptable for use. The federal legislature passed a law broadly regulating pesticides but delegated the authority for specific regulation to an agency, the EPA, and the EPA enforces its rules by limiting which pesticides can be registered (licensed). Also, under FIFRA, states are allowed to additionally regulate pesticide registration, but those regulations are limited by preemption. Therefore, the state regulations are only applicable in the state passing the regulations, the state's regulations cannot violate the federal law (FIFRA), and the EPA can deny a registered use allowed by a state.

Federal and state governments apply both civil and criminal penalties to punish those who fail to comply with the provisions and requirements established by the legislature. Civil penalties are the lighter of the two, and have less of a condemnation and punishment effect than their criminal counterparts. Civil penalties are imposed for doing some act that is prohibited, or for omitting to do some act which is required to be done. Civil penalties are usually handed down in the form of fines or monetary damages. Criminal penalties, on the other hand, are far more serious in commission, effect, and, consequentially, punishment. A criminal penalty may be understood as the legal system's punitive response to an individual's actions done in violation of duties the individual owes to the community, and for which the law has provided (via statute) that the defender shall make satisfaction to the public. Criminal penalties include imprisonment, severe fines, and a permanent criminal record.

A good way to illustrate the relationship between civil and criminal penalties is to examine their application in an actual federal statute. FIFRA regulates pesticide sale, use, handling, and disposal. Under FIFRA, if a pest control specialist violates the statute (ignorance of the law is not an excuse), he or she will be assessed a civil fine up to $5,000 per offense. If a private pesticide user violates FIFRA, EPA can seek a $1,000 civil penalty for each offense, after the private user has been warned about misuse. If the pesticide use violation was knowing (the offender knew the action would violate the law), a criminal penalty will be assessed, which for a pest control professional means a combination of fines of up to $25,000 and one year in prison. If a private pesticide user knowingly violates FIFRA, there is a criminal penalty of a $1,000 fine or 30-day jail term. Clearly, at least in the case of FIFRA, the threshold between lighter civil penalties and more damning criminal punishment is based on whether the violator knowingly violated the statute.

Common law

The second major division of the American legal system is common law. Common law stems from the roots of pre-Revolutionary War English law. It is based on the judgments and decrees of the courts. The primary distinction between statutory law and common law is the manner of creation. Statutory law is created by the enactment of legislatures, while common law is based solely on court decisions and, in some states, all the unwritten laws and court decisions of pre-Revolutionary England. An example of this can be found in Florida law F.S. §2.01, which states, "The common and statute laws of England, which are of a general and not local nature, with the exception hereinafter mentioned, down to the 4th day of July, 1776, are declared to be of force in this state; provided, the said statutes and common law be not inconsistent with the Constitution and laws of the United States and the acts of the Legislature of this state."

Common law is based on precedent, which is the concept that a court decision should be considered as an example or authority for an identical or similar case afterwards arising on a similar question of law. Rarely, if ever, are two cases exactly identical in the issue at hand. Lawyers draft arguments and courts draft opinions that draw parallels between the current case and previous ones, and court decisions are supported by deferring to the logic of these similar, previous cases. This deference to previous court decisions is known as *stare decisis*; the doctrine that when a court has laid down its principle of law as applicable to a certain set of facts, it will adhere to that principle, and apply it to all future cases, where facts are substantially the same, regardless of whether the parties or the property are the same. Decisions within a higher court's appellate jurisdiction (the geographic area in which that court holds authority) are binding upon the lower courts of that jurisdiction, which means those lower courts must follow the decision of the higher court regarding a similar set of facts. Decisions from other appellate jurisdictions can be used as references, and if these decisions form a trend of deciding an issue one way or another, courts will usually respect such a trend, though they are not absolutely bound to do so. For instance, a Florida appellate court must adhere to the decisions of the Florida Supreme Court, but if the Florida Supreme Court has not spoken on the issue, the lower appellate court may examine the decisions of other Florida or out-of-state courts to come to its decision.

The common law of torts

The common law of torts is arguably the largest body of common law. It imposes society wide standards of behavior designed to deter wrongful, negligent or unreasonably dangerous conduct, and to compensate victims of such conduct. A tort is an act or omission that is blameworthy because the act or omission is either careless, shortsighted, unreasonably dangerous, or against a law or public policy. Unlike statutes or regulations, which are often specific, the common law is much broader, addressing the reasonableness of all aspects of the use of such chemicals and other pest control practices. A person injured by such acts or omissions must bring a lawsuit in court as a plaintiff and show that the actions of the defendant harmed him or her in some way and that the defendant violated some principle or theory of law.

Negligence

The common law of torts is divided, for our purposes here, into two categories – negligence and strict liability. Negligence is the theory most widely used to impose liability, a legal form of responsibility, for unintentional acts. Any unintentional act or omission that creates an unreasonable risk of harm to another constitutes negligence. If a negligent act results in harm to another, a court will award damages, usually monetary restitution appropriate to the cost of the injury, to an injured party.

The plaintiff must prove four elements to prevail in a negligence lawsuit: duty, breach, causation and damages. Duty is basically a person's responsibility to govern his or her own conduct so that others are not harmed. Such a duty exists whenever the defendant ought to foresee that there is a risk of harm to another person or property. When a duty of care is not fulfilled, there is a breach of duty, which is a failure to act with the degree of caution or foresight that a reasonably prudent person would have exercised under the same or similar circumstances. Causation refers to the requirement that the plaintiff must prove the defendant's action was the actual cause of the plaintiff's harm. Proving this step can be difficult if the damage is only indirectly related to the defendant's act or if there are other possible causes for the harm. Finally, the damage requirement must be examined. To satisfy this requirement, the plaintiff must prove that he or she suffered actual damage as a result of the defendant's act. If no damage resulted, even if the defendant admits his or her negligence, the plaintiff has no claim for negligence.

Regarding liability for pesticide use, a pesticide user can be liable for negligence if the user fails to exercise a reasonable duty of care in applying a toxic pesticide, and others are injured as a direct result of the negligent behavior. In negligence cases based on pesticide use, breach of duty and causation often relate to the same action – the pesticide dispersal. Pesticide users have a duty to act carefully when spraying pesticides, so as to avoid spraying pesticide on unintended targets. If a pesticide user does not breach that duty, then it is unlikely the pesticide caused a plaintiff's injury. To prove causation, the plaintiff must prove exposure to the pesticide and have an expert testify that exposure to the chemicals in the pesticide caused plaintiff's injury. Damages from pesticide use are usually related to personal injury or property damage. Personal injury damages result from exposure to the toxic chemicals in pesticides, and property damages, at least in agriculture, are usually for harm to currently growing crops, livestock, other farmed animals, or the loss of property utility, if the pesticide causes property to lose agricultural value.

There is a heightened level of liability for a defendant found guilty of gross negligence. Gross negligence is attained when the lack of reasonable care on the part of the defendant is so great as to raise the belief that the act or omission complained of was the result of a conscious indifference to the right or welfare of the person or persons to be affected by it. The difference between negligence and gross negligence rests in the state of mind of the defendant. To prove gross negligence, the plaintiff must show that the defendant knew about the danger, but his acts or omissions show that he didn't care. The plaintiff needs to show either that the defendant had actual knowledge that his or her conduct created an extreme degree of risk, or that, under the same or similar circumstances, a reasonably prudent person would have realized that such conduct would create a extreme risk of injury to others. Another important difference between the two is that when a jury finds gross negligence, it may award general damages as restitution for the injury conferred on the plaintiff, but then it may also award exemplary or punitive damages, an additional award designed to punish the defendant for his extreme lack of care. Punitive damages may not be awarded for findings of negligence, only gross negligence.

Another nuance of tort theory, which is important in agriculture, and any other realm dealing in employee-employer relations, is respondeat superior. Respondeat superior refers to the idea that the employer is liable for the negligent actions of employees. Therefore, if an employee acts negligently within the scope of his or her employment, that person's employer, whether an individual or a corporation, is liable for the negligent acts of that individual. Generally, an employee's activities are considered within the scope of employment if the actions are of the type that the employee was hired to perform, occur when and where the employee was supposed to be working, and the purpose of the action was to benefit the employer.

Case study – A useful way to better understand how these concepts should be applied to a fumigation treatment is to examine an actual case dealing with negligence in a fumigation job: *Terminix v. Right Away Foods Corporation*, 771 S.W. 2d 675 (1989). In this case a fumigation applicator was, through the negligent act of their employee, found to be negligent in the application of phosphine. Right Away Foods (RAF) hired Terminix to do a fumigation job on a building, which contained equipment containing silver and copper, both of which are known to be highly subject to corrosion upon extreme exposure to phosphine. The Terminix employee miscalculated the volume of the structure to be fumigated, and subsequently, twice the amount of phosphine as necessary was applied. The employee admitted in his testimony that he knew that high levels of phosphine would cause corrosion in copper, brass, silver, and gold, and that high temperatures and humidity, like those at the time of application, would worsen the effect. He failed to adequately advise RAF's employees on how to secure equipment and what equipment should be removed, advising them that certain implements such as copying machines were not at risk. In fact, the application of the phosphine caused severe corrosion damage to RAF equipment, and they sued Terminix for damages. Terminix claimed that RAF shared part of the blame for not adequately preparing their facilities. The jury agreed with RAF, found Terminix guilty of gross negligence and awarded RAF general and exemplary damages.

The Texas Court of Appeals agreed with the jury's verdict, except for the finding of gross negligence. The court noted that there was ample evidence the Terminix employee was negligent both by his use of twice the normal quantity of phosphine and in failing to properly instruct RAF on the precautions to take before fumigation. However, the court failed to see any evidence that the fumigator had any knowledge that he was placing RAF at an extreme risk or that a reasonable person under the same or similar circumstances would have realized such a risk. Therefore the exemplary damage award against Terminix was nullified. The court failed to find any fault in the conduct of RAF in preparing its facilities or with the manufacturer of the phosphine for not including more specific warnings about heat and preparation in the corrosion information found on the container label. The responsibility for the damage was placed solely on Terminix, the applicator.

This case clearly illustrates the four basic elements of negligence theory in action. Terminix was responsible for the conduct of its employee acting within the scope of his employment. Terminix breached its duty to RAF by misapplying the phosphine, and by failing to properly advise RAF of its corrosive effect. This breach of duty was a direct cause of the corrosive injuries to RAF equipment, and RAF suffered damages. The four elements are satisfied, thus the finding of negligence against Terminix. Negligence theory would apply, by analogy, in the same manner to stored product management. The damage to personnel and property would serve as an actionable injury, and assuming the other elements of negligence are present, a pesticide applicator who fails to exercise proper care and preparation could suffer the same consequences as Terminix.

Liability

The second major division of tort law discussed here is strict liability. Strict liability imposes the highest standards of care, holding persons liable for damages resulting from their actions without proof of fault. Unlike negligence, in a strict liability suit, courts will not consider whether the defendant acted reasonably. They will only consider whether the activity caused the harm complained of. The basis of strict liability is a policy decision by the courts or by the legislature that the person conducting the dangerous activity should be responsible for harm caused to innocent persons as a result of that activity, regardless of fault.

Courts of most states will apply strict liability if the defendant's activity is "abnormally dangerous" or "ultra hazardous". The Restatement of Torts lists six factors to be considered in determining whether an activity is abnormally dangerous: "(1) The existence of a high degree of harm to the person, land, or chattels of another; (2) The likelihood that the harm that results from it will be great; (3) The inability to eliminate the risk by the exercise of reasonable care; (4) The extent to which the activity is not a matter of common usage; (5) Whether the activity is totally inappropriate for the place it is being carried on; and, (6) The extent to which its dangerous attributes outweigh its value to the community." (Restatement (Second) of Torts §520 (*current through* August 2010)

An important limitation on the doctrine of strict liability is that the defendant is liable only for injury caused by those aspects of the activity that are abnormally dangerous. Therefore, a person engaged in an abnormally dangerous activity will not be strictly liable for any and all harm resulting from the operation, but rather only for those injuries caused by the danger inherent in the activity. For example, a transporter of hazardous waste would not be held strictly liable for striking a pedestrian, but would likely be held strictly liable for damage caused by the spill of hazardous waste.

Case study – Courts have held fumigators strictly liable for harm resulting from application. A good example is the case of *Old Island Fumigation v. Kathleen Barbee,* 604 So. 2d 1246 (Fla. 3d DCA 1992). Old Island was asked to fumigate two of four buildings in a condominium complex. They evacuated the buildings to be treated, but erroneously assumed that a firewall between the fumigated structures and their adjoining neighbors would contain Vicane gas in the area intended for treatment. Residents in the condominiums in the adjoining building suffered medical harm as a result of the fumigation. Despite the fact that Old Island found the firewall was defectively constructed by the original contractor, they were held strictly liable for the harm to the residents. The court determined that fumigation was an ultrahazardous activity because the risk it imposes cannot be eliminated by the use of the utmost care, and it is not a common usage of the complex. The court held that alleged negligence assigned to a third party does not excuse the fumigator from being strictly liable.

Whether fumigation is considered an ultrahazardous activity depends greatly upon the jurisdiction and state in which the applicator operates. In Florida, it is likely that other appeals courts would follow the logic of *Old Island*. The picture is less clear in some other states.

Actions also can be brought under the theory of strict liability in products liability cases. In *Schroeder v. Reddick Fumigants Incorporated*, 471 N.E.2d 621 (1984), the wife of a fumigator who allegedly died as a result of methyl bromide inhalation brought a wrongful death action against the manufacturer of both the chemical company and the company that manufactured the mask and canister used by the deceased. The deceased was a manager whose duties included fumigation of the plant. When the deceased prepared to fumigate the plant with a co-worker they checked their gas masks and canisters (which were designed to absorb noxious fumes) before fumigating and observed an expiration date that had expired almost a year before the day in question. The men then fumigated the plant with methyl bromide utilizing the masks and canisters that had expired. The next morning the deceased became ill and was admitted to the hospital where he died hours later.

In affirming the trial courts ruling in the *Schroeder* case the appellate court found in favor of the manufacturers and stated that the manufacturers could not have reasonably anticipated that its product would be used after its expiration date. The court went on to say that the warning labels on the methyl bromide cylinders were adequate as a matter of law. The warning label on the cylinders contained the word "DANGER" in bold face type with a skull and crossbones on either side of the word "POISON." The warning also stated that the vapor was extremely hazardous, that one was not to breath the vapor and to wear a full-face gas mask when applying.

This case is a good example of why risk management, which is discussed below, is so important to prevent injuries or even death. The fumigator in this case could have prevented his death by following the expiration date on the mask and canister and implementing sound risk management.

Another liability consideration to keep in mind in regard to work related injuries is workers' compensation laws. The workers' compensation law of the state that the case arises in could have a major impact on any suit filed. An example case of pesticide liability and Workers' Compensation is *U.S. Sugar Corp. v. Henson*, 787 So. 2d 3 (Fla. 1st DCA 2000). Henson worked as an agricultural mechanic for U.S. Sugar until he became disabled by a number of neurological illnesses. While Henson worked in fields repairing equipment, there were usually machines spraying pesticides, Henson frequently would be required to lay on ground that had been recently sprayed with pesticides, and he was often covered by aerial sprayings of pesticides. Notably for an agricultural professional, U.S. Sugar also built a makeshift mosquito fogger that used malathion in a manner contraindicated by the manufacturer's material safety data sheet (MSDS). Until the 1990s, U.S. Sugar did not provide employee training on pesticide MSDSs or any equipment to help protect the employees from pesticide exposure. In the late 1990s, Henson reported to a doctor with health problems, and based on U.S. Sugar spray records of the pesticides used during Henson's employment the doctor concluded that Henson's health problems were caused by pesticide exposure. The workers' compensation court, designated in Florida as the judge of compensation claims, found that Henson was entitled to workers' compensation because the work related cause (pesticide exposure) of the injury (disability) was proven by objective medical findings established to a reasonable degree of medical certainty. Basically, the U.S. Sugar records of Henson's pesticide exposure, combined with medical testimony that Henson's symptoms were consistent with exposure to those particular pesticides, was sufficient for the court to find in Henson's favor. The Florida standard for workers' compensation is similar to many other states, such as in Nebraska where the worker must "prove that it is more probably true than not true that he or she suffers from a disabling physical condition which is the result of his or her work." *Sheridan v. Catering Management, Inc.*, 558 N.W.2d 319 (Neb.App. 1997). However, because many states have higher or lower standards for proving employer responsibility, an agricultural professional should consult his or her state workers' compensation laws.

Risk Management

The most effective way to avoid liability in stored product management is to practice sound risk management. Risk management is a process of identifying and analyzing risks and selecting the best options for limiting liability. Practically, then, risk management can be defined as 1% law and 99% common sense. Careful application of essential steps in treating and working with stored grain can mean the difference between a job well done and tragedy.

First, when working around stored grain, the applicator should identify and analyze the risks at hand. For example, the Terminix employee discussed earlier failed to fully investigate and research the possible damage to equipment. Similarly, the pesticide control methods U.S. Sugar later implemented would have probably minimized the employee risk of health problems. Also, while the U.S. Sugar spray records were used against that company, maintaining accurate spray logs could protect an agricultural professional from liability if a plaintiff's symptoms are inconsistent with the pesticides used. Second, consider alternative ways of handling the risk. Third, select the best alternative: one that provides the most protection from possible harms, and therefore liability. Had Terminix or Old Island applicators better reviewed and investigated the situation at hand, they would not have missed the key irregularities that led to damages and injury and subsequent lawsuits. As seen in the *U.S. Sugar* case, sometimes the best alternative is simply following the pesticide manufacturer's directions when requiring an employee to handle pesticides.

When beginning a job, certain helpful hints might allow you to prevent an error that would otherwise lead to legal concerns. When working with chemicals, always read the label thoroughly, and scrutinize warnings for side effects you might be unaware of. Have a clear and concise understanding of your work environment. Make sure you have an exact grasp of the environment's size, contents and possible vulnerabilities. Be sure to take every possible step to avoid the most remote possibility of harm to other people. Use proper protection and application equipment in the exact manner they were designed to be employed. Once the procedure is complete, make sure that every effort has been made to properly aerate the facility or otherwise make it safe for its common usage. If all appropriate precautions have been taken and a problem still arises, consult with the state environmental protection agency to determine if the pesticide itself has a flaw.

Conclusion

The current environment of American law allows many possible pitfalls for individuals involved in stored product management. The possible emergence of strict liability in these areas, especially fumigation, raises the stakes for risk management even higher. The cases discussed in this chapter illustrate what not to do. In both instances, possibilities were overlooked and the situation was not thoroughly investigated, which resulted in a high damage awards against the applicators. To avoid making the same mistakes investigate federal, state, and local laws governing the activity and employ sound risk management. In view of the enormous cost of litigation and the magnitude of potential damages, using smart risk management approaches is essential in stored product management.

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This publication is intended to provide a basic overview of the law and risk management. However, the reader should be aware that because the laws, administrative rulings, and court decisions on which this publication is based are subject to constant revision, portions of this publication could become outdated at any time. This publication should not be viewed as a comprehensive guide to liability basics and the importance of risk management. Additionally, many details of cited laws are left out due to space limitations. This publication should not be seen as a statement of legal opinion or advice by the authors on any of the legal issues discussed within. This publication is not a replacement for personal legal advice, but only as a guide to inform about the issues discussed herein. For these reasons, the use of this publication by any person constitutes an agreement to hold the authors, the Institute of Food and Agricultural Sciences, the Center for Agricultural and Natural Resource Law, and the University of Florida harmless for any liability claims, damages, or expenses that may be incurred by any person as a result of reference to or reliance on the information contained in this publication.

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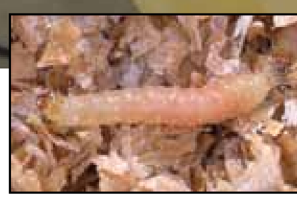

Stored Product Protection

This book is a practical guide to protecting grains and other raw commodities, food processing facilities, finished food, and durable plant and animal products from insects, molds, and vertebrate pests.

The 31-chapter training manual is an updated companion to the 1995 Oklahoma State publication, E912, *Stored Product Management*. All-new chapters from the world's leading experts will give readers an understanding of pest biology, behavior, and ecology in the marketing system; pest management methods; and relevant economic and regulatory considerations. Edited by David W. Hagstrum, Thomas W. Phillips and Gerrit Cuperus, this should be a valuable reference for anyone involved in stored product protection.

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