Fundamentals of Stored-Product Entomology

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Preface

A book entitled *Pests of Stored Grain and Grain Products* by Richard T. Cotton and one entitled *Pests of Stored Products* by James W. Munro were last published 40 or more years ago. A wealth of new insights into the fundamentals of stored-product insect biology, ecology, and pest management has been published during the last 40 years. A new stored-product entomology book is needed to cover these advances.

Efforts to improve the quality and safety of our food supply have resulted in the banning of many of the chemicals that were used in the past to manage stored-product insect pests. In the future, a thorough understanding of insect biology, ecology, and behavior will be even more important in developing, implementing, and evaluating pest management programs for stored-product insects. Therefore, this new book provides the fundamental knowledge and training needed to plan, implement, and evaluate a pest management program for stored-product insects. The book also should be useful to readers developing research programs to improve pest management programs for stored-product insects. The objective of our book is to help the readers learn to think about stored-product insect problems in a way that will result in improved pest management programs for stored-product insects. This should enable the readers to apply the information and concepts presented in this book in new situations.

The book has a total of 24 chapters. The first two discuss the scope of stored-product entomology and the techniques useful 1) in choosing live insects to assay the effectiveness of insect pest management methods, 2) in processing and interpreting data from sample units taken to monitor stored-product insect populations, and 3) in understanding the susceptibility and response of stored-product insects to pest management methods. These chapters provide insight into the diversity of foods and habitats utilized by stored-product insects, the types of economic losses attributable to these insects, and the ways in which an understanding of their biology can be used to study or manage them.

Pictures are provided that allow the most damaging of the stored-product insect pest species to be identified to family. The reader is referred to publications with pictures, keys, and descriptions for the identification of these insects to genus and species and for the identification of other stored-product pests and beneficial insect species. Some quick methods of separating closely related stored-product insect species are given in Chapter 2. Study questions provided at the end of many chapters emphasize the main concepts covered in that chapter. Additional reading that exposes readers to a variety of stored-product literature, including books, conference proceeding papers, literature reviews, research papers, government publications, and (in a few cases) even popular articles, is recommended to support and supplement the material discussed in many chapters. A comprehensive reference list at the end of the book gives the sources of studies cited in tables and figure captions.

Chapters 3–7 cover insect mobility, sources of insect infestation, sampling, life history, and population growth. Because stored-product insects are so mobile, managing source populations before these insects can spread to uninfested commodities is very important. Consideration of the frequency, direction, pattern, and

speed of insect movement can be important in developing an effective sampling program. A good sampling program can increase the effectiveness and reduce the cost of pest management programs for stored-product insects. Most of the computer simulation models for predicting the growth of stored-product insect populations are based on the effects of temperature and moisture on insect life history. Forecasting insect population growth using computer simulation models can reduce the frequency of sampling and optimize the timing and targeting of insect pest suppression. Insect pests are managed by modifying their life histories (developmental times, mortality, and egg production) and thus their population growth rates. Therefore, understanding the life history and behavior underlying insect population growth can improve insect pest suppression. Preventing reproduction by the first insects that infest a commodity is more effective than killing all their offspring because the damage caused by the developing offspring is prevented. A combination of sampling to estimate insect distribution and abundance and predicting insect population growth using computer simulation models can be a powerful tool for developing and implementing cost-effective insect pest management programs or research programs that will improve pest management programs for stored-product insects.

The next three chapters (8–10), on insect pest management decision aids, the cost of insect pest management methods, and the resistance of insects to insect pest management methods, are pivotal. The readers should be able to assume the role of an insect pest manager or research scientist and to start using the basic understanding of stored-product insect biology acquired from the first seven chapters to plan an insect pest management program that implements, or a research program that improves, the insect pest management methods discussed in the next eight chapters.

These next chapters discuss pest management methods for stored-product insects. Biological (Chapter 11), physical (Chapters 12–16), and chemical (Chapters 17–18) methods have been developed for managing stored-product insect pests. These methods either slow the growth of insect pest populations by delaying or preventing reproduction, or they kill the insect pests. Each of the eight chapters includes a statement of the basic operating principle for that method and some background information. The advantages, disadvantages, and implementation options for each pest management method are given, to take the reader through the thought process involved in choosing the best pest management method or methods for an insect pest management program. Examples of the integration of more than one insect pest management method also are given for most of these chapters. A similar structure is used for each of these chapters to encourage the readers to compare different insect pest management methods. Table 19.1 provides a summary comparison of the advantages and disadvantages across insect pest management methods, and Chapter 19 provides an overview of the ideas discussed in the book. The reader is referred to other publications for more-detailed information on the safe and effective use of these pest management methods for stored-product insects.

The book discusses the solutions to stored-product insect pest problems ranging from those of the subsistence farmer to those encountered at various points in a complex commodity-marketing system. Much of the discussion is as applicable to the subsistence farmer as to other food storage, processing, transportation, and marketing situations. The extensive discussions of field infestation may be of greatest importance for stored-product insect pest management at the subsistence farmer level. The more expensive and high-technology methods may not be appropriate at the subsistence

farmer level but could be used at central stores or export facilities in their countries. Expensive equipment will be cost effective only when large quantities of commodities are handled at a facility.

Available evidence suggests that simple technology such as using aeration during the coolest part of the day, could be quite effective in reducing insect damage in tropical climates. Some of the methods such as vegetable oils, botanicals, inert dusts, tumbling beans to prevent insect infestation, and small-scale solar heating have been investigated primarily for use by the subsistence farmer. The only example of a large-scale introduction of natural enemies to suppress stored-product insect pests is the release of *Teretrius nigrescens* (formerly *Teretriosoma nigrescens*) against *Prostephanus truncates*. This biological control was to help subsistence farmers in Africa. Expert systems are discussed for the management of stored-product insect pests in bagged storage of rice in the tropics and in other situations. The criteria used by the maize traders in Africa and those used for the sale of wheat in the United States are discussed.

Many questions about stored-product insects and their management are still unanswered. The mobility of stored-product insects has only rarely been studied in detail under the conditions found in storage, processing, and marketing facilities and transportation vehicles. The majority of quantitative studies on the population dynamics of stored-product insect pests have been done in the laboratory at unrealistically high densities. Crowding is much more important in these laboratory studies than in storage, processing, and marketing facilities, where food is so abundant that insects generally reach high densities only in the food residues, near the surface of bulk commodities, or at locations in the bulk commodities where the moisture is high. Insect pests should be managed before they reach these high densities even in the food residues.

Insect pest management decisions are still often based upon past experience rather than current information about the distribution and abundance of stored-product insect pest populations obtained from a sampling program. Few pest management methods for stored-product insects have been tested on more than a small scale, and generally there has been little follow-up sampling to evaluate their effectiveness. The contributions of diapause, natural enemies, and insect mortality from impact during grain handling to the overall success of pest management programs for stored-product insects have rarely been measured. Studies on integrating more than one insect pest management method have most often been done only on a small scale in the laboratory. Many laboratory studies do not cover the range of environmental conditions under which stored-product insects live in the marketing system. When using information from laboratory or field studies to make insect pest management decisions, careful consideration must be given to whether the environmental conditions in these studies were equivalent to those under which actual insect pest suppression is to be done.

Chapters 20 and 21 provide lists and discussions of many of the published books, reviews, and conference proceedings that are available on stored-product entomology. Roughly every two years, there has been an international meeting of scientists working on stored-product insect problems that occur during storage, processing, transportation, and marketing of stored products. The proceedings of these meetings contain a wide variety of information on stored-product insects. Expanded explanations are provided in Chapter 22 for some of the terms used in the book. These

terms are printed in bold type throughout the book. A sampling exercise is provided in Chapter 23 to illustrate how the accuracy of estimating insect density increases with the number of sample units examined. Chapter 24 discusses a computer program that simulates stored-product insect population growth and how it can be modified for different insect species, insect pest management methods, and types of facilities or transportation vehicles.

We have attempted to make the book easy to read and understand. We hope that it will be a useful resource for students, extension educators, consultants, food industry sanitarians and managers, legislators, regulators, and insect pest management professionals. Our book cites a large number of papers, books, and conference proceedings and provides access to a large portion of the available literature on stored-product insects through the references cited in these articles, books, and conference proceedings. For undergraduate college students, the text can be supplemented by lecture material from the suggested readings. For graduate students, the text and suggested readings can be assigned. For advanced classes, the text, suggested readings, references cited in tables and figures, and books and conference proceedings can be utilized.

We thank Drs. Sonny Ramasawamy, Carl Reed, and Rizana Mahroof for reviewing the book and offering constructive criticisms for its improvement. We also thank Drs. Paul Flinn and Jim Throne for their help with Chapter 24. Finally, we thank AACC International for its interest, independent reviews of the book chapters, and publication of this book. We welcome constructive criticism of the book contents from readers.

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Dedication

The authors dedicate this book to the students of the 2002 and 2004 Stored-Product Insects classes at Kansas State University, whose enthusiasm for the subject encouraged the writing of this book.

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Part I

Ecology and Decision Aids

Insect pest management is applied insect ecology. Chapters 1 and 2 cover insect habitats, the influences of regulations and business practices, and methods for identifying and working with insects. Chapters 3, 4, and 5 emphasize the spatial aspects and Chapters 6 and 7 the temporal aspects of stored-product insect ecology. Decision aids (Chapter 8) include sampling information, cost-benefit analysis, consultants, expert systems, and the predictions of computer simulation models. The economics of insect pest management (Chapter 9) are important when using cost-benefit analysis. Resistance management (Chapter 10) is necessary because insect populations readily adapt and are likely to eventually become resistant to any pest management method.

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Chapter 1

Introduction

Raw and processed commodities must be protected from rodents, birds, insects, mites, and microorganisms throughout the marketing system. The mobility and the ability of many stored-product insects to find and reproduce on many different foods throughout the marketing system make them particularly difficult to manage. This chapter provides an overview of the relative importance of different stored-product insect species and the types of economic losses that can be attributed to these insects. The types of regulations and business practices that can impact pest management programs for stored-product insects and the resources available for identifying stored-product insects also are covered in this chapter.

Storage habitat

Crops are harvested at the end of a growing season, and the harvested grain must be stored with minimal loss of quality until needed for human and animal consumption during the year. Grain reserves also are stored to prevent famine in years when the harvested crop is insufficient. The moisture and temperature at which the grain is stored determine its susceptibility to stored-product insects.

Traditional grain storage structures are still used in some parts of the world (see recommended reading by Reed).[1] Storage structures made of materials available locally are designed to protect grain from weather, insects, mites, fungi, rodents, and birds. Grain may be stored in the field in piles or on vertical poles for varying periods after the harvest. Underground storage in pits is among the most ancient methods still in use today. Grain may be stored in the attic over the kitchen or the living space. It is stored in boxes, baskets, jars, gourds, clay pots, jute bags, and metal drums. Unthreshed grain may be covered with a thatched roof or left uncovered when stored on horizontal poles or platforms. Larger traditional granaries are made of stone, brick, or mud.

The first step toward the development of a marketing system involved production of cash crops by subsistence farmers. As cash-crop production grew and fewer people were needed to grow food crops, a more elaborate marketing system developed. Grain was stored on farms, first in wooden granaries and cribs and later in metal bins. More grain could be produced after mechanical harvesting equipment was invented, and larger storage and marketing facilities were necessary to handle the large quantities of harvested grain. This resulted in increased quantities of grain being stored at grain **elevators**[2] rather than on the farm. The first elevators were constructed of wood. Later elevators were made of concrete (see recommended reading by Bailey). Recently, large metal bins or flat storage sheds have been added at elevators because of their lower cost and larger capacities.

[1] Recommended readings cited in the text can be found at the end of the chapter as well as in the list of references at the end of the book.

[2] Explanations of the words in bold letters in the text and more information on the subject can be found in Chapter 22.

Insects are moved through the marketing system along with the grain and grain products. Habitats of stored-product insects include the entire marketing system, from the fields in which a crop is grown to the storage and processing facilities, transportation vehicles, warehouses, and retail stores in which many raw and processed commodities spend some time. For subsistence farmers, only the field and storage environments may be important. Insects have adapted to this diversity of habitats by moving to find essential resources, eating many types of food, and producing lots of offspring. Large numbers of offspring can ensure a new generation even when insect mortality is high. Many stored-product insect species are thought to have been spread by international trade and now have a worldwide distribution (see recommended readings by Buckland and by Howe). The geographical origin of most stored-product insect pests is not known, because they were distributed worldwide by 1800, before the precise identification of insect species was possible. Heated facilities and bulk storage have allowed insects to survive in geographical regions and during seasons in which outside temperatures would otherwise kill them.

Species associated with stored products

Many insect species have adapted to survive and multiply on raw, dry, durable cereal grains, their processed products, and many other stored commodities (Table 1.1). The majority of these species are beetles (order Coleoptera), but several species of moths (order Lepidoptera) also are serious pests. Booklice (order Psocoptera) are often found under warm, humid conditions and can cause economic losses when they reach high numbers. On the other hand, several species of mites (order Acarina), wasps (order Hymenoptera), and bugs (order Hemiptera) often attack insect pest species in stored commodities. Knowing which species of pests and beneficial insects are present is important in developing and implementing the best insect pest management program.

Figure 1.1, which includes one species from each of the nine families of Coleoptera and one species of Lepidoptera, may allow the species capable of causing significant or extensive damage to stored commodities to be identified to the family level, narrowing the list of possible species. Sixteen of the insect pest species listed in Table 1.1 are capable of rapidly causing extensive damage, and another 16 species are capable of causing significant damage. An additional 51 species of insect pests in Table 1.1 can cause some damage to commodities or are minor pests that rarely cause damage. Although the insect species ranked as minor pests in Table 1.1 may not reproduce on stored commodities, they may be contaminants that reduce the market value of a commodity. Several hundred species of minor insect pests have been reported to infest stored commodities and facilities that store, handle, and process commodities for human and animal food.

Stored-product insect species that belong to the families Bostrichidae, Bruchidae, Curculionidae, and Gelechiidae feed and complete their immature development inside a seed. Larvae of *Cryptolestes ferrugineus* and *Ephestia elutella* feed within the germ of wheat kernels. Larvae of *Cadra cautella* and *Plodia interpunctella* feed on peanuts inside their shells and between the two halves of the peanut kernels. All of the Hymenoptera are parasitoids, and *Acaropsis docta*, *Blattisocius keegani*, *B. tarsalis*, *Cheyletus malaccensis*, *C. eruditus, Teretrius nigrescens*, *Xylocoris flavipes*, *X. sordidus*, *Lyctocoris campestris*, and some psocids are predators. Many of these stored-

Table 1.1. Species associated with stored commodities

Family	Genus and species	Common name[a]	Com-modity[b]	Pest status[c]	Phero-mone[d]
		Coleoptera (beetle)			
Anobiidae	*Lasioderma serricorne* (Fabricius)	cigarette beetle	T	3	Y
Anobiidae	*Stegobium paniceum* (Linnaeus)	drugstore beetle	D	3	Y
Anthribidae	*Araecerus fasciculatus* (DeGeer)	coffee bean weevil		2	
Bostrichidae	*Dinoderus minutus* (Fabricius)	bamboo powder post beetle	W	2	
Bostrichidae	*Prostephanus truncatus* (Horn)	larger grain borer	G	4	Y
Bostrichidae	*Rhyzopertha dominica* (Fabricius)	lesser grain borer	G	4	Y
Bruchidae	*Acanthoscelides obtectus* (Say)	bean weevil	L	4	N
Bruchidae	*Bruchidius atrolineatus* (Pic)		L	2	
Bruchidae	*Callosobruchus analis* (Fabricius)		L	4	N
Bruchidae	*Callosobruchus chinensis* (Linnaeus)	southern cowpea weevil	L	4	N
Bruchidae	*Callosobruchus maculatus* (Fabricius)	cowpea weevil	L	4	N
Bruchidae	*Callosobruchus phaseoli* (Gyllenhal)		L	3	
Bruchidae	*Callosobruchus rhodesianus* (Pic)		L	3	
Bruchidae	*Callosobruchus subinnotatus* (Pic)		P	2	N
Bruchidae	*Callosobruchus theobromae* (Linnaeus)		L	2	
Bruchidae	*Zabrotes subfasciatus* (Boheman)	Mexican bean weevil	L	4	
Cleridae	*Necrobia rufipes* (DeGeer)	red-legged ham beetle		2	
Cryptophagidae	*Cryptophagus varus* Woodroffe and Coombs	sigmoid fungus beetle			
Curculionidae	*Sitophilus granarius* (Linnaeus)	granary weevil	G	3	N
Curculionidae	*Sitophilus oryzae* (Linnaeus)	rice weevil	G	4	Y
Curculionidae	*Sitophilus zeamais* Motschulsky	maize weevil	G	4	Y
Dermestidae	*Anthrenus flavipes* LeConte	furniture carpet beetle	C	2	Y
Dermestidae	*Anthrenus sarnicus* Mroczkowski	Guernsey carpet beetle	C		Y

(*continued on next page*)

Table 1.1 (continued)

Family	Genus and species	Common name[a]	Commodity[b]	Pest status[c]	Pheromone[d]
Dermestidae	*Anthrenus scrophulariae* (Linnaeus)	carpet beetle	C		
Dermestidae	*Anthrenus verbasci* (Linnaeus)	varied carpet beetle	C	2	Y
Dermestidae	*Attagenus brunneus* Faldermann			2	N
Dermestidae	*Attagenus unicolor* (Brahm)	black carpet beetle	G	2	Y
Dermestidae	*Dermestes maculatus* Degeer	hide beetle	H	3	N
Dermestidae	*Dermestes lardarius* Linnaeus	larder beetle	H	2	
Dermestidae	*Trogoderma glabrum* (Herbst)	glabrous cabinet beetle	G	2	Y
Dermestidae	*Trogoderma granarium* Everts	khapra beetle	G	4	Y
Dermestidae	*Trogoderma inclusum* LeConte	larger cabinet beetle	G	2	Y
Dermestidae	*Trogoderma variabile* Ballion	warehouse beetle		3	Y
Dermestidae	*Trogoderma versicolor* (Creutzer)	European larger cabinet beetle			
Histeridae	*Teretrius nigrescens* (Lewis)		G		
Laemophloeidae	*Cryptolestes ferrugineus* (Stephens)	rusty grain beetle	G	4	N
Laemophloeidae	*Cryptolestes pusillus* (Schonherr)	flat grain beetle	G	3	N
Laemophloeidae	*Cryptolestes turcicus* (Grouvelle)	Turkish grain beetle	G	3	N
Lophocateridae	*Lophocateres pusillus* (Klug)	siamese grain beetle	G	1	
Mycetophagidae	*Typhaea stercorea* (Linnaeus)	hairy fungus beetle	G	1	
Nitidulidae	*Carpophilus dimidatus* (Fabricius)	corn sap beetle	F	2	
Nitidulidae	*Carpophilus hemipterus* (Linnaeus)	dried fruit beetle	F	3	
Nitidulidae	*Carpophilus pilosellus* Motschulsky			1	
Ptinidae	*Ptinus ocellus* Brown	Australian spider beetle		2	
Ptinidae	*Ptinus villiger* (Reitter)	hairy spider beetle		1	
Silvanidae	*Ahasverus advena* (Waltl)	foreign grain beetle	G	2	N
Silvanidae	*Cathartus quadricollis* (Guerin)	squarenecked grain beetle	G	2	N

Silvanidae	*Oryzaephilus mercator* (Fauvel)	merchant grain beetle	G	3	N
Silvanidae	*Oryzaephilus surinamensis* (Linnaeus)	sawtoothed grain beetle	G	4	N
Tenebrionidae	*Alphitobius diaperinus* (Panzer)	lesser mealworm		2	
Tenebrionidae	*Cynaeus angustus* (LeConte)	larger black flour beetle	G	2	
Tenebrionidae	*Gnatocerus cornutus* (Fabricius)	broadhorned flour beetle	G	2	N
Tenebrionidae	*Gnatocerus maxillosus* (Fabricius)	slenderhorned flour beetle	G	2	
Tenebrionidae	*Latheticus oryzae* Waterhouse	longheaded flour beetle	G	2	
Tenebrionidae	*Palorus ratzeburgii* (Wissmann)	smalleyed flour beetle		2	
Tenebrionidae	*Palorus subdepressus* (Wollaston)	depressed flour beetle	G	2	
Tenebrionidae	*Tenebrio molitor* (Linnaeus)	yellow mealworm		1	N
Tenebrionidae	*Tribolium audax* Halstead	American black flour beetle	G	2	
Tenebrionidae	*Tribolium castaneum* (Herbst)	red flour beetle	G	4	Y
Tenebrionidae	*Tribolium confusum* Jacquelin du Val	confused flour beetle	G	4	Y
Tenebrionidae	*Tribolium destructor* Uyttenboogaart	false black flour beetle	G	3	
Tenebrionidae	*Tribolium freemani* Hinton		G		Y
Tenebrionidae	*Tribolium madens* (Charpentier)	black flour beetle	G	2	
Trogositidae	*Tenebroides mauritanicus* (Linnaeus)	cadelle	G	2	
		Lepidoptera (moth)			
Gelechiidae	*Sitotroga cerealella* (Olivier)	Angoumois grain moth	G	3	Y
Gelechiidae	*Phthorimaea operculella* (Zeller)	potato tuber moth			Y
Oecophoridae	*Endrosis sarcitrella* (Linnaeus)	Whiteshouldered house moth	G	1	
Pyralidae	*Amyelois transitella* (Walker)	navel orangeworm	F		N
Pyralidae	*Anagasta kuehniella* (Zeller)	Mediterranean flour moth	G	3	Y
Pyralidae	*Cadra calidella* (Guenee)	carob moth	F	1	
Pyralidae	*Cadra cautella* (Walker)	almond moth	P	4	Y

(*continued on next page*)

Table 1.1 (continued)

Family	Genus and species	Common name[a]	Com-modity[b]	Pest status[c]	Phero-mone[d]
Pyralidae	*Cadra figulilella* (Gregson)	raisin moth	F	1	Y
Pyralidae	*Corcyra cephalonica* (Stainton)	rice moth	G	2	N
Pyralidae	*Ephestia elutella* (Hübner)	tobacco moth	T	3	Y
Pyralidae	*Galleria mellonella* (Linnaeus)	greater wax moth			N
Pyralidae	*Plodia interpunctella* (Hübner)	Indianmeal moth	F	4	Y
Pyralidae	*Pyralis farinalis* Linnaeus	meal moth	F	1	
Tineidae	*Tineola bisselliella* (Hummel)	webbing clothes moth	C	2	Y
Tineidae	*Tinea pellionella* Linnaeus	case-making clothes moth	C		N
		Psocoptera (booklice)			
Liposcelidae	*Liposcelis bostrychophila* Badonnel		G	2	
Liposcelidae	*Liposcelis brunnea* Motschulsky			2	
Liposcelidae	*Liposcelis decolor* (Pearman)		G	2	
Liposcelidae	*Liposcelis entomophila* (Enderlein)		G	2	
		Hymenoptera (wasp)			
Bethylidae	*Cephalonomia tarsalis* (Ashmead)		G		
Bethylidae	*Cephalonomia waterstoni* Gahan		G		
Bethylidae	*Holepryis sylvanidis* (Brethes)		F		
Bethylidae	*Laelius pedatus* (Say)				
Braconidae	*Habrobracon hebetor* Say		F		
Eupelmidae	*Eupelmus vuilleti* (Crawford)		L		
Ichneumonidae	*Venturia canescens* (Gravenhorst)		F		
Pteromalidae	*Anisopteromalus calandrae* (Howard)		G		
Pteromalidae	*Dinarmus basalis* (Rondani)		L		

Pteromalidae	*Lariophagus distinguendus* Forster	G
Pteromalidae	*Pteromalus cerealellae* (Ashmead)	G
Pteromalidae	*Theocolax elegans* (Westwood)	G
Trichogrammatidae	*Trichogramma evanescens* (Westwood)	
Trichogrammatidae	*Trichogramma pretiosum* Riley	P
Trichogrammatidae	*Uscana lariophaga* (Steffan)	L
	Hemiptera (bug)	
Anthocoridae	*Lyctocoris campestris* (Fabricius)	G
Anthocoridae	*Xylocoris flavipes* (Reuter)	G
Anthocoridae	*Xylocoris sordidus* (Reuter)	P
	Acarina (mite)	
Ascidae	*Blattisocius keegani* (Fox)	G
Ascidae	*Blattisocius tarsalis* (Berlese)	G
Cheyletidae	*Acaropsis docta* (Berlese)	G
Cheyletidae	*Cheyletus malaccensis* (Oudemans)	G
Cheyletidae	*Cheyletus eruditus* (Schrank)	G

[a] Some species, most often the natural enemies, do not have common names.

[b] Cloth fabric or carpet (C), drugs (D), dried fruits and nuts (F), cereal grains and products (G), hides (H), legumes (L), peanuts (P), tobacco (T), and wood and dried cassava (W).

[c] Rees 2004 divided stored-product insect pest species into 4 categories with 1 = minor pest, rarely causes much damage; 2 = pest capable of causing damage; 3 = pest capable of significant damage; and 4 = major pest rapidly capable of extensive damage.

[d] Data from Phillips et al 2000. Species of beetles and moths for which pheromones have been identified are marked with a Y if the pheromone is commercially available or N if it is not. Shu et al 1999 identified *Callosobruchus subinnotatus* pheromone; Rodin et al 1969 identified the *Trogoderma inclusum* pheromone; Tebayashi et al 1998a,b and Tashiro et al 2004 identified the *Gnatocerus cornutus* pheromone; Susuki et al 1987 identified the *Tribolium freemani* pheromone; Persoons et al 1976 identified the *Phthorimaea operculella* pheromone; and Coffelt et al 1979 identified the *Amyelois transitella* pheromone.

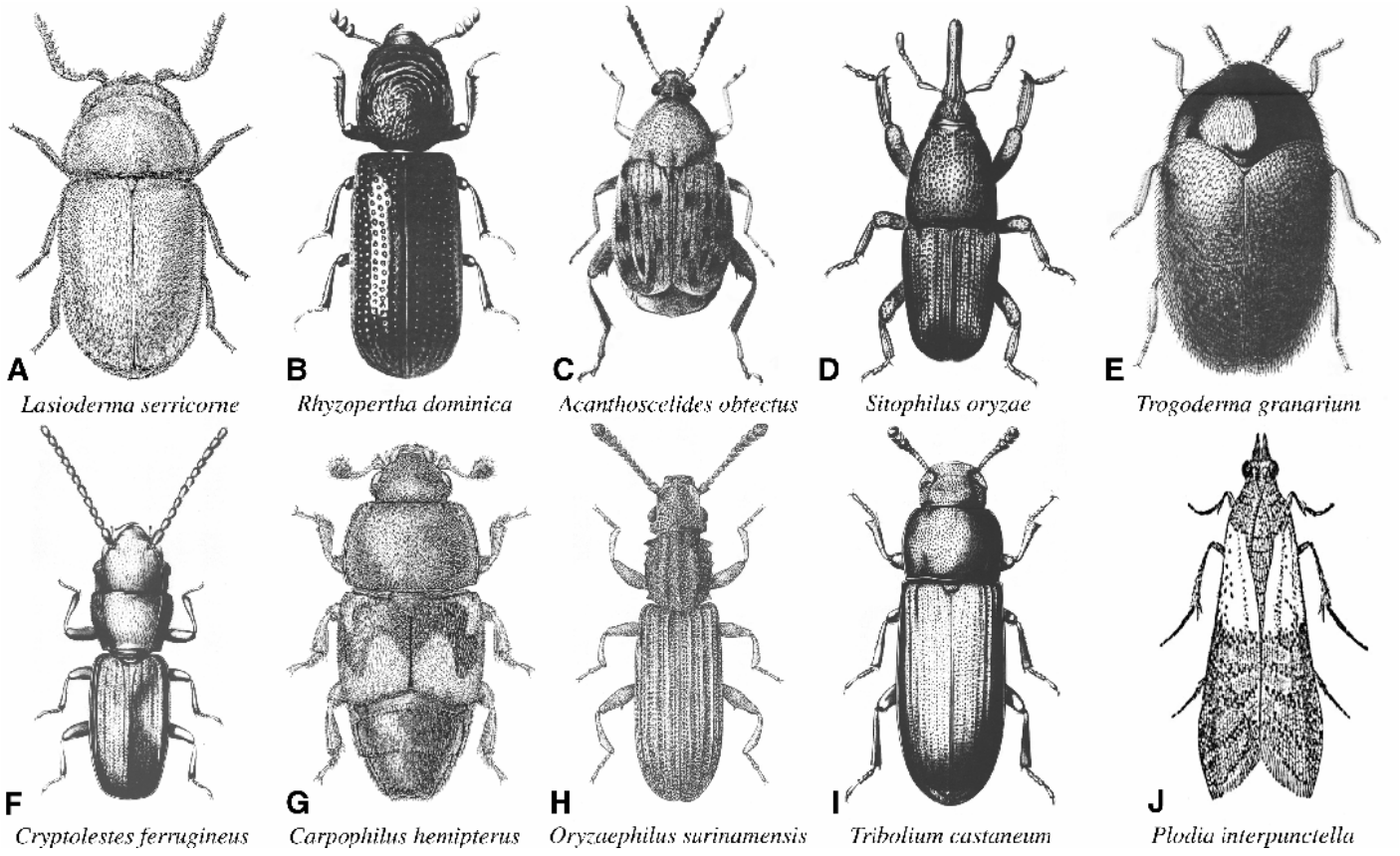

Figure 1.1. Insects capable of causing significant or extensive damage to stored products. Insect lengths: *L. serricorne,* 2–3.5 mm; *R. dominica,* 2–3 mm; *A. obtectus*, 2–3.7 mm; *S. oryzae*, 3–4.6 mm; *T. granarium,* 1.8–3.8 mm; *Cryptolestes ferrugineus,* 1.6–2.2 mm; *Carpophilus hemipterus,* 2–4.1 mm; *O. surinamensis,* 1.7–3.2 mm; *T. castaneum,* 2.3–4.4 mm; *P. interpunctella*, 8 mm. (A and G, reprinted from *Beetles associated with stored products in Canada: An identification guide* [Bousquet 1990], Figs. 176 and 216, Agriculture and Agri-Food Canada, 1990, reproduced with the permission, of the Minister of Public Works and Government Services Canada, 2005; J from Linsley and Michelbacher 1943; B–F, H, and I used with permission of the Central Science Laboratory of the U.K. Ministry of Agriculture, Fisheries and Food)

product insect species have a worldwide distribution. Exceptions include *Prostephanus truncatus*, *Zabrotes subfasciatus*, and *Cadra calidella*, which are pests mainly in countries with tropical climates. *Sitophilus granarius*, *Cynaeus angustus*, and some dermestid species are pests mainly in countries with temperate climates. **Pheromones** have been identified for many of the beetles and moths, and their importance for insect pest reproduction, host finding by **natural enemies,** and insect pest management programs is discussed in Chapter 3.

Table 1.1 lists the types of commodities infested by each stored-product insect species. Table 1.2 gives a more complete description of the foods infested by three of these species. However, the lists in Table 1.2 use categories that include many different foods, such as grain; dried fruit; drugs; nuts; spices; herbs; herbarium specimens; packaged processed foods from all types of cereals, oil seeds, and pulses; pulses and pulse products; and seeds of trees and other plants. Also, not all of the foods in these lists are equally suitable for insect development, and insect developmental times are longer on the less-suitable foods. When insect developmental times exceed 100 days, survival is often very low.

Studies identifying the stored-product insect species found at various locations in the marketing system are one way to document the role of commerce in spreading these insects throughout the world (Table 1.3). *Alphitobius diaperinus* or *Alphitobius* spp., *Lasioderma serricorne*, *Oryzaephilus surinamensis, Rhyzopertha dominica*, and *Tribolium castaneum* were found in all 12 of these studies. *Cadra cautella* was found in all of these studies that looked for Lepidoptera, and *Plodia interpunctella* was found in all except the study on packaged-food warehouses. In total, 76 species of stored-product insects were found in more than one of these studies, and 86 other species were identified in only one study.

In these studies, imports into England were from West Africa; those into California and Arizona were from Mexico and South America but mostly Asia; and those into Japan were mostly from Asia but came from all over the world. Empty shipping containers were studied in Australia; food and food-handling areas were studied for ships docking in New Orleans, Louisiana, and in Miami, Florida; bakeries, food stores, restaurants, warehouses, processing plants, a school, and a vending operation were studied in Connecticut; and warehouses were studied in California, Hawaii, Latin America, Africa, and Asia. The study in Hawaii used light traps, food-bait traps, and facility inspections. Insects were found in 93% of the cargos from West Africa and, more recently, in 12.6% of the commodities imported into California. Insects were found in 61% of the Los Angeles, California, port warehouses and all of the 20 packaged-food warehouses in nine countries.

One of the recommended readings for this chapter (by Freeman) is a study of insect infestations in raw commodities imported into Great Britain. This study was not included in Table 1.3 because it does not include a complete list of the stored-product insect species found. The percentage of cargos infested decreased from 52% in 1957 to 34% in 1966 and 23% in 1973. The ranked order by country of the percentage of cargos infested remained fairly constant between 1967 and 1973. The number of cargos received in shipping containers increased from 0.7% in 1968 to 33% in 1973. *Cadra cautella* and *Tribolium castaneum* were the predominant species. Interceptions of *Trogoderma granarium* 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.

Table 1.2. Foods infested by three species of stored-product insect pests[a,b]

Lasioderma serricorne

Aniseed (*Pimpinella anisum,* 31.9), areca nuts (betel nuts, *Areca catechu*), bamboo, beans, beet (65.1), biscuits, cassava (*Manihot esculenta*), cayenne pepper (71), chickpeas, chilli powder (135), cocoa beans (crushed, 55.2; whole 105.6), coconut meal (31.2), coffee beans, copra, coriander, cottonseed (39.8), cottonseed meal (26.9), cowpeas (crushed, 27.5; whole, 31.6), cumin (42.7), curry powder (122), dates, dried banana, dried cabbage, dried carrots (54.5), dried fish, dried fruit, dried insects, drugs, fish meal, flax tow, ginger (63.7), grain, peanuts (34.4), peas (33.0), herbarium specimens, herbs, horse-bean (36.9), juniper seeds, laboratory diet (35), leather, licorice root, locust beans (crushed, 33.6; whole, 68.5), maize (34.7), nutmeg, papers and books, paprika (70), raisins, residual insecticides containing pyrethrum, rhubarb, rice, seeds of trees and other plants, spices, tobacco, upholstery, wheat feed (26.1), wheat flour (26.5), whole wheat (44.8), yeasts (28.4)

Plodia interpunctella

Acorns, alfalfa hay, almonds (38.6, 45.3), almond hull meal, barley, beans, bilberries, biscuits, bran (28), bread, bread-making ingredient mixtures (47.4), breakfast cereal, cacao, canary grass seed, candied fruit, cantaloupe seed, caraway seeds, chestnuts (cooked and raw), chickasaw plums, chickpeas, chicory roots, chillies, chilli pepper, chocolate, chocolate-covered candies, chocolate-covered almonds, cinnamon bark, clover seeds, corpra, cottonseed meal cake, currants, dandelion root, dead insects, dried fruit (apples, apricots, bananas, cherries, grapes, loganberries, peaches, pears and prunes), dried meat scraps, dried Opuntia, dried roots, dried vegetables (cabbage [43.7], carrots [44.5], green onion [36.2], green paak ts'oi [42.8], onion [43.7]. and pepper [41.3]), drugs (*Archangelica officinalis*, *Cannabis sativa*, *Cydonia vulgaris*, *Datura stramonium*, *Juniperus communis*, *Prunus spinosa, Rosa canina*, *Sambucus nigra, Sarothamus scoparius*, *Secale cornutum*, *Tussilago farfara,* and *Verbascum thapsiforme*), figs, flour (123.0), fruit of *Zizyphus spinachristi*, fur, garlic, hazelnuts, herbarium specimens, herbs, iris rhizomes, jellies, lettuce, lettuce seed, locust beans, lozenges, lupins, macaroni, maize (meal 53.5, whole 65.9), maize germ meal, malt, marzipan, millet, milo (40.6), mixed feed, nougat, nut bars, oats, old books, orange pulp, packaged breakfast cereals, palm seeds, peanuts (47.2), peas, pecans, pepper seed, pineapples, pistachios (38.2), plums, prunes, pollen in bee hives, popcorn, powdered milk, preserves, pulses and pulse products, pumpkin seed, raisins, rice, rice hulls, rolled barley, rolled oats, rye, seeds of *Pinus pinea*, seeds of salamander, seeds of spruce, sliced beets, soybeans, spices, sultans (38.8), sugar beet pulp, sunflower seed, vetch seed, walnuts (47.2), watermelon seed, wheat (40.7), wheat germ, yeast cake

Tribolium castaneum

Alfalfa seed, almonds, Arhar (43.0), Bajra (20.1), baking powder, barley (20.8), beans, black gram (29.1), cayenne pepper, chocolate, cocoa beans, copra meal, maize, cotton gin trash, cotton seed, cottonseed meal, dried fruits, dried plant roots, English walnuts, flax, flour, food spices, ginger, insect collections, Jowar (23.4), masur (51.7), milk powder, millet, milo, Moong (26.4), moth (28.6), nuts, oilseed cakes and their products, orrisroot, packaged processed foods from all types of cereals, oilseeds and pulses, peanuts, peas (40.4), pulses, rapeseed, red rawan (32.0), rice (30.8), rice bran, rye, sago, snuff, soya bean (45.1), soyflour, soy grits, sunflowers, wheat (23.9), wheat bran, white gram (30.1), white rawan (35.1), yeast

[a] Numbers in parenthesis are egg-to-adult developmental times in days at a temperature between 25 and 30°C.

[b] Sources: *Lasioderma* data from Howe 1957, Ali et al 1972, and LeCato 1978; *Plodia* and *Tribolium* data from Johnson et al 1992, Locatelli and Biglia 1995, Na and Ryoo 2000, Pant and Dang 1969, Richards and Thomson 1932, Sinha and Watters 1985, and Williams 1964.

Table 1.3. Studies identifying stored-product insect species found at various locations in the marketing system

Type of study	No. samples	No. species	Source
Imports into California	902	37	Olsen 1981
Imports into California	3,381	63	Zimmerman 1990
Imports into England	3,632	81	Howe and Freeman 1955
Imports into Japan	650	34	Kiritani et al 1959
Empty cargo containers	3,001	22	Stanaway et al 2001
Food-handling areas of ships	1,428	16	Evans and Porter 1965
Facilities in Hawaii and light traps	>550	54	Loschiavo and Okumura 1979
Bakeries, food stores, etc. in Connecticut	290	11	Hankin and Welch 1991
Food-bait traps California	172	46	Strong 1970
Food-bait traps Mexico	>700	32	Leos-Martinez 1991
Packaged food warehouses	20	24	Highland 1978
Import warehouses in California	18	26	Olsen et al 1987
Total	>14,744		

Identification

Identification of insects to species is the first step in their management (see Chapter 8). Identification helps in obtaining published information on the biology, ecology, and behavior of an insect species to use in designing a study or a pest management program. In addition, identification is important because the type and amount of damage that insects can 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.

Important resources available for the identification of stored-product insect species are given in Table 1.4. Some of the stored-product insect species found together appear very similar to the naked eye. Simple methods have been developed for separating some of these species (see Chapter 2). Pictures may be useful for quickly recognizing the major stored-product insect pests (Figure 1.1), but for other species, keys may be necessary to ensure that the identification is correct or that similar-looking species are not present. Only pictures are available for the identification of some species of moth eggs, but both pictures and keys are available for identifying some species of beetle eggs.

Insects are most easily identified to genus or species in the adult stage because more keys have been developed for this stage. Immature insects generally are reared to the adult stage for identification when keys are not available for the immature stages. A key also is available for identifying insect mandibles to species when insect fragments are separated from commodities. Pictures are available to identify some other fragments for the most-common insect species. Some of the publications provide references to more-detailed taxonomic descriptions that can be consulted. It may be necessary to send specimens to a taxonomist to be sure that the species found is not just a species that is closely related to the species in the published keys.

Table 1.4. Published pictures and keys for stored-product insect identification

Pictures	Keys
Anon. 1978. Stored-Grain Insects. United States Department of Agriculture Handbook 500.	Bousquet, Y. 1990. Beetles Associated with Stored Products in Canada: An Identification Guide. Pub. 1837. Research Branch, Agriculture Canada, Ottawa
Arbogast, R. T., LeCato, G. L., and Van Byrd, R. 1980. External morphology of some eggs of stored-product moths (Lepidoptera: Pyralidae, Gelechiidae, Tineidae). Int. J. Insect Morphol. Embryol. 9:165-177.	Gorham, J. R. 1991. Insect and Mite Pests in Food: An Illustrated Key. Vols. 1 and 2. Agricultural Handbook 655. USDA, Washington, DC.
Gentry, J. W., Harris, K. L., and Gentry, J. W., Jr. 1991. Microanalytical entomology for food sanitation control. LithoGraphics Altamonte Springs, FL.	Halstead, D. G. H. 1986. Keys for the identification of beetles associated with stored products. I. Introduction and keys to families. J. Stored Prod. Res. 22:163-203.
Klein, R. M. 1986. Pictorial guide for rapid identification of common adult storage insects. J. Food Prot. 49:154-160.	Halstead, D. G. H. 1993. Keys for the identification of beetles associated with stored products II. Laemophloeidae, Passandridae and Silvanidae. J. Stored Prod. Res. 29:99-197.
LeCato, G. L. 1974. Description of eggs of selected species of stored-product insects. (Coleoptera and Lepidoptera). J. Kans. Entomol. Soc. 47:308-317.	Hinton, H. E. 1945. A Monograph of the Beetles Associated with Stored Products. British Museum of Natural History, London.
Rees, D. P. 1996. Coleoptera. Pages 1-39 in: Integrated Management of Insects in Stored Products. B. Subramanyam and D. W. Hagstrum, Eds. Marcel Dekker, Inc., New York.	Kucerova, Z., and Stejskal, V. 2002. Comparative egg morphology of silvanid and laemophloeid beetles (Coleoptera) occurring in stored products. J. Stored Prod. Res. 38:219-227.
Sedlacek, J. D., Weston, P. A., and Barney, R. J. 1996. Lepidoptera and Psocoptera. Pages 41-70 in: Integrated Management of Insects in Stored Products. B. Subramanyam and D. W. Hagstrum, Eds. Marcel Dekker, Inc., New York.	Peace, D. M. 1985. Key for Identification of Mandibles of Stored-Product Insects. Association of Official Analytical Chemists, Arlington, Virginia.
	Pratt, H. D. and Scott, H. G. 1962. A key to some beetles commonly found in stored foods. Proc. Entomol. Soc. Wash. 64:43-59.
	Rees, D. 2004. Insects of Stored Products. Manson Publishing, London.

Economic losses

Insects cause several types of economic losses (see recommended reading by Hill). The extent and importance of these losses vary with insect species, commodity, and location in the marketing system. Insects and their cast skins, webbing, or fecal material may simply be contaminants that reduce the market value of commodities. As insect populations grow, insect feeding may reduce the amount of the commodity available for consumption or sale. Economic losses may increase when the storage conditions become more favorable for insect population growth. Insect feeding on the

Table 1.5. Relative weight losses caused by different species of stored-product insects during their lifetimes[a]

Insect species	Diet	Weight loss (mg)			Equivalency
		Larva	Adult	Total	
Cynaeus angustus	maize	32	453	485	1.00
Tribolium castaneum	flour	13	315	328	0.68
Prostephanus truncatus	maize	13	223	236	0.49
Rhyzopertha dominica	wheat	5	149	154	0.32
Sitophilus granarius	wheat	19	67	86	0.18
Cadra cautella	wheat	36	···	36	0.07
Oryzaephilus surinamensis	oats	2	33	35	0.07
Plodia interpunctella	maize	34	···	34	0.07
Sitophilus oryzae	wheat	7	25	32	0.07
Cryptolestes ferrugineus	wheat	1	14	15	0.03

[a] Data from Hagstrum and Subramanyam 2000.

germ of seeds stored for planting can reduce germination. Stored-product insects can vector diseases and can be allergens, but neither the prevalence nor the economic losses associated with these types of insect problems have been studied extensively. Inspection programs may look for the insects or signs of insect presence (trails left in dust, their silk, damage caused by insect feeding, insect fragments in flour, or **hotspots**). The costs of insect sampling and insect pest management programs also are economic losses that must be attributed to insects.

The potential weight loss (Table 1.5) caused by stored-product insect feeding is important in determining how much should be spent to prevent this economic loss. Some stored-product insect species cause more weight loss than others. The equivalency column in Table 1.5 shows the weight losses caused by several insect species compared with that for the species causing the greatest weight loss, *Cynaeus angustus*. The equivalencies among other species may also be calculated; for instance, 32 *Cryptolestes ferrugineus*, 16 *Sitophilus oryzae*, or three *Rhyzopertha dominica* may cause the same amount of weight loss as two *Prostephanus truncatus*.

Sampling a commodity throughout the storage period is the best way to assess the weight losses caused by insect feeding. Insect-feeding damage accumulates over time, so grain that is used first will often have lost less weight than that used later. The weight of a standard volume (**bulk density**) or a standard number of kernels (thousand-grain mass) can be used to assess the weight loss over time. When weight loss can be assessed only once, damaged kernels can be separated from undamaged kernels and each group counted and weighed separately. The average weight loss per kernel can be calculated by subtracting the average weight of a damaged kernel from that of an undamaged kernel. The total weight loss can be calculated when the number of damaged kernels is estimated and the estimated average weight loss per kernel is used.

The cost of the weight loss caused by stored-product insects has been better quantified in the published literature than have the reductions in market value caused by insect contamination and the cost of pest management programs for stored-product insects. However, the economic losses from the weight losses caused by insects may

Table 1.6. Postharvest loss assessment in several developing countries[a]

Location	Crop	Storage period (months)	Estimated weight loss (%)
		Farm storage	
Zambia	maize	7	1.7–5.6
India	unhusked rice	7	4.26
Malawi	maize	<9	3.2
Nepal	sorghum	<9	1.7
Nepal	unhusked rice	8	3.4
Tanzania	maize	3–6.5	8.7
Swaziland	maize		3.66
Bangladesh	unhusked rice	3–4	2.4
Honduras	maize	7	5.5
		Central stores	
Cyprus	barley, wheat	3.5	3.54
Mali	millet	8	1
Sind	wheat	6.2	1.4
Baluchistan	wheat	2.7	1.5
Karachi	wheat	5.9	4.6

[a] Data from Boxall 1991.

be much smaller than those from reduced market value and expenditures on insect pest management programs. Worldwide estimates show that the percent weight loss can be very high at the end of the storage period. However, most of the grain is not stored that long, and the reported average weight losses caused by stored-product insects over three to nine months generally have been less than a few percent (Table 1.6).

Recognition of the type of damage caused by stored-product insects can be important. In the United States, the presence of too many insect-damaged kernels can reduce the value of wheat or other grains. In some years, grain inspectors have mistaken the feeding damage caused by the moth larvae of field crop pests and grasshoppers in the field before harvest for feeding damage caused by stored-product insect pests during storage.[3] Field pests feed from outside, leaving holes with rounded edges, while stored-product insect pests feed from inside, producing holes with a sharp edge.

The location of insect damage on a kernel can vary with the insect species and the grain moisture. Table 1.7 shows the locations of the damage done by five stored-product insect species to wheat kernels stored at two moisture levels. *Rhyzopertha dominica* and *Sitophilus granarius* damaged the germ less frequently than did the other three species. Germ damage was 100% at 9 and 17% grain moistures for *Oryzaephilus surinamensis*, but the germ was damaged more frequently at 9% than at 17% grain moisture by the other four species. The softer germ may be easier for the insects to eat than the other parts of the kernel when the grain moisture is low. Pyralid moth larvae often remove the entire germ from kernels.

[3] Walkden 1951 and Reed and Pedersen 1988 have found that damage by crop pests in the field can be mistaken for damage by stored-product insects.

Table 1.7. Percentage damage to germ (G), beard end (B), dorsal surface (D), ventral surface (V), or lateral surface (L) or to kernel by dorsal-to-ventral tunneling by adult insects[a]

Species	Site of Damage						Total Sites
	G	B	D	V	L	D/V	
	17% Grain moisture						
Cryptolestes ferrugineus	92.5	0.8		5.5	0.8		126
Oryzaephilus surinamensis	100						91
Rhyzopertha dominica	19.4	1.7	16.8	12.2	10.9	38.6	237
Sitophilus granarius	19.2	7.9	39.5	20.2	13.1		114
Tribolium castaneum	98.4		0.5	0.5	0.5		390
	9% Grain moisture						
Cryptolestes ferrugineus	97			3			64
Oryzaephilus surinamensis	100						66
Rhyzopertha dominica	29	0.8	11.3	40.3	3.2	15.3	124
Sitophilus granarius	65	2.6	15.5	14.3	2.6		77
Tribolium castaneum	99			1			110

[a] Data from Surtees 1964.

Events such as the introduction of *Prostephanus truncatus* into Tanzania in East Africa during the late 1970s and Togo in West Africa during the early 1980s can temporarily increase the economic losses caused by insects until pest management programs can be developed to reduce the extensive damage they cause and contain the spread of that species. Since its introduction, *P. truncatus* has spread to at least 14 other African countries. The predator, *Teretrius nigrescens*, was released in 1991 in Togo and has established and spread. The predator also was later released in Benin, Ghana, Kenya, Malawi, and Zambia. Sampling methods have been developed, and insect pest management recommendations, such as shelling and treating maize with a residual insecticide before storing it, have been adopted.[4] Insect pest management efforts have been hampered because residual insecticides are hard to find in remote areas, expensive, and sometimes poor in quality. The prevalence of *P. truncatus* and the damage caused by this species have decreased, but the insect continues to spread to other countries. Phytosanitary effort has been increased, but enforcement is difficult for small shipments by farmers.

For flour, the number of insect fragments is used as an indicator of whether wheat was stored and milled under sanitary conditions. Bakers reject flour with too many insect fragments. Insects break into more fragments when they are killed before the wheat is milled (Table 1.8). Adults produced many more detectable fragments than the immature stages. Even the cast (shed) skins of insect larvae and pupae that remained in

[4] *Prostephanus truncatus* damages maize on the cob more than maize removed from the cob (see recommended reading by Cowley et al). The reverse is true for other stored-product insect species. *P. truncatus* must need to brace itself against something to bore into sound kernels. It also damages more of the kernels when some of the pericarp is scraped away to expose the endosperm. Laboratory observations suggest that shelling maize before storing it would reduce the damage caused by *P. truncatus* but would increase the damage caused by *Sitophilus zeamais*.

Table 1.8. Numbers of insect fragments per insect when insect-infested wheat is milled into flour

Insect species[a]	Stage	Treatment before milling	
		None	Killing
Rhyzopertha dominica	adult	143	234
	shed skins	21	28
	prepupa	20	0
	large larva	16	2
	small larva	0	0
Sitophilus oryzae	adult	130	213
	large larva	…	6
	small larva	…	2

[a] Data from Sachdeva 1978 for *Sitophius oryzae,* and Hagstrum, *unpublished data*, for *Rhyzopertha dominica.*

a kernel after the adult insect had emerged produced a small number of insect fragments when these kernels were milled into flour.

For raw, processed, and packaged commodities, the economic losses caused by insects are often measured by recording the number of customer complaints or by the number of packages returned to the manufacturer. Large numbers of complaints about insect contamination may damage a company's reputation and reduce its sales.

Regulations

Tolerances for the number of insects in food have been established to ensure the wholesomeness of food. The regulations of several government agencies in the United States (Table 1.9) influence the pest management programs for stored-product insects. The Grain Inspection, Packers and Stockyards Administration (GIPSA)-Federal Grain Inspection Service (FGIS) inspects raw grain for insects. Wheat is designated as "infested" when two or more live insects injurious to grain are found per kilogram. Infested wheat may be sold at a discount that covers the cost of the fumigation needed to remove the "infested" designation. However, when GIPSA-FGIS finds more than 32 insect-damaged kernels (IDK) per 100 g, the wheat is given the designation "sample grade"; then it cannot be sold for human consumption, and its value is drastically reduced. Wheat with 32 IDK per 100 g has 320 IDK per kilogram and 8,640 IDK per bushel. Each IDK is the result of one adult of an internal-feeding insect species emerging from a kernel of grain, and IDK accumulate over time. Fumigation to kill insects does not reduce the number of IDK. Other grains have similar standards.

With an average density of one insect per kilogram, wheat is not heavily infested, but there are still many insects in this wheat. A truck carrying 22 metric tons (t), i.e., 800 bushels, would have 21,600 insects; a railroad hopper car carrying or a farm bin storing 82 t (3,000 bushels) would have 81,000 insects; an **elevator** bin storing 544 t (20,000 bushels) would have 540,000 insects; a barge carrying 1,360 t (50,000 bushels) would have 1,350,000 insects; and a ship carrying 2,720 t (100,000 bushels) would have 2,700,000 insects. Some countries have a nil (zero) tolerance for insects. Grain in these countries is considered infested whenever one insect is found. Whether

Table 1.9. Regulatory agencies in the United States

Agency and function	Website
Grain Inspection, Packers and Stockyards Administration (GIPSA), **Federal Grain Inspection Service** (FGIS) Inspects grain and provides grade.	http://www.usda.gov/gipsa
Food and Drug Administration (FDA) Determines that food is prepared using good manufacturing practices (GMP), is shipped and stored under sanitary conditions, and does not present a health hazard.	http://www.fda.gov
Environmental Protection Agency (EPA) Registers the pesticides used on stored commodities and in storage and processing facilities; sets and enforces tolerances for pesticide residues on raw commodities	http://www.epa.gov
Animal and Plant Health Inspection Service (APHIS) Regulates importation and interstate movement of commodities that may carry harmful insect pests	http://www.aphis.usda.gov/

or not insects are found in a given lot of grain depends upon the number of sample units examined. Because only a few sample units generally are examined, insects may not be detectable until their density approaches an average of one insect per kilogram.

The quality of stored commodities also is maintained by market contracts and standards. Customer complaints may be the first warning of problems in the marketing system. The Food and Drug Administration (FDA) inspects flour for insect fragments. It also inspects facilities to ensure that raw commodities are stored and food is processed, packaged, stored, and shipped under sanitary conditions. The presence of >75 insect fragments per 50 g of flour exceeds the **defect action level** (DAL), and that flour cannot be sold for human consumption. Flour mills often use a lower threshold of 5 IDK for rejecting wheat and keep the fragment counts in the flour they mill well below the DAL to meet the stricter standards of bakers. Similar DALs have been developed for other commodities (see Table 22.1). One of the recommended readings (by the American Institute of Baking) illustrates how the industry prepares for regulatory inspections and responds to inspectors.

The Environmental Protection Agency (EPA), established in 1972, registers the pesticides used on grain and in food-processing facilities and enforces how these pesticides are used (see recommended reading by Arthur and Rogers). For a pesticide to be registered for use, the manufacturer must prove that it is safe. The label on a registered pesticide is very specific about how, where, and for which insect pest species and commodities a pesticide can be used. Not using a pesticide according to label instructions makes the user liable, but if a pesticide is used according to the label instructions, the manufacturer may be liable. The EPA establishes and enforces the level of residual insecticides (residue tolerances) that are permissible on raw commodities. The FDA establishes and enforces the tolerances on processed foods. Much of enforcement is delegated by these federal agencies to state governments.

The Animal and Plant Health Inspection Service (APHIS) regulates the importation and interstate movement of insect pests along with commodities. Each state has its own quarantine regulations, but these are preempted by APHIS regulations. Introduc-

tion of *Trogoderma granarium* into the United States is a major concern, and interceptions have averaged 100 per year.[5] In 1953, *T. granarium* was discovered in California. It was found to have arrived in California no later than 1946, incorrectly identified as *Attagenus piceus*, and by early 1955, it had been found in 121 premises in 16 California counties, 27 in five Arizona counties, and three in two New Mexico counties. A massive state-federal campaign to eradicate this species, estimated to cost US$14.9 million, was undertaken. By 1958, 51,000 premises in 27 states had been inspected. Eight species of *Trogoderma* were found in California on 132 different types of foods and *T. granarium* was found on 37 of these. Assuming that *T. granarium* would have spread throughout the United States if not eradicated, the eradication of this insect was estimated to have prevented US$825 million per year in losses.

To eradicate *T. granarium*, all buildings in which infestations were discovered were covered with plastic sheeting and fumigated for 48 hr with **methyl bromide**. All litter and trash within 30 m (100 ft) of the fumigated building were destroyed, and the ground around them was thoroughly sprayed with **malathion** in diesel oil. Also, ships were fumigated. All known infestations were eradicated by June 1966. From 1978 to 1983, *T. granarium* was discovered in food-processing facilities, bagging, wooden crates, and other protected facilities in California, Maryland, Michigan, New Jersey, New York, Pennsylvania, and Texas, and these 25 infestations were eradicated.

Other countries have similar agencies and regulations. Internationally, the Food and Agriculture Organization (FAO) of the United Nations issues Phytosanitary Certificates to reduce the spread of stored-product insect pests by commerce, and 116 countries are members of the International Plant Protection Convention (IPPC). The IPPC is a multilateral agreement that promotes international cooperation in preventing and controlling the spread and introduction of harmful insect pests. A joint FAO and World Health Organization (WHO) committee establishes residue tolerances (CODEX tolerances) for all pesticides, including the ones used on stored commodities. The CODEX tolerances help in the marketing of grain internationally.

Business practices

Pest management decisions for stored-product insects are interrelated with many other business practices (see recommended reading by Hagstrum). Mergers and consolidations have reduced the number and increased the size of elevator companies in the United States, which may promote more-centralized and more-uniform insect pest management programs and more-rapid adoption of new insect pest management methods. Insect pest suppression is easier in the United States now that government programs are not encouraging multiple-year storage. Marketing of commodities on a wet-weight basis encourages storage at moisture contents favorable for insect development. Also, most of the new grain elevator storage capacity will not be in concrete bins but in the less costly metal bins, which are generally larger and easier to aerate but more difficult to fumigate. Establishment of stringent safety requirements by the EPA has resulted in more of the fumigation at elevators being done by commercial fumigators.

[5] Armitage 1956, 1958; Kennedy et al 1991; Klassen 1959; and Lindgren et al 1955 describe aspects of the *Trogoderma granarium* eradication program in the United States and the number of interceptions per year. Strong et al 1959 discuss the host range of *T. granarium*.

Wheat is generally stored six to nine months in the United States, but it may be moved to make room for autumn crops such as maize, grain sorghum, or soybeans. Grain moved from a country to a terminal elevator is more likely to be fumigated. Because of increased railroad rates, more of the grain moves by trucks and is less likely to be officially inspected. Some elevators fumigate grain in railcars and barges or before loading it into trucks to avoid an entire load being rejected when a single insect is found. When a load is rejected, the seller pays the cost of transporting the grain to another buyer or to a location where it can be fumigated. The seller also pays to keep the railcars during the fumigation period. The total cost of a rejected load may be 10–20% of a load's value.

Examining business practices to be sure that they favor effective insect pest management programs as much as possible may suggest cost-effective ways to improve pest management programs for stored-product insects.

Summary

This chapter has provided an overview of the various types of grain storage facilities; the variety of commodities infested by stored-product insects; the species of insects that are commonly found in storage, transportation, processing, and marketing habitats; the types of economic losses that can be attributed to these insects; the regulation of insect infestations and insect pest suppression methods; and the types of business practices that affect insect pest management programs.

The chapter has also emphasized the importance of correctly identifying insects to species. This identification is necessary to obtain published information on their biology, ecology, and behavior that can be used in designing a study, a sampling program, or an insect pest management program for stored-product insects.

The cost of the weight loss caused by stored-product insects has been better quantified in the published literature than have the reductions in market value caused by insect contamination and the cost of insect pest management programs. However, the economic losses from the weight losses caused by insects may be much smaller than those from reduced market value and expenditures on insect pest management programs.

Study questions

1. In what kinds of habitats do stored-product insects live, and how have these insects adapted to this diversity?
2. What resources are available for identifying stored-product insects to species, and why is it important to know which insect species are present?
3. How are insect habitats, species of insect pest, economic losses attributed to insects, regulations, and other business practices important to pest management programs for stored-product insects?

Recommended readings

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Chapter 2

Techniques

Stored-product insects are often the preferred organisms for basic physiological, behavioral, and ecological studies because large numbers of healthy insects can be reared easily. This has resulted in the development of relatively simple methods for extracting the insects from foods, enumerating the insects feeding inside seeds, separating closely related species, and determining their physiological state (sex, age, and whether or not they have fed or mated). These methods can be invaluable in planning and implementing a stored-product insect pest management program or a research program to improve insect pest management. They can be useful in preparing live stored-product insects to monitor the effectiveness of insect pest management methods such as heat treatments and fumigations, in processing and interpreting data from sample units taken to monitor stored-product insect populations, and in understanding the susceptibility and response of stored-product insects to an insect pest management program.

Rearing

Insects are generally reared at 28°C, 60–65% relative humidity (rh), and a 14-hr light:10-hr dark **photoperiod** on 240–390 g of diet in 0.95-L glass canning jars with a wire-mesh screen and filter paper lid. Jars of 3.85-L capacity are used for rearing the pyralid moths. Table 2.1 gives the rearing diet and initial densities of adults used to culture several species of stored-product insects, but there are many variations of these procedures. Adults are taken from several three- to nine-week-old cultures to start the next generation. Adults from several cultures are generally used to minimize inbreeding. In the case of beetles, adults are generally removed from new cultures after seven days, but this is not necessary for moths. For *Oryzaephilus*, the eggs and yeast are separated from the adults and rolled oats using a U.S. standard No. 30 (0.6-mm openings) or No. 40 (0.425-mm openings) sieve and placed on 180 g of fresh rolled oats and yeast diet.

Adult beetles can be removed after less than seven days to reduce crowding or to narrow the age range of offspring. When adult beetles of a specific age are needed, all of the adult beetles can be removed from a culture, and those emerging over the next 24 hr can be collected. Instead of adding adult moths to the rearing diet to start a new culture, moth eggs can be collected by placing adults in a 0.95-L jar fitted with a wire-mesh lid and inverting the jar to permit eggs to drop through and collect in a glass petri dish (25 mg = 1,000 eggs). Plastic petri dishes should not be used because the static electricity can make handling of the eggs difficult. The insect density and the age range of larvae in these cultures are controlled by adding to the rearing diet a measured volume of eggs that have been laid over a 24-hr period.

Each culture will generally produce 1,000 to several thousand insects in one generation. Diets for *Lasioderma* and *Tribolium* are generally autoclaved for 20 min at 1 kg/cm^2 (15 lb/in^2) pressure before adding yeast; the diet for *Cryptolestes* is ground and passed through a U.S. standard No. 20 (0.85-mm openings) sieve; and the diet for *Lasioderma* is compacted in the rearing jar before being used. The pyralid moth diet is

Table 2.1. Initial numbers (volumes) of adult insects used to start a new culture, ages of cultures from which these adults are taken, and diets for culturing stored-product insects[a]

Insect species	Number (volume)	Age (weeks)	Diet (quantity used)
Cadra cautella	20–25	3 to 4	See text
Callosobruchus maculatus	50	4 to 5	Dried black-eyed peas (325 g)
Cryptolestes pusillus	1,200 (0.5 ml)	5 to 7	14 parts soft red winter wheat, 14 parts rolled oats, 1.5 parts yeast (240 g)
Lasioderma serricorne	300	6 to 7	10 parts wheat flour, 10 parts maize meal, 1.5 parts yeast (390 g)
Oryzaephilus surinamensis	750 (1 ml)	4 to 6	90 g rolled oats, 5 g yeast
Oryzaephilus mercator	850 (1.5 ml)	4 to 6	90 g rolled oats, 5 g yeast
Plodia interpunctella	20–25	3 to 4	See text
Rhyzopertha dominica	600 (1.5 ml)	7 to 8	380 g soft red winter wheat, 5 g yeast
Sitophilus granarius	300 (1.5 ml)	5 to 7	380 g soft red winter wheat, 5 g yeast
Sitophilus oryzae	300 (1.0 ml)	5 to 7	380 g soft red winter wheat, 5 g yeast
Sitophilus zeamais	300 (1.5 ml)	5 to 7	190 g soft red winter wheat, 190 g maize, 5 g yeast
Sitotroga cerealella	20–25	5 to 7	1 part wheat, 1 part maize (380 g)
Tribolum castaneum	300 (2 ml)	7 to 9	10 parts wheat flour, 10 parts maize meal, 1.5 parts yeast (260 g)
Tribolum confusum	300 (2 ml)	7 to 9	10 parts wheat flour, 10 parts maize meal, 1.5 parts yeast (260 g)
Trogoderma variabile	100–150	8 to 9	20 parts Purina Lab. Chow meal, 1.5 parts yeast (240 g)

[a] Source: Procedures used at U.S. Department of Agriculture, Stored-Product Insects Research and Development Laboratory, Savannah, GA. Simpler diets for these and other stored-product insect species are described in Tribolium Information Bulletin 14:43-48 (1971) and in Howe 1991b. *Callosobruchus maculatus* (Shade et al 1986), three species of *Sitophilus* (Baker and Mabie 1973), and *Sitotroga cerealella* (Chippendale and Mann 1972) have been reared on artificial seeds, and *Rhyzopertha dominica* (Howe 1950) and *Prostephanus truncatus* (Scholz et al 1998b) have been reared on compacted ground diet.

prepared by mixing a granular or pelletized dog food and rolled oats in a 2:1 ratio. The mixture is ground and passed through a U.S. standard No. 8 (2.362-mm openings) sieve before mixing three parts of this mixture with four parts of white maize meal, four parts of white wheat flour, 0.5 part of wheat germ, one part of glycerin, one part of honey, and one part of yeast.

For insect species that are normally reared on whole seeds, ground diet may be compacted into artificial seed for nutritional studies or for times when larvae or pupae are needed for experiments. *Rhyzopertha dominica* can be reared on ground diet, but development will be slower than on whole wheat kernels. *R. dominica* eggs can be collected by holding the adults with whole-kernel wheat on a No. 20 sieve so that the eggs fall through. Individual kernels can be infested by placing a single egg or newly hatched larva on each kernel.

Several species of **parasitoids** of stored-product insects can be reared by placing 20–50 adults in a standard culture of their host species. Parasitoids may survive and

reproduce better at 75% rh. To start a new culture, parasitoid adults can be sieved or aspirated from a culture in which a new generation of adult parasitoids has **eclosed**. For many species of parasitoids, this would be after two to three weeks because their generation times are only two weeks, much shorter than that of their host species. The age of host cultures when parasitoids are added is critical because the right host stages must be available for the parasitoid. Many of the parasitoid species prefer mature host larvae.

Rearing techniques can impact the health of the insects and alter the results of experiments (see recommended reading by Howe). Overcrowding and pathogen infections that stress insects should be avoided. Microbial contamination and mixed-species cultures can be avoided by washing and autoclaving sieves and by using a different sieve for each insect species that is being reared. Starting new cultures of different insect species on different days also helps prevent cross contamination. Unused rearing diet should be kept in a freezer to avoid infestation and thawed in the rearing jars one day before the insects are added.

Large populations of insects need to be maintained to retain insect variability in long-term laboratory cultures. Adults from several culture jars are generally pooled to set up the next generation of insect cultures. Bringing in field-collected insects to maintain insect variability in long-term laboratory cultures is risky; mixtures of several insect species, highly pesticide-resistant insects, insect pathogens, and mites may be introduced into cultures when the field-collected insect strains are added to existing standard laboratory strains. This risk is difficult to justify because much of this variability is likely to be lost in one or two generations of rearing. Also, repeatability of experiments may be more important than insect variability for some laboratory bioassays such as dose-response studies requiring susceptible insects or pheromone identification using the response of insects to many different chemicals to monitor progress. An alternative may be introducing insects from other laboratory cultures.

Using the offspring of field-collected insects rather than insects from long-term laboratory cultures may be a better way to be sure that the results of laboratory experiments are representative of field populations. This may be particularly important in studies such as those developing a pheromone lure for trapping or doing bioassays for the registration of a new insecticide, because it is important to be sure that the pheromone lure and insecticide will be effective in the field. A compromise may be doing most of the work with the laboratory strain and comparing the response of the laboratory strain with that of the field strains.

Insect extraction and detection

Examination of stored-product insects often requires extracting them from the commodity. Extraction methods include sieving, flotation, **aspiration**, and **Berlese funnels** (Table 2.2). Extraction efficiencies vary with the species and stage of the insects. Mesh sizes for extracting different species of adult beetles are given in Table 2.3. Hand sieves can be used for small samples, and inclined or shaker sieves are better for larger samples. A thin layer of grain and several shakes of a hand sieve or passes over an inclined or shaker sieve are required for efficient extraction. An inclined sieve can remove 88–97% of the adult *Tribolium castaneum*, *Sitophilus oryzae,* and *Rhyzopertha dominica* from a 25-kg wheat sample with two passes over the sieve, and most of the remaining insects are extracted with an additional one to four passes. A dockage tester can remove 84–91% of the adult *Cryptolestes ferrugineus* and 57–81% of the

larvae from a 1-kg sample. Shaker or aspirated sieves can remove similar percentages of *Sitophilus granarius*, *Oryzaephilus surinamensis*, and *Cryptolestes ferrugineus*. A rotary sieve can remove 100% of the living and dead adults from flour.

Table 2.2. Insect extraction and detection methods

Method	Source[a]
	Destructive
Cracking-flotation	Trauba 1981
Electrical resistance	Wirtz and Shellenberger 1963
ELISA	Chen and Kitto 1993, Schatzki et al 1993, Stuart and Burkholder 1991, Stuart et al 1994
Emergence	Chao et al 1953, Perez-Mendosa et al 2004a, Storey et al 1982, White 1985
Flotation in salt solution	Richter and Tchalale 1994, White 1956
Ninhydrin	Dennis and Decker 1962
Staining *Sitophilus* spp. egg plugs	
Acid fuchsin or iodine	Frankenfeld 1948, Holloway 1985, Sharifi 1972b
Gentian violet	Goosens 1949
Berberine sulfate	Milner et al 1950
Translucence	Apt 1950, Koura 1958
Uric acid	Wehling et al 1984
	Nondestructive
Acoustical detection	Pittendrigh et al 1997, Shuman et al 1997
Aspirated sieving	Armitage et al 1996
Berlese funnel principle	Karunakaran et al 2003a, Laudani 1948, Robertson 1944, Rutter and Ferkovitch 1973, Smith 1977
Carbon dioxide	Bruce et al 1982
Dockage tester	Demianyk et al 1997
Fluorescence of larvae	Abels and Ludescher 2003
Inclined sieve	White 1983
Machine vision	Keagy and Schatzki 1993, Ridgway et al 2002, Zayas and Flinn 1998
Microwave radar	Mankin 2004
Near infrared spectroscopy	Baker et al 1999, Dowell et al 1998, Maghirang et al 2003
Nuclear magnetic resonance	Chambers et al 1984
Rotary sieve	Pedersen and Gwirtz 1998
Shaker sieve	Hagstrum 1985, Wilkin and Van Natto 1996, Wilkin et al 1994
Sorter	Pasikatan and Dowell 2001
X-ray	Haff and Slaughter 2004; Karunakaran et al 2003a,b, 2004; Keagy and Schatzki 1993; Pedersen and Brown 1960; Schatzki and Fine 1988

[a] Russell 1988, Xingwei et al 1999, and Brader et al 2002 compared the effectiveness of various insect detection methods.

Insects and other debris drop through a sieve, and insects must be separated from the debris. Stacks of sieves can be used to separate whole kernels, different insect species, and fine material from each other. Live adults are easier to find than larvae or dead adults because they can be seen more easily moving around. An aspirator can be used to pick up the insects as they are counted. It may be possible to find more of the larvae using a black light to cause the larvae to fluoresce.

In a salt solution with a specific gravity of 1.19 g/cm^3, uninfested kernels or beans sink while those infested with older larvae, pupae, and adults float because of their greater buoyancy. The flotation method does not separate the kernels infested with eggs or young larvae from the uninfested kernels. For rice, a specific gravity of 1.27 g/cm^3 is better for separating infested from uninfested kernels. Using a salt solution with a specific gravity that is 12–13% below that of the commodity instead of at standard levels has been shown to improve the recovery of young larvae of *Sitophilus oryzae* and *Zabrotes subfasciatus*. The flotation method does not work as well for hulled seeds or large seeds like maize.

The Berlese funnel method is based upon slowly heating a sample to force the insects to move down. The sample is held on a screen over a funnel so that the insects eventually fall through and are collected at the bottom of the funnel. It is important to heat the sample slowly so that the insects have time to escape before the heat kills them. A good recovery for *Cryptolestes ferrugineus* would be 80% for the third and fourth **instars** and adults. Younger larvae feeding inside the germ of wheat kernels are harder to recover, but recoveries as high as 67% for first instars and 51% for second

Table 2.3. Mesh sizes of sieves for extracting different species of adult stored-product insects from commodities[a]

	Mesh size (mm)	
Insect species	**Retain 100%**	**Pass 100%**
Cryptolestes pusillus	0.25	0.71
Cathartus quadricolis	0.33	0.93
Oryzaephilus surinamensis and *O. mercator*	0.53	0.93
Rhyzopertha dominica	0.53	1.20
Sitophilus oryzae	0.71	1.35
Stegobium paniceum	0.71	1.40
Sitophilus zeamais	0.93	1.70
Tribolium castaneum and *T. confusum*	1.05	1.40
Lasioderma serricorne	1.05	1.70
Trogoderma inclusum	1.05	2.25
Trogoderma glabrum	1.20	2.25
Callosobruchus maculatus	1.20	>2.25
Attagenus unicolor	1.35	>2.25
Anthrenus flavipes	1.40	2.25
Dermestes maculatus	2.00	>2.25
Tenebrio molitor	2.00	>2.25
Tenebroides mauritanicus	2.00	>2.25

[a] Data from Cline and Highland 1981. These data were collected by allowing 24 hr for laboratory-reared insects to crawl through the holes in a sieve.

instars have been reported. The Berlese method principle also has been used to remove *Oryzaephilus surinamensis* adults from tea, and *Plodia interpunctella* and *Anthrenus scrophulariae* from rearing medium. For *P. interpunctella*, 96.5% of seven-day-old larvae were removed in 18 min without affecting larval or pupal development, adult **eclosion**, egg production, or egg viability.

A variety of destructive and nondestructive methods have been developed for determining the numbers of insects in a sample of commodity (Table 2.2 and recommended reading by Rajendran). Destructive methods destroy the commodity or alter its quality, but nondestructive methods do not. With most of these methods, only a small sample of commodity (50–200 g) generally is analyzed, and insect infestations are likely to be detected only after insect densities are quite high. Therefore, these methods are useful research tools but generally have been unsuitable for early detection of insect infestations. Also, many of these methods underestimate the insect population, and some, particularly the nondestructive methods, require expensive equipment. However, some of the nondestructive methods can be automated to process large quantities of commodities and have been or could be used on a commercial scale with a high-speed sorter to separate beans, peanuts, coffee, peas, rice, and many other raw commodities into "accept" and "reject" categories. Acoustical detection can be used to automate the monitoring of insect populations in bulk grain storage.

The simplest method for quantifying the internal insect infestation is to incubate grain samples at 27°C for four weeks for *Sitophilus* spp. or six weeks for *Rhyzopertha dominica*. Emergence records have shown that two to five times more of the sample units were infested and that, on average, these sample units had two to ten times more insects than were found by sieving before incubation. This method underestimates the insect infestation level because the insects that die inside the kernels are not counted. Using the **x-ray** method to count the number of insects remaining inside the kernels after two or three weeks could cut in half the time required to incubate samples.

The cracking and flotation method involves coarse grinding of kernels in a cutting-type mill, digestion of grain to separate the insects, flotation of insects in a light mineral oil, depositing of insects on a filter paper, and examination of the filter paper under a microscope. More than 95% of the whole insects and head capsules can be recovered by the cracking and flotation method.

Several species of *Sitophilus* chew a hole in kernels of grain in which to lay an egg and then cover the egg with a mucilaginous plug. These egg plugs can be stained to detect insect infestation. Feeding punctures and mechanical injuries to the kernels stain a lighter color than the egg plugs. Iodine does not stain egg plugs in the germ and does not work for maize or sorghum. Acid fuchsin staining of *S. oryzae* or *S. zeamais* egg plugs does not significantly change the success or duration of development when kernels have an opportunity to dry out. However, when the kernels are kept in a vial after the staining and do not dry out, *S. oryzae* insects develop faster and are more likely to survive than those for which the egg plugs are not stained.

The ninhydrin method detects the free amino acids from the insect body fluid that are released when the insect-infested kernels are crushed on paper impregnated with 0.3% ninhydrin. Purple spots develop after less than an hour at 20–25°C and 5–10 min at 50°C. This method does not work for dry, dead insects and has not been used to determine the stage of the insect. Crushing kernels and measuring their resistance to the flow of electricity also will detect infested kernels. These kernels have a lower resistance than uninfested kernels.

Boiling for 10 min in a 10% sodium hydroxide solution makes wheat kernels translucent so that the insects inside are visible. Soaking kernels in two parts phenol, two parts lactic acid, one part glycerin, and two parts distilled water solution will make wheat kernels translucent in 2–4 hr. However, this method will not work for pulses or maize.

An **enzyme-linked immunosorbent assay** (ELISA) method has been used to detect larvae or adults of 17 species of stored-product insect pests. The insect muscle protein, myosin, is extracted from a 200-g ground grain sample with a dilute salt solution and allowed to react with an antibody. The test takes 2 hr for 20 samples. One adult *Sitophilus granarius* per 50 g of wheat can be detected. Species-specific ELISAs also have been developed for identification of *S. granarius*, *Trogoderma granarium* and two species of **parasitoids** (*Habrobracon hebetor* and *Laelius pedatus*). Uric acid excreted by insects also can provide evidence of internal or external insect infestation. The ELISA and uric acid methods do not give the number of insects per sample. Calibration curves must be developed to convert the measurements made using these methods into an estimate of insect density.

The **acoustic**, **microwave radar**, and carbon dioxide methods depend upon the insects being alive. These methods can be used to detect insects in commodities without extraction. The acoustic method detects the audible or ultrasonic sounds made by insects; microwave radar detects insect motion; and the carbon dioxide method detects insect respiration. Egg and pupal stages are immobile, non-feeding, and do not produce detectable sounds or motion. Using carbon dioxide as a measure of insect infestation level can be inaccurate because the grain and storage fungi also produce carbon dioxide, and carbon dioxide can be **sorbed** and desorbed by the commodity. Also, the production of sounds and carbon dioxide and the detectability of insect motion increase as an insect grows. Calibration curves must be developed to convert the measurements made using these methods into an estimate of insect density.

The **x-ray** method, which is a standard method in many grain quality laboratories, can provide information on the age structure of the population as well as the number of infested kernels. However, recognition of eggs (51%) and young larvae (75–87%) of *Sitophilus granarius* on radiographs is not as good as the recognition of the more mature insects (>96%). As many as 99% of the older larvae, pupae, and adults of *Rhyzopertha dominica* and *S. oryzae* have been detected using the x-ray method, and infestations by *Cryptolestes ferrugineus*, *Plodia interpunctella*, and *Tribolium castaneum* also have been detected with it. Distinguishing live from dead insects is difficult. The motion of live insects can be detected using an x-ray microscope or by comparing the positions of insects on two x-rays.

The **nuclear magnetic resonance** (NMR) method depends upon the insects inside infested kernels giving the kernels a higher water and lipid content than is found in uninfested kernels. NMR can detect 10 kernels infested with *S. granarius* in 500 kernels, but it does not detect larvae before they become third **instars.**

Near-infrared reflectance spectroscopy (NIRS) is widely used in many grain quality laboratories and has been shown to detect kernels that are infested with *S. oryzae*, *Rhyzopertha dominica*, and *Sitotroga cerealella*. Live pupae of *S. oryzae* can be classified correctly 94% of the time, while large larvae can be classified correctly 93%, medium larvae 84%, and small larvae 63% of the time. NIRS can detect live or dead *S. oryzae* and can distinguish a kernel with the pupae of the parasitoid *Anisopteromalus calandrae* from a kernel with the pupae of its host, *S. oryzae*. NIRS can view a kernel every 4 sec with a 95% probability of detecting third or fourth instar *S.*

oryzae. The single-kernel measurement system to which the NIRS was added also measures kernel moisture and detects insect-infested kernels because of their higher moisture.

Machine vision can recognize >89% of six species of adult stored-product insects (*Ahasverus advena*, *Cryptolestes ferrugineus*, *Oryzaephilus surinamensis*, *Rhyzopertha dominica, Sitophilus granarius*, and *Tribolium castaneum*) in wheat samples and at least 50% of fourth instar *S. zeamais* larvae on radiographs.

In comparative studies, rearing, ninhydrin, and x-ray methods generally provided the most complete count of the number of internal feeding insects in a sample unit. Cracking and flotation tended to underestimate insects more. Comparisons have been made for *Callosobruchus chinensis* on mung bean; *Rhyzopertha dominica*, *S. granarius,* and *Sitotroga cerealella* on wheat; and *S. zeamais* on rice and wheat.

Sorting species

Often, more than one insect species will be found, and insects will need to be sorted by species to determine the number of each species. For some closely related species, the insects will need to be viewed under a dissecting microscope to do this sorting. In alcohol, an adult *Cryptolestes ferrugineus* can be readily separated from an adult *C. pusillus* by its darker abdomen (Fig. 2.1).

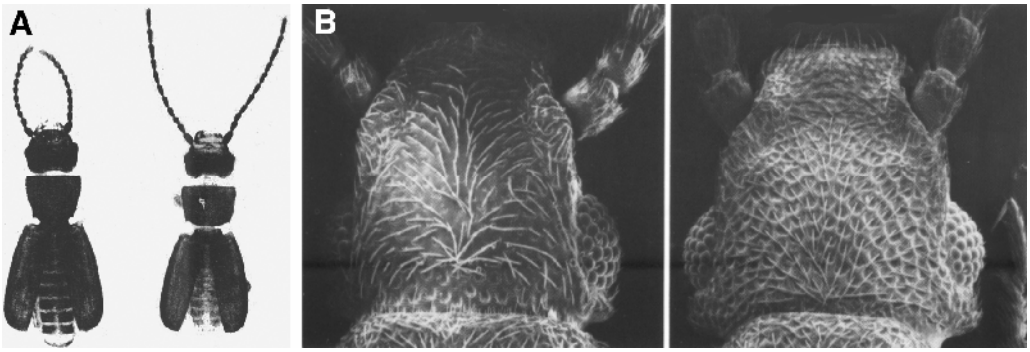

Figure 2.1. Characteristics for separating species. **A,** *Cryptolestes ferrugineus* (left) and *C. pusillus* (right). **B,** *Oryzaephilus mercator* (left) and *O. surinamensis* (right). (A, reprinted, with permission, from Arbogast 1991a. B, used with permission of the Natural Resources Institute, Chatham, England)

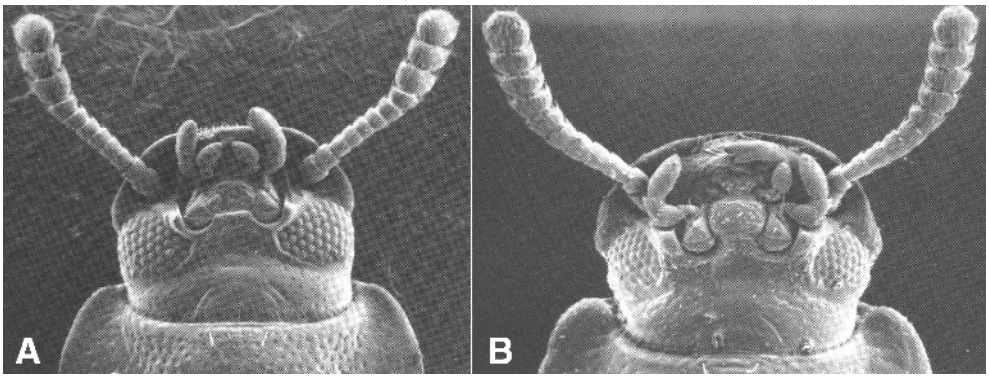

Figure 2.2. Characters for separating two species of *Tribolium*. **A,** *T. castaneum*; **B,** *T. confusum*. (Used with permission of the Natural Resources Institute, Chatham, England)

The greater distance between the eyes and back of head separates an adult *Oryzaephilus surinamensis* from an adult *O. mercator* (Fig. 2.1). Adults of two species of *Tribolium* can be quickly distinguished because, ventrally, the eyes of *Tribolium castaneum* are closer together than those of *T. confusum* and the antenna of *T. castaneum* tapers to a club less gradually than the antenna of *T. confusum* (Fig. 2.2). Differences in the extruded male reproductive organs separate the adults of *Sitophilus zeamais* and *S. oryzae* (Fig. 2.3). Three species of adult pyralid moths can be separated by their color pattern on the dorsal thorax with the scales removed (Fig. 2.4). *Cadra cautella* has the darkest pigmentation and *Plodia interpunctella* the lightest.

Sexing

Methods are available for separating the male pupae and adults from the females for many species of stored-product insects (see recommended reading by Halstead). In most cases, this requires a dissecting microscope for viewing and forceps for handling the insects. Sexing insects as early as possible can minimize the influence of this handling on experiments. Separation of sexes for studies must be done without damaging

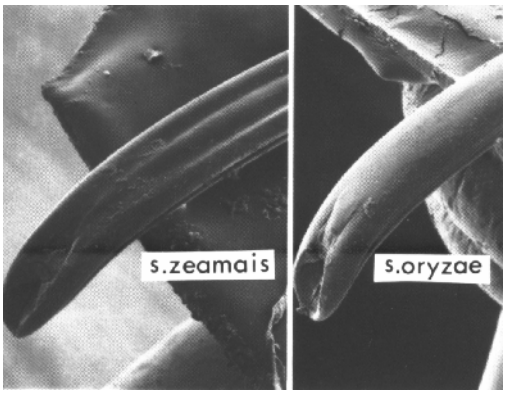

Figure 2.3. Apex of reproductive organ of male *Sitophilus*. (Used with permission of the Natural Resources Institute, Chatham, England)

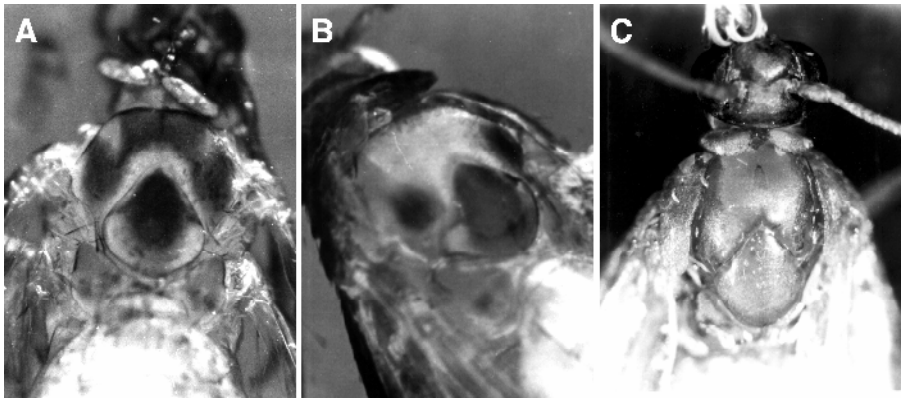

Figure 2.4. Differences in the coloration of thorax, with scales removed, for separating three species of pyralid moths. **A,** *Cadra cautella*; **B,** *C. figulilella*; **C,** *Plodia interpunctella*. (Courtesy E. L. Soderstrom)

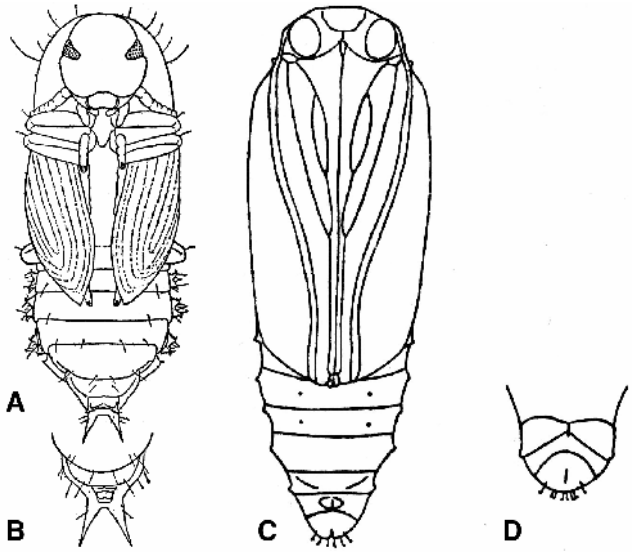

Figure 2.5. Morphological differences (posterior ventral) for sexing *Tribolium castaneum* female (**A**) and male (**B**) and *Ephestia elutella* male (**C**) and female (**D**) (A and B, reprinted from Good 1936; C and D, reprinted from Richards and Thomson 1932)

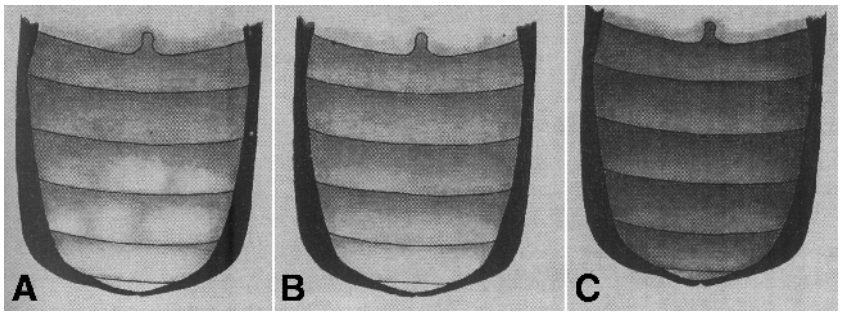

Figure 2.6. Ventral view of the abdomen of adult female *Rhyzopertha dominica* (**A, B**) and male (**C**). (Reprinted, with permission, from Stemley and Wilbur 1966)

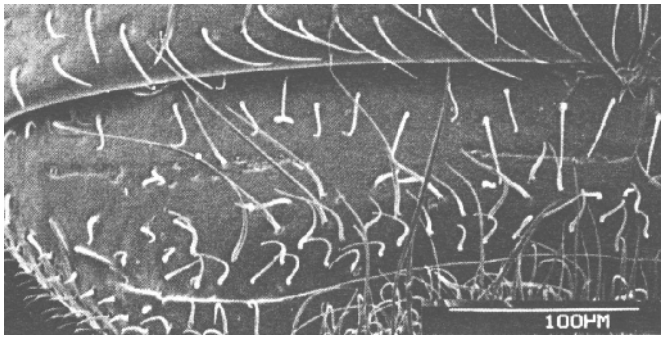

Figure 2.7. Ventral side of the last abdominal segment of male *Rhyzopertha dominica.* (Reprinted from Ghorpade and Thyagarajan 1980, with permission from Elsevier) Also, see Shires and McCarthy 1976 for *Prostephanus truncatus*.

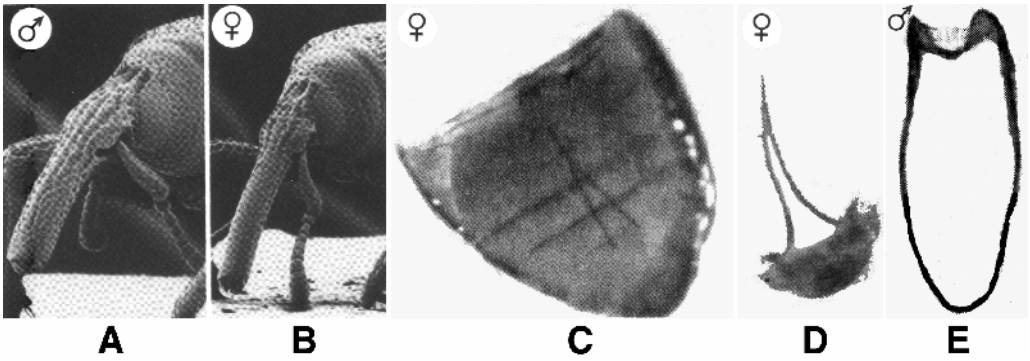

Figure 2.8. Characters for separating males (**A**) from females (**B**) of *Sitophilus zeamais* and *S. oryzae* and of *Lasioderma serricorne* (**C** and **D**, female; **E**, male). (A and B, used with permission of the Natural Resources Institute, Chatham, England. C–E, reprinted from Papadopoulou and Buchelos 2002a, with permission from Elsevier). Also, see Lum and Baker 1975 for *Sitophilus oryzae* and Howe 1957 for *Stegobium paniceum*.

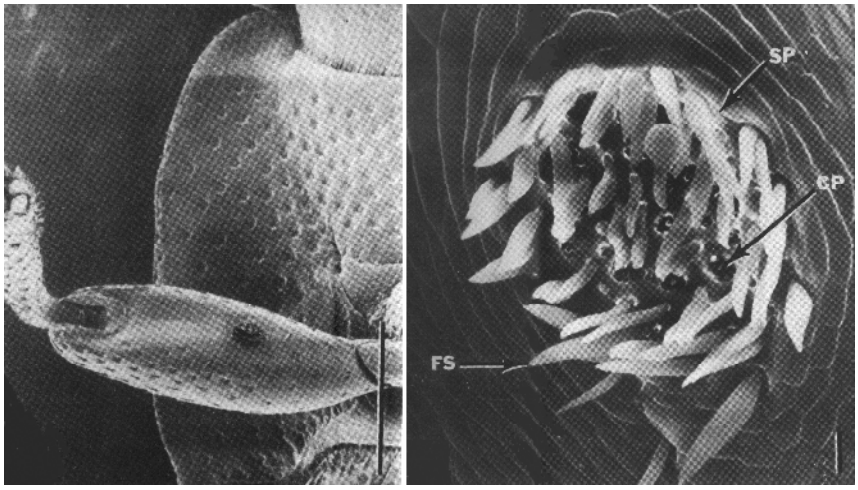

Figure 2.9. Anterior leg of *Tribolium castaneum* with setiferous patch (left, bar = 200 μm) and enlargement of setiferous patch (SP) (right, bar = 5 μm), showing flutted setae (FS) and cribiform plates (CP). (Reprinted from Faustini and Halstead 1982, with permission from Wiley-Liss, Inc., a subsidiary of John Wiley & Sons, Inc.)

the insects. Knowing the sex ratio of insects also can be important in interpreting sampling data and making insect pest management decisions. Figure 2.5 shows the typical characteristics used for the pupal stage of a beetle and a moth. The female *Tribolium castaneum* pupa has two papillae at the distal posterior end of the abdomen where there is only a depression in the male. The male *Ephestia elutella* pupa has two adjacent dome-shaped structures on the ventral side of the last abdominal segment, and the female has a slit.

For internal-feeding *Rhyzopertha dominica*, it is difficult to obtain large numbers of pupae to sex, and adults can be sexed because the additional amount of fat body accumulated by females gives the abdomen a pale coloration (Fig. 2.6). Discarding insects that are not clearly male or female may be necessary. An alternative method for sexing live *R. dominica* adults is to look for a transverse punctuate groove present on the ventral side of the last abdominal segment of males but not of females (Fig. 2.7).

Adults of two *Sitophilus* species can be separated because the male rostrum (snout) is shorter than that of the female (Fig. 2.8). In alcohol, the V-shaped apodeme of female *Lasioderma serricorne* separates them from males because males have a U-shaped apodeme (Fig. 2.8). The sex of *Tribolium castaneum* adults can be determined by the setiferous (bristly) patch on the first pair of legs of the males only (Fig. 2.9). The dark testes showing through the dorsal **cuticle** of the males can be used to determine the sexes of pyralid moth larvae. When sexes are separated at the end of a study, the sex of adults can be determined by squeezing the abdomen with forceps to extrude the genitalia.

Mating

Sometimes it is important to know whether insects have mated. This is particularly important in judging whether an insect pest management program was successful when using sex pheromones to reduce the mating frequency (see Chapter 3). Frequency of mating also can be important in interpreting sampling data and making insect pest management decisions. For most species, only the mated females produce offspring, and the hatching of a female's eggs can be used to indicate mating. Females of some insect species can be dissected to determine whether they have sperm. With pyralid moths, a spermatophore is transferred from the male to the female during mating. The number of times that a female has mated can be determined by counting the number of spermatophores in the bursa copulatrix.

Feeding

For *Prostephanus truncatus*, the presence of lignin in the gut has been used to indicate their feeding on trees, while the presence of starch in the gut has been used to indicate their feeding on stored dried cassava (see recommended reading by Borgemeister et al). **Electrophoretic** analyses have shown that *Teretrius nigrescens* from pheromone traps and grain stores had fed mainly on *Prostephanus truncatus* (see recommended reading by Camara et al). Out of the 18 species of stored-product beetles for which the analysis was done, *Sitophilus zeamais*, *Tribolium castaneum*, and *Cathartus quadricollis* were the only other species that had been preyed upon by *T. nigrescens*. Knowing an insect's diet sometimes can provide evidence of the source of an insect infestation or the potential of a predator for suppressing an insect pest species.

Age grading

Knowing the age structure of an insect population can be important in making insect pest management decisions. The behavior and ecology of insect pests and **natural enemies** and their susceptibility to insect pest management methods can vary with age. Age grading also can be an important tool when studying insect life history. It can be used to determine the number of insects in each **instar**, or stage, and the number of adults that are of pre- or post-reproductive age.

Two methods have commonly been used in life history studies to determine the age of internal-feeding stored-product insects. For *Sitophilus* and several other species of internal-feeding insects (Table 2.4), insect-infested kernels were **x-rayed** daily to visually determine the stage of insect development. Instar was determined by measuring the size of the larval feeding cavities. Also, a period when the size of the feeding

Table 2.4. Stored-product insect species for which the instar of insects developing inside grain kernels has been determined using x-rays

Insect species	Source
Callosobruchus maculatus	Osuji 1982
Rhyzopertha dominica	Stemley 1962
Sitophilus granarius	Kirkpatrick and Wilbur 1965
Sitophilus oryzae	Dobie 1973, Sharifi and Mills 1971a
Sitophilus zeamais	Sharifi and Mills 1971b
Sitotroga cerealella	Mills and Wilbur 1967
Theocholax elegans	Sharifi 1972a

Table 2.5. Measurements for distinguishing instars of five stored-product insect species[a]

Species and Instar	Mean head width (mm)	Range (mm)
Prostephanus truncatus[b]		
1	0.36	0.32–0.39
2	0.54	0.45–0.60
3	0.80	0.73–0.85
Rhyzopertha dominica		
1	0.13	0.11–0.18
2	0.21	0.19–0.22
3	0.34	0.25–0.38
4	0.47	0.40–0.53
Sitophilus granarius		
1	0.24	0.20–0.28
2	0.35	0.30–0.39
3	0.51	0.42–0.58
4	0.68	0.60–0.76
Sitophilus oryzae		
1	0.20	0.19–0.22
2	0.28	0.25–0.32
3	0.38	0.34–0.40
4	0.53	0.49–0.57
Sitophilus zeamais		
1	0.20	0.17–0.24
2	0.29	0.25–0.32
3	0.43	0.37–0.49
4	0.63	0.55–0.74

[a] Data from Subramanyam et al 1985 for *Prostephanus truncatus*, Stemley 1962 for *Rhyzopertha dominica*, Richards 1947 for *Sitophilus granarius*, Sharifi and Mills 1971a for *Sitophilus oryzae*, and Sharifi and Mills 1971b for *Sitophilus zeamais.*

[b] For *Prostephanus truncatus*, the distance between two sutures on the head also can be used to determine instar.

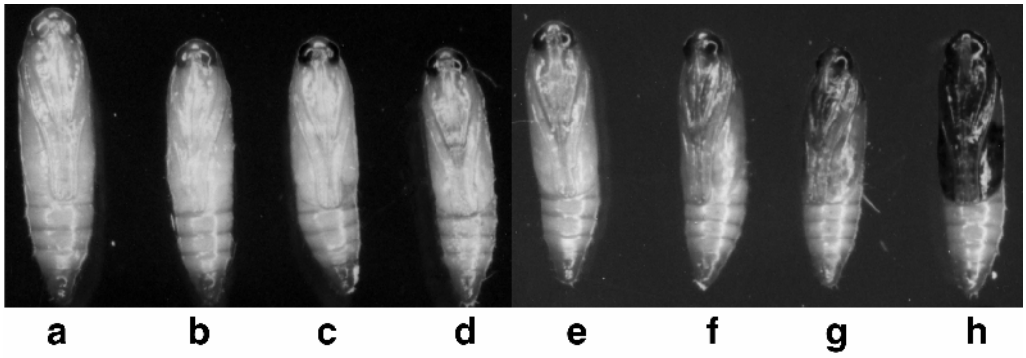

Figure 2.10. Variation of color of *Plodia interpunctella* pupae with time until adult eclosion. Days or hours before eclosion: a, six to seven days; b, five to six days; c, three to four days; d, two to three days; e, one to two days; f, one day; g, 18–20 hr; h, 12–15 hr. (Courtesy of D. L. Silhacek and G. P. Whitmer.) Smithwick and Brady 1971 describe the color changes over time.

chamber did not change indicated the time when a larva molted to the next instar. For *Sitophilus* species, females were allowed to lay eggs on kernels for several days; the egg plugs were stained to determine which kernels were infested; some of the infested kernels were cut open periodically to remove insects; and the widths of the larval heads were measured to determine instar (see recommended reading by Vowotor et al and Table 2.5). The heads of external-feeding larvae also have been measured to determine instar. Studies with *S. oryzae* found that, over time, insects killed by fumigation became increasingly more difficult to detect with x-rays. This may be a result of the x-rays more easily penetrating dry, shriveled tissue than water-filled tissue.

Moth pupae are initially very pale and become darker as they age (Fig. 2.10). The eyes darken first, then the overall **cuticle**, and finally the wing pads. The age of *S. oryzae* and *Prostephanus truncatus* females can be estimated based upon the size and darkness of the accumulation of egg chamber relics at the base of their ovaries (see recommended readings by Perez-Mendoza et al and by Scholz et al). For mated *Sitophilus*, the first relics were observed five days after they emerged from a wheat kernel, and by day 10, some relic accumulations had visible gray spots. The accumulations of relics darken with age, and by day 40, the accumulation of relics was a dark brownish black.

For mated *P. truncatus* insects, no relics were observed five days after emergence from their pupal chamber. By day 10, all three levels of egg chamber relic accumulation were observed, and the number of females for which the accumulation of relics had gray spots or was brownish black gradually increased up to 30 days. The spermatheca may need to be examined for sperm to establish whether a female has mated, because ovarian development is faster in mated females. Also, starvation can result in an accumulation of egg chamber relics due to egg resorption.

Characteristics such as wing fraying or mandible wear can provide some information about adult insect age, but these can also vary with the extent of flight activity, the environmental conditions, and the type of food eaten.

Utilization of entomological techniques

With increased emphasis on using residual insecticides and fumigants more effectively and integrating residual insecticides and fumigants with other insect pest man-

agement methods to better manage insect resistance, the entomological techniques discussed in this chapter should be more widely used. Monitoring to determine whether insect pest management was effective should become an essential part of every insect pest management program. Preparing the insects that are to be used to monitor the effectiveness of such programs involves rearing and extracting them, and determining their physiological state may allow more precise interpretation of this monitoring data.

Extraction and detection methods can reduce the time required to process commodity sample units. Insects must be sorted by species before counting, and determination of the physiological state of the insects found in sample units may provide useful information. It may provide a better understanding of the susceptibility and response of stored-product insects to pest management programs, increase the amount of information obtained from a sampling program, and result in better insect pest management decisions. The influence of physiological state on insect mobility is discussed in the next chapter. The techniques described here may be adapted to other stored-product insect species, and similar methods that have been used with other stored-product insect species are described in the recommended readings at the end of chapters and the references cited at the end of the book.

Study Questions

1. What precautions need to be taken in rearing and handling stored-product insects to ensure high quality?
2. Why are stored-products insects often the preferred organisms for basic physiological, behavioral, and ecological studies?
3. How can the advantages of stored-product insects for basic studies be beneficial to an insect pest management program?

Recommended readings

Borgemeister, C., Tchabi, A., and Scholz, D. 1998. Trees or stores? The origin of migrating *Prostephanus truncatus* collected in different ecological habitats in southern Benin. Entomol. Exp. Appl. 87:285-294.

Camara, M., Borgemeister, C., Markham, R. H., and Poehling, H. M. 2003. Electrophoretic analysis of the prey spectrum of *Teretrius nigrescens* (Lewis) (Col., Histeridae), a predator of *Prostephanus truncatus* (Horn) (Col., Bostrichidae), in Mexico, Honduras and Benin. J. Appl. Entomol. 127:360-368.

Halstead, D. G. H. 1963. External sex differences in stored-products Coleoptera. Bull. Entomol. Res. 54:119-134.

Howe, R. W. 1991. Principles of rearing stored-product insects and of insectary management. Pages 535-544 in: Ecology and Management of Food-Industry Pests. J. R. Gorham, Ed. Assoc. Official Analytical Chem., Arlington, VA.

Perez-Mendoza, J., Throne, J. E., and Baker, J. E. 2004. Ovarian physiology and age-grading in the rice weevil, *Sitophilus oryzae* (Coleoptera: Curculionidae). J. Stored Prod. Res. 40:179-196.

Rajendran, S. 1999. Detection of insect infestation in stored food commodities. J. Food Sci. Technol. 36:283-300.

Scholz, D., Borgemeister, C., Markham, R. H., and Poehling, H. M. 1998b. Physiological age-grading and ovarian physiology of *Prostephanus truncatus*. Physiol. Entomol. 23:81-90.

Vowotor, K. A., Bosque-Perez, N. A., and Ayertey, J. N. 1995. Effect of maize variety and storage form on the development of the maize weevil, *Sitophilus zeamais* Motschulsky. J. Stored Prod. Res. 31:29-36.

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Chapter 3

Mobility

The mobility of stored-product insects allows them to find essential resources such as food, mates, suitable sites for laying eggs, and a safe environment. The internal physiological state of insects and their response to many environmental factors influence their mobility and their success in finding essential resources. Stored-product insects tunnel through stored commodities and move within a facility among stored commodities, residual food, and hiding places. They may even move between storage and processing facilities, and humans often help these insects disperse by moving them along with the commodities. Mobility also allows insects to escape from **natural enemies** and unfavorable environments.

An awareness of insect mobility can be important to the success of a pest management program for stored-product insects. The observed spatial distribution pattern of insect populations is a result of their moving to find essential resources. Their mobility makes it difficult to exclude them from a facility and from bulk or packaged commodities. Once they enter, their mobility, longevity, and ability to survive and reproduce on small amounts of many different types of foods make them hard to manage. Some insects in inaccessible areas of bins, warehouses, food-processing facilities, transportation vehicles, and retail stores may not be killed by an insect pest management method. Their mobility then results in the surviving insects quickly reinfesting the areas in which an insect pest management method was successful.

Conversely, insect mobility also can facilitate insect pest management by increasing the effectiveness of residual insecticides and traps. Because residual insecticides often are not applied uniformly, insects can survive in untreated areas, but many of them eventually will be killed by picking up a lethal dose of residual insecticide when they move into treated areas (see recommended reading by Toews et al). Also, because insects are so mobile, a trap can capture insects from a large area. Therefore, understanding the extent and pattern of insect mobility is important in planning, implementing, and evaluating the effectiveness of an insect pest management program.

Three examples of resource-finding behavior are included in this chapter to give the reader a better appreciation of what insects might be doing when they are seen flying, walking across the floor, or sitting on a wall in a food storage or processing facility, transportation vehicle, or retail store—or when they cannot be seen but are moving around within a commodity.

Example 1—Exploitation of food sources by *Tribolium castaneum*

Tribolium castaneum is a major pest of both raw and processed commodities. The following example describes adult tunneling within a stored commodity and walking among residual food patches and shelters similar to those in storage, processing, and retail facilities or transportation vehicles (see recommended readings by Campbell and by Hagstrum).

Adult *T. castaneum* were found to continuously leave a large food source (60 g of flour). The distance that adults tunneled in flour increased from almost none at two days of age to 48 cm/day for eight-day-old males and 33 cm/day for 10-day-old

females. Increased tunneling resulted in more of the insects reaching the edge of the flour mass, from which they could leave the flour. All but 3% of the adults remained in the flour for seven days after **eclosion,** and 12% of those remaining adults emigrated on the eighth day. After that, 23% of the adults emigrated each day. Many of these adults laid some eggs in the flour during the one-to-four day period before their leaving the flour. The number of adults emigrating from the bags of flour increased from 0.4 to 24 per day as the population grew over time. However, the percentage of the adults emigrating did not increase, suggesting that **pheromones**, uric acid waste products, and defensive chemicals such as quinones did not build up sufficiently over several generations to change the emigration rate. Lower emigration rates would be expected from larger quantities of food and from bags that were sealed to prevent insect infestation. However, even in these cases, some insects are likely to leave the infested bags to infest other commodities.

After *T. castaneum* adults left the flour, they moved at an average speed of 14 cm/min (5.6 in./min) but they were moving only 26% of the time. On average, an adult moved 53 m/day (175 ft/day). With 16 evenly spaced, 1-g piles of flour in a 1.2- × 1.2-m (4- × 4-ft) area, 62% of the adults were in the piles of flour and 32% were seeking shelter near the walls of the enclosure at any given time. Those near the walls were likely to hide in cracks and crevices in storage, processing, or retail facilities or a transportation vehicle. The remaining 6% of the adults were moving among the piles of flour. Eggs were laid in 78% of the piles during a 24-hr period by 25 females.

Residual food that is not removed immediately by a good sanitation program can continuously produce emigrants that actively search for new food sources. The intensity of their search explains why the commodities brought into a facility can become infested so quickly.

Example 2—*Cadra cautella's* response to calling females and food

Cadra cautella is a major pest of in-shell peanuts stored in bulk, but it is also a problem at food-processing plants. The behavior of a closely related species, *Plodia interpunctella*, may be similar. This second example includes the flight behavior of a male moth seeking a mate, the mobility of a female seeking a place to lay eggs within a facility, the mobility of newly hatched larvae walking between the places where eggs were laid and feeding sites, and the mobility of mature larvae walking between feeding sites and the shelters used for pupation (see recommended readings by Hagstrum and by Mankin). The extensive mobility of adults and larvae ensures that insects find essential resources even when such resources are rare. Because mature larvae move away from food residues or commodities to pupate, they remain within a facility to start a new generation even after the commodity has been shipped and its residues have been removed by sanitation. Studies on the mobility of *C. cautella* help to explain why this species is such an important pest of so many different commodities and why it can be effectively monitored using pheromone traps.

Females sat on the walls with the tips of their abdomens raised in a calling position and released sex pheromones. In a 6.1- × 6.1-m (20- × 20-ft) room, males flew 300 m (984 ft) during an average flight that lasted 10 min. There was little air movement in this room, and males could not fly upwind to find a female. Male flight behavior changed as the male flew closer to a female and detected increasingly higher concentrations of sex pheromone (Figure 3.1).

Within 40 cm (16 in.) of a female, the turning rate (angular velocity) increased from 500 to 1,000 degrees per second, and this increased turning brought the male closer to the female. At around 20 cm (8 in.) from a female, the velocity of the male's flight decreased from 40 to 5 cm/sec, and the male had more time to detect the sex pheromone. A turn bias of the male toward the female occurred when the male was roughly 10 cm (4 in.) from a female. The male soon landed a short distance from the female,

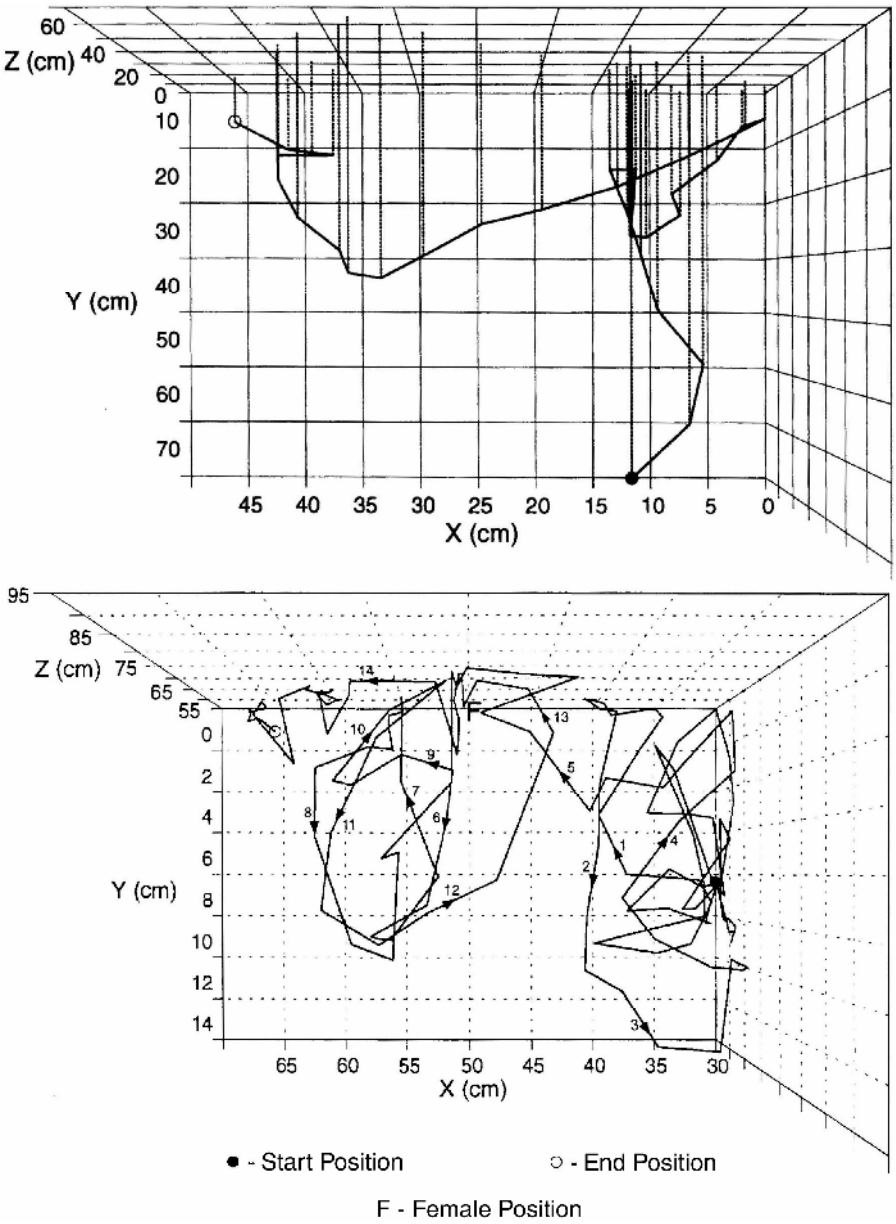

Figure 3.1. Flight path of male *Cadra cautella* with no female present (top) or with a female (F) present at wall-ceiling junction in middle of back wall (bottom) (Reprinted, with permission, from Mankin and Hagstrum 1995). Phelan and Baker 1990 describe courtship after male finds female.

walked toward the female, and mated. This extensive flight activity of the males results in these insects frequently being seen flying in storage, processing, and retail facilities and transportation vehicles.

C. cautella females flew in search of egg-laying sites in an empty peanut warehouse. Egg-laying sites were scattered patches of a few peanuts. When the distribution of peanuts among egg-laying sites was varied from 48 at one location to two at each of 24 evenly spaced locations in a 6.1- × 6.1-m (20- × 20-ft) room, the total number of eggs laid by four females over a three-day period was not influenced by the peanut distribution. However, the average number of eggs per location varied from 31 when there were two peanuts to 558 with 44 peanuts. Only 8–20% of the offspring from these eggs survived on the available food. The more closely the distribution of the eggs matched that of the food resource, the higher the population growth rate will be. 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 some peanuts increased from one to 24. Because female moths found only a small amount of the food during each generation, population growth was supported for several generations. Sweeping up these food residues and killing the insects that were infesting them would reduce the number of insects that were around to infest the peanuts stored in the warehouse after the next harvest.

In addition to adult dispersal, the dispersal of *C. cautella* larvae also can be important. Newly hatched larvae searched for food, which allowed more of these larvae to survive. Mature larvae searched for pupation sites away from their feeding site. **Parasitoids** follow the trails left by these mature larvae wandering in search of a pupation site (see Chapter 11). Larvae wandering away from the commodities to pupate remain in a facility after the stored commodities have been shipped. *C. cautella* larvae diapause, remaining in the larval stage for several months, and can carry over the population from one storage season to the next.

Reducing the ability of males to find mates has been shown to be a potential method of managing five species of moths and two species of beetles (Table 3.1). Studies with moths at low densities have shown that permeating the atmosphere with their sex **pheromone** or a pheromone mimic can reduce mating by 90–100%. Mating of *Attagenus unicolor* (formerly *Attagenus megatoma*) was reduced by roughly 60%. Permeating the atmosphere with sex pheromones can delay mating in three ways: 1) high concentrations of pheromone result in habituation or adaptation of male olfactory receptors, 2) high concentrations of pheromone make the female-released pheromone more difficult to locate, and 3) pheromone dispensers attract males, reducing their chances of finding a female.

For pyralid moths, the main component of the sex pheromone seemed to work as well as the natural blend of several chemicals. Mating reduction was greater at low male densities than at high male densities because, at high densities, males found females visually without using the pheromone (see Chapter 5). Mating also was reduced more in dark environments, probably because males were less likely to fly or to be able to locate a female visually. Using a combination of sterile males and an atmosphere permeated with sex pheromones was more effective than either condition alone because some of the few females mating in a sex-pheromone-permeated atmosphere mated with sterile males. Using a pheromone inhibitor instead of the pheromone to permeate the atmosphere has been suggested as a way of reducing mating without

Table 3.1. Studies using pheromones, mimic, and mass trapping to reduce mating

Insect species	Source[a]
	Permeation with pheromone
Attagenus unicolor	Burkholder 1973
Cadra cautella	Brady and Daley 1975, Brady et al 1975, Hagstrum and Davis 1982, Hagstrum et al 1978, Haines 1977, McLaughlin and Hagstrum 1976, Schofield et al 2003, Shani and Clearwater 2001, Sower and Whitmer 1977, Süss and Trematerra 1987, Vick et al 1985, Wakamura et al 1975
Plodia interpunctella	Brady et al 1975, Fadamiro and Baker 2002, Fleurat-Lessard et al 1976, Hodges et al 1984, Mafra-Neto and Baker 1996, McLaughlin and Coffelt *unpublished* (See Phillips et al 2000), Pimaud et al 1976, Prevett et al 1989, Ryne et al 2001, Sower and Whitmer 1977, Sower et al 1975
Sitotroga cerealella	Fadamiro and Baker 2002, Stockel 1976, Vick et al 1978
	Permeation with mimic
Amyelois transitella	Curtis et al 1987
	Mass trapping
Anagasta kuehniella	Cravedi and Fogliazza 1994, Sifner et al 1983, Süss and Trematerra 1987, Trematerra 1994
Cadra cautella	Ryne et al 2002, Sifner et al 1983
Lasioderma serricorne	Buchelos and Levinson 1993, Carvalho and Mexia 2003, Pierce 1994, 1999
Plodia interpunctella	Pierce 1994, Süss and Trematerra 1987

[a] Inhibitors have been identified for *Cadra cautella* by Sower et al 1974, for *Ephestia elutella* by Krasnoff et al 1984, for *Lasioderma serricorne* by Levinson and Levinson 1987, and for *Stegobium paniceum* by Kodama et al 1987. Bruce and Lum 1976 showed that pheromone was degraded by UV radiation.

attracting additional males into an orchard or a facility. Using UV radiation to degrade pheromone also has been suggested as a way of disrupting pheromone communication.

Mating also can be reduced by mass trapping of the males using pheromone lures. Mass trapping has been shown to reduce populations of *Anagasta kuehniella*, *C. cautella*, *Lasioderma serricorne*, or *P. interpunctella* by 50–99.6% in a bakery, a chocolate factory, flour mills, a grain elevator, a cigarette factory, and warehouses over a period of a year or more. The trap densities used in these facilities ranged from one per 150 m^3 to one per 530 m^3. Because the males mate more than once, a large percentage of the males must be captured to reduce mating by females. Water also has been used to attract both males and females of *C. cautella*, and roughly 60% of these females were unmated. Before large amounts of pheromones are used for mass trapping in storage, processing, and marketing facilities or transportation vehicles, tolerances may need to be established for their residues in food commodities.

Example 3—Insects in stored grain

The third example discusses the rates at which two species of stored-product insect pests that are rapidly capable of extensive damage and two less-important species of stored-product insect pests immigrate into bins containing newly harvested wheat (see

recommended readings by Hagstrum). This example also discusses the extent to which these insects tunnel into wheat, walk on the grain surface, and fly in the headspace over the grain. Because of species differences in the pattern of insect mobility, trap catch can be very sensitive to trap placement. Also, top dressing of grain with a residual insecticide can be ineffective when insects quickly move through the insecticide-treated layer.

Insect mobility is evident from the high rate of immigration of insects into grain storage bins. An estimated average of 14 *Cryptolestes ferrugineus*, six *Rhyzopertha dominica*, six *Ahasverus advena*, and 21 *Typhaea stercorea* adults immigrated into wheat storage bins each day on farms in Kansas. The number of insects entering a bin through the ventilation opening between the roof and the sidewalls increased as the circumference of the bin increased. However, the numbers of insects entering the bins through the ventilation opening between the cap and the roof were as much as 18 times larger than the numbers entering at the eaves.

The distribution of the insects after entering a bin varied with species. *C. ferrugineu*s and *A. advena* were most evenly distributed among three regions of the bins (flying in the bin headspace, walking on the grain surface, and tunneling through the grain mass). The distribution of *C. ferrugineus* among the three regions remained the same throughout the first four months of storage. *R. dominica* was most active in the headspace and grain mass early in the storage period and was active mainly in the grain mass during the autumn as the grain cooled. *T. stercorea* was found mainly in the headspace and on the grain surface. *Sitophilus oryzae* and *Tribolium castaneum* were less abundant and were found most often on the grain surface. *Oryzaephilus surinamensis* was found mostly in the grain mass.

C. ferrugineus and *R. dominica* move down into the grain after entering a bin, and insect densities decrease logarithmically with the depth below the grain surface. When bins have residual infestations at the bottom, insects also move upward into the grain mass. Similar vertical distributions of insects with depth below the grain surface have been observed in concrete bins at grain **elevators**.

Environmental factors

Environmental factors such as those in Table 3.2 influence the propensity for insects to move and the direction, pattern, and speed of their movement. A large number of examples are given to illustrate the many insect responses to many different environmental factors. In comparing the results of different studies, differences in the number of replicates (accuracy of estimates), the genetic strains of insects used (see recommended reading by McFarlane et al), the physiological states of the insects studied, and the environmental conditions under which the studies were done need to be considered.

The flight and walking activity of stored-product insects can be regulated by **photoperiod** or thermoperiod. Flight was greatest at dusk for *Callosobruchus maculatus*, *Cadra cautella*, *Prostephanus truncatus*, *Rhyzopertha dominica*, *Sitophilus zeamais*, *Sitotroga cerealella*, and *Tribolium castaneum*, with a smaller or no peak in flight activity at dawn. The flight activity of *S. cerealella* was sometimes shifted to later in the night by high winds. The flight activity of *Trogoderma variabile* (formerly *T. parabile*) males peaked at 4.6 hr after sunrise, and female flight activity peaked at 7.9 hr after sunrise. *Teretrius nigrescens*, a **predator** of *P. truncatus*, was attracted to host

Table 3.2. Environmental factors influencing extent and pattern of insect mobility

Species	Environmental factor	Source
Amyelois transitella	female attractant, residual insecticide	Phelan and Baker 1987
Anagasta kuehniella	female attractant	Toth et al 2002
Cadra cautella	grain odor, carbon dioxide, wind	Barrer and Jay 1980
	light	Hagstrum et al 1977
	male odor, food odor	Barrer 1977
	wind, pheromone	Mafra-Neto and Carde 1994
Callosbruchus maculatus	temperature, light, humidity	Taylor and Agbaje 1974
Carpophilus hemipterus	pheromone, food odor	Dowd and Bartlett 1991
Cryptolestes ferrugineus	carbon dioxide	White et al 1993
	fumigants	Bell 1986
	gravity, carbon dioxide, humidity	Parde et al 2004
	gravity, moisture, temperature, dockage	Jian et al 2004a,b; 2005a,b
	temperature	Flinn and Hagstrum 1998, Hanec et al 1975
	temperature, humidity	Surtees 1965
C. pusillus	food	Obeng-Ofori 1993b, Subramanyam et al 1992
	hastisetae	Kokubu and Mills 1980
Dinarmus basalis	host odor	Caubet and Jaisson 1991
Eupelmus vulleti	host odor, host food odor	Cortesero et al 1993, 1995
Habrobracon hebetor	host larvae	Hagstrum and Smittle 1978
	host odor, wind, light	Parra et al 1996
Laelius pedatus	host setae	Ma et al 1978
Lariophagus distinguendus	host food odor, feces of host larva	Steidle and Fischer 2000, Steidle and Ruther 2000, Steidle and Schöller 1997, Steidle et al 2001
	humidity	Steidle and Reinhard 2003
Lasioderma serricorne	temperature	Papadopoulou and Buchelos 2002b
Oryzaephilus mercator	food	Loschiavo 1976
O. surinamensis	carbon dioxide, oxygen	Navarro et al 1981
	food odor	Mikolajczak et al 1984, Oehlschlager et al 1988, Pierce et al 1990, Stubbs et al 1985, White 1989

(*continued on next page*)

Table 3.2 (continued)

Species	Environmental factor	Source
	food, shelter	Obeng-Ofori 1993b, Subramanyam 1992
	fumigants	Bell 1986
	light	Bell 1991
	light, tactile, humidity	Arbogast and Carthon 1970
	temperature, humidity	Surtees 1965
	wind, vibration, temperature	Armitage et al 1983
Plodia interpunctella	female attractant	Nansen and Phillips 2003, Toth et al 2002
	food, wind, larval contamination	Phillips and Strand 1994
	residual insecticide	Nansen and Phillips 2004
	wind, pheromone	Marsh et al 1978
Pteromalus cerealellae	host odor	Mbata et al 2004
Prostephanus truncatus	food odor	Fadamiro et al 1998, Obeng-Ofori 1993b, Pike et al 1994, Scholz et al 1997b
	humidity, temperature, light	Hodges et al 2003, Nansen et al 2001
	light	Birkinshaw et al 2004
	light, temperature, humidity, food	Fadamiro and Wyatt 1995
	other adults of same species, food	Scholz et al 1997a, 1998a
	pheromone	Boughton and Fadamiro 1996, Fadamiro 1997, Fadamiro and Wyatt 1996
	wind speed	Fadamiro 1996
Rhyzopertha dominica	light	Leos-Martinez et al 1986
	light, humidity	Perttunen 1973
	other adults of same species, food	Aslam et al 1994, Barrer et al 1993, Perez-Mendoza et al 1998, 1999
	pheromone, food odor	Dowdy et al 1993
	residual insecticides	Collins et al 1988
	temperature, humidity	Surtees 1965
	temperature, humidity, light	Dowdy 1994, Wright and Morton 1995
	wind, vibration, temperature	Armitage et al 1983
Sitophilus granarius	carbon dioxide, oxygen	Adler 1992
	fumigants	Bell 1986
	pheromone, food	Wakefield et al 2005

(*continued on next page*)

Table 3.2 (continued)

Species	Environmental factor	Source
	temperature, humidity	Surtees 1965
	wind, vibration, temperature	Armitage et al 1983
S. oryzae	bacterial symbiotes	Baker and Lum 1976, Grenier et al 1994
	food	Subramanyam et al 1992
	hastisetae	Kokubu and Mills 1980
	pheromone, food	Phillips et al 1993, Wakefield et al 2005
	residual insecticides	Collins et al 1988, Hodges and Meik 1986
	temperature, light	Bishara 1968
Sitophilus zeamais	bacterial symbiotes	Grenier et al 1994
	food odor	Pike et al 1994
	humidity, food	Weston and Hoffman 1992
	humidity, shelter	Weston and Hoffman 1991
	pheromone, food	Walgenbach et al 1987, Wakefield et al 2005
	residual insecticides	Collins et al 1988, Hodges and Meik 1986
	temperature, light	Bishara 1968, Taylor 1971
Sitotroga cerealella	light	Barney and Weston 1996
	light, visual, wind, host odor	Weston et al 1997
	shelter, food	Weston and Rattingourd 1999
Teretrius nigrescens	light, host pheromone	Birkinshaw et al 2004
Tribolium castaneum	carbon dioxide, humidity, food	Willis and Roth 1950a,b; 1954
	death feigning	Prohammer and Wade 1981
	dockage	McGregor 1964
	food	Subramanyam et al 1992, Seifelnasr et al 1982
	food, pheromone	Phillips et al 1993
	food, shelter	Stejskal 1995
	fumigants	Bell 1986
	light	Taylor 1971
	pheromone	Obeng-Ofori and Coaker 1990a,b
	quinones	Howard 1987
	residual insecticides	Collins et al 1988, Hodges and Meik 1986
	temperature	Hagstrum et al 1998, Jian et al 2005c
	temperature, humidity	Surtees 1965

(*continued on next page*)

Table 3.2 (continued)

Species	Environmental factor	Source
T. confusum	carbon dioxide	Willis and Roth 1954
Trichogramma evanescens	host pheromone	Schöller and Prozell 2002
Trogoderma glabrum	food odor	Nara et al 1981
T. variabile	temperature, light, humidity	Wright and Morton 1995
Uscana lariophaga	host odor, host food odor	van Huis et al 1994
Venturia canescens	geraniol as host habitat odor	Arthur 1971
Xylocoris flavipes	defensive secretion	Klein and Burkholder 1983

aggregation **pheromone** and was caught throughout the day in Ghana. The walking activity of *Oryzaephilus surinamensis* was greatest at night, reaching a peak at 4–8 hr after the onset of darkness. Once established, this activity pattern persisted in continuous darkness.

Stored-product insects tended to fly only when the temperature was above a certain threshold. Humidity was generally a less-important stimulus for flight than temperature or light intensity. *T. variabile* males flew at temperatures of 12°C and above and females at temperatures of 16°C and above. *C. maculatus*, *P. truncatus*, *R. dominica,* and *S. zeamais* flew at temperatures of 20–21°C and above. The temperature threshold for flight was only 16°C for *R. dominica* in Australia. *Lasioderma serricorne* flew at temperatures above 13°C soon after they became adults. *C. cautella* flew less in a dark environment, and flight activity increased with light intensity. The walking speed of *Cryptolestes ferrrugineus* increased from 1.75 mm/sec at 9°C to 10.48 mm/sec at 30°C.

Oryzaephilus surinamensis moved within the grain bulk in response to the cooling, dampening, or drying that occurred during aeration of wheat that was initially at 25°C. During aeration, *Sitophilus granarius* moved in the grain bulk only in response to dampening at 10°C and drying at 25°C. *O. surinamensis* moved in the grain bulk in response to a high airflow of 300 m^3/hr per ton at 10°C but not at 25°C, while *S. granarius* and *Rhyzopertha dominica* did not respond to high airflow at either temperature. Only *S. granarius* moved in response to the vibration from the aeration fan.

The attraction of *Prostephanus truncatus* males and females to aggregation pheromone decreased with age. *R. dominica* and *P. truncatus* flew more often when other adults of the same species were present or they were deprived of food for a few days. Accumulated wastes such as insect-damaged kernels, frass, and uric acid increased the number of *R. dominica* taking flight. Wind was not necessary for *P. truncatus* adults to take flight, and the portion of adults taking off decreased slightly as the wind speed increased from 0 to 32 cm/sec. The majority of *P. truncatus* initiated flight and landed upwind at wind speeds of less than 20 cm/sec, but at increased wind speeds, the number of downwind takeoffs and landings increased. Light intensity influenced the time of flight, and temperature influenced the frequency and duration. Young (one- or two-week-old) adults of both species flew more often than older adults. Young *P. truncatus* also flew longer than older adults. *R. dominica* adults reared on rice or wheat have been shown to fly more than those reared on maize or sorghum. Outside, the flight activity of *P. truncatus* resulting in their capture in traps has been predicted from local humidity, temperature, and day-length data.

In laboratory studies, *Sitophilus zeamais* flew more than *Sitophilus oryzae*, and males (65 versus 36% for these two species) of both species flew more than females (39 versus 12% for these two species). Two-week-old *S. oryzae* did not fly, but two-week-old *S. zeamais* did. The numbers of *S. zeamais* taking flight were influenced by light intensity, but the numbers of *S. oryzae* taking flight were not. Temperature increased the frequency of flight by *S. oryzae* more than that by *S. zeamais*. *S. oryzae* and *S. zeamais* did not fly unless internal bacterial symbiotes were present. Heat-treatments can remove the symbiotes. Killing these symbiotes may help in managing these insect pests. *Lasioderma serricorne* and *P. truncatus* also have symbiotic micro-organisms. These symbiotes may extend the host range for *L. serricorne*, allowing them to develop on poor diets. The symbiotes also may help *L. serricorne* detoxify toxins.

Pheromone, food, and other odors can be attractive to insects. *Cadra cautella* and *Plodia interpunctella* males fly upwind in a zig-zag pattern, following the sex pheromone released by a calling female. *Prostephanus truncatus* moved upwind to find the source of aggregation pheromone but not the source of food odors. *C. cautella* and *P. interpunctella* females fly upwind in response to food odor to find a place to lay their eggs. Gravid *P. interpunctella* females flew upwind more often in response to volatiles from food infested by mature larvae of the same species than to volatiles from food alone. Walnut oil also has been shown to attract gravid *P. interpunctella* females. Females laid more eggs when they were able to contact the walnut oil. *Sitotroga cerealella* males were attracted to the vicinity of tall vegetation such as maize or sunflowers, and maize attracted more males to traps than sunflowers.

Cadra cautella females were attracted to the odor of other adults of the same species, particularly males, and the response to a combination of adult odor and food odor was additive. Attraction of females to food odor increased when the carbon dioxide concentration was 30% and decreased when the concentration was 95%. Leakage of carbon dioxide from a modified-atmosphere treatment could result in insects laying eggs near leaks and newly hatch larvae entering through small holes.

Other female attractants have been discovered for *Amyelois transitella*, *Anagasta kuehniella*, and *Plodia interpunctella*. Attraction of females or both sexes may be an advantage for mass trapping (discussed earlier in this chapter) and when a combination of attractant and residual insecticide is used (see Chapter 17). To most effectively suppress insect populations, females must be attracted before they can lay their eggs. Crude almond oil was attractive to gravid *A. transitella* females. Isoamyl alcohol and acetic acid in a 1:1 or 1:10 blend were attractive to both sexes of *A. kuehniella* and *P. interpunctella*, with a female bias of 68 and 83% females, respectively.

The parasitoid *Habrobracon hebeto*r flies upwind to find its host, *A. kuehniella*, using volatiles associated with the host infestation. The parasitoid *Pteromalus cerealellae* showed up-wind response to whole-body extracts from the virgin female host *Callosobruchus maculatus*. *Lariophagus distinguendus* responded to the odors of the host food (rice, wheat, and cowpea) and the odors from the feces of the larval hosts *C. maculatus*, *Rhyzopertha dominica,* and *Sitophilus granarius* but not *Sitotroga cerealella*. *L. distinguendus* preferred seed infested by *R. dominica* and *S. granarius* over uninfested seed. Females of the egg parasitoid *Uscana lariophaga* responded to the odors of cowpeas, cowpeas infested by the host *C. maculatus*, virgin host females, and host eggs but not to the odor of male hosts. Females of *Eupelmus villeti*, a parasitoid of *Bruchidius atrolineatus*, responded to the odors of host food, larvae, larval

feces, or pupae but not to the odor of the host adults or their pheromone. *E. vuilleti*, *L. distinguendus*, and *Venturia canescens* have been shown to use associative learning of odors to locate a host. *Dinarmus basalis* learned to prefer *Zabrotes subfasciatus* as a host but not *Acanthoscelides obtectus*. *E. vuilleti* learned to use two different odor cues. *Trichogramma evanescens* learned to use the sex pheromone of its host, *Plodia interpunctella*, to localize its search for host eggs.

Short-range attraction and arrestment by food odors have been reported for *Oryzaephilus surinamensis*, *Prostephanus truncatus*, *Sitophilus granarius*, *S. oryzae*, *S. zeamais*, *Tribolium castaneum*, and *Trogoderma glabrum*. For *Carpophilus hemipterus*, *O. surinamensis*, *S. granarius*, *S. oryzae*, and *S. zeamais*, food odors improved the short-range attraction of aggregation pheromones.

Males of *T. castaneum*, *T. confusum*, *P. truncatus*, and *Rhyzopertha dominica* produce an aggregation pheromone to which both sexes respond either by walking upwind or, in the case of *R. dominica*, by short flights. Both sexes of three out of four of these species responded equally, but *T. castaneum* males responded more than females. Both sexes of both species of *Tribolium* were responsive immediately after **eclosion** and reached maximum responsiveness by 16–21 days. Mating did not change the response for any of these species. All four species were most receptive between noon and 3 p.m. and recovered from habituation after 48 hr.

Having food or shelter nearby reduced the number of *T. castaneum* caught in a trap. Retention of *Oryzaephilus surinamensis* adults in cracked maize or rolled oats was consistently better than in cracked wheat, cracked sorghum, or kibbled carob. Cracked maize and a mixture of all five of these foods retained twice as many adults as rolled oats. Retention of *Cryptolestes pusillus* and *T. castaneum* was equal for cracked maize, cracked wheat, cracked sorghum, rolled oats, and the mixture of all five foods, but the retention of 3 and 5%, respectively, of these two species for kibbled carob was similar to the retention percent for autoclaved gravel. Gravel provided only shelter and retained a mean 2.6% of *C. pusillus*, 7% of *T. castaneum*, 0.8% of *Sitophilus oryzae*, and 0.2% of *Oryzaephilus surinamensis* when three of the cracked grains were also present nearby. Kibbled carob retained 3% of *O. surinamensis* and 4% of *S. oryzae*. Cracked maize and cracked wheat retained more *S. oryzae* than the other three foods. *T. castaneum* and *S. oryzae* were attracted to just the volatiles from maize, oats, rice, soybeans, and wheat, and *T. castaneum* also was attracted to millet volatiles. In other studies, volatiles of carob increased the catch of *C. pusillus*, *O. surinamensis*, and *Prostephanus truncatus* by 50%. How long the insects remain with the food probably depends upon other environmental factors as well as the food odor.

In a comparison of 18 household foods and oil seeds, *Oryzaephilus mercator* preferred bran, shelled sunflower seed, rolled oats, and brown rice. Walnuts and flaxseed ranked next among the preferred foods. *O. mercator* preferred foods with a high oil content. These foods were less preferred when pulverized, possibly because the dense packing made them more difficult to penetrate. Few insects were found in wheat germ flakes, cornflakes, whole rapeseed, or raisins. Preferences became less evident as the number of foods in the choice tests increased, but having a high-preference food next to a low-preference food did not consistently increase the number of beetles in the low-preference food.

The studies on potential food-baits were done to help interpret trap catch and to determine whether better food-baits could be used to trap each of several stored-product insect species. The studies were designed to determine whether certain food-

baits work best for each insect species. The behavior of an insect before being caught in a food-bait trap may be similar to its behavior before infesting commodities, so studies such as these also may suggest ways of reducing insect infestations. The complexity of food and egg-laying site selection by insects in the marketing system is apparent if one imagines expanding theses studies to include all of the foods listed in Table 1.2.

Some stored-product insect species may avoid areas treated with certain residual insecticides. Some *Rhyzopertha dominica* adults avoided areas treated with **bioresmethrin** and **pyrethrins** but not those treated with **carbaryl** and **fenithrothion**. Some *Tribolium castaneum* adults avoided areas treated with **DDT**, **lindane**, bioresmethrin, and pyrethrins but not those treated with **chlorpyrifos-methyl**, **malathion**, **pirimiphos-methyl**, or **permethrin**. However, food treated with primiphos-methyl was avoided by some *T. castaneum* larvae. Some *Sitophilus oryzae* and *S. zeamais* males, but not females, avoided permethrin-treated areas, and neither sex avoided fenitrothion-treated areas. *Amyelois transitella* was not repelled by 0.5% permethrin or cypermethrin and 1% **fenvalerate**. *Plodia interpunctella* males were not repelled by permethrin. Residual insecticides that are avoided by stored-product insect pests may be less effective than those that do not repel insects.

The defenses of some stored-product insect species can influence the mobility of other insect species. The easily detachable hastisetae from *Trogoderma inclusum* and *T. variabile* have been found attached to the setae of *Cryptolestes pusillus*, *Sitophilus oryzae*, and other species, binding their antennae and legs together and reducing their mobility. Entanglement resulted in 83% mortality of *C. pusillus* and 93% mortality of *S. oryzae* in 72 hr. The setae of *Anthrenus flavipes* prevent attack by the parasitoid *Laelius pedatus*. *Habrobracon hebetor* can be chased away when host larvae try to bite them. Secretions from the sawtooth projections of *Oryzaephilus surinamensis* pupae repelled *Xylocoris flavipes* upon contact but not from a distance. *Tribolium castaneum* and other stored-product tenebrionids produce quinones that can repel other insects. This species also escapes predators by feigning death. The duration of feint for both sexes ranged from 2 to 26 sec and was negatively correlated with the propensity for feigning among five strains.

Some species have been shown to respond to a gradient, by spending more time at their preferred carbon dioxide or fumigant concentration, dockage level, humidity, or temperature. In a gradient, *Cryptolestes ferrugineus* favored higher carbon dioxide concentrations up to 37% and warmer temperatures. *Oryzaephilus surinamensis* dispersed into areas of 36–66% carbon dioxide and 0.9–1.7% oxygen and died. In choice tests, *Tribolium castaneum* and *T. confusum* were increasingly attracted to carbon dioxide concentrations from 0.25 to 15%, but higher concentrations of 60–90% were repellent. More *Sitophilus granarius* dispersed further in response to purging of a column of wheat from above with 1% oxygen or 19% carbon dioxide than to purging from below. With 1% oxygen, more of the insects were attracted, and they moved closer to the inlet. With a combination of 19% carbon dioxide and 1% oxygen, more of the insects moved away from the inlet. With a combination of 95% carbon dioxide and 1% oxygen, insects were anesthetized and did not move.

Susceptible *Sitophilus granarius* strains were repelled by a **phosphine** concentration of more than 0.5 mg/L or a **methyl bromide** concentration of 2 mg/L, but a resistant strain was not. *Cryptolestes ferrugineus* did not respond to the fumigant, and *Oryzaephilus surinamensis* and *Tribolium castaneum* were attracted to phosphine. In a

gradient ranging from 0 to 13.5% dockage, *T. castaneum* spent more time at the locations where wheat had the highest dockage levels. *C. ferrugineus* moved more slowly in wheat with 10% dockage, and its positive response to gravity was stronger than that to dockage. The **parasitoid** *Lariophagus distinguendus* favored a relative humidity of 32.5% over higher humidities between 53 and 97.5%. Knowing the types of gradients that exist and the way that insects respond to them may allow insect pests to be suppressed more effectively.

Stored-product insects may respond to combinations of environmental factors. For *O. surinamensis* larvae, a low light intensity or a tight hiding place influenced mobility more than favorable humidity. For *Sitophilus zeamais*, tactile stimulus preference took precedence over humidity preference, and starvation or dehydration increased the response toward high humidity. Flour with the highest moisture was most attractive to *Tribolium castaneum*, and attraction increased with starvation. In the absence of food odor, well-fed *T. castaneum* favored the lowest humidity, but after starvation, more of them favored the highest humidity. For *Cryptolestes ferrugineus*, positive response to gravity is strongest, but this is overcome by temperature or a combination of high carbon dioxide concentration and humidity. For adult *Sitotroga cerealella*, the physical stimulus provided by a crevice was more important in choosing an egg-laying site than was food odor.

Rhyzopertha dominica adults generally favored low humidities and light intensities, and their response to humidity was stronger than their response to light. Desiccated adults favored high humidities. The average distance traveled during one half hour was higher for undesiccated than for desiccated adults (247 versus 139 cm). In a two-choice chamber, undesiccated beetles moved at an average speed of 10.0 cm/min on the moist side and 8.1 cm/min on the dry side. Desiccated adults moved at an average speed of 3.9 cm/min on the moist side and 7.0 cm/min on the dry side. The number of undesiccated or desiccated adults crossing the boundary between the dry and the moist sides was very small, with 97% of the undesiccated adults turning back to the dry side as they approached the boundary, and 86% of the desiccated adults turning back to the moist side as they approached the boundary. Knowing that insects respond to combinations of environmental factors rather than responding to each environmental factor independently may be important in planning and implementing the most-effective insect pest management program.

Insect pest management practices such as aeration, cleaning, or heat treatments can increase insect mobility. Insect pest management methods such as sanitation and fumigation may be most effective when done while insects are not moving, whereas space treatments with residual insecticides may be most effective at a time when insects are on the move.

Physiological state

Insect behavior generally depends upon the physiological processes of the nervous, endocrine, and muscular systems. Thus, the internal physiological state of an insect influences its propensity to move and the direction, pattern, and speed of the movement. The response of insects to environmental factors can vary with their physiological state, and therefore it is important to determine the physiological state of insects when sampling insect populations. The age or sex of an insect and whether it has fed or mated can provide a simple measure of its physiological state. A variety of methods

have been developed for determining the age or sex of insects and whether they have fed or mated (see Chapter 2).

Often, only the numbers of each stored-product insect species caught in traps are recorded. However, converting the trap catch to absolute estimates of insect population density also may require information about the physiological state of these insects as well as their environment. Insects in some physiological states may not readily be caught in traps, resulting in an underestimation of the overall insect population density, while insects in other physiological states may be so readily caught as to result in an overestimation of the overall insect population density. More studies are needed on the effect of the physiological state of stored-product insects on their response to environmental factors and the likelihood of insects being caught in traps.

The following three examples illustrate how the physiological state can influence insect dispersal and thus the ecology, sampling, and management of stored-product insect pests. First, the tendencies for male *Tribolium castaneum* to tunnel more in flour than females and for the tunneling by both sexes to increase with age determine when and how many insects will leave the flour. Second, when *Rhyzopertha dominica* or *Prostephanus truncatus* adults do not disperse from grain during the first week or two after **eclosion**, they may be less likely to disperse. Third, two morphologically and physiologically distinct forms of *Callosobruchus maculatus* behave differently (see recommended reading by Utida). The flightless form breeds in stored seeds, and the active (flying) form breeds on seeds in the fields before harvest. Crowding larvae, high temperatures, dry food, and very short or very long **photoperiods** induce the flight form.

Distance moved

The distances moved by dispersing insects have been studied for several species of stored-product insects (Table 3.3). Their mobility results in stored-product insects infesting crops in the field before harvest, infesting other commodities stored within the same facility, and possibly moving among storage and processing facilities. *Tribolium castaneum* adults can walk 53 m (175 ft) per day, and adult *Cadra cautella* males fly 300 m (984 ft) during an average 10-min flight. Using the **mark-recapture** method in a warehouse, *Trogoderma variabile* adults were captured up to 216 m (708 ft) from where they were marked. Outdoors, *T. variabile* adults have been shown to fly 75 m (246 ft) from marking stations over several months. *Sitotroga cerealella* adults flew up to 400 m (1,320 ft) over a three-week period after leaving bins; *Plodia interpunctella* adults flew 135.6 m (445 ft) during their lifetime; *Prostephanus truncatus* adults flew 340 m (1,115 ft) in 24 hr; and *Sitophilus zeamais* adults flew up to 400 m (1,320 ft) over several weeks. These insects are not likely to fly in a straight line, and their flight paths are likely to be longer than the measured linear distances of 75–400 m.

When *Teretrius nigrescens*, a predator of *P. truncatus*, was first released in Kenya in 1992, it moved 16 km (9.9 miles) downwind over an eight-month period. In Texas, *Cynaeus angustus* adults moved 0.8 km (0.5 miles) downwind from the cotton-ginning residues in which they were breeding. Before 1900, this species was found breeding in decomposing plants in the southwestern United States. Between 1900 and the early 1970s, it spread across the United States and became a pest of several cereal grains. In 1964, it was intercepted in a shipment of tobacco from Georgia to Dublin, Ireland.

Cryptolestes ferrugineus adults in the laboratory moved at a speed of >10.8 m/day (>35.6 ft/day) down into a column of wheat, and on-farm, they moved to a depth of >2 m (>6.6 ft). In flat storage, *Lariophagus distinguendus* was able to locate its hosts, *Sitophilus granarius*, up to 4 m (13 ft) vertically or horizontally from a **parasitoid** release point in wheat.

Although experimental containers often limited the distance moved, laboratory tests have shown that the adults of several stored-product insect species are capable of moving considerable distances within bulk commodities. In laboratory tests, 62% of *Sitophilus zeamais* and 13% of *Prosephanus truncatus* moved down through maize more than 2.5 m (8.2 ft) in three weeks. *Sitophilus* spp. moved as much as 2 m (6.6 ft) through wheat. *Rhyzopertha dominica*, *Sitophilus oryzae*, and *Latheticus oryzae* moved 1.2 m (4 ft) down through stacked bags of wheat in two weeks. *Oryzaephilus surinamensis* moved 1 m (3.3 ft) in 24 hr, but only 0.3% of *R. dominica* and *S. oryzae* moved more than 0.5 m (1.65 ft) in 72 hr.

The **natural enemies** *Anisopteromalus calandrae*, *Theocolax elegans*, and *Xylocoris flavipes* moved to a depth of >2 m (>6.6 ft) in wheat or peanuts; *Eupelmus vuilleti* moved to a depth of greater than 0.6 m (2 ft) in cowpeas; *Trichogramma evanescens* moved up to 0.55 m (1.8 ft) in wheat; and *Trichogramma pretiosum*

Table 3.3. Studies on distances moved by stored-product insects

Insect species	Source
Anisopteromalus calandrae	Press 1988, 1992
Cadra cautella	Hagstrum and Davis 1980
Cryptolestes ferrugineus	Hagstrum 1989, Jian et al 2004b
Cynaeus angustus	Dunkel et al 1982
Ephestia elutella	Richards and Waloff 1946
Eupelmus vuilleti	Cortesero et al 1997
Lariophagus distinguendus	Steidle and Schöller 2002, Steidle et al 2003
Latheticus oryzae	Sharangapani and Pingale 1956
Oryzaephilus surinamensis	Navarro et al 1981
Plodia interpunctella	Campbell and Mullen 2004
Prostephanus truncatus	Farrell and Key 1992, Hodges et al 1999
Rhyzopertha dominica	Navarro et al 1981, Sharangapani and Pingale 1956
Sitophilus spp.	Howe 1951
S. oryzae	Navarro et al 1981, Sharangapani and Pingale 1956
S. zeamais	Chestnut 1972, Hodges et al 1999
Sitotroga cerealella	Barney and Weston 1996
Teretrius nigrescens	Giles et al 1996
Theocolax elegans	Press 1992
Tribolium castaneum	Campbell and Hagstrum 2002
Trichogramma evanescens	Schöller et al 1994
T. pretiosum	Brower 1990
Trogoderma granarium	Nutting and Gerhardt 1964
T. variabile	Campbell and Mullen 2004, Campbell et al 2002
Xylocoris flavipes	Press et al 1978, 1979

moved up to 0.2 m (0.7 ft) in peanuts. In the case of *X. flavipes*, the depth reached in a commodity was influenced by the particle size. *A. calandrae* tended to move upward in wheat.

Mature larvae of *Trogoderma granarium* and *Ephestia elutella* generally move only a short distance, but some move as far as 12–15 m (39–49 ft). Adults of *Oryzaephilus mercator*, *O. surinamensis*, *Sitophilus granarius*, *Tribolium confusum*, *Trogoderma granarium*, and some *Callosobruchus maculatus* (flightless morph) rarely fly, do not fly, or have no wings and cannot fly, and these insects depend upon adult and larval dispersal by walking and the movement of commodities by commerce.

Utilization of mobility information

Knowledge of stored-product insect mobility can be used in at least three ways. First, knowledge of insect mobility can be used to predict insect spatial distribution. Second, it can be used to convert trap catch to absolute estimates of insect population density. Third, it can be used to manipulate insect spatial distribution so as to improve stored-product insect pest suppression. The authors hope that the detailed descriptions of insect behavior and the many factors influencing insect mobility given in this chapter and the cited research papers will make the readers more aware that many environmental factors and the physiological state of the insects caught in traps may often need to be considered in converting trap catch to absolute estimates of insect population density and that there are many opportunities to manage insect behavior by manipulating their environment.

Predicting stored-product insect spatial distribution can be useful in directing insect pest management programs toward areas where insect densities are greatest. Knowing the propensity of different stored-product insect species to move, the distance they can move, and the direction, pattern, and speed of their movement will be important in predicting changes in insect spatial distribution over time. With a constant percentage of insects leaving, a larger number of insects will leave areas of high insect density than areas of low insect density. This will be moderated by the tendency for insects to remain in favorable environments for a longer time. Given the many environmental factors (at least 10 types of biological, four chemical, and seven physical factors are included in the studies listed in Table 3.2) that influence insect movement, the importance of an insect's physiological state in determining its response to these environmental factors, and the response of insects to combinations of environmental factors rather individual environmental factors, it should be clear why computer-simulation models that predict insect spatial distribution can be important in fully using this information to plan and implement studies, sampling programs, and insect pest management programs.

Traps can detect infestations at much lower densities than other sampling methods, but the effects of physiological state and many environmental factors on insect mobility may need to be considered in converting trap catches to absolute densities. The example in Chapter 5 showing trap catches in grain bins declining in the autumn because of low insect mobility at cooler temperatures while the insect populations are still increasing illustrates the importance of converting trap catches to absolute insect densities.

A simple example of manipulating stored-product insect behavior to improve insect pest suppression is treating small areas with a combination of an insect attractant and a

residual insecticide. For the best results, many of the environmental factors in the studies in Table 3.2 such as temperature, light intensity, air movement, and the proximity to food or shelter should be considered in choosing the area or areas to treat with the residual insecticide and insect attractant combination.

Study questions

1. What benefits does their mobility provide for the stored-product insect pests?
2. How do environmental factors and the physiological state of insects influence the success of insects in finding essential resources?
3. What sequences of behaviors allow *Tribolium castaneum* females to find places to lay eggs, *Cadra cautella* adults to find mates, and stored-product insects to infest stored grain?
4. How does their mobility make stored-product insect pests difficult to manage?
5. How can knowledge of insect mobility be exploited in insect pest management programs for stored-product insects?

Recommended readings

Campbell, J. F., and Hagstrum, D. W. 2002. Patch exploitation by *Tribolium castaneum*: Movement patterns, distribution and oviposition. J. Stored Prod. Res. 38:55-68.

Hagstrum, D. W. 1984. Growth of *Ephestia cautella* (Walker) population under conditions found in an empty peanut warehouse and response to variations in the distribution of larval food. Environ. Entomol. 13:171-174.

Hagstrum, D. W. 1989. Infestation by *Cryptolestes ferrugineus* of newly-harvested wheat stored on three Kansas farms. J. Econ. Entomol. 82:655-659.

Hagstrum, D. W. 2000. Using five sampling methods to measure insect distribution and abundance in bins storing wheat. J. Stored Prod. Res. 36:253-262.

Hagstrum, D. W. 2001. Immigration of insects into bins storing newly harvested wheat on 12 Kansas farms. J. Stored Prod. Res. 37:221-229.

Hagstrum, D. W., and Davis, L. R., Jr. 1980. Mate-seeking behavior of *Ephestia cautella*. Environ. Entomol. 9:589-592.

Hagstrum, D. W., and Gilbert, E. E. 1976. Emigration rate and age structure dynamics of *Tribolium castaneum* populations during growth phase of a colonizing episode. Environ. Entomol. 5:445-448.

Hagstrum, D. W., and Smittle, B. J. 1980. Age- and sex-specific tunneling rates of adult *Tribolium castaneum*. Ann. Entomol. Soc. Am. 73:11-13.

Mankin, R. W., and Hagstrum, D. W. 1995. Three-dimensional orientation of male *Cadra cautella* (Lepidoptera: Pyralidae) flying to calling females in a windless environment. Environ. Entomol. 24:1616-1626.

McFarlane, J. A., Gudrups, I., and Fletcher, H. 1993. Biotype differences affecting the pest status of stored-grain insects. Int. J. Pest Manage. 39:35-43.

Toews, M. D., Campbell, J. F., Arthur, F. H., and West, M. 2005. Monitoring *Tribolium castaneum* (Coleoptera: Tenebrionidae) in pilot-scale warehouses treated with residual applications of (S)-hydroprene and cyfluthrin. J. Econ. Entomol. 98:1391-1398.

Utida, S. 1972. Density dependent polymorphism in the adult of *Callosobruchus maculatus* (Coleoptera: Bruchidae). J. Stored Prod. Res. 8:111-126.

Chapter 4

Sources of Infestation

Finding the source populations for insect infestations may be critical to the success of an insect pest management program. Several sources of stored-product insect infestation are often important, and they may be found at many locations in the marketing system. Finding these source populations is difficult because of the range of foods on which stored-product insects feed and the insects' mobility. Some species of stored-product insects can breed on wild hosts. However, such species generally reach much higher numbers on stored commodities and commodity residues in storage, processing, and marketing facilities and in transportation vehicles. Thus, insects infesting stored commodities and their residues may often be a more important source of new infestations than insects breeding on wild hosts. Insects infesting crops in the field before harvest often have been shown to come from nearby storages. In many cases in which stored-product insects have been found in natural habitats (such as bird, rodent, and insect nests or under tree bark), there is little evidence that they are breeding in these habitats and not simply migrants from the food-marketing system.

Wild hosts

Species of wild hosts on which stored-product insects are known to complete their development in the laboratory are given in Table 4.1. Little information is available on how well these stored-product insect species breed on these wild hosts in the field. In the 13 studies included in Table 4.1, 14 stored-product insect species were found to develop on wild host species. Acorns were utilized by 10 species, and the other wild hosts were each utilized by one to six species. Only acorns, horse chestnuts, and beechnuts that were cracked were utilized. In many cases, stored-product insect developmental times were longer and mortalities were higher on wild hosts than on stored products.

Sitotroga cerealella and *Callosobruchus chinensis* are each known to breed on several species of seeds while the seeds are still on the plants. *Prostephanus truncatus* is capable of breeding in the laboratory on the roots and branches of 35 species of trees in 11 families. However, the adults and larvae of this species have been recovered only from cerambycid-girdled branches of one tree species, *Lannea nigritana*, in the forests of Benin, Kenya, and Mexico. The majority of the *P. truncatus* adults trapped in the forested areas of Benin had fed on trees (see recommended reading by Borgemeister et al). In agricultural areas, more of the captured *P. truncatus* had fed on maize or cassava, but there were still substantial numbers that had fed on trees. Although newly stored maize or cassava may be infested with large numbers of *P. truncatus* from stored maize or cassava, these crops may also be infested with a substantial number of the insects that have bred on trees. Bringing firewood from the forest and storing it may bring *P. truncatus* closer to grain and cassava stores.

Other species breed on seeds stored by ants and rodents. The marginal quality of seeds and fruits from grasses, trees, and shrubs as food for stored-product insects, in addition to their small quantities, limits the importance of these foods in breeding source populations. Flowering plants have been reported to attract stored-product

Table 4.1. Wild hosts on which stored-product insects can develop

Wild host	Insect species	Source[a]
Acorn	*Anagasta kuehniella*	Stein 1990
	Cadra cautella	Joubert 1966
	Oryzaephilus surinamensis	Joubert 1966, Stein 1990
	Rhyzopertha dominica	Stein 1990, Wright et al 1990
	Sitophilus granarius	Howe 1965, Stein 1990
	Sitophilus oryzae	Howe 1965, Joubert 1966, Stein 1990
	Sitophilus zeamais	Mills 1989
	Stegobium paniceum	Stein 1990
	Plodia interpunctella	Stein 1990
	Tribolium castaneum	Joubert 1966
Amphicarpaea edgeworthii	*Callosobruchus chinensis*	Shinoda et al 1991
Beechnut	*Anagasta kuehniella*	Stein 1990
	Oryzaephilus surinamensis	Stein 1990
	Plodia interpunctella	Stein 1990
	Rhyzopertha dominica	Stein 1990
	Stegobium paniceum	Stein 1990
	Tribolium confusum	Stein 1990
Buckbrush	*Rhyzopertha dominica*	Wright et al 1990
Dunbaria villosa	*Callosobruchus chinensis*	Shinoda et al 1991, 1992
Hackberry	*Rhyzopertha dominica*	Wright et al 1990
Hipberries	*Rhyzopertha dominica*	Stein 1990
	Stegobium paniceum	Stein 1990

(*continued on next page*)

insects. Adults of three species—*Sitophilus oryzae*, *S. zeamais,* and *Lasioderma serricorne*—have been found feeding on flowers, and this may increase their longevity and reproduction. Therefore, such attractive flowering plants should not be planted around food storage, processing, and marketing facilities because they can attract insects that may enter the facility.

Field infestation

Infestation of grain in the field by stored-product insects of the families Bruchidae, Bostrichidae, Curculionidae, and Gelechiidae is quite common in many countries (Table 4.2). Insects in these families generally develop inside seeds, although only members of the family Curculionidae lay their eggs inside the seeds. In the 54 studies cited in Table 4.2, 19 insect species were found to infest 16 crops in one or more of 18 countries and eight states in the United States. Seven stored-product insect species are known to infest cowpeas and sorghum in the field; six infest maize; and one to three species infest other crops. *Callosobruchus chinensis* infests six crops in the field, and *C. maculatus* and *Sitotroga cerealella* each infest five crops in the field. The other stored-product insect species each infest one to four crops in the field.

Table 4.1 (continued)

Wild host	Insect species	Source[a]
Horse chestnut	*Anagasta kuehniella*	Stein 1990
	Oryzaephilus surinamensis	Stein 1990
	Plodia interpunctella	Stein 1990
	Stegobium paniceum	Stein 1990
Prunus aucuparia fruit	*Anagasta kuehniella*	Stein 1990
	Oryzaephilus surinamensis	Stein 1990
	Plodia interpunctella	Stein 1990
	Rhyzopertha dominica	Stein 1990
	Stegobium panaceum	Stein 1990
Pueraria lobata	*Callosobruchus chinensis*	Shinoda et al 1991
Various seeds	*Oryzaephilus surinamensis*	Wicklow et al 1994
	Sitotroga cerealella	Joubert 1966
	Tribolium castaneum	Wicklow et al 1994
Trees of 35 species	*Prostephanus truncatus*	Borgemeister et al 1998b; Nang'ayo et al 1993, 2002; Nansen et al 2004b; Ramirez Martinez et al 1994
Vigna angularis	*Callosobruchus chinensis*	Shinoda et al 1991, 1992

[a] Linsley 1944 lists many natural habitats, including the nests of insects, birds, and rodents in which stored-product insects have been found, but he provides little information on the suitability of the food available in these habitats for insect development, survival, and reproduction. Insect population growth may be very limited in these habitats. Attraction of stored-product insects to flowers has been reported by Buchelos 1989 for *Lasioderma serricorn*e, Williams and Floyd 1971a for *Sitophilus zeamais*, and Yoshida and Takuma 1959 for *Sitophilus oryzae*, and the effect of water and pollen on egg production by *Lasioderma serricorne* has been reported by Shinoda and Fujisaki 2001.

Threshing separated 10–20% of *Sitophilus zeamais* from maize. These internal-feeding insects are less likely to be separated from the grain during harvest than external-feeding insects. Field infestation by external-feeding stored-product insects can be a problem when grain is stored without threshing or shelling. *Cathartus quadricollis* has been found to infest maize in substantial numbers in the field before harvest. *Ahasverus advena*, *Tribolium castaneum*, and *Typhaea stercorea* infest maize and sorghum in the field. Also, insects from storage facilities may infest commodities during drying, which may be mistaken for field infestation.

Field infestation rates have been estimated for several stored-product insect species in many countries (see recommended reading by Hagstrum et al). Preharvest *Callosobruchus maculatus* infestations ranged from 0.001% of cowpea seeds in the United States to 3–13% of the pigeonpea seeds in India. *Callosobruchus chinensis* adults were reported to lay eggs on 14% of azuki beans in the field in Japan, but on only 41% of these beans did the eggs hatch and the larvae bore into seeds. Field infestations of 16 *Acanthoscelides obtectus* per 1,000 beans (1.6%) were reported for Colombia. Field infestations by *Sitotroga cerealella* varied from 0 to 13% of maize ears between regions of southern Indiana and from 0.4 to 0.03% of wheat kernels in

Maryland over a distance of 185 m (607 ft) from the probable source of infestation. Densities of *S. cerealella* infesting grain in the field in India varied from three to one insect per infested maize cob and three to 0.3 insect per infested rice head over distances of 200–1,000 m (656–3,281 ft) from villages. Field infestation by *S. cerealella* infesting rice in the field in Bangladesh was found to be zero at 11–12 days before

Table 4.2. Studies dealing with field infestation of crops by stored-product insects

Insect species	Crop	Location	Source
Acanthoscelides obtectus	beans	California	Larson 1924, Larson and Fisher 1924, 1925
	beans	Colombia	Schmale et al 2002
	beans	Russia	Vasil'ev 1935
	beans	Uganda	Nyiira 1970
	cowpea	Kenya	Olubayo and Port 1997
Ahasverus advena	maize	Mexico	Tigar et al 1994, Rodriguez-del-Bosque et al 1998
	sorghum	Uganda	Nyiira 1970
Amyelosis transitella	almond	California	Kuenen and Barnes 1981
	walnuts	California	Johnson et al 1998
Bruchidius atrolineatus	cowpea	Kenya	Warui 1984
	cowpea	Nigeria	Prevett 1961
Callosobruchus analis	cowpea	Kenya	Warui 1984
Callosobruchus chinensis	azuki beans	Japan	Shinoda and Yoshida 1985
	cowpea	India	Rai 1979
	cowpea	Kenya	Olubayo and Port 1997, Warui 1984
	cowpea	South Africa	Oosthuizen and Laubscher 1940
	mungbean	Thailand	Promsatit et al 1986
	pigeonpea	India	Singal 1987, Singh et al 1989
	pigeonpea	Uganda	Nahdy 1999a,b; Nahdy et al 1998
	redgram	India	Gunathilagaraj et al 1977
	soybean	Thailand	Promsatit et al 1986
Callosobruchus maculatus	beans	Uganda	Nyiira 1970
	cowpea	Nigeria	Booker 1967, Prevett 1961
	cowpea	Florida	Hagstrum 1985
	cowpea	Kenya	Olubayo and Port 1997
	mungbean	Thailand	Promsatit et al 1986
	pigeonpea	India	Patnaik et al 1986, Sharma and Ali 1991
	soybean	Thailand	Promsatit et al 1986

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harvest and increased up until harvest. Densities at harvest varied from 1.3 to 0.4 insects per rice head over distances of 10–1,440 m (32.8–4,725 ft) from storage. Densities of *Sitophilus zeamais* infesting maize in the field varied from 0.4 to 1.2 insects per 0.6 L of grain for 38 varieties in Australia and from 2.5 to 0.3 insect per infested cob in India over distances of 200–800 m (656–2,625 ft) from villages. Field

Table 4.2 (continued)

Insect species	Crop	Location	Source
Callosobruchus phaseoli	cowpea	Kenya	Warui 1984
Callosobruchus rhodesianus	cowpea	Kenya	Olubayo and Port 1997, Warui 1984
Callosobruchus theobromae	pigeonpea	India	Singal 1987
Cathartus quadricollis	maize	Benin	Borgemeister et al 1998a
	maize	Mexico	Rodriguez-del-Bosque et al 1998
	maize	South Carolina	Cartwright 1939
Phthorimaea operculella	potato	Tunisia	Fuglie et al 1993
Prostephanus truncatus	maize	Benin	Borgemeister et al 1994, 1998a
	maize	Mexico	Tigar et al 1994
Rhyzopertha dominica	maize	Mexico	Rodriguez-del-Bosque et al 1998
	sorghum	Nigeria	Giles 1964
	sorghum	Philippines	Carino and Morallo-Rejesus 1976
	wheat	India	Doharey et al 1979
Sitophilus oryzae	barley	Japan	Kiritani et al 1957
	maize	Georgia	LaHue 1958
	maize	India	Sharma 1995
	maize	Uganda	Nyiira 1970
	sorghum	Nigeria	Giles 1964
	sorghum	Uganda	Nyiira 1970
	wheat	Australia	Rossiter 1970
	wheat	India	Agrawal et al 1977
	wheat	Japan	Kiritani et al 1957
Sitophilus zeamais	maize	Australia	Turner 1976
	maize	Georgia	Brown and Lee 2002, Keever et al 1988
	maize	Kenya	Giles and Ashman 1971
	maize	Mexico	Rodriguez-del-Bosque et al 1998, Tigar et al 1994

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infestations generally decreased with the distance from the probable source, suggesting that stored grain is a primary source of field infestations.

Sitotroga cerealella must lay eggs on maize with 50–55% moisture in the field and complete development as maize dries to <31% moisture. *Sitophilus zeamais* completes development as maize dries from 60–65 to 20–25% moisture in the field. Field infestation rates are highest when the crop is allowed to dry in the field, insects develop on the standing crop, and their offspring lay eggs on the standing crop before harvest. However, on cowpea pods in the field in Niger, 75% of *Callosobruchus maculatus* eggs were parasitized by *Uscana lariophaga* or knocked off of the pods by wind and rain, and, under these circumstances, only 6.1% of the insects became adults (see recommended reading by Sagnia).

For 49 fields in Florida, an average of one cowpea seed out of every 100,000 was infested by *C. maculatus* in the field before harvest (see recommended readings by Hagstrum). The one or two bushels of cowpeas left in the field as a result of combine inefficiency were probably infested at the same level and may have been important in carrying over insect populations from one crop year to the next. In the warehouse,

Table 4.2 (continued)

Insect species	Crop	Location	Source
	maize	Philippines	Bernabe-Adalla and Bernardo 1976, Schwettmann 1988
	maize	South Carolina	Cartwright 1939
	sorghum	Philippines	Carino and Morallo-Rejesus 1976
Sitotroga cerealella	maize	Australia	Turner 1976
	maize	Georgia	Blickenstaff 1960
	maize	India	Sharma 1995, Singh et al 1978
	maize	Indiana	Russell 1962
	maize	Kentucky	Weston et al 1993
	maize	Louisiana	Floyd et al 1959
	maize	South Carolina	Cartwright 1939
	millet	Senegal	Seck 1991
	rice	Bangladesh	Howlander and Matin 1988
	rice	India	Singh et al 1978, Sundararaj and Sundararajan1990
	rice	Louisiana	Douglas 1941
	rice	Sri Lanka	Ganesalingam and Krishnarajah 1979
	sorghum	Nigeria	Giles 1964
	wheat	India	Agrawal et al 1977
	wheat	Maryland	Simmons 1927
Tribolium castaneum	maize	Mexico	Rodriguez-del-Bosque et al 1998
	sorghum	Nigeria	Giles 1964
Typhaea stercorea	maize	Mexico	Rodriguez-del-Bosque et al 1998
	sorghum	Uganda	Nyiira 1970

more than one *C. maculatus* emerged from the seed in only 30% of the one-bushel bags of cowpeas. Low temperatures soon after the cowpeas were stored in the autumn apparently delayed the development of the *C. maculatus* breeding inside the bags of cowpeas, and the insect population density remained low for 18 weeks. In the spring, insect populations grew 10-fold every six weeks in 25% of the infested bags. In the other infested bags, the *C. maculatus* populations died out, probably because the insect densities were too low for the insects to find a mate.

Delayed planting of maize reduced field infestation by *Sitotroga cerealella* in Kentucky, but this technique was not practical. The yield decreased by 1% for each day that planting was delayed, and other preharvest insect pests were more of a problem. Also, early harvest increased the cost of drying. Harvesting the maize crop sooner decreased field infestation by *Prostephanus truncatus* in Benin, but molds and aflatoxins were likely to be a greater problem. Intercropping cowpeas and maize reduced field infestation in Kenya. Insect infestation is often highest near the edge of a field. The edge rows could serve as a trap crop if they were harvested first and fumigated to kill insects. Preharvest application of residual insecticides to kill postharvest insect pests also has been considered a means of reducing field infestations of *C. maculatus* and *Callosobruchus chinensis* on mungbeans in Thailand, *Sitotroga cerealella* and *Sitophilus oryzae* on maize in India, and *Sitophilus zeamais* and *Rhyzopertha dominica* on sorghum in the Philippines (see Chapter 8). Preharvest application of residual insecticides generally had to be used in combination with other insect pest management methods to effectively manage these stored-product insect pests.

Amyelois transitella infestation of walnuts or almonds, *Bruchidius atrolineatus* infestation of cowpeas, and *Phthorimaea operculella* infestation of potatoes occur primarily before harvest. However, reproduction of these insect species during storage is limited. These three internal-feeding insect species are some of the most prominent, but not the only, insect pests in the field that also are a problem during storage. Management of these insect pests involves a reduction of the field populations before harvest and disinfestations of the incoming commodities to reduce damage. Early harvest and keeping the soil wet so that the moth larvae cannot reach the potatoes is effective for *P. operculella*. Reduction of the *A. transitella* populations that are carried over in the orchards by reducing the numbers of nuts remaining on the trees after harvest can be effective in reducing storage problems. Resistant varieties may be effective in reducing *B. atrolineatus* infestations in the field.

Residual infestation

Only a small amount or a thin dust layer of food residue is necessary for many stored-product insect species to develop, survive, and reproduce. Insect populations living on food residues in storage, processing, transportation, and marketing habitats are difficult to study because sampling the food residues can alter the distribution and abundance of these insect populations and the availability of food. Except for food-bait traps, traps do not directly alter the availability of food, but traps may alter the distribution and abundance more than other sampling methods because of their high capture rates. Furthermore, traps provide less-precise information about insect distribution and abundance.

Insects infesting food residues in storage, processing, and marketing facilities and in transportation vehicles (Table 4.3) include many of the stored-product insect pest species that are capable of causing significant or extensive damage. Locations in the mar-

keting system at which residual infestations of stored-product insects were sampled included six types of storages, seven types of processing facilities, two types of transportation vehicles, and four types of retail stores, as well as combines, residences, and stables. Out of the 49 species of stored-product insect pests commonly found in the 41 studies, 17 species were found in raw commodity storages, 36 species in

Table 4.3. Stored-product insect species most commonly found infesting commodity residues

Insect species	Location	Source[a]
Ahasverus advena	cargo container	Stanaway et al 2001
	elevator	Dowdy and McGaughey 1998
	farm	Barker and Smith 1987, 1990; Smith and Barker 1987
	feed mill	Pellitteri and Boush 1983
	pet store	Roesli et al 2003a
Alphitobius diaperinus	cargo container	Stanaway et al 2001
	feed mill	Loschiavo and Okumura 1979, Pellitteri and Boush 1983
	flour mill	Buchelos 1980
	stable	Loschiavo and Okumura 1979; Salama and Salem 1973
Anagasta kuehniella	barley mill	Imura 1981
	feed mill	Pellitteri and Boush 1983
	flour mill	Buchelos 1980, Dyte 1965, Hosny et al 1968, Salama and Salem 1973
	warehouse	Soderstrom et al 1987
Anthrenus verbasci	pet store	Roesli et al 2003a
Attagenus brunneus	feed mill	Trematerra and Sciarretta 2004
Attagenus unicolor	feed mill	Pellitteri and Boush 1983
Cadra cautella	cargo container	Soderstrom et al 1987, Stanaway et al 2001
	central store	Graham 1970
	cereal factory	Rees 1999a,b
	feed mill	Roesli et al 2003c
	flour mill	Buchelos 1980
	peanut shelling plant	Payne and Redlinger 1969
	peanut warehouse	Hagstrum and Stanley 1979
	railroad car	Cogburn 1973b
	warehouse	Cogburn 1973a, Loschiavo and Okumura 1979, Soderstrom et al 1987, Vick et al 1986
Cadra figulilella	raisin processing plant	Soderstrom et al 1987

(*continued on next page*)

processing facilities, 18 species in transportation vehicles, 14 species in retail stores, nine species in processed-commodity storages, and nine species in residences, stables, or combines. *Cadra cautella*, *Plodia interpunctella*, *Oryzaephilus surinamensis*, and *Tribolium castaneum* were found in storages for both raw and processed commodities.

Seven species (*Ahasverus advena, Lasioderma serricorne, O. surinamensis, P. interpunctella, Rhyzopertha dominica, T. castaneum,* and *Typhaea stercorea*) were com-

Table 4.3 (continued)

Insect species	Location	Source[a]
Carpophilus dimidatus	elevator	Dowdy and McGaughey 1998
	feed store	Loschiavo and Okumura 1979
	peanut shelling plant	Payne and Redlinger 1969
Carpophilus hemipterus	cargo container	Stanaway et al 2001
	feed mill	Pellitteri and Boush 1983
Carpophilus pilosellus	port warehouse	Cogburn 1973a
	railroad car	Cogburn 1973b
Corcyra cephalonica	elevator	Dowdy and McGaughey 1998
	flour mill	Hosny et al 1968
Cryptolestes ferrugineus	elevator	Dowdy and McGaughey 1998
	farm	Barker and Smith 1987, 1990; Smith and Barker 1987
	feed mill	Pellitteri and Boush 1983
	flour mill	Buchelos 1981
Cryptolestes pusillus	elevator	Dowdy and McGaughey 1998
	feed mill	Roesli et al 2003c
	retail store	Arbobast et al 2000a
Cryptolestes turcicus	feed mill	Pellitteri and Boush 1983
	flour mill	Dyte 1965, 1966
Cryptolestes spp.	cargo container	Stanaway et al 2001
	elevator	Reed et al 2003
	farm	Ingemansen et al 1986, Sinclair 1982
	flour mill	Good 1937
	pet store	Roesli et al 2003a,b
	railroad car	Cogburn 1973b
Cryptophagus varus	cargo container	Stanaway et al 2001
	farm	Barker and Smith 1987, 1990; Smith and Barker 1987
Cynaeus angustus	feed mill	Pellitteri and Boush 1983
Dermestes maculatus	cargo container	Stanaway et al 2001

(*continued on next page*)

monly found in storage, processing, and retail facilities and in transportation vehicles. *O. surinamensis, P. interpunctella, R. dominica*, and *T. castaneum* are capable of rapidly causing extensive damage to stored commodities. Five of these seven species, but not *A. advena* and *T. stercorea*, have a wide geographical distribution and were found in all or most of the studies listed in Table 1.3. Learning more about the ecology

Table 4.3 (continued)

Insect species	Location	Source[a]
Dinoderus minutus	cargo container	Stanaway et al 2001
Endrosis sarcitrella	flour mill	Dyte 1965
Ephestia elutella	tobacco redrying plant	Tenhet 1956
	warehouse	Soderstrom et al 1987
Gnatocerus cornutus	flour mill	Dyte 1965
Lasioderma serricorne	cargo container	Stanaway et al 2001
	feed mill	Roesli et al 2003c
	flour mill	Buchelos 1981
	noodle factory	Suezawa et al 1987
	pet store	Roesli et al 2003a
	port warehouse	Cogburn 1973a
	railroad car	Cogburn 1973b
	residences	Loschiavo and Okumura 1979
	retail store	Arbogast et al 2000a
	tobacco redrying plant	Tenhet 1956
	warehouse, grocery	Loschiavo and Okumura 1979
Liposcelis bostrychophila	residences	Baz and Monserrat 1999, Turner and Maude-Roxby 1989
Liposcelis brunnea	residences	Baz and Monserrat 1999
Liposcelis decolor	residences	Baz and Monserrat 1999
Liposcelis entomophila	feed mill	Roesli et al 2003c
	tobacco processing	Mashaya 1999, 2001
Necrobia rufipes	cargo container	Stanaway et al 2001
	pet store	Roesli et al 2003a,b
Oryzaephilus mercator	cargo container	Stanaway et al 2001
	feed store	Loschiavo and Okumura 1979
	flour mill	Buchelos 1981
	grocery	Platt et al 1998

(*continued on next page*)

of residual insect populations from the following summary and the studies cited in Table 4.3 should result in a better understanding of what needs to be done to suppress residual insect infestations.

The insect species found and the prevalence of each species varied among **elevators** in Kansas**.** The distribution patterns of insects among locations within and outside elevators differed among elevators. At elevators, spilled grain residues are often found

Table 4.3 (continued)

Insect species	Location	Source[a]
	peanut shelling plant	Payne and Redlinger 1969
	pet store	Roesli et al 2003a,b
	residences	Loschiavo and Okumura 1979
	retail store	Arbogast et al 2000a
	warehouse, grocery	Loschiavo and Okumura 1979
Oryzaephilus surinamensis	cargo container	Stanaway et al 2001
	elevator	Dowdy and McGaughey 1998
	farm	Ingemansen et al 1986, Walker 1960
	feed mill	Pellitteri and Boush 1983, Trematerra and Sciarretta 2004
	flour mill	Buchelos 1981
	pet store	Roesli et al 2003a,b
	port warehouse	Cogburn 1973a
Oryzaephilus spp.	elevator	Reed et al 2003
Palorus ratzeburgii	elevator	Dowdy and McGaughey 1998
	feed mill	Pellitteri and Boush 1983
Palorus subdepressus	flour mill	Buchelos 1981
Plodia interpunctella	cargo container	Stanaway et al 2001
	cereal factory	Rees 1999a,b
	elevator	Dowdy and McGaughey 1998
	feed mill	Pellitteri and Boush 1983
	flour mill	Buchelos 1980
	grocery	Platt et al 1998
	peanut shelling plant	Payne and Redlinger 1969
	peanut warehouse	Hagstrum and Stanley 1979
	pet store	Roesli et al 2003a,b
	raisin processing plant	Soderstrom et al 1987
	retail store	Arbogast et al 2000a

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along the railroad lines that are used to bring in railcars for loading and unloading, and these residues may breed insects if they are not cleaned up. However, when the residues are dampened by rain, the species breeding in them may be very different from those breeding in dry grain.

The amount of residual grain on farms and at elevators often is no more than a few bushels, but a fairly large number of insects can be attracted to these grain residues. On

Table 4.3 (continued)

Insect species	Location	Source[a]
	warehouse	Loschiavo and Okumura 1979, Soderstrom et al 1987, Vick et al 1986
Pyralis farinalis	feed mill	Pellitteri and Boush 1983
	flour mill	Buchelos 1980
Rhyzopertha dominica	barley mill	Imura 1981
	cargo container	Loschiavo and Okumura 1979, Stanaway et al 2001
	combine	Sinclair and White 1980
	elevator	Dowdy and McGaughey 1998, Reed et al 2003
	farm	Sinclair 1982
	feed mill	Loschiavo and Okumura 1979, Pellitteri and Boush 1983
	feed store	Loschiavo and Okumura 1979
	flour mill	Buchelos 1981, Good 1937
	railroad car	Cogburn 1973b
	stable	Loschiavo and Okumura 1979
Sitophilus granarius	feed mill	Pellitteri and Boush 1983
	flour mill	Buchelos 1981
Sitophilus oryzae	barley mill	Imura 1981
	combine	Sinclair and White 1980
	elevator	Dowdy and McGaughey 1998
	farm	Sinclair 1982
	feed mill	Loschiavo and Okumura 1979, Trematerra and Sciarretta 2004
	feed store	Loschiavo and Okumura 1979
	flour mill	Buchelos 1981, Good 1937, Salama and Salem 1973
	stable	Loschiavo and Okumura 1979
Sitophilus spp.	elevator	Reed et al 2003
	pet store	Roesli et al 2003a,b
Sitotroga cerealella	flour mill	Buchelos 1980
Stegobium paniceum	feed mill	Loschiavo and Okumura 1979, Pellitteri and Boush 1983, Trematerra and Sciarretta 2004

(*continued on next page*)

Australian farms, the number of insects in grain residues, as a percentage of the total number infesting the grain stored in bins and bags, was estimated to be 10% for *Cryptolestes* spp., 9% for *Rhyzopertha dominica*, 13% for *Sitophilus oryzae*, and 19% for *Tribolium castaneum*. In the United States, *S. oryzae* was found to be more common in the grain residues at elevators than in the grain stored in bins (see recommended reading by Arthur et al). The densities of this and other insect species in grain residues can

Table 4.3 (continued)

Insect species	Location	Source[a]
	grocery	Platt et al 1998
	noodle factory	Suezawa et al 1987
	pet store	Roesli et al 2003b
Tenebrio molitor	elevator	Dowdy and McGaughey 1998
	farm	Barker and Smith 1987, 1990; Smith and Barker 1987
	feed mill	Pellitteri and Boush 1983
Tenebriodes mauritanicus	elevator	Dowdy and McGaughey 1998
	feed mill	Pellitteri and Boush 1983
	flour mill	Salama and Salem 1973
Tribolium audax	farm	Barker and Smith 1987, 1990; Smith and Barker 1987
Tribolium castaneum	barley mill	Imura 1981
	cargo container	Loschiavo and Okumura 1979, Stanaway et al 2001
	central store	Boon and Ho 1988, Graham 1970, Hodges et al 1992
	combine	Sinclair and White 1980
	elevator	Dowdy and McGaughey 1998, Subramanyam and Nelson 1999
	residences	Subramanyam and Nelson 1999
	farm	Barker and Smith 1987, 1990; Ingemansen et al 1986; Sinclair 1982; Smith and Barker 1987; Walker 1960
	feed mill	Loschiavo and Okumura 1979, Pellitteri and Boush 1983, Roesli et al 2003c, Trematerra and Sciarretta 2004
	feed store	Loschiavo and Okumura 1979
	flour mill	Buchelos 1981
	peanut shelling plant	Payne and Redlinger 1969
	pet store	Roesli et al 2003a,b
	port warehouse	Cogburn 1973a
	railroad car	Cogburn 1973b

(*continued on next page*)

average 10 times more than those of insects in the grain stored in bins. This must be, in part, a result of the greater accessibility and smaller size of the grain residues.

Release-recapture studies in empty wood-crib grain-storage bins with a capacity of 22–220 t (800–8,000 bushels) in the state of Washington found that four bins had no *T. castaneum* adults or too few to detect, seven had populations ranging from 143 to 1,000 adults, and another 15 had populations ranging from 2,600 to 160,667 adults. Adults of *Oryzaephilus surinamensis* were more abundant in many of these empty bins than *T. castaneum* adults. In South Dakota, the levels of insect infestation in oats stored on farms were directly related to levels of insect infestation during the previous storage season, suggesting that insect infestations were carried over in empty bins from the previous storage season. Bins with steel floors or aeration ducts had higher insect infestations than those with cement or wooden floors. Cleaning empty bins with a vacuum cleaner reduced the insect infestations more than cleaning them with a scoop shovel or broom.

In the Canadian provinces of Alberta, Manitoba, and Saskatchewan, *Cryptolestes ferrugineus*, *Tribolium audax*, *Tenebrio molitor,* and *Cryptophagus varus* were found in 14–78% of the empty bins sampled, and *T. castaneum* and *A. advena* were found in 1–14% of these bins. Infestations of *A. advena* and *T. castaneum* in these empty bins

Table 4.3 (continued)

Insect species	Location	Source[a]
	residences	Loschiavo and Okumura 1979
	retail store	Arbogast et al 2000a
	stable	Loschiavo and Okumura 1979
	warehouse, grocery	Loschiavo and Okumura 1979
Tribolium confusum	feed mill	Pellitteri and Boush 1983, Trematerra and Sciarretta 2004
	flour mill	Buchelos 1981, Salama and Salem 1973
Tribolium spp.	elevator	Reed et al 2003
	flour mill	Good 1937
Trogoderma glabrum	feed mill	Pellitteri and Boush 1983
Trogoderma variabile	feed mill	Pellitteri and Boush 1983
Trogoderma spp.	cargo container	Loschiavo and Okumura 1979, Stanaway et al 2001
	pet store	Roesli et al 2003a
	railroad car	Cogburn 1973b
Typhaea stercorea	cargo container	Stanaway et al 2001
	elevator	Dowdy and McGaughey 1998
	feed mill	Loschiavo and Okumura 1979, Pellitteri and Boush 1983
	pet store	Roesli et al 2003a

[a] Basak 1993 and Hardy-Smith 1971 reported on stored-product insects associated with used sacks and containers, packaging materials, and refuses in marketplaces.

were more likely on farms that had experienced insect infestations the previous year. Barley, wheat, oat, and canola residues were found in these empty bins, and *T. audax* and *T. molitor* seemed to prefer oats. However, *C. ferrugineus* showed no preference. Empty bins that had been sprayed with residual insecticides or cleaned with a vacuum cleaner were more likely to be infested by *C. ferrugineus*. However, this could have been because more of the bins known to have heavy insect infestations were sprayed with a residual insecticide and cleaned with a vacuum cleaner. *C. varus* and *T. audax* were found less frequently in bins in which a residual insecticide was used, and *C. ferrugineus* and *T. molitor* were more likely to be found on farms with livestock. Farmers with livestock may be more likely to buy feed and bring insects onto the farm with it.

Without a thorough sanitation program, food residues can be the source of the insects infesting the grain stored in bins. Cleaning empty bins before refilling them with newly harvested wheat significantly reduced the number of insects in the first grain that was released from a bin at elevators in Kansas. Residual grain found outside the bins could be used (as trap crops are used for pests of field crops) to manage the residual insect pest populations on farms and at elevators. However, at elevators, this residual grain is often swept into the closest bin. Picking up the grain residues and killing the insects could reduce the number of insects on farms or at elevators.

In the tropics, stacks of bagged rice or maize are covered with a tarpaulin before fumigation. The insects outside the tarpaulin survive and may reinfest the grain soon after the fumigation (see recommended reading by Boon and Ho, and Chapter 8). Although reinfestation of grain by insects from grain residues is important when the fumigation is effective, the number of insects surviving inside the bags may be more important when the fumigation is not very effective.

In an empty peanut warehouse in the southeastern United States, *Cadra cautella* and *Plodia interpunctella* populations increased twofold per month on the scattered peanuts that remained in the warehouse. The population growth rate was much higher (37-fold per month) when the warehouse was stocked with peanuts.

The stored-product insect species found and their prevalence varied among mills, years, and locations within a mill. In 1934, when bucket elevators moved flour between steps in the milling process, *Tribolium* spp. and *Cryptolestes* spp. were common in the residues in the elevator boots. *Rhyzopertha dominica* and *Sitophilus oryzae* were common in the wheat and wheat sievings, but few were found after the first break. Conversion of flour mills to pneumatic conveying systems greatly reduced the number of insect problems because pneumatic systems are self-cleaning and because impact in a pneumatic conveying system kills more insects than in other conveying systems (see Chapter 15).

In an old stone flour mill in Egypt, *Rhyzopertha dominica* was the most important pest infesting wheat. Populations of *Anagasta kuehniella*, *S. oryzae*, *Tenebroides mauritanicus*, and *Tribolium confusum* in waste flour were found to decrease as a result of the annual maintenance and cleaning. Webbed flour from moth infestations clogging the pipes conveying flour was a problem. Small numbers of *Alphitobius diaperinus* were found in waste flour. In another study in Egypt, *A. kuehniella* was the dominant species in some flour mills, while *Corcyra cephalonica* was the dominant species in others.

In flour mills in Greece, *A. kuehniella*, *Cryptolestes ferrugineus*, *Oryzaephilus surinamensis*, *S. oryzae*, *Sitotroga cerealella*, *T. castaneum,* and *T. confusum* were the most common species. More insects were found in the basement storage area, where there was

more residual food, than on the upper floor. Insect populations increased as temperature increased in January, grew until late summer or early fall, and then declined.

In flour mills in England, *A. kuehniella* populations increased from early in the year until fumigation during the summer in at least one of three years at all three of the mills that were studied. *Cryptolestes turcicus*, *Endrosis sarcitrella*, and *Gnatocerus cornutus* populations each increased in a different one of the three mills during at least one year. *C. turcicus* populations built up in the centrifugal sieves when the flour residues were damp. In the thick accumulation of barley dust in a barley mill in Japan, *T. confusum*, *A. kuehniella*, *S. oryzae*, and *R. dominica* were the most prevalent insect pests.

In Italy, the six most prominent species differed in distribution and abundance in a feed mill. *T. confusum* was most abundant and widely distributed, being found in the raw-grain weighing room, the processing and bagging room, and the storage room for bagged feed. *T. castaneum* was less abundant but was found in the same three rooms. *Attagenus brunneus* was found mainly in the processing and bagging room. *O. surinamensis* and *S. oryzae* were found most often in the raw-grain receiving area and the storage room for bagged feed. *Stegobium paniceum* was most often found in the processing and bagging room, but some insects were found in the raw-grain receiving area and the storage room for bagged feed.

In 34 tobacco redrying facilities in Virginia, drying killed *Lasioderma serricorne* and *Ephestia elutella* in cured tobacco, but the tobacco was reinfested by insects from the tobacco residues in the facility. In Zimbabwe, *Liposcelis entomophila* remained in the building after the annual cleaning and infested tobacco brought into the processing building during its conditioning. Using steam to soften cured tobacco leaves raised the relative humidity and temperature and promoted the growth of *L. entomophila* populations. In 16 noodle factories in Japan, adult *L. serricorne* were trapped from May to November. *S. paniceum* was less prevalent. Although these species were trapped throughout the noodle factories, they were most prevalent near the wheat flour, noodles, or trash and in the corners of the room and the cracks in the floor.

Without an insect pest management program, 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. *Cadra cautella*, *Plodia interpunctella*, *Tribolium castaneum*, *Oryzaephilus mercator*, and *Carpophilus dimidiatus* made up 93% of the residual insect population, although more than 15 other species were found. An effective insect pest management program reduced the residual insect populations by 50% or more during the summer and by more than 70% during the rest of the shelling season. An effective insect pest management program included periodic cleaning of all elevators and equipment and biweekly aerosol applications of residual insecticide throughout the shelling plant. Floor sweepings and the infested peanut residues were removed from the premises and destroyed by burning or burying. At the end of the shelling season, in early summer, a residual insecticide spray was applied to floors, walls, and equipment.

The insect species associated with raisins changed as they moved through the marketing system (see recommended reading by Soderstrom et al). *P. interpunctella* was the primary insect pest in a raisin-processing plant. *Cadra figulilella* was common outside this plant but rarely was found inside. *Cadra cautella* was found in one out of 15 cargo-shipping containers delivering raisins to Rotterdam, Netherlands. *P. interpuctella* was the primary stored-product insect pest found in European warehouses, but some *Anagasta kuehniella*, *C. cautella*, and *Ephestia elutella* also 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. *T. castaneum*, *Trogoderma* spp., *Cryptolestes* spp., *Cadra cautella*, and *R. dominica* were the most abundant species. In Hawaii, *T. castaneum*, *Trogoderma* spp., *R. dominica*, and *S. oryzae* were found in cargo containers. In Australia, stored-product insects were found in 10% of the cargo containers examined. *T. castaneum* was by far the most prevalent and abundant species in this study.

Large numbers of *Lasioderma serricorne* and *C. cautella* were recovered from food-baited traps in four port warehouses on the U.S. Gulf Coast. Few adults were found in the food-baited traps, and both the contents of the traps and the food-residue sample units from the pallets were incubated so that the immature stages of insects could become adults before being identified and counted. Large numbers of *Carpophilus pilosellus* were found in two of these warehouses, and large numbers of *T. castaneum* were found in one. Insects were caught throughout the year, but catches were highest in August and September. *C. cautella* and *L. serricorne* were found in the food residues on the pallets in all four of the port warehouses, with average densities of 6.14 and 2.18 per sample unit, respectively, and *T. castaneum*, *Oryzaephilus surinamensis*, and *C. pilosellus* were found in the food residues in three warehouses, with average densities of 4.83, 1.20, and 0.96 per sample unit, respectively. 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 retail stores, insect captures were highest in the pet food and flour aisles. Species and densities of insects varied among stores. Traps on the lower shelves caught more insects than those on the upper shelves, and traps on top of the shelves caught more insects than those on the underside.

In Australia, insects were found in 92% of the headers of the 72 combine harvesters sampled. *T. castaneum*, *R. dominica*, and *S. oryzae* accounted for 92% of the insect species that were found in an average 46-kg of residual grain per header. Most of the residual insect population was flushed into newly harvested grain, but approximately 250 insects remained in protected areas of the header. Cleaning the headers reduced the insect infestations in the combines by 96%.

In Minnesota, large numbers of *T. castaneum* from a grain-cleaning facility dispersed into residential neighborhoods and established residual infestations inside and outside homes. *Liposcelis* spp. have been found in residences in England and Spain. In 1986, *L. bostrychophila* were found in 14% of the kitchens studied in England, and in 1987 they were found in 17%. In Spain, psocids were found in 90% of the apartments studied; *L. decolor* and *L. brunnea* were the dominant species, and their densities were similar in bathrooms and kitchens. They were active indoors during all months but were most prevalent during July and August, one or two months ahead of nondomestic psocids. This was probably a result of warmer indoor temperatures. In Hawaii, *T. castaneum* was found at 100% of the stables sampled, and *Alphitobius diaperius*, *R. dominica*, and *S. oryzae* were found at 50–75% of them.

This summary of what we know about residual infestations indicates that our knowledge is very incomplete for most storage, processing, and marketing facilities and for transportation vehicles. Much of this information has probably been underutilized in planning and implementing insect pest management programs because it is buried in the vast published literature. The population ecology of residual infestations is complex, and we should be able to find many new and more cost-effective ways to

implement insect pest management programs as we more fully utilize the available information and learn more about the ecology of residual insect infestations.

Commodities

With thorough inspection of the incoming commodities for insects, stock rotation, regular monitoring of stored commodities for insects, and a thorough sanitation and exclusion program, infested commodities rarely should be the source of an insect infestation. However, because the stored commodities often have much larger volumes than the commodity residues do, larger insect infestations can develop on stored commodities. As discussed under regulations in Chapter 1, an average density of one insect per kilogram of wheat extrapolates to 2,700,000 insects for a ship carrying 2,720 t of wheat. The recommended reading by Hamlin and Benton estimates that 15,000–154,000 *Oryzaephilus surinamensis* may be cleaned from 3 t of raisins. Infestations may also come from processed commodities; an example in the previous chapter noted that one to 24 *Tribolium castaneum* adults emigrated from a small quantity of flour every day. Insects breeding on grain in farm storage or elevator bins can be the source population for insects infesting grain in the field.

Locating source populations

Locating and eliminating source populations can be one of the least-expensive and most-productive components of an insect pest management program. Simple examples of identifying source populations are studies showing that field infestation before harvest decreased with the distance from grain storage. Many of the source populations can be found with a thorough inspection or during cleaning. However, traps in combination with careful inspection of the area around the traps with high catches may be a more-efficient way to locate source populations (see recommended reading by Arbogast et al and by Bowditch and Madden).

Spatial mapping of the locations of source populations using traps is complicated by insect mobility. Because of extensive insect mobility, even the traps that are not close to a source population will capture insects. Use of a short trapping interval, unbaited traps, and large numbers of traps may be necessary to locate source populations. A shorter trapping interval may make the traps that are closest to the source populations, where insect population densities are highest, more likely to capture insects than those further away. Unbaited traps should be less likely than baited traps to attract insects from far away. However, many lures are known to attract insects from only a short distance away when used indoors. Baiting indoor traps with these lures may help to distinguish areas of high insect density from those with low insect density by increasing the likelihood of catching nearby insects during a short trapping interval. Large numbers of traps increase the precision of spatial mapping by increasing the likelihood that one of the traps is close enough to a source population to catch more insects than the other traps.

Relative importance

Several types of source populations may be important in most situations. When grain is infested by stored-product insects in the field before harvest, insect pests may need to be suppressed before or soon after grain is stored. Infested commodities are

often the most important source because they can produce the largest number of insects. However, insect densities per unit of commodity may be highest in commodity residues in storage, processing, or marketing facilities and in transportation vehicles. Also, because of their smaller volume, insects may disperse more readily from commodity residues than from stored commodities. When stored commodities are not infested, then insects from commodity residues become the primary source of new insect infestations. Limited insect population growth on wild hosts may make wild hosts the least significant source of infestation in most cases.

Utilization of source population information

Knowing the sources of an insect infestation is important in making insect pest management decisions. When grain is infested in the field, an insect pest management program that prevents infestation before harvest may be the most effective way to manage stored-product insect pests. Growing a variety of maize that has a tight husk can reduce insect infestation before harvest and insect infestation of unhusked maize during storage. In some cases, more than one source population may exist. Insect pest management programs may often be more cost-effective when the source populations are located and targeted. Exclusion, inspection of incoming commodities for insects, stock rotation, and sanitation are important methods of minimizing the number and size of source populations. Storage, processing, and marketing facilities and transportation vehicles can be designed to make excluding, finding, and removing source populations easier.

Study questions

1. How diverse are the wild hosts on which stored-product insects can develop?
2. How are preharvest and residual infestations of stored-product insects important?
3. How can source populations of stored-product insects be located?
4. What is the relative importance of the different sources of stored-product insect infestations?
5. Why is it important to find and target the sources of insect infestations when managing stored-product insect pests?

Recommended readings

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Hagstrum, D. W. 1985. Preharvest infestation of cowpeas by the cowpea weevil, *Callosobruchus maculatus* (Coleoptera: Bruchidae) and population trends during storage in Florida. J. Econ. Entomol. 78:358-361.

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Chapter 5

Sampling

The distribution and abundance of stored-product insects are often estimated by taking a small number of representative samples. This is a practical alternative to finding, or extracting, and counting all of the insects. Sampling can provide information on various characteristics of the insect population being sampled such as density, the species and stages of insects that are present, age structure, spatial distribution, and population growth rate.

Sampling plan

Researchers, consultants, or pest managers must decide which sampling device or method to use; the time and frequency of sampling; and the location, size, and number of the sample units to examine. Methods of extracting insects from commodities and detecting internal-feeding insects during the processing of sample units are discussed in Chapter 2. Before sampling, a decision must be made about whether to determine the number of sampling units with insects (presence-absence or binomial sampling) or to count the number of insects in each sample unit (enumerative). Making these decisions will result in a sampling plan that is uniquely suited to a particular situation and provides a representative sample of the stored-product insect population.

The decisions about the type of sampling plan that is needed are not independent of one another. For example, the size of a sample unit may be determined by the choice of a sampling device or method. Binomial sampling often requires an examination of more sampling units than enumerative sampling does, but less time is required for each sample unit.

The cost of a sampling program must be justified by the potential economic losses attributed to insects that can be prevented when the insect sampling information is available for making a pest management decision. The costs of sampling and of an insect pest management program are economic losses caused by insects. Sampling may indicate that fumigation of a commodity to ensure that a buyer does not find insects is unnecessary (see recommended reading by Mabbett).

Sampling device or method

A variety of devices and methods have been used to sample commodities, facilities, transportation vehicles, and the outdoors for stored-product insects (Table 5.1). The best device or method depends upon the purpose of the sampling, the insect species and developmental stage being sampled, and the type of commodity being sampled or where samples are being taken. Visual inspection has been used to estimate insect numbers in farm storage and processing plants. Diverter, **Ellis cup,** and **pelican** samplers are used commercially to sample moving grain. **Triers**, **deep-bin cups, probe traps,** and **acoustical detection** have been used to estimate insect numbers in bulk commodities. **Vacuum probes** allow samples to be taken from deeper in bulk commodities. Quadrat samples have been taken from the surfaces of raw commodities stored in bulk. Triers also are used for bagged commodities.

Table 5.1. Sampling devices and methods used for stored-product insects

Method	Source
	Absolute estimate
Deep-bin cup	Arbogast and Throne 1997, Lippert and Hagstrum 1987, Meagher et al 1986, Vela-Coiffier et al 1997
Diverter sampler	Parker et al 1982, Storey et al 1982
Ellis cup	Parker et al 1982
Pelican sampler	Parker et al 1982
Quadrat	Keever et al 1985, White 1988
Suction trap	Leos-Martinez et al 1986, White et al 1995
Trier	Athanassiou et al 2001, 2003, 2005; Athanassiou and Buchelos 2000; Buchelos and Athanassiou 1999; Hagstrum et al 1985, 1996b, 1998; Ingemansen et al 1986; Parker et al 1982; Vela-Coiffier et al 1997; White and McGregor 1957
Truck trap	Sinclair and Haddrell 1985
Vacuum probe	Flinn et al 1996, 2004a,b; Hagstrum 1989; Mahmood et al 1996; Meagher et al 1986; Perez-Mendoza et al 2004a; Reed et al 2003
Visual observations	Hodges 1984, Rees 1999b
	Relative estimate
Acoustical detection	Fleurat-Lessard et al 1994, Hagstrum et al 1996b
Food-baited trap	Cogburn 1973a; Collins and Chambers 2003; Hodges et al 1985; Papadopoulou and Buchelos 2002c; Platt et al 1998; Strong 1970; Throne and Cline 1991,1994
Light trap	Abreu and Williams 1981, Broce 1993, Gilbert 1984, Rees 1985, Hagstrum et al 1977, Papadopoulou and Buchelos 2002c
Multifunnel trap	Fields et al 1993, Leos-Martinez et al 1995, Trematerra and Daolio 1990
Pheromone-baited trap	Ahmad and Ali 1991; Arbogast et al 2000a; Bowditch and Madden 1996; Compton et al 1997; Doud and Phillips 2000; Dowdy and Mullen 1998; Hodges et al 1998; Leos-Martinez et al 1986, 1995; Lindgren et al 1985; Mankin et al 1983, 1999; Mullen et al 1998; Nansen et al 2004e; Papadopoulou and Buchelos 2002c; Platt et al 1998; Rees 1999a; Roesli et al 2003a–c; Soderstrom et al 1987; Toews et al 2005a; Vick et al 1979, 1986; Walgenbach et al 1987
Pitfall trap	Athanassiou and Buchelos 2000, Collins and Chambers 2003, Obeng-Ofori 1993a, Wakefield 1995
Probe trap	Arbogast et al 2000b; Athanassiou 2001; Athanassiou and Buchelos 2000; Athanassiou et al 2001; Buchelos and Athanassiou 1999; Epsky and Shuman 2004; Hagstrum et al 1998 and references cited; Javer et al 1990; Shuman et al 2003, 2005; Toews and Phillips 2002; Toews et al 2003a, 2005c; Trematerra 1998; Weston and Barney 1998

(*continued on next page*)

Table 5.1 (continued)

Method	Source
Refuge trap	Barak et al 1990, Collins and Chambers 2003, Hagstrum and Sharp 1975, Hodges et al 1998, Likhayo and Hodges 2000, McGaughey 1978, Nansen et al 2004c, Parajulee and Phillips 1995, Trematerra et al 1996
Sticky trap	Arbogast et al 2004; Barak et al 1990; Barney and Weston 1996; Hagstrum et al 1994; Javer et al 1990; Likhayo and Hodges 2000; Nansen et al 2004c; Papadopoulou and Buchelos 2002c; Parajulee and Phillips 1995; Platt et al 1998; Quartey and Coaker 1992; Throne and Cline 1989, 1994; Vela-Coiffier et al 1997, Weston and Barney 1998
Vent trap	Barney and Weston 1996, Hagstrum 2001, Schwitzgebel and Walkden 1944
Water trap	Ryne et al 2002, Watters and Cox 1957
	Indirect absolute estimate
Calibration of trap	Hagstrum et al 1998, Haines et al 1991
Release-recapture	Hagstrum and Stanley 1979, Wakefield and Cogan 1999, Walker 1960, Wileyto 1994, Wileyto et al 2000

Sticky or refuge traps baited with **pheromones** or food odors are the most commonly used traps. These have been used throughout the marketing system. A disadvantage of sticky traps is the difficulty of removing insects from the sticky substance so that they can be identified to species and their physiological state determined. Probe traps are most commonly used for grain stored in bulk. Light traps have been used in warehouses and food processing plants; water traps in stored grain and food-processing plants; and suction traps and truck traps outdoors. Suction traps also have been used in warehouses and vent traps in grain bins.

Insect numbers or some indices of insect activity such as commodity damage, uric acid, or insect sounds can be detected or estimated. Some sampling devices or methods provide absolute estimates of the insect density per sample unit, while others provide only relative estimates such as the number of insects caught per trap or some indices of insect activity per sample unit. Indirect methods such as trap calibration and **release-recapture** also can be used to obtain absolute estimates. Relative estimates can be converted to absolute estimates by adjusting the trap catch for the influences of insect physiological state and environmental factors (such as temperature, residual food, and air movement) on insect mobility (see Chapter 3). Automation of insect monitoring with acoustical sensors can provide more up-to-date information and reduce the cost of sampling (see recommended readings by Hagstrum et al).

The sampling unit for absolute estimates can be a volume of commodity or air or a surface area of commodity or wall. For example, suction and truck traps can provide absolute estimates of the insect density per volume of air. However, to assess the potential economic losses that can be attributed to insects, absolute estimates of insect density per volume of air, area of commodity surface, or area of wall surface may need to be converted to estimates of the number of insects per volume of commodity.

For pyralid moths, pheromone-baited sticky traps may mimic a female releasing pheromone, and males may approach these traps as they would approach a calling

female. Traps near the wall, ceiling, and floor (where females are likely to be calling) caught more males. Observing why some of the insects that approach a trap are not caught provides information on trap efficiency and may allow the trap design to be improved. In still air with an insect density of 50–75 male *Plodia interpunctella* per 89 m^3, direct observations have shown that 30% of the males were captured—but males were captured only 62% of the times that they approached the sticky trap.

With a pheromone release rate of 2.3 ng/hr, similar to that of a female *P. interpunctella*, the distance from which traps attracted insects was initially 4 m (13 ft), but this was reduced to 2–3 m (6.6–9.8 ft) within 5–10 min by habituation. The main component of the *P. interpunctella* pheromone has been used as a lure in traps to capture *Anagasta kuehniella*, *Cadra cautella*, *C. figulilella*, and *Ephestia elutella*. Captures of *Sitotroga cerealella* in sticky traps were reduced moderately when pheromones of both *S. cerealella* and *P. interpunctella* were used in the same trap. Using *Cryptolestes ferrugineus* and *Tribolium castaneum* pheromones in the same trap did not reduce the capture of either species. Even with the small repellent effect of *T. castaneum* pheromone on *Trogoderma variabile*, the pheromones of these species and that of *Rhyzopertha dominica* could be used together in a trap. Using a trap to monitor more than one insect species can reduce the cost of a sampling program.

The responses of both *P. interpunctella* and *C. cautella* to pheromones were influenced by the shapes of figures associated with the pheromone source. In still air, the catch of *C. cautella* in sticky traps was increased from 35 to 80% by using visual cues (vertical rectangles or stripes). In moving air, the catch was increased from 70 to 90% by providing visual cues. Traps may be more efficient near the doors and outside, where air movement is more directional and males can fly upwind to more readily locate an odor source. Insects may fly for longer times and distances outdoors, where there may be fewer obstructions to flight than indoors, and thereby increase their chances of their being caught in a trap. Also, traps located inside may compete with a larger number of other odor sources such as calling females and food than the traps located outside. Temperature and air movement are not uniform in a facility or over time, and this can contribute to the variation in trap catch. Visual cues may also be used by *C. ferrugineus*, *R. dominica*, *Sitophilus oryzae*, and *T. castaneum* when multifunnel traps are used.

Using aggregation **pheromones** as lures in traps increased the capture of *C. ferrugineus*, *Cryptolestes pusillus*, *Oryzaephilus surinamensis*, or *O. mercator* by as much as 65–97%, but aggregation pheromones were not very effective as lures for *T. castaneum* or *T. confusum*. Aggregation pheromone also increased the captures of *Prostephanus truncatus*, *S. oryzae*, and *Sitophilus zeamais*. For several species at close range, a combination of aggregation pheromone and food odors resulted in a higher trap catch than either alone (see Chapter 3). However, food odors did not improve the long-range attraction and capture of *S. zeamais* or *P. truncatus* in traps. More adult *T. castaneum* were captured in traps placed in corners and under shelving than in traps at other locations or when no residual food was present. The number of *T. castaneum* adults caught in refuge traps was influenced by the number of adults that were already present in the trap, and this also could be true for other insect species and types of traps.

The capture rates for nine species of beetles in pitfall traps placed in millet and the speed of movement of these insect species on the grain surface have been determined by direct observation (Table 5.2). Traps with the rim below the grain surface caught

Table 5.2. Capture rates of beetles in pitfall traps and their speed on surface of millet[a]

	Captures/100 encounters		
Species	**Rim exposed**	**Rim submerged**	**Speed (cm/sec)**
Sitophilus oryzae	58.8	98.0	0.44
Sitophilus zeamais	67.3	99.0	0.40
Sitophilus granarius	66.8	98.3	0.42
Tribolium confusum	68.0	98.3	0.35
Tribolium castaneum	67.8	97.8	0.33
Oryzaephilus surinamensis	35.8	62.5	0.52
Cryptolestes pusillus	10.5	26.3	0.19
Rhyzopertha dominica	65.5	95.8	0.07
Prostephanus truncatus	67.3	96.3	0.15

[a] Data from Obeng-Ofori 1993a.

more of the insects than those with the rim exposed. The smaller *Cryptolestes pusillus* and *Oryzaephilus surinamensis* avoided capture more often than the other insect species. *C. pusillus*, *Prostephanus truncatus*, and *Rhyzopertha dominica* were the slowest moving and *O. surinamensis* the fastest. Beetles displayed three types of avoidance behavior: probing down into trap with their heads, skirting the rim of the trap, and retreating. Retreating was the most effective in avoiding capture, and probing was the least.

Outdoors, a trap originally designed for Japanese beetles and baited with the *P. truncatus* aggregation pheromone caught two to three times more of this species than sticky traps baited with this pheromone. One reason for this higher catch was that insects visited the sticky traps several times before entering and being caught on the sticky surface. For *P. truncatus*, a 1:1 ratio of trunc-call 1 and trunc-call 2 pheromone components or the trunc-call 2 component alone caught 26 and 30 times, respectively, as many adults as trunc-call 1 component alone, and a multifunnel trap caught more adults than a sticky trap. For *R. dominica*, pheromone traps estimated as well as suction traps the numbers of insects in a seed and feed warehouse in Texas, and also the daily pattern of activity. For *Lasioderma serricorne* in tobacco stores in Greece, baiting sticky traps with lights increased the catch by 86%; baiting them with pheromone increased the catch by 81%; and baiting them with food attractant increased the catch by 38%.

The equations for converting probe trap catch to an absolute estimate of insect density for wheat stored in 87-, 98-, and 109-t bins on farms in Kansas varied with insect species and over the storage period (see recommended readings by Hagstrum et al). Traps caught 107 times more *C. ferrugineus*, 6.4 times more *R. dominica*, 33.7 times more *Ahasverus advena*, and 296.5 times more *Typhaea stercorea* than were found in 1-kg grain samples during the first 90 days of storage. *A. advena* and *T. stercorea* evidently immigrated into the bins but did not breed in the stored wheat, and few were found after day 90. Between day 90 and day 135 of the storage period, when insect density was higher and grain temperatures were between 23 and 14°C, traps caught 18.7 times more *C. ferrugineus* and 1.6 times more *R. dominica* than were found in 1-kg grain samples. Trap catch needed to be adjusted for temperature. In the autumn, after 135 days of storage, the trap catch decreased as a result of lower temperature (<14°C) even though the insect populations were still increasing. The traps caught

only 1.8 times more *C. ferrugineus* than were in grain samples and only half as many *R. dominica* as were in the samples.

In central bagged-rice storage in Indonesia, food-bait trap catches of *T. castaneum* increased from 10 at an average density of 0.3 insect per kilogram of rice to 250 at a density of 26 insects per kilogram (see recommended reading by Haines et al). The average catch of *R. dominica* increased from 0.1 at a density of one insect per kilogram to 2.5 at a density of 25/kg. The catches of *Oryzaephilus* spp. and *Sitophilus* spp. increased from one at an insect density of two per kilogram to 25 at a density of 45/kg. The equations for converting trap catch to absolute insect density were curvilinear for *T. castaneum* and linear for the other species. At high densities, the activity of other insects may have caused more of the *T. castaneum* to leave the food-bait trap.

During a one-day period using six suction ultraviolet (UV) light traps, 7% of female and 20% of male *Cadra cautella* were recaptured in an unstocked peanut warehouse measuring 19.5 × 32 m (64 × 105 ft), and 31% of the males were recaptured when this peanut warehouse was stocked. In a 100-t flat store of wheat in England, 75 pitfall and probe traps caught 0.3% of 100,000 released *Sitophilus granarius* adults at winter temperatures (<14°C), and 108 traps caught 1.1% at summer temperatures (13–18°C). In the laboratory, few of the *S. granarius* reaching the trap were caught although some visited the trap two to 13 times.

Green light increased the catch the most for two insect species, and UV light increased the catch the most for nine insect species (Table 5.3). Ten species were either caught in equal numbers with green and UV or white and UV light, or the type of light that was most effective differed among studies. Studies measuring the electrical response of the eye showed that *Attagenus unicolor*, *Tenebrio molitor*, *Tineola bisselliella*, and *Trogoderma glabrum* responded most to green light. More males than females of five species were caught; more females than males of six species were caught; and, in three studies, equal numbers of males and females were caught.

The increased capture with green, UV, or white light may be because the light increased insect flight activity rather than attracting the insects to the light. For *Cadra cautella*, placing a green or UV light in the opposite corner of the room increased the number of males captured by the same amount as placing the light on the trap. Moving the UV light from the trap to the opposite corner did reduce the number of females caught. Using light and sex pheromone lures with a suction trap caught more *C. cautella* than using either alone.

Although traps have been used extensively to capture more than 36 species of stored-product insects, relatively little is known about how traps work, and only in a few cases have traps been used to obtain absolute estimates of stored-product insect density. Many of the insects visiting a trap were not caught; visual stimuli have been shown to be important for several species of stored-product insects; lures often are more attractive to one sex; traps may catch fewer insects when residual food is present in a facility; and the number of insects already in a trap may influence the number of insects caught. In many cases, the differences in insect capture rate between trap types, lures, and insect species were only 1.5 to 2-fold (50–100%). This was equivalent to trapping for two days instead of one day or using twice as many traps. However, using an optimal combination of pheromone components or the best pheromone component increased the trap capture by 26- and 30-fold. For several species, baiting traps with pheromones for more than one species of stored-product insects has been shown to be practical.

Table 5.3. Insect species differences in attraction to light[a]

Insect species	Differences between males (m) and females (f)
Green light caught more	
Anagasta kuehniella	···
Corcyra cephalonica	···
Ultraviolet light caught more	
Callosobruchus maculatus	m = f
Cathartus quadricollis	f > m
Ephestia elutella	m > f
Lasioderma serricorne	···
Tribolium confusum	···
Trichogramma evanescens	f > m
Trichogramma pretiosum	f > m
Venturia canescens	···
Xylocoris sordidus	m > f
Equal or effectiveness differed among studies	
Anisopteromalus calandrae	m = f
Cadra cautella	m > f, f > m
Cryptolestes spp.	···
Habrobracon hebetor	···
Oryzaephilus mercator	···
Plodia interpunctella	m > f, f > m, m = f
Rhyzopertha dominica	···
Sitophilus oryzae	···
Sitotroga cerealella	m > f
Tribolium castaneum	f > m

[a] Data from Keever and Cline 1983, Brower and Cline 1984, Rees 1985.

Time and frequency of sampling

Sampling needs to be done early enough in the storage period that the potential economic losses caused by insects can be prevented. However, when large quantities of commodities are stored, insect infestations may not reach detectable levels for some time, so sampling too early can be unproductive. When newly harvested wheat is stored at elevators, insect infestations are not easily detected in grain samples during the first two months. When the rate of insect immigration into grain is known or can be predicted, insect population growth **models** can predict when grain will first need to be sampled. Automation shifts the cost of sampling from labor to equipment and can provide accurate information about insect infestation continuously.

Taking a large number of sample units to accurately estimate or classify the stored-product insect pest population may be more efficient than sampling more frequently. The time required to reach and enter a facility with the sampling equipment is the same regardless of how many sample units are taken. With accurate estimates, insect

Table 5.4. Sampling plans, attractive distance of lures, and influence of trap height for stored-product insect species

Facility or species	Source
	Sampling plans by type of facility
Bag storage	Hodges et al 1985, Haines et al 1991
Breakfast cereal factory	Rees 1999a,b
Bulk peanut storage	Keever et al 1985
Confectionary factory	Bowditch and Madden 1996
Flat grain storage	Arbogast and Mullen 1987; Athanassiou et al 2001, 2003, 2005; Nansen et al 2004c; Parajulee and Phillips 1995; Wakefield and Cogan 1999; White 1988
Flour mill	Doud and Phillips 2000
Grain bins on farms	Arbogast and Throne 1997, Hagstrum 1989, Hagstrum et al 1985, Ingemansen et al 1986, Meagher et al 1986, Subramanyam and Harein 1990, Vela-Coiffier et al 1997, White and McGregor 1957
Grain elevators	Flinn et al 2003a,b, 2004a; Mahmood et al 1996; Smith 1985; Toews et al 2005c; White 1985
Grocery distribution warehouse	Vick et al 1986
Railroad hopper car	Perez-Mendoza et al 2004a
Retail store	Arbogast et al 2000a, Platt et al 1998, Roesli et al 2003a,b
	Attractive distances for pheromone lures
Plodia interpunctella	Mankin et al 1999
Prostephanus truncatus	Farrell and Key 1992
	Trap height on catch
Cadra cautella	Ahmad 1987
Callosobruchus maculatus	Keever and Cline 1983
Cathartus quadricollis	Keever and Cline 1983
Cryptolestes ferrugineus	Nansen et al 2004a
Plodia interpunctella	Nansen et al 2004d
Prostephanus truncatus	Keys et al 1994
Teretrius nigrescens	Keys et al 1994
Tribolium castaneum	Ho and Boon 1995

population growth models can be used to predict when to sample again. The sampling frequencies for commodities in the studies cited in Table 5.4 ranged from weekly to once every two months. Sampling at elevators once every six weeks starting in September worked very well when sampling was intensive and insect population growth models were used to predict the need for insect pest suppression (see Chapter 8).

Electrocuting light traps do need to be emptied frequently so that an accumulation of the insects caught in these traps does not become a breeding place for other stored-product insect pests. The offspring of some species of stored-product insects, such as *Trogoderma variabile*, can complete development by feeding on dead insects.

Sampling locations

Taking small sample units from many locations is important because this method is more likely to provide a representative sample of the stored-product insect population, and it allows information on the distribution of insect population to be used in making insect pest management decisions. Taking a representative sample is important because of the unevenness of insect distribution that results from their response (see Chapter 3) to the uneven environmental conditions in storage, food processing, and marketing facilities or in transportation vehicles. When only a small number of sample units are taken, such as fewer than 30 sample units per 27 t (1,000 bushels) of grain or 929 m^2 (10,000 sq ft) of facility, systematic or stratified random sampling may provide a more-representative sample than random sampling. An example of systematic sampling is placing traps evenly spaced in a grid pattern. For stratified random sampling, the area to be sampled is divided into regions, and sample units are taken from randomly chosen locations within each region.

Sampling plans developed for several different types of facilities (Table 5.4) specify the locations at which sample units were taken or traps were located. There is some information for a few species of stored-product insects on the attractive distance of pheromones lures and the influence of trap height on the number of insects caught. The stored grain example in Chapter 3 (Example 3) illustrates the complex relationship between the type of trap, its location, and the insect species being monitored. That example clearly illustrates the importance of trap placement for effective insect monitoring.

On farms and at **elevators** in Kansas, insects were found to infest wheat after it had been stored in a bin, and the insect numbers decreased with the distance below the grain surface. In farm bins, the most-common insect species were most abundant in the center of the grain mass near the surface, although some species were more abundant near the wall (see recommended reading by Hagstrum et al). A representative sample for estimating insect population density in a farm storage bin would involve taking sample units from the center, from near the edge, from midway between, and from several depths. For several species of insects infesting wheat stored in farm bins in Kansas, the variation in the number of insects per sample unit was greatest between two samples taken by pushing a grain **trier** into the grain twice at the same location. This suggests that insects were responding to the heterogeneity in the grain environment that occurred over the distance of only a few centimeters. Sampling more regions was more beneficial than taking more samples within a region.

Flat grain storages and peanut storages have been sampled by dividing them into regions and taking sample units from each region at one or more depths. Wheat also has been sampled as it was unloaded from trucks and as it was loaded onto railroad cars. Railroad hopper cars have been sampled by taking sample units from each compartment at several depths and locations. Sample units also have been taken as the grain was unloaded from hopper cars.

For bagged storage, the numbers of food bait traps located on the sides of each stack were proportional to the size of the stack. Locating traps in a grid or along shelves or aisles in a warehouse, food processing plant, or retail facility and spending an equal amount of time for visual inspection at each location can provide a representative sample.

Other considerations in deciding where to place the traps may be concerns about contamination. Placing **pheromone** or light traps near outside doors may attract

insects from outside. Some of these insects from outside may contaminate commodities or add to the residual insect infestation inside. Electrocuting light traps produce airborne insect fragments and should be placed where they will not contaminate food or food-handling equipment.

Traps should not be placed so close to other traps that they interfere with one another. The range of attraction for *Plodia interpunctella* inside was 2–4 m (6.6–13 ft), and that for *Prostephanus truncatus* outdoors was 50–100 m (164–328 ft). Also, trap height can influence the capture rate. In a date grove, the most adult *Cadra cautella* were caught in the highest traps at 3–6 m (9.8–20 ft) above the ground. Adult *P. interpunctella* were caught most often near the ceiling, floor, or wall in a building 6 m (20 ft) high. There was no statistical difference in the number of adult *Cryptolestes ferrugineus* caught in traps at five heights between the ground and the eaves outside metal grain storage bins 15 m (49 ft) high. Also, the numbers of *Callosobruchus maculatus* and *Cathartus quadricollis* caught at 1.8 m (5.9 ft) did not differ significantly from the numbers caught at 3.7 m (12 ft). When traps were placed at 1–12 m (3.3–39.4 ft) in a rice warehouse, the maximum number of *Tribolium castaneum* were captured at 6 m (19.7 ft), and catch was lower for traps either higher or lower. Catch was lowest at 1 m (3.3 ft). In grass, maize, and sorghum, more adults of *P. truncatus* and its predator, *Teretrius nigriscens*, were caught 0 or 1 m (3.3 ft) off the ground than at 2 m (6.6 ft). *P. truncatus* adults landed near the trap and walked to the trap.

Size of sample unit

Taking many small sample units provides a more representative sample than taking a few large sample units. However, the sample units must be large enough that there is a good probability of finding insects. Another advantage of small sampling units is that less time is required to separate and count the insects. Checking traps more frequently reduces the sample unit size.

For the sampling plans for raw commodities (maize, oats, peanuts, rice, sorghum, and wheat) in the 24 studies cited in Table 5.4, the typical sample unit sizes ranged from 130 g to 45 kg. In 11 out of 24 of these sampling plans, the sample unit size was ≥1 kg of commodity. For the studies in Table 5.4, both commodity samples and traps were used for raw commodities, but only traps were used in these studies to sample in facilities storing processed commodities. The duration of trapping for 14 studies cited in Table 5.4 ranged from 1 hr to six weeks, and a one-week trapping period was the most common. One study determined the number of adult *Cadra cautella* and *Plodia interpunctella* per 5 m^2 of wall surface two to three times per week at several locations in breakfast cereal factories.

Number of samples

The number of samples taken or the time spent making visual observations should be sufficient to detect stored-product insect infestations before the insect pest populations reach economically damaging levels. Any one sample is likely to under- or overestimate the average insect density. The sampling exercise in Chapter 23 is provided to illustrate the importance of taking enough samples to provide the information needed to make good pest management decisions for stored-product insects.

The numbers of sample units needed to achieve the desired accuracy or the accuracy that can be achieved with the number of sample units that a manager can afford to take can be calculated as discussed later in this chapter. For several insect species infesting wheat stored in farm bins in Kansas, a 1-kg sample unit had a 0.76 probability of detecting an infestation with a mean density of two insects per kilogram of wheat. Five 1-kg wheat sample units had a 0.99 probability of detecting insects at this density. Any single sample unit had a 0.95 probability of having, on average, 0.5–3.5 insects when the mean insect density was two per kilogram of wheat. Because this range included sample units with one insect per kilogram, as well as sample units with two insects per kilogram, one sample unit generally could not determine whether the insect infestation had reached two or more insects per kilogram. Taking 10 samples better estimated the insect population density. With 10 samples, there was a 0.95 probability of having, on average, 1.5–2.5 insects per sample unit when the mean insect density was two per kilogram of wheat.

Two simple sampling plans have been developed for subsistence farmers in Africa (see recommended reading by Hodges). For both, sampling maize after two or three months of storage is recommended. One recommendation is for estimating the numbers of insects. After dehusking, each cob is tapped against a white tray to dislodge the insects. The number of insects present on the cobs is estimated by multiplying the numbers of *Prostephanus truncatus* and *Sitophilus zeamais* by two and the numbers of the predator, *Teretrius nigrescens*, by 1.3. If all of the insect pests are dead, then their numbers are multiplied by only 1.5. The other recommendation suggests taking 11 maize cobs haphazardly from accessible areas of the store and counting the insects. If any *P. truncatus* are found, then consuming or selling the maize as soon as possible is recommended. The error rate for misdiagnosing a high infestation was found to be only 5%, and that for misdiagnosing a low infestation was 30%.

The sampling rate also can determine the level of stored-product insect infestation that will be tolerated in a food-processing facility. In the flour industry, examining the tailings from the final sieving provided a very high sampling rate for the insects in flour, and the insect populations in flour could be kept at a very low density. However, the sampling rate for the residual insect infestation in the building was likely to be lower, and insect populations were likely to reach higher densities before being detected and suppressed. Sieving or using a **Berlese funnel** to separate the insects from the sweepings or the contents of vacuum cleaners after cleaning could provide a way to detect residual insect infestations earlier.

Sampling statistics

Sampling statistics have been used primarily to optimize the number of sample units examined. Taking too many sample units is wasteful and taking too few can be misleading. Unnecessary insect pest management or economic losses caused by stored-product insects can be avoided when the reliability is known for the estimates of the probability of detection, the estimates of insect density, or the classification of insect infestation level.

Predicting variance of means

On an arithmetic scale, the relationship between sample variance (s^2) and mean number of insects per sample unit (x) is described by the Taylor's power law equation:

$$s^2 = A' * x^b \tag{1}$$

where A' is the antilog of a in equation (2). The linear form of equation (1) is:

$$log_{10}\, s^2 = a + b\ log_{10}\, x \tag{2}$$

When the data used to fit equation (2) span only a narrow range of insect densities, the parameter b in equation (2) increases each time another part of a data set with a higher range of insect densities is fit. Because parameter b is correlated with insect density, it is not a good indicator of the degree of **aggregation**. The variance-mean relationship is described best by the curvilinear equation:

$$log_{10}\, s^2 = a + b * \left[e^{(0.22 * log_{10}\, x)} - 1\right] \tag{3}$$

When sampling *Ahasverus advena*, *Cryptolestes ferrugineus*, *Oryzaephilus surinamensis*, *Rhyzopertha dominica*, *Tribolium castaneum,* and *Typhaea stercorea* populations infesting grain with a **trier**, **probe trap**, or sticky trap, the asymptotic slopes for equation (3) with a = 0.45 and b = 7.46 were 1.06, 1.32, 1.64, 2.05, and 2.55 at insect densities of 0.01, 0.1, 1, 10, and 100 insects per sample unit, respectively (see recommended readings by Hagstrum et al). In practice, using equation (2) with a = 0.55 and b = 1.67 was nearly as good as using equation (3) when the data set used to fit these equations spans this wide range of insect densities.

When new sampling data are available only for a range of insect densities of less than four orders of magnitude, using a = 0.55 and b = 1.67 in equation (2) may provide better results than fitting equation (2) to the new sampling data. However, behavioral differences between insect species and different sampling methods can result in variance-mean equations that have other values for a and b. Insect species that lay eggs in batches may have larger variances at low insect densities. Sampling methods such as visual observations or food-baited traps that may become less effective at high insect densities may have smaller variances at high densities.

Probability of detection (*P*)

Presence-absence, or binomial, sampling can be used to estimate the probability of insect detection. Mean insect density (x) can be estimated from the relationship between the fraction of the sample units that have insects (P) and the mean insect density, as shown in Figure 5.1. The relationship is described by the Wilson and Room equation:

$$P = 1 - e^{-Z} \tag{4}$$

where $Z = x * [(\ln (A' * x^{b-1}) * (1/(A' * x^{b-1}) - 1)]$, A' = antilog of a from the variance-mean equation (2), e = 2.71828, and ln = natural logarithm. The solid line in Figure 5.1 shows the results of substituting the antilog of a (A') and b from the variance-mean equation (2) into the Wilson and Room equation (4). The dashed lines show P_{DL} and 95% confidence limits for fitting the double-log equation (5) to the same data:

$$P_{DL} = 1 - \left[A * e^{(-B*x)} + (1 - A) * e^{(-C*x)}\right] \tag{5}$$

where A, B, and C are estimated to describe the nonlinear relationship between the fraction of sample units infested (P_{DL}) and mean insect density (x). At mean insect densities below 1 or greater than 4, the line for the Wilson and Room equation (4) is very similar to that for the double-log equation (5).

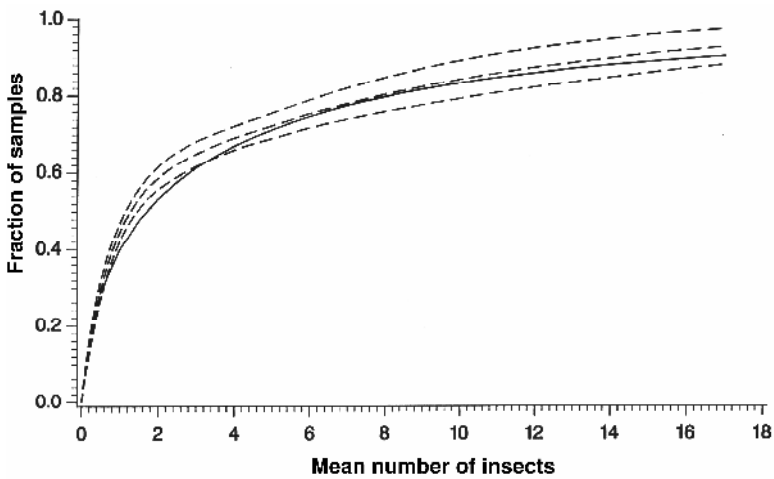

Figure 5.1. Relationship between the fraction of samples with insects and mean insect density. Lines are fitted to the same data set for the Wilson-Room equation and double-log equation. See text for explanation.

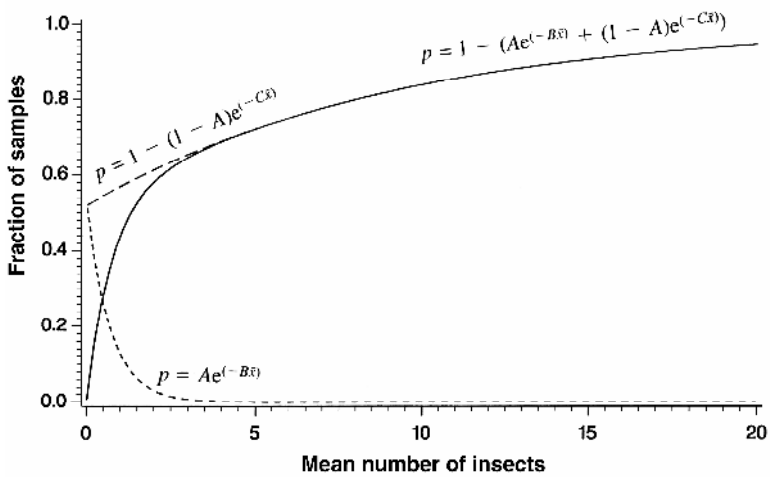

Figure 5.2. Diagram showing two-stages of a process by which insects may become distributed among sampling units. See text for explanation.

Figure 5.2 illustrates the two halves of the double-log equation separately, showing how the changes in the distribution of insects among sample units as insect density increases is a two-stage process: 1) a logarithmic increase in the number of sample units with insects at low densities [$1 - A * e^{(-B * x)}$] and 2) a logarithmic increase in the number of sample units with more than one insect as insect density increases [$1 - (1 - A) * e^{(-C * x)}$]. When sample units receive more than one insect, the number of sampling units receiving their first insect is reduced.

The relationship between the number of sample units taken from wheat stored in farm bins in Kansas and the probability of detection of *Rhyzopertha dominica* after one day of trapping or in a 0.5-kg grain sample unit is shown in (Figure 5.3). The

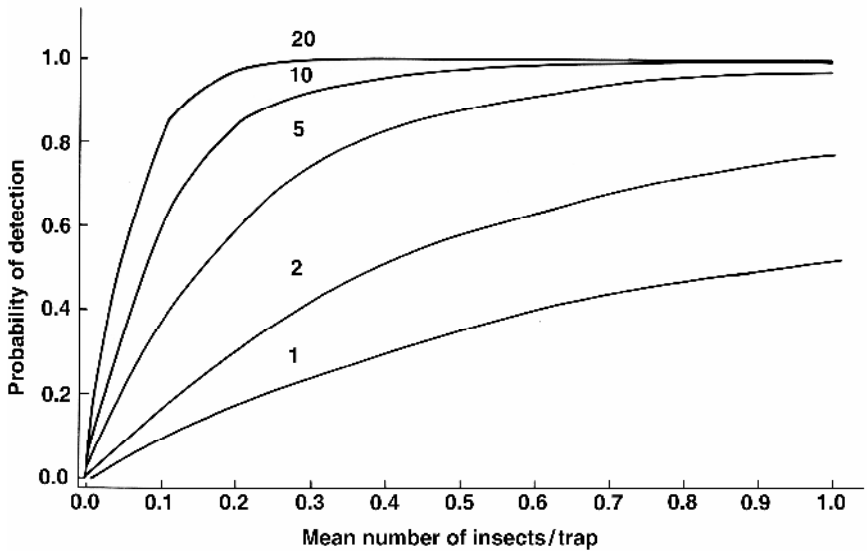

Figure 5.3. Relationship between probability of detection and insect density when 1 to 20 traps are used. The number of traps used is given above each line. (Adapted, with permission, from Lippert and Hagstrum 1987)

relationship between the number of sample units and probability of detection can be calculated as:

$$P_{\mathrm{N}} = 1 - \left(1 - P_{\mathrm{DL}}\right)^{\mathrm{N}} \tag{6}$$

where P_{DL} is the double-log equation (5), and N = number of sample units taken.

Estimation of insect density

Two methods have been used to describe the relationship between the number of sample units examined and the accuracy of an insect-density estimate. In this book, parameters from an empirical variance-mean regression equation are used to make these calculations. For the other method, it is necessary to first determine which of five mathematical distributions (negative binomial, Poisson with zeros, Neyman type A, logarithmic with zeros, or Poisson-binomial) describes the frequency distribution of the numbers of insects per sample unit. Although the negative binomial distribution generally fits the sampling data for most species of stored-product insects, different sets of the sampling data often fit different mathematical distributions. Also, the parameter k of the negative binomial distribution must be known before the number of sample units needed to estimate insect density with a particular level of accuracy can be calculated. However, k generally varies with insect density. For *Cadra cautella* infesting peanuts, k equaled 0.17, 0.28, 0.38, and 0.47 at mean densities of one, two, three, and four eggs per square centimeter, respectively.

The number of sample units (N) needed to obtain a particular accuracy (C) with 95% confidence can be calculated as:

$$N = \left(100 \div C\right)^2 * t^2 * A' * x^{\mathrm{b}-2} \tag{7}$$

where the parameters A' and b are from the variance-mean equation (2) and $t = 1.96$. C is given as a percentage of the mean. Lower values of C may be used at high insect densities than at low densities. For example, when the insect density is 1, a C of 100% may be most satisfactory, giving an estimate of 1 ± 1 insect. However, when the insect density is 5, a C of 20% may be sufficient, giving an estimate of 5 ± 1 insect. At high insect densities, more than the calculated number of sample units may be needed to provide a representative sample.

The accuracy of an estimate that is achieved by taking a particular number of sample units can be calculated as:

$$C = 100 * t * \left[\frac{\left(A' * x^{\mathrm{b}-2}\right)}{N} \right]^{0.5} \tag{8}$$

Relationship between probability of detection and variance of estimates

The random distribution of insects among sampling units explains the shape of both the double-log equation (5) for the probability of insect detection and the variance-mean equations (1–3) used to predict the accuracy of estimates. As the first insects arrive, the number of sampling units with one insect increases logarithmically. The fraction of sampling units with one insect determines how fast the variance increases. At some insect densities, a sampling unit will eventually have more than one insect. At this point, the variance will begin to increase more rapidly as the number of sampling units with more than one insect begins to increase logarithmically. In many studies, as a result of these relationships, aggregation appears to increase as insect density increases.

Sequential sampling

Sequential sampling plans have been developed for several species of stored-product insects (Table 5.5 and recommended reading by Subramanyam et al). Plans have been developed for insects in stored grain, at a cigarette factory, and at retail stores that either estimate insect densities or classify populations as either being above a threshold and needing pest suppression or below a threshold and not needing pest suppression.

Sequential sampling can reduce the number of sample units needed to estimate insect density. Fewer sample units are needed at high insect densities than at low densities. A stop line for such a sequential plan is calculated using the equation:

$$log_{10}\left(T_{\mathrm{n}}\right) = ln \frac{\left(\frac{D^2}{A'}\right)}{\left(b-2\right) + \left(\frac{b-1}{b-2}\right) ln\left(n\right)} \tag{9}$$

where T is the cumulative total number of insects found in sample units, n is the cumulative total number of sample units examined, A' and b are parameters from the variance-mean regression equation (1), and D is the precision expressed as a fixed proportion of the mean. A typical value of D is 0.25. The cumulative number of insects

Table 5.5. Sequential sampling plans for stored-product insects

Insect species	Type[a]	Source
Cryptolestes ferrugineus	E, C	Subramanyam et al 1997
Lasioderma serricorne	C	Carvalho et al 2006
Prostephanus truncatus	E, C	Meikle et al 1998b, 2000
Sitophilus oryzae	E, C	Meikle et al 1998b, 2000
Sitophilus spp.	E, C	Toews et al 2003b

[a] Type E estimates insect densities; type C classifies populations as either above a threshold and needing pest suppression or below a threshold and not needing pest suppression.

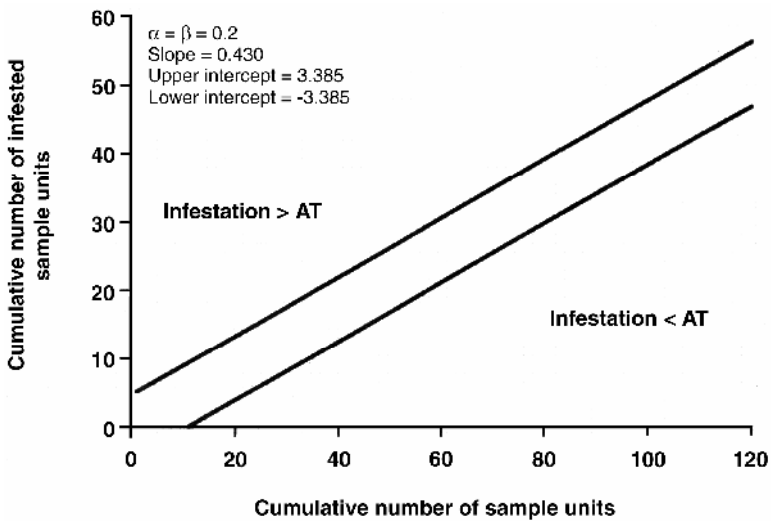

Figure 5.4. Binomial sequential stop lines for classifying *Cryptolestes ferrugineus* infestation levels. AT = action threshold. (Reprinted from Subramanyam et al 1997, with permission from Elsevier)

found in sample units is plotted against the total number of sample units taken. Sampling continues until the cumulative total number of insects in the cumulative total number of sample units taken (T_n) is above the stop line. T_n/n at this point estimates the mean insect density.

Generally, fewer sample units are required to classify an insect population as being above or below an insect density threshold at which insect pest management action is required (AT) than to estimate actual insect density. Figure 5.4 shows stop lines for a sequential classification plan. Sampling continues until the cumulative number of infested sample units crosses either the upper or lower stop lines. When the cumulative total number of infested sample units crosses the upper stop line, insect pest suppression is required. When the lower stop line is crossed, insect pest suppression is not required, and the insect pest population will be sampled again later. The performance of a sampling plan can be evaluated by plotting the operating characteristic (OC) and the average sample number (ASN) graphs (Figure 5.5). An OC curve shows the decrease in the probability that no insect pest suppression will be required as insect density or the proportion of sample units with insects increases.

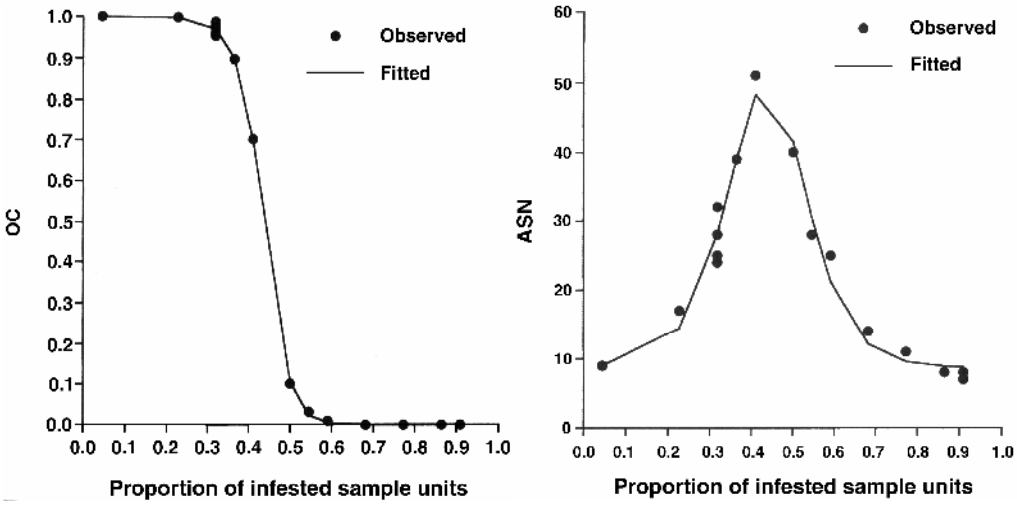

Figure 5.5. Operating characteristic (OC) and average sample number (ASN) curves for binomial sequential sampling plan. (Reprinted from Subramanyam et al 1997, with permission from Elsevier)

The ASN curve gives the average number of sample units needed to reach a decision at different insect infestation levels. When the actual insect density is close to the insect density at which insect pest suppression is required, more sample units will be needed to make the decision. A maximum number of sample units might be set, but the maximum must be high enough not to alter the performance of the sampling plan. When the maximum number of sample units is reached, the insect pest population will be sampled again later.

With sequential sampling plans, each sample unit generally is examined to decide whether additional sample units are needed. This can be done when examining grain in the field for field infestation or when taking **trier** samples from a stack of bags. However, this may be impractical in some stored-product sampling situations. There may not be time to extract and count the insects in a sample unit before taking the next sample unit when commodities are moving, as in the case of the inspection of incoming ingredients or grain being received or shipped from an elevator. In these situations, it may be necessary to take as many sample units as is practical and process only as many sample units as necessary to accurately estimate insect density or classify the insect infestation level.

Utilizing sampling information

Sampling is essential in determining when and where insect pest suppression will be needed and whether insect pest suppression was effective. Sampling also can provide information such as which insect pest species are present, whether **natural enemies** are present, and the age structures and densities of the insect pests and natural enemies. This information can be useful in determining which insect pest management method to use. When an insect pest management program is ineffective, it is important that this be discovered so that additional insect pest suppression can be done. Also, finding the reason for the ineffectiveness may allow an insect pest management method to be used more successfully the next time.

In making insect pest management decisions, a manager's objective is to classify an insect pest population as being above or below an insect density threshold at which insect pest suppression is required. Taking and processing too many sample units wastes money, while too few or unrepresentative sample units can result in incorrect insect pest management decisions and economic losses. Fewer sample units generally are required to classify an insect population than to estimate the actual insect density.

While traps can often detect insect pests at lower densities than other sampling methods, they may not provide reliable information about insect densities. The example of trap catches in grain bins declining in the autumn because of low insect mobility at cooler temperatures while insect populations were still increasing illustrates the importance of converting trap catches to absolute densities. Trap catch is influenced by environmental factors such as temperature, residual food, and air movement and by the physiological states of the insect pests that influence insect mobility. Because the environment and the physiological states of insect pests generally change over time, trap efficiency can change over time. Converting trap catch to absolute insect density can adjust for this variation in trap efficiency and allow managers to better classify insect pest populations as being above or below an insect density threshold at which insect pest suppression is required.

Study questions

1. Why should stored-product insect populations be sampled, and why is sampling before and after insect pest suppression important?
2. What decisions need to be made in developing a sampling plan, and how is each of these important?
3. How are sampling statistics useful in studying or managing stored-product insect pests?

Recommended readings

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Chapter 6

Life History

Stored-product insects in the orders Lepidoptera, Coleoptera, and Hymenoptera have complete **metamorphosis**. They go through three morphologically distinct immature stages (egg, larva, and pupa) before becoming adults. Larvae and adults are mobile, and eggs and pupae are immobile. Larvae grow by **molting**, and the number of instars differs between individual insects and among insect species, usually ranging from three to seven but possibly more.

Psocoptera, Hemiptera, and Acarina have incomplete metamorphosis, going through the egg and several morphologically similar nymphal stages before becoming adults. Development, mortality, egg production, and longevity differ with insect species and environmental conditions.

Developmental time

On a suitable food, the temperature and moisture of a commodity are the primary factors influencing the duration of insect development. However, diet (see Chapter 1) and **photoperiod** (see Table 22.4) can influence insect developmental time. Egg-to-adult developmental times of 17 stored-product insect species are given in Table 6.1. Developmental times were shortest between 27.5 and 37.5°C (at 30, 32.5, or 35°C for 12 species) and longer at higher or lower temperatures. Low moisture can increase insect developmental times as much as twofold. Table 6.2 lists the published studies on the influence of temperature on the developmental times of other insect species associated with stored products, including six species of **natural enemies**. Tables 6.1 and 6.2 include all 16 of the stored-product insect species that can rapidly cause extensive damage, 14 out of the 15 insect species that can cause significant damage, 13 out of 33 insect species that can cause some damage, and five minor insect pest species.

The percentage of the total developmental time spent in each stage is similar for different insect species and does not vary with temperature (Table 6.3). On commodities with <12% moisture, stored-product beetles may spend 67–78% of their total egg-to-adult developmental times in the larval stage, while on commodities with >12% moisture, they may spend only 61–72% of their total developmental time in the larval stage. Stored-product moths spend 61–79% of their total developmental time in the larval stage when on commodities with ≥12% moisture. On high-moisture diets, larvae use less of the food eaten to maintain the water content of their body and can use more for growth than when they are on low-moisture diets. The percentage of total developmental time that is spent in the nonfeeding egg and pupal stages is not influenced by moisture. The pupal stage (11–26%) tends to be a little longer than the egg stage (7–17%).

The percentage of the total developmental time spent in each developmental stage can be used to estimate the duration of each developmental stage when only the total egg-to-adult developmental time is known. This method may be particularly useful for the internal-feeding insects, for which determining the duration of each developmental stage is more difficult. Because some insect pest management methods are more

effective on some developmental stages than others, knowing the duration of each developmental stage may be very important in determining the best time to suppress the insect pest population. The percentage of developmental time spent in each stage also can be useful in predicting the age structure of a population because the number of insects in each developmental stage tends to be proportional to the duration of that developmental stage after an insect population has reached a stable age distribution (see Figure 7.2). Before insects reach a stable age distribution, the duration of a developmental stage may provide an estimate of the average proportion of insects in that stage over a generation.

Table 6.1. Egg-to-adult developmental times, in days, for stored-product insects, as predicted using fitted equations[a]

	Temperature (°C)[b]								
Insect species	**17.5**	**20**	**22.5**	**25**	**27.5**	**30**	**32.5**	**35**	**37.5**
Moths (Lepidoptera)									
Anagasta kuehniella	···	69.1	56.0	46.5	40.6	39.2	···	···	···
Cadra calidella	94.2	62.7	43.6	32.9	28.2	28.7	34.2	45.8	···
Cadra cautella	108.9	76.7	57.1	45.3	38.3	34.4	32.5	31.8	···
Cadra figulilella	129.2	98.7	76.6	60.9	50.8	45.9	46.5	54.1	···
Corcyra cephalonica	192.0	92.6	57.6	44.8	39.7	37.4	36.1	35.2	···
Plodia interpunctella	150.9	99.3	67.3	48.1	37.9	34.9	38.4	49.1	···
Long-lived beetles (Coleoptera)									
Cryptolestes ferrugineus	···	···	53.4	37.0	28.1	23.2	20.6	19.0	18.2
Cryptolestes pusillus	···	···	53.1	45.1	38.5	32.9	28.4	25.1	24.5
Oryzaephilus surinamensis	···	···	48.5	36.4	27.9	22.4	19.8	20.8	27.0
Rhyzopertha dominica	···	···	···	58.8	49.9	42.4	36.1	31.0	···
Sitophilus oryzae	···	52.9	43.2	35.9	30.6	27.4	26.7	29.1	36.7
Tribolium castaneum	···	···	···	41.8	32.7	28.4	26.3	23.4	21.7
Tribolium confusum	···	···	56.2	44.6	35.6	28.5	23.0	20.0	34.1
Short-lived beetles (Coleoptera)									
Acanthoscelides obtectus	82.0	60.4	45.4	35.7	30.2	28.9	···	···	···
Callosobruchus maculatus	167.4	72.5	42.0	31.5	27.3	25.3	23.9	22.8	21.9
Lasioderma serricorne	···	94.8	62.1	43.1	32.9	28.3	27.9	30.7	36.5
Stegobium paniceum	153.5	105.4	73.4	52.9	41.9	41.6	58.4	···	···

[a] Data from Subramanyam and Hagstrum 1993 for Lepidoptera; from Hagstrum and Milliken 1988 for long-lived Coleoptera; from Menusan 1934 for *Acanthoscelides obtectus;* from El Sawaf 1956, Giga and Smith 1983, and Mookherjee and Chawla 1964 for *Callosobruchus maculatus*; from Howe 1957 for *Lasioderma serricorne*; and from Lefkovitch 1967 and Momoi and Sadamori 1982 for *Stegobium paniceum*.

[b] Dots indicate that the temperature is outside the temperature range at which a species completes development.

Table 6.2. Other stored-product insect species for which developmental times are known for a broad range of temperatures

Insect species[a]	Source
Ahasverus advena	Jacob 1996
Alphitobius diaperinus	Rueda and Axtell 1996, Wilson and Miner 1969
Anisopteromalus calandrae	Chun et al 1992
Callosobruchus analis *	Utida 1971
Callosobruchus chinensis *	Utida 1971
Callosobruchus phaseoli	Utida 1971
Callosobruchus rhodesianus	Giga and Smith 1983, Howe and Currie 1964, Utida 1971
Carpophilus dimidatus *	Lefkovitch 1966, Porter 1986
Carpophilus hemipterus	James and Vogele 2000
Cephalonomia waterstoni	Flinn and Hagstrum 1995
Dermestes maculatus	Bellemare and Brunelle 1950, Richardson and Goff 2001, Scoggin and Tauber 1949
Ephestia elutella	Bell 1975
Gnathocerus maxillosus	Ntifo and Nowosielski-Slepowron 1973
Habrobracon hebetor	Harries 1937
Lariophagus distinguendus	Ryoo et al 1991
Latheticus oryzae	Hafez and Chapman 1966, Nowosielski-Slepowron and Aryeetey 1980
Liposcelis bostrychophila	Wang et al 2000
Lophocateres pusillus	Halstead 1968
Lyctocoris campestris	Parajulee et al 1995
Oryzaephilus mercator	Komson and Stewart 1968, Lale et al 1996
Palorus ratzeburgii	Halstead 1967
Palorus subdepressus	Halstead 1967
Prostephanus truncatus	Subramanyam and Hagstrum 1991
Sitophilus granarius	Eastham and Segrove 1947
Sitophilus zeamais	Throne 1994
Sitotroga cerealella	Perez-Mendoza et al 2004c, Weaver and Throne 1994
Theocolax elegans	Imamura et al 2004
Tribolium audax	Smith and Barker 1991
Tribolium destructor	Mathlein 1943
Tribolium freemani	Imura and Nakakita 1984
Tribolium madens	Howe 1962, Smith and Barker 1991
Trogoderma glabrum *	Archer and Strong 1975
Trogoderma granarium *	Hadaway 1956
Trogoderma inclusum *	Strong 1975
Trogoderma variabile *	Partida and Strong 1975
Typhaea stercorea	Jacob 1988
Zabrotes subfasciatus *	Utida 1971

[a] Asterisks indicate short-lived, stored-product beetles for which adult longevity data are available.

Table 6.3. Percentage of total stored-product insect developmental time spent in egg, larval, and pupal stages[a]

Insect species	Percent time in stage		
	Egg	Larval	Pupal
Beetles at <12% moisture			
Cryptolestes ferrugineus	11	78	11
Oryzaephilus surinamensis	12	70	18
Prostephanus truncatus	12	74	15
Tribolium castaneum	11	74	15
Tribolium confusum	15	67	18
Average	12	73	15
Beetles at >12% moisture			
Cryptolestes ferrugineus	16	65	19
Cryptolestes pusillus	13	70	17
Oryzaephilus surinamensis	15	62	23
Prostephanus truncatus	15	66	19
Rhyzopertha dominica	16	72	12
Tribolium castaneum	15	66	19
Tribolium confusum	17	61	21
Average	15	66	19
Moths at >12% moisture			
Anagasta kuehniella	7	79	14
Cadra calidella	14	61	26
Cadra cautella	7	79	14
Cadra figulilella	8	75	17
Corcyra cephalonica	12	68	20
Plodia interpunctella	11	73	16
Average	10	72	18

[a] Data from Hagstrum and Milliken 1988, Subramanyam and Hagstrum 1991, and Subramanyam and Hagstrum 1993. Jarosik et al 2002 found for 342 species in 11 orders that the percentage of the total developmental time spent in each stage did not vary with temperature. Fraenkel and Blewett 1944 showed that, at low moisture, *Anagasta kuehniella* and *Tribolium confusum* maintained their body water at 64–68 and 57%, respectively, by eating more food, and this resulted in longer developmental times for the larval stage.

Survival of immature stages

The egg-to-adult survival rate for long-lived beetles at high moistures is generally ≥75% between 24 and 35°C; survival decreases outside this temperature range, and few insects develop at 18 or 40°C (Figure 6.1). Survival of immature stages tended to decrease as the grain moisture decreased; such survival also can be influenced by diet and **photoperiod**. Mortality was often higher for the eggs and young larvae than for the other developmental stages. Figure 6.1 describes the survival of the immature stages of several species of stored-product beetles (Table 6.4) and probably some other stored-product insect species as well.

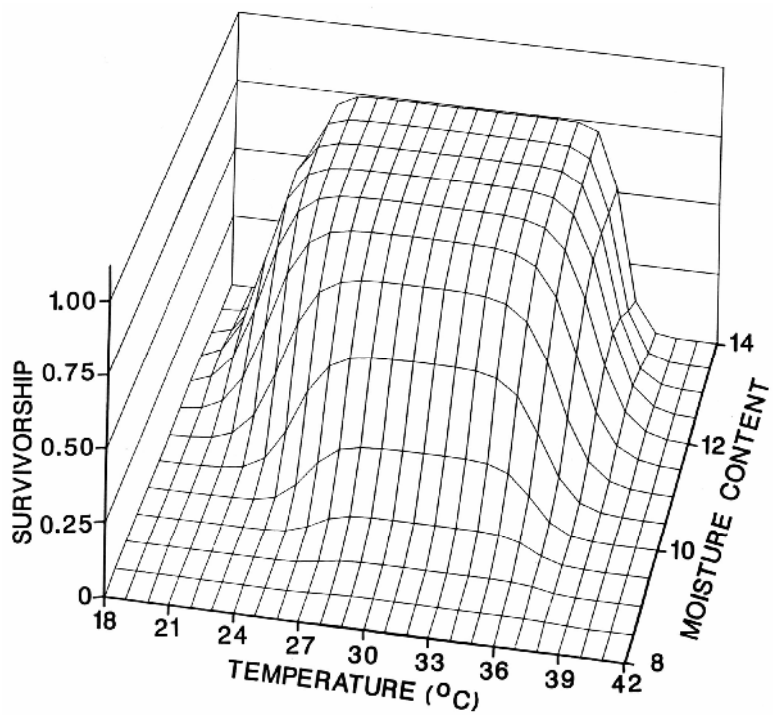

Figure 6.1. Effects of temperature and moisture on the survival of *Rhyzopertha dominica*. (Reprinted from Hagstrum et al 1996a, by permission of Routledge/Taylor & Francis Group, LLC; data from Birch 1945)

Table 6.4. Species of stored-product insects for which mortality of immature stages has been studied over a broad range of temperatures

Insect species	Source
Cryptolestes ferrugineus	Smith 1965
Cryptolestes pusillus	Currie 1967
Oryzaephilus mercator	Arbogast 1976a, Komson and Stewart 1968
Oryzaephilus surinamensis	Arbogast 1976a, Komson and Stewart 1968
Rhyzopertha dominica	Birch 1945
Tribolium castaneum	Hagstrum et al 1996a
Tribolium confusum	Howe 1960

Very high temperatures kill insects more quickly than very low temperatures. When a slow heating rate was used, young *Tribolium castaneum* larvae survived at very high temperatures better than the other developmental stages (Figure 6.2). At 50°C, exposure for 7.2 hr killed most of the young larvae. Other developmental stages were killed at this temperature by exposure of less than 1.8 hr. The cumulative total number of degrees above a threshold of 49.1°C summed over the minutes of exposure ("degree minutes") can be used to predict the mortality caused by heating (Figure 6.3). Older larvae of *T. castaneum* were the most tolerant at a more-rapid heating rate, and older larvae of *Tribolium confusum* were the most tolerant at a slow heating rate. Heating rate also influenced the mortality of *Rhyzopertha dominica*.

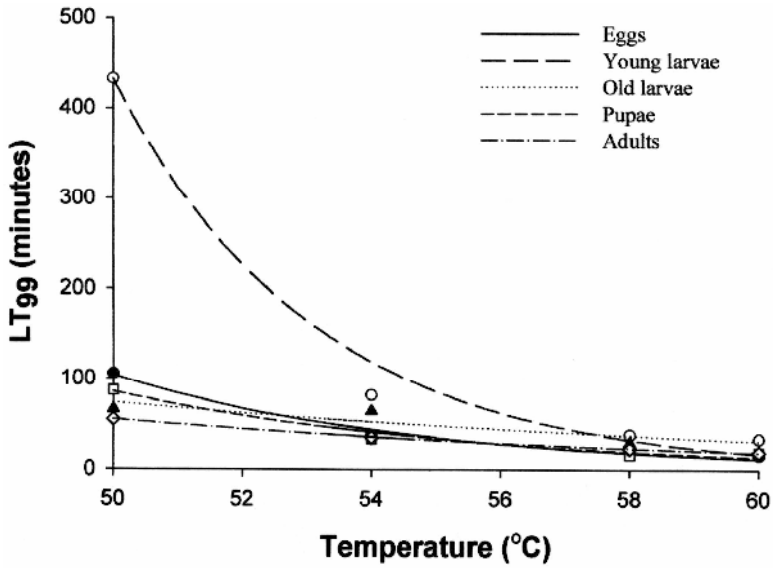

Figure 6.2. Mortality of *Tribolium castaneum* at high temperatures. (Reprinted, with permission, from Mahroof et al 2003) Other studies on the relationship between developmental stage, species, or heating rate and insect mortality at high temperatures include Beckett and Morton 2003, Boina and Subramanyam 2004, and Johnson et al 2004.

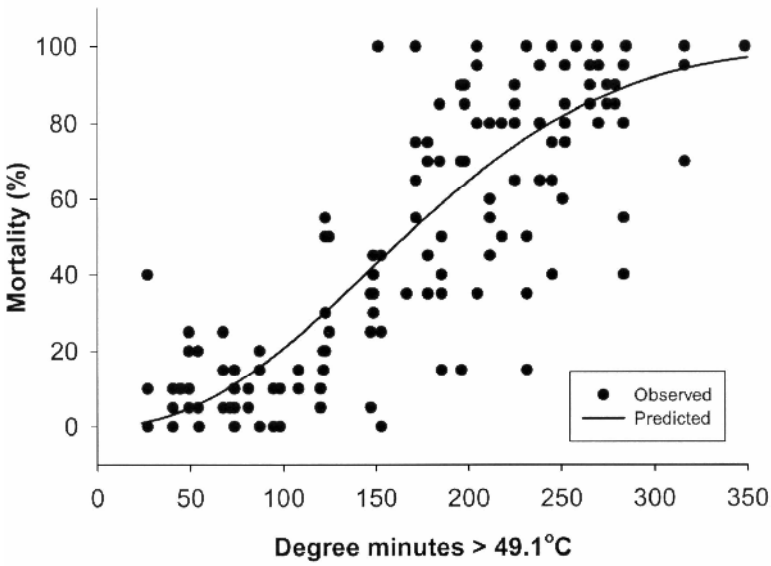

Figure 6.3. Mortality of young *Tribolium castaneum* larvae as exposure period to high temperature increased. (Reprinted, with permission, from Subramanyam et al 2003)

The survival of adults and immature *R. dominica* at low temperatures between 5 and 17°C is shown in Figure 6.4. No adults survived an exposure time of 56 days at 5°C or 84 days at 9°C. No immature insects survived an exposure time of 72 days at 5°C or 112 days at 9°C. Immature insects were killed less rapidly than adults at 5 and 9°C and more rapidly at 13 and 17°C. At temperatures between 13 and 17°C, after an initial

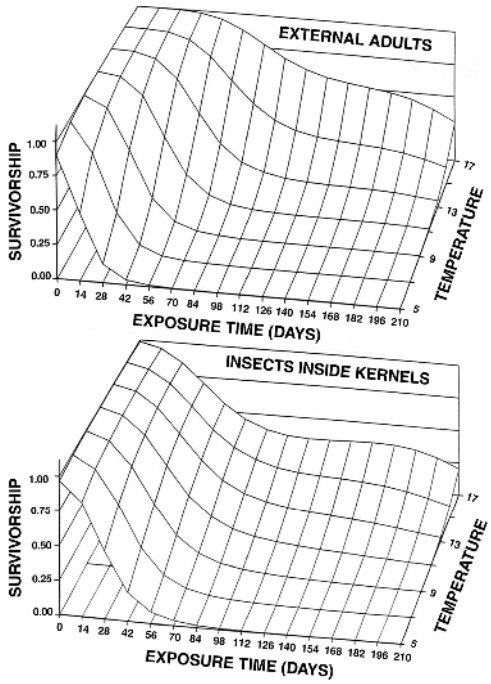

Figure 6.4. Survival times for adult and immature *Rhyzopertha dominica* at temperatures of 5, 9, 13, and 17°C. (Reprinted, with permission, from Hagstrum and Flinn 1994)

period of high mortality, mortality leveled off some after day 84 for immature insects and day 112 for adults and then increased again after day 168.

Releasing **natural enemies** often resulted in higher stored-product insect pest mortalities than have been observed for natural populations of stored-product insects (Table 6.5). Only 11 out of 46 estimates of insect pest mortality attributed to naturally occurring natural enemies showed 70% mortality or more, compared to 162 out of 212 estimates for released natural enemies. The **functional response** of natural enemies to host or prey densities has been studied for six of the 13 species listed in Table 6.5 (see Table 22.2).

The 212 estimates of the mortality for 19 stored-product insect pest species caused by releasing one of 13 species of natural enemies ranged from 0 to 100%. Fewer of the insect pest mortality estimates were 70% or more when the amount of commodity was large (65 out of 98 estimates) than when it was small (97 out of 114). Natural enemies may suppress the insect pest populations in food residues more than those in bulk commodities because the densities per volume of commodity are higher for both the natural enemies and for the host or prey. Generally, insect pest mortalities of less than 70% were the result of releasing too few natural enemies. *Liposcelis bostrychophila* an insect pest itself and would not be released, but naturally occurring populations of this species are likely to reduce the *Plodia interpunctella* egg populations.

The effectiveness of biological control differed among natural enemy and host species and was influenced by other factors. Some natural enemies such as *Trichogramma* were less effective than others. *Theocolax* was less effective against *Sitophilus zeamais* than against other host species. *Theocolax elegans* was more effective against *Rhyzopertha dominica* at 25°C than at 32°C (88 vs. 50% reduction).

Table 6.5. Records of stored-product insect host or prey mortality caused by natural enemies

Host or prey species	Natural enemy	Commodity[a]	% Mortality	Source
		Natural populations		
Cadra cautella	*Habrobracon hebetor*	peanuts	26–73	Keever et al 1985
Callosobruchus maculatus	*Uscana* spp.	cowpea	1–73	van Alebeek 1996
Callosobruchus maculatus	*Dinarmus* spp., *Eupelmus* spp.	cowpea	0–71	van Alebeek 1996
Cryptolestes ferrugineus	*Cephalonomia waterstoni*	wheat	>50	Hagstrum 1987
Prostephanus truncatus	*Teretrius nigrescens*	maize	73–84	Hill et al 2003, Mutlu 1994
Sitophilus zeamais	*Anisopteromalus calandrae*	maize	0–79	Arbogast and Mullen 1990
		Natural enemies released in 19 kg to 409 t of commodity		
Acanthoscelides obtectus	*Dinarmus basalis*	beans	95–100	Schmale et al 2006
Cadra cautella	*Habrobracon hebetor*	peanuts	50–79	Nickle and Hagstrum 1981
Cadra cautella	*Habrobracon hebetor*	peanuts	77–88	Hagstrum 1983
Cadra cautella	*Habrobracon hebetor*	peanuts	55–83	Keever et al 1986
Cadra cautella	*Habrobracon hebetor*	peanuts	97	Brower and Press 1990
Cadra cautella	*Trichogramma pretiosum*	peanuts	12–47	Brower 1988
Cadra cautella	*Trichogramma pretiosum*	peanuts	97	Brower and Press 1990
Cadra cautella	*Xylocoris flavipes*	peanuts	79	Brower and Mullen 1990
Cadra cautella	*Xylocoris flavipes*	peanuts	51	Brower and Press 1992
Cathartus quadricollis	*Xylocoris flavipes*	peanuts	30–84	Press et al 1979
Cryptolestes ferrugineus	*Cephalonomia waterstoni*	wheat	49	Hou et al 2004
Oryzaephilus mercator	*Xylocoris flavipes*	peanuts	60–93	Press et al 1979
Oryzaephilus surinamensis	*Xylocoris flavipes*	maize	97–99	Arbogast 1976b
Plodia interpunctella	*Habrobracon hebetor*	peanuts	66	Brower and Press 1990
Plodia interpunctella	*Trichogramma pretiosum*	peanuts	11–57	Brower 1988
Plodia interpunctella	*Trichogramma pretiosum*	peanuts	37	Brower and Press 1990
Plodia interpunctella	*Xylocoris flavipes*	peanuts	71	Brower and Mullen 1990

Prostephanus truncatus	*Teretrius nigrescens*	maize	39, 56	Richter et al 1998
Rhyzopertha dominica	*Theocolax elegans*	wheat	88, 91	Flinn et al 1996
Rhyzopertha dominica	*Theocolax elegans*	wheat	50, 99	Flinn 1998
Sitophilus oryzae	*Anisopteromalus calandrae*	wheat	46	Hou et al 2004
Sitophilus oryzae	*Anisopteromalus calandrae*	wheat	70–99	Wen and Brower 1995b
Sitophilus oryzae	*Theocolax elegans*	wheat	42–99	Wen and Brower 1995b
Sitophilus zeamais	*Anisopteromalus calandrae*	maize	50–90	Wen et al 1994
Sitophilus zeamais	*Anisopteromalus calandrae*	maize	90–96	Wen and Brower 1995a
Sitophilus zeamais	*Theocolax elegans*	maize	24–42	Wen et al 1994
Sitotroga cerealella	*Xylocoris flavipes*	maize	32–82	LeCato and Arbogast 1979
Tribolium castaneum	*Xylocoris flavipes*	peanuts	91–98	Press et al 1975
Tribolium castaneum	*Xylocoris flavipes*	peanuts	86–95	Press et al 1979
	Natural enemies released in food residues or <9 kg of food			
Cadra cautella	*Habrobracon hebetor*	residual food	97	Press et al 1982
Cadra cautella	*Venturia canescens*	residual food	92	Press et al 1982
Cadra cautella	*Xylocoris flavipes*	residual food	80–96	LeCato et al 1977
Cadra cautella	*Xylocoris flavipes*	residual food	78	Press et al 1982
Callosobruchus chinensis	*Anisopteromalus calandrae*	residual food	55–98	Islam and Nargis 1994
Callosobruchus chinensis	*Dinarmus basalis*	red lentil	69–100	Islam and Kabir 1995
Callosobruchus maculatus	*Dinarmus basalis*	cowpea	27–83	Ouedraogo et al 1996
Callosobruchus maculatus	*Dinarmus basalis*	cowpea	80–99	Sanon et al 1998
Callosobruchus maculatus	*Uscana lariophaga*	cowpea	68–86	van Huis et al 1998
Carpophilus sp.	*Xylocoris flavipes*	residual food	100	Brower and Press 1992
Cryptolestes pusillus	*Xylocoris flavipes*	residual food	70	Brower and Press 1992
Dinoderus minutus	*Teretrius nigrescens*	maize	91	Rees 1991
Oryzaephilus surinamensis	*Xylocoris flavipes*	residual food	80–98	LeCato et al 1977
Oryzaephilus surinamensis	*Xylocoris flavipes*	residual food	100	Brower and Press 1992

(*continued on next page*)

Table 6.5 (continued)

Host or prey species	Natural enemy	Commodity[a]	% Mortality	Source
Plodia interpunctella	*Liposcelis bostrychophila*	residual food	71,72	Lovitt and Soderstrom 1968
Prostephanus truncatus	*Anisopteromalus calandrae*	maize	70	Helbig 1998
Prostephanus truncatus	*Teretrius nigrescens*	maize	83	Rees 1991
Prostephanus truncatus	*Teretrius nigrescens*	maize	37, 66	Hill et al 2003
Prostephanus truncatus	*Teretrius nigrescens*	*Commiphora riparia*	16, 77	Hill et al 2003
Rhyzopertha dominica	*Theocolax elegans*	wheat	45–98	Toews et al 2001
Rhyzopertha dominica	*Teretrius nigrescens*	maize	36	Rees 1991
Rhyzopertha dominica	*Xylocoris flavipes*	residual food	40	Brower and Press 1992
Sitophilus granarius	*Lariophagus distinguendus*	wheat	79–94	Reppchen et al 2003
Sitophilus oryzae	*Anisopteromalus calandrae*	residual food	50–95	Press et al 1984
Sitophilus oryzae	*Anisopteromalus calandrae*	rice	79	Lucas and Riudavets 2002
Sitophilus oryzae	*Lariophagus distinguendus*	rice	98	Lucas and Riudavets 2002
Sitophilus zeamais	*Anisopteromalus calandrae*	maize	95	Williams and Floyd 1971b
Sitophilus zeamais	*Lariophagus distinguendus*	maize	72–93	Zhaohui et al 1999
Sitophilus zeamais	*Theocolax elegans*	maize	89	Williams and Floyd 1971b
Sitophilus spp.	*Xylocoris flavipes*	residual food	65	Brower and Press 1992
Sitotroga cerealella	*Pteromalus cerealellae*	maize	67–99	Wen and Brower 1994
Tribolium castaneum	*Xylocoris flavipes*	residual food	77–98	LeCato et al 1977
Tribolium castaneum	*Xylocoris flavipes*	residual food	77	Brower and Press 1992
Typhaea stercorea	*Xylocoris flavipes*	residual food	100	Brower and Press 1992

[a] Residual food for *Callosobruchus chinensis* was red lentils, for *Liposcelis bostrychophila* was 1 mg of *Plodia interpunctella* diet, and for other species was maize, rolled oats, or a mixture of shelled peanuts, maize, and rolled oats.

Releasing the predator *Teretrius nigrescens* three weeks instead of six weeks after the initial infestation reduced *Prostephanus truncatus* populations on maize by 45% and those on the dry stem wood of a natural host tree, *Commiphora riparia*, by 79%. *Habrobracon hebetor* and *Trichogramma pretiosum* together reduced *P. interpunctella* populations by 84%, compared to 66 and 37%, respectively, for one of these species alone. Providing paralyzed hosts and releasing *H. hebetor* resulted in an 85–99% reduction in *Cadra cautella* populations compared to a 50–79% reduction when only the parasitoids were released. Inducing diapause may be another way to increase the number of hosts available for *H. hebetor*.

Egg laying

The number of eggs laid over the lifetime of a female varies with insect species, temperature, moisture, and diet. **Photoperiod** can influence the time when eggs are laid and the number and fertility of eggs (see Table 22.4). For stored-product moths and some of the short-lived stored-product beetles (anobiids, bruchids, and dermestids), larvae accumulate food reserves for adult reproduction. These species generally lay 100–400 eggs over a three- to four-day period after **eclosion,** and adults live for only a few days after reproducing. For long-lived stored-product beetles, adults feed and accumulate food reserves for egg production. An adult may live for six months to a year or more, laying one to 20 eggs each day and 100–500 eggs over its lifetime. The influence of temperature and adult age on the daily egg laying by *Cryptolestes ferrugineus*, *Sitophilus oryzae*, and *Tribolium castaneum* is shown in Table 6.6. *T. castaneum* on whole grain laid only half as many eggs as reported in Table 6.6 for wheat flour. Larger stored-product beetles such as *Carpophilus*

Table 6.6. Daily egg laying by three species of long-lived stored-product beetles, as predicted using fitted equations[a]

	Temperature (°C)							
Age (days)	**20**	**22.5**	**25**	**27.5**	**30**	**32.5**	**35**	**37.5**
				Cryptolestes ferrugineus				
7 to 14	0.1	0.2	0.7	1.7	3.0	4.0	3.7	2.5
28 to 35	0.1	0.4	1.1	2.7	4.5	5.3	4.3	2.5
56 to 63	0.1	0.3	0.9	2.0	3.0	3.0	2.1	1.0
				Sitophilus oryzae				
7 to 14	4.2	6.4	7.3	6.8	5.5	4.0	2.7	1.7
28 to 35	6.8	9.3	9.6	8.3	6.3	4.4	2.8	1.7
56 to 63	4.3	5.0	4.5	3.5	2.5	1.6	1.0	0.6
				Tribolium castaneum				
7 to 14		2.6	2.8	9.2	18.4	20.2	17.4	
28 to 35		2.5	2.7	8.8	17.0	17.9	14.7	
56 to 63		2.5	2.6	8.2	15.3	15.2	11.8	

[a] Equations from Hagstrum and Throne 1989 and Hagstrum and Flinn 1990. The effect of water on egg production was studied by Hagstrum and Tomblin 1975, Jacob and Fleming 1982, and Ryne et al 2004.

dimidatus, *Carpophilus hemipterus*, and *Tenebroides mauritanicus* can lay up to 1,000 eggs in their lifetimes. Moths and short-lived beetles are more likely than long-lived beetles to live long enough to lay most of their eggs, but fewer of their offspring may survive because eggs are not spread out as much over time and space.

The period between adult eclosion and the first egg laying is two days for *S. oryzae* at 25°C and eight days for *T. castaneum* at 27°C. The duration of the period between eclosion and egg laying varies with temperature. The numbers of eggs laid per day increases for several weeks and then decreases. The egg production by *Cadra cautella* and *Dermestes lardarius* have been shown to be increased twofold when the commodity moisture is high or water is available for drinking.

Adult longevity

Adult longevity is generally most important for long-lived stored-product beetles because they often lay a few eggs each day over several months and are more likely than stored-product moths or short-lived stored-product beetles to die before they lay all of their eggs. However, the eggs that they lay after their offspring have **eclosed** and began reproducing is a small portion of the population's total egg production.

Among the five long-lived stored-product beetle species shown in Figure 6.5, the longevity tended to be highest for adult *O. surinamensis* (up to 230 days) and lowest for adult *T. castaneum* (up to 80 days). Longevity at 32°C tended to be shorter than that at 13.5°C (Figure 6.6). Immature stages did not survive as long as adults at 13.5°C, and the survivorship of the two stages was more similar at 9°C. Insects **acclimate** when they are cooled slowly, and the acclimated insects can survive better at low temperatures.

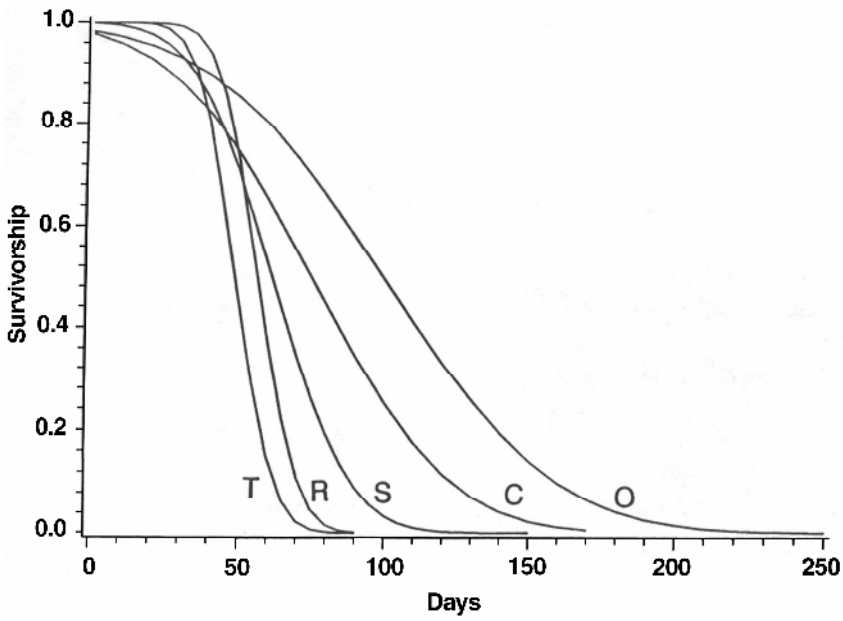

Figure 6.5. Survivorship of *Tribolium castaneum* (T), *Rhyzopertha dominica* (R), *Sitophilus oryzae* (S), *Cryptolestes ferrugineus* (C), and *Oryzaephilus surinamensis* (O) at 9°C. The rearing temperature of 32°C was reduced to 9°C at a rate of 4.5 degrees C per week. (Reprinted from Hagstrum et al 1996a, by permission of Routledge/Taylor & Francis Group, LLC; data from Evans 1983)

For the 12 species of short-lived stored-product beetles (those in Table 6.1 and those marked with an asterisk in Table 6.2), adult longevity increased from five to 18 days at temperatures between 32.5 and 40°C to 13–70 days at temperatures between 15 and 20°C. Living longer did not increase the total number of eggs laid at temperatures below the optimal temperature for egg production (22.5–35°C), and low temperatures delayed egg-laying. However, living longer at low temperatures may increase the chances of these beetles being found as contaminants in stored commodities.

For female moths, delaying mating increased their longevity and reduced the number of eggs laid and their fertility. For *Plodia interpunctella*, female longevity increased from 6.2 days with a one-day delay to 6.6 days with a four- or five-day delay (see recommended reading by Huang and Subramanyam). The total number of eggs laid decreased by 25 for each day that mating was delayed, and egg fertility decreased from 96.3% with a one-day delay to 0% with a five-day delay. For *Cadra cautella*, female longevity increased from 6.8 days without a delay to 11.4 days with an eight-day delay (see recommended reading by Barrer). The total number of eggs laid decreased from 248 without a delay to 85 with a six-day delay. The fertility of the eggs decreased from 75% without a delay to 0% with an eight-day delay. These reductions in fertility resulting from delayed mating may be particularly important when **pheromones** are used to reduce mating (see Chapter 3).

Diapause

Diapause has been reported for 40 species of stored-product insects in the families Pyralidae, Dermestidae, Ptinidae, and Bruchidae (see recommended reading by Bell). This arrested development is generally initiated or terminated by **photoperiod**,

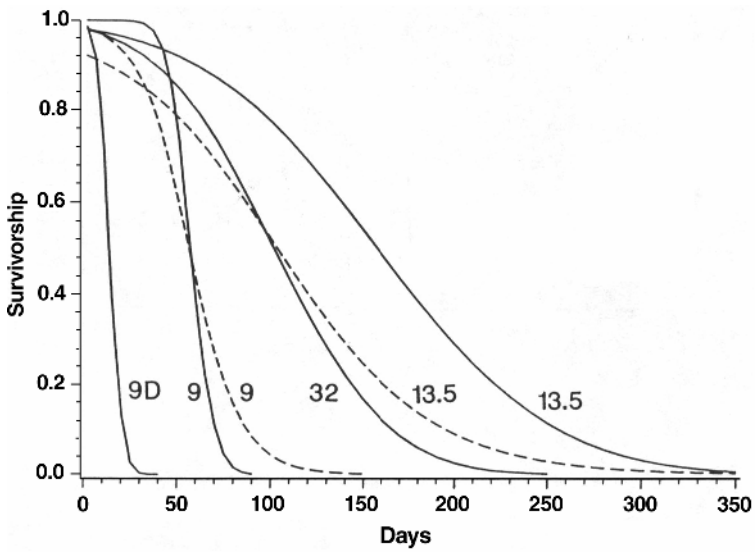

Figure 6.6. Effect of temperature on the survivorship of immature (dashed line) and adult (solid line) insects. The rearing temperature of 32°C was reduced to 9°C at a rate of 4.5 degrees C per week except for one case in which insects were transferred directly from 32 to 9°C (line 9D). (Reprinted from Hagstrum et al 1996a, by permission of Routledge/Taylor & Francis Group, LLC; data from Evans 1983, 1987)

thermoperiod, temperature, moisture, food quality, crowding, or some combination of these cues. The relative importance of the cues generally has not been investigated by field studies. Such information is likely to be important in considering the effect of diapause on an insect pest management program.

Diapausing insects may be more tolerant to food shortages, adverse environments (temperature or moisture), or toxic chemicals. This tolerance may allow diapausing insects to better survive an insect pest management program, synchronize their life cycle with that of the host plant, carry over populations between storage seasons, and infest other locations in the marketing system. Bruchid adults often have a reproductive diapause, while insects in other families usually diapause as larvae. No stored-product insect species has been shown to diapause in the egg stage, and only *Ptinus villiger* has been shown to diapause in the pupal stage. The lack of egg or pupal diapause in stored-product insects may indicate that the combination of diapause and dispersal is important.

The contribution of diapausing larvae to insect pest population dynamics and management can be illustrated using the *Cadra cautella* populations that infest stored **citrus pulp** in Florida. When warm citrus pulp from the dryer is first stored in March, many of the diapausing larvae that overwintered in the warehouse pupate, emerge as adults, and lay eggs. During the first generation, 10–20% of the larvae enter diapause. The percentage of larvae that enter diapause increased to 60% by December as several generations developed on the citrus pulp. Diapause is induced when insects are reared on a diet from crowded cultures, and the diapause-inducing activity of this diet can be removed by extraction. Temperatures below 25°C, short photoperiods, or darkness also induce diapause. Diapausing larvae move around and become adults at a rate of 5–11% per week. Diapause delays reproduction by four to 10 weeks. Diapause results in the larval host being available for *Habrobracon hebetor* for a longer period of time.

Knowing that diapause is induced by contaminated diet, photoperiod, and temperature should allow the number of larvae entering diapause to be used to manage this insect pest. Increasing the number of larvae that diapause early in the citrus pulp storage period can delay reproduction and slow insect population growth. *H. hebetor* should be more effective when more of host larvae diapause. Preventing *C. cautella* larvae from entering diapause late in the storage period could prevent insects from overwintering in the warehouse and infesting the commodity the next year.

Diapause may be overlooked because diapausing insects generally cannot be distinguished from nondiapausing insects without holding the larvae to see whether they pupate or dissecting adults in reproductive diapause to see whether eggs are developing in the ovaries. Because diapausing insects look just like nondiapausing insects, we may underestimate the prevalence of diapause. Diapause may be important more often than we realize in reducing the effectiveness of insect pest management programs by making insect pests more resistant and allowing them to be carried over in empty facilities or transportation vehicles.

Handling and processing

Harvesting, drying, moving, cleaning, and processing commodities can affect the development and survival of stored-product insects (Table 6.7). These are not part of a stored-product insect pest management program, but they can substantially change insect population densities and must be considered when developing and implementing

Table 6.7. Studies on effects of handling and processing commodities on insect life history

Insect species	Source
	Harvesting
Cryptolestes ferrugineus	Rilett 1949, Throne and Culik 1989, Tuff and Telford 1964, White and Bell 1990
Cryptolestes pusillus	Cline 1991
Oryzaephilus surinamensis	Fleming 1988
Sitophilus oryzae	Khare et al 1979, Williams and Mills 1980
Tribolium castaneum	White 1982
	Drying
Callosobruchus chinensis	Shinoda and Yoshida 1985
Callosobruchus maculatus	Ntoukam et al 1997
Cryptolestes pusillus	Farrar and Reed 1942
Oryzaephilus surinamensis	Farrar and Reed 1942
Rhyzopertha dominica	Farrar and Reed 1942
Sitophilus granarius	Farrar and Reed 1942
Sitophilus oryzae	Farrar and Reed 1942, Takahashi and Mizuno 1982
Sitophilus zeamais	Keever et al 1988, Takahashi and Mizuno 1982, Yoshida 1974
Sitotroga cerealella	Farrar and Reed 1942
Tribolium confusum	Farrar and Reed 1942
	Moving
Cryptolestes ferrugineus	Bahr 1973, Bryan and Elvidge 1977, Muir et al 1977, Paliwal et al 1999, Rees et al 1994, Watters and Bickis 1978, White et al 1997
Liposcelis spp.	Rees et al 1994
Oryzaephilus surinamensis	Armitage et al 1999, Bahr 1973, Bryan and Elvidge 1977
Rhyzopertha dominica	Bahr 1973, 1975
Sitophilus granarius	Armitage et al 1999, Bahr 1973, Bailey 1969, Bryan and Elvidge 1977, Rodinov 1938
Sitophilus oryzae	Bahr 1973, Joffe and Clarke 1963
Tribolium castaneum	Bahr 1973, Bryan and Elvidge 1977, Paliwal et al 1999, White et al 1997
	Cleaning
Cadra cautella	Payne et al 1970
Carpophilus dimidiatus	Payne et al 1970
Cryptolestes ferrugineus	Sinha 1975
Oryzaephilus mercator	Payne et al 1970, Sinha 1975
Oryzaephilus surinamensis	Sinha 1975
Plodia interpunctella	Payne et al 1970
Sitophilus oryzae	Nansen et al 2004e
Stegobium paniceum	Nansen et al 2004e, Sinha 1975
Tribolium castaneum	Nansen et al 2004e, Payne et al 1970, Sinha 1975

(*continued on next page*)

Table 6.7 (continued)

Insect species	Source
	Milling
Cadra cautella	McGaughey 1974, Yamanouchi and Takano 1980
Lasioderma serricorne	McGaughey 1974
Oryzaephilus surinamensis	McGaughey 1974
Plodia interpunctella	McGaughey 1974
Rhyzopertha dominica	McGaughey 1974
Sitophilus oryzae	Ducom-Gallerne and Vinghes 2001, Lucas and Riudavets 2000, McGaughey 1974, Takahashi and Mizuno 1982
Sitophilus zeamais	Takahashi and Mizuno 1982, Yamanouchi and Takano 1980
Tribolium castaneum	McGaughey 1974, Miller 1944, Yamanouchi and Takano 1980
Tribolium confusum	Cotton and Wagner 1935, McGaughey 1974, Miller 1944, Smallman and Loschiavo 1952

a study or an insect pest management program. Examining these business practices to be sure that they favor effective insect pest management programs as much as possible may suggest cost-effective ways to improve these programs.

Combine harvesting can result in damage to 20–50% of wheat kernels. Although stored-product insects are immersed in food, some species may need to search for damaged kernels. Setting the combine to minimize kernel damage can be an important part of a stored-product insect pest management program.

Drying may be directly important to stored-product insect pest management by killing insects or indirectly important by changing the susceptibility of commodities to insects. Some insects survive even when most of the commodity is maintained at a lethal temperature for sufficient time because commodities are not heated uniformly. In grain, temperature differences of 28°C may occur over a distance of 5–10 cm (2–4 in.). Heating also can result in cracks that make grain suitable for insect development. Lowering moisture increases insect mortality and reduces the susceptibility of the commodities to insects.

Moving grain can result in insect mortality (see Chapter 15). Depending upon the insect species, the stage of development, and the velocity of grain before impact, mortality has ranged from 24 to 100%. Pneumatic conveying generally causes higher mortality than augering. Grain handling also can damage kernels, making them more suitable for insects.

Cleaning of in-shell peanuts is worthwhile in reducing insect infestation, but a single cleaning in a retail store did not reduce the numbers of insects caught in traps. Cleaning wheat to remove dockage may reduce the numbers of *Oryzaephilus surinamensis* but is likely to be less effective in reducing the numbers of *Cryptolestes ferrugineus*, *O. mercator*, or *Tribolium castaneum*.

Milling may not kill all of the insects; mortality depends upon the stage and species of insect and the stage in the milling process. For *Sitophilus oryzae*, rice milling killed ≥99% and was as effective as fumigation when insect densities were less than 10 insects per kilogram. Eggs and young larvae were less susceptible than large larvae and pupae. Also, the suitability of commodities for insect development varies with the degree of milling.

Utilization of life history information

Knowledge of how environmental factors influence the life histories of stored-product insects should allow the variation in insect life histories among locations within bulk commodities, locations in a facility, and geographical locations, as well as over time to be considered in planning a study, a sampling program, or an insect pest management program. Considering the complexity of the interactions among environmental factors (temperature, moisture, diet, natural enemies, handling, and processing) and the many different components of insect life histories (developmental time, mortality, egg production, longevity, and diapause), it should be clear why computer simulation **models** that predict stored-product insect population growth can be important in planning and implementing a study, a sampling program, or an insect pest management program.

Study questions

1. How is stored-product insect life history influenced by environment?
2. What are the advantages of diapause for stored-product insect survival?
3. How can knowledge of insect life histories be used to manage stored-product insect pests?

Recommended readings

Arbogast, R. T. 1991. Beetles: Coleoptera. Pages 131-176 in: Ecology and Management of Food-Industry Pests. J. R. Gorham, ed. Association of Official Analytical Chemists, Arlington, VA.

Barrer, P. M. 1976. The influence of delayed mating on the reproduction of *Ephestia cautella* (Walker) (Lepidoptera: Phycitidae). J. Stored Prod. Res. 12:165-169.

Bell, C. H. 1994. A review of diapause in stored-product insects. J. Stored Prod. Res. 30:99-122.

Cox, P. D., and Bell, C. H. 1991. Biology and ecology of moth pests of stored foods. Pages 181-193 in: Ecology and Management of Food-Industry Pests. J. R. Gorham, Ed. Association of Official Analytical Chemists, Arlington, VA.

Hagstrum, D. W., and Milliken, G. A. 1988. Quantitative analysis of temperature, moisture and diet as factors affecting insect development. Ann. Entomol. Soc. Am. 81:539-546.

Hagstrum, D. W., Flinn, P. W., and Howard, R. W. 1996. Ecology. Pages 71-91 in: Integrated Management of Insects in Stored Products. B. Subramanyam and D. W. Hagstrum, Eds. Marcel Dekker, Inc., New York.

Huang, F., and Subramanyam, B. 2003. Effects of delayed mating on reproductive performance of *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae). J. Stored Prod. Res. 39:53-63.

Sedlacek, J. D., Weston, P. A., and Barney, R. J. 1996. Lepidoptera and Psocoptera. Pages 41-70 in: Integrated Management of Insects in Stored Products. B. Subramanyam and D. W. Hagstrum, Eds. Marcel Dekker, Inc., New York.

Subramanyam, B., and Hagstrum, D. W. 1993. Predicting development times of six stored-product moth species (Lepidoptera: Pyralidae) in relation to temperature, relative humidity, and diet. Eur. J. Entomol. 90:51-64.

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Chapter 7

Population Growth

Computer simulation **models** that predict insect population growth and distribution can be powerful tools that allow managers to choose the best method or methods for managing insect pests, to effectively implement an insect pest management program, and to use insect pest management methods when and where they will be most effective.

Temperature and moisture are the most important environmental factors influencing insect population growth. Computer simulation models predicting insect population growth are useful because air or commodity temperature and commodity moisture or the relative humidity of the air often can be measured more easily than the insect population growth rate in stored commodities and in storage, processing, transportation, and marketing habitats. However, air temperature and relative humidity may be misleading. Insect microhabitats may be warmer than the air temperature inside heat-producing equipment or cooler than the air temperature within the cracks in concrete floors that are in contact with the soil. In small spaces, the relative humidity of the air may be lowered by **sorption** or raised by desorption of moisture from the commodity, making the space less or more favorable for insects. Bulk commodities gradually warm from the outside to the center in the spring and gradually cool from the outside to the center in autumn, resulting in temperature gradients. Information on the differences in the environmental conditions among locations and on the insect distribution in commodities; in storage, processing, and marketing facilities; and in transportation vehicles should be used to determine the temperatures and relative humidities to which insects are actually exposed.

Grain and other commodities are good insulators, and only the temperature in the outer 15 cm (6 in.) of the mass may change with day-to-night changes in air temperature. However, insect densities are often high near the surface, where temperatures fluctuate. Also, the insects infesting the small quantities of commodity residues that can accumulate in storage, processing, and marketing facilities and in transportation vehicles may be exposed to fluctuating temperatures.

Because stored-product insect populations can increase roughly 10-fold per generation when the environment is suitable, an insect pest population can return to previous levels within one generation after a 90% reduction and two generations after a 99% reduction. When temperature and moisture are above or below the optimal ranges, egg-to-adult development takes longer; egg production is lower; mortality is higher; population growth is slower; and pest populations take longer to return to the previous level.

Types of models

Degree-days (DD), an iterative method of predicting insect developmental time at fluctuating temperatures, and computer simulation models have been used for stored-product insects. Before computer models were available, the possible range of insect population growth rates over one generation was calculated at a variety of temperatures and moistures. For 43 species of stored-product insects, the maximum

population growth rates ranged from a little more than onefold to 70-fold per generation (see recommended reading by Howe).

The calculation of DD assumes a linear relationship between temperature and insect developmental time. This is a valid assumption between 20 and 30°C, but it often is not valid outside this temperature range, and this can cause errors in predictions. Events like the **eclosion** of the first adult in a warehouse can be predicted by calculating when insects will have been exposed to an expected number of DD (Table 7.1). The numbers of DD above the lower temperature threshold required for insects to complete development from egg to adult varied from 260.4 to 1,470. The lower temperature thresholds varied from 8.8 to 18.3°C. For *Plodia interpunctella*, DD varied from 345 on wheat bran to 1,616 on prunes. There was a tendency for moths to require more DD than beetles to complete development. DD accurately predicted the emergence of several species of pyralid moths in date palm orchards in Iraq (see recommended reading by Ahmad and Ali).

Several studies have shown that the developmental times of insect species when temperature fluctuates between day and night can differ from those observed at constant temperatures (Table 7.2). An iterative method can be used to predict insect developmental time at fluctuating temperatures. Differences in the developmental time between fluctuating and constant temperatures tend to be largest when the mean of the fluctuating temperatures is above 30°C or below 25°C. Short exposures to normally lethal temperatures above 30°C can slow insect development when temperatures fluctuate. Some insect development may occur during short exposures

Table 7.1. Degree-days (DD) required for egg to adult development[a]

Insect species	Lower temperature threshold (°C)	DD
Carpophilus hemipterus	14.6	260.4
Tribolium confusum	18.3	293.1
Tribolium castaneum	17.6	299.4
Cryptolestes ferrugineus	15.5	359.2
Prostephanus truncatus	15.1	403.9
Plodia interpunctella	15.3	435.7
Cadra calidella	11.9	470.4
Corcyra cephalonica	14.7	491.6
Cryptolestes pusillus	14.2	493.1
Cadra cautella	11.5	619.2
Oryzaephilus surinamensis	8.8	620.4
Rhyzopertha dominica	13.2	685.9
Anagasta kuehniella	9.5	724.1
Cadra figulilella	12.3	758.7
Dermestes maculatus	15.0	1,470.0

[a] Data from Subramanyam et al 1991; Subramanyam and Hagstrum 1991, 1993; James and Vogele 2000; and Richardson and Goff 2001. Johnson et al 1995 determined DD for *Plodia interpunctella* on several different commodities. Papadopoulou 2001 reported the DD above a threshold of 14°C required for *Lasioderma serricorne* pupae to complete development.

to temperatures below the lower developmental threshold, and insects may develop faster than expected at fluctuating temperatures when means are below 25°C. Developmental times at fluctuating temperatures can be best predicted by equations fitted to insect developmental time data collected by rearing insects at fluctuating temperatures.

Using computer simulation **models** is more complex than using the accumulated DD or the iterative method for predicting insect developmental times at fluctuating temperatures, but computer simulation models can predict the numbers of insects as well as when the first adult will **eclose**. Computer simulation models predict the growth of stored-product insect populations using information about the effects of temperature and moisture on insect life history. Many of the computer simulation models for stored-product insects predict population growth by moving insects through a series of age classes representing immature development and adult longevity (see Chapter 24). The duration of insect developmental time from egg to adult determines how soon adults will reproduce. The number of offspring produced by the surviving insects determines how large the next generation will be. Mortality determines how many of the insects will reach reproductive age and how long adults have to produce offspring. Many of the figures and tables in the previous chapter gave the predictions of the equations that have been used in the computer simulation models to describe the relationship between environment (temperature and moisture) and life histories (developmental time, mortality, and age-specific egg production).

Insects in the first **instar** (I) molt to the second instar (II) over several days (Figure 7.1). The variation in the developmental time for each instar results in a progressive increase in the times between the first and the last individual molting to the next instar. Using this distributed delay to simulate the variation in developmental times between individual insects improves model predictions.

Figure 7.1 shows the changes in age structure over time for the offspring of a short-lived stored-product insect, *Ephestia elutella*, that lays all of its eggs over a period of a few days. The changes in the age structure of the offspring of a long-lived stored-product beetle over time are shown in Figure 7.2. Over several generations, *Rhyzopertha dominica* populations reach a stable age distribution in which roughly

Table 7.2. Stored-product insects for which developmental times at constant and fluctuating temperatures have been compared

Insect species	Source[a]
Anagasta kuehniella	Hase 1927, Siddiqui and Barlow 1973, Voute 1936
Galleria mellonella	Destouches 1921
Sitophilus oryzae	Hagstrum and Leach 1973
Tenebrio molitor	Payne 1932
Tribolium castaneum	Hagstrum and Milliken 1991
Tribolium confusum	Mikulski 1936
Trogoderma inclusum	Hagstrum and Leach 1973

[a] Insect developmental times at constant and fluctuating temperatures have been compared for 76 species of insects in nine orders, and an iterative method has been developed for predicting developmental time when temperatures fluctuate. See Hagstrum and Milliken 1991.

81% of the insects are larvae, 4% are pupae, and 15% are adults. Long-lived beetles that lay eggs over the entire generation may be able to reach a stable age distribution more quickly than short-lived insects.

Knowledge of the age distribution for stored-product insect pests can be important in the interpretation of sampling data. Often only the adult insect population is

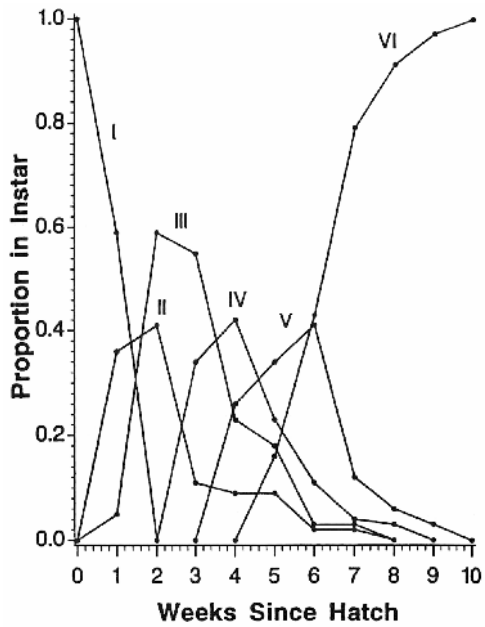

Figure 7.1. Changes in age structure of the larval population of *Ephestia elutella.* Roman numerals designate curves for first through sixth instars. (Reprinted from Hagstrum et al 1996a, by permission of Routledge/Taylor & Francis Group, LLC; data from Richards and Waloff 1946)

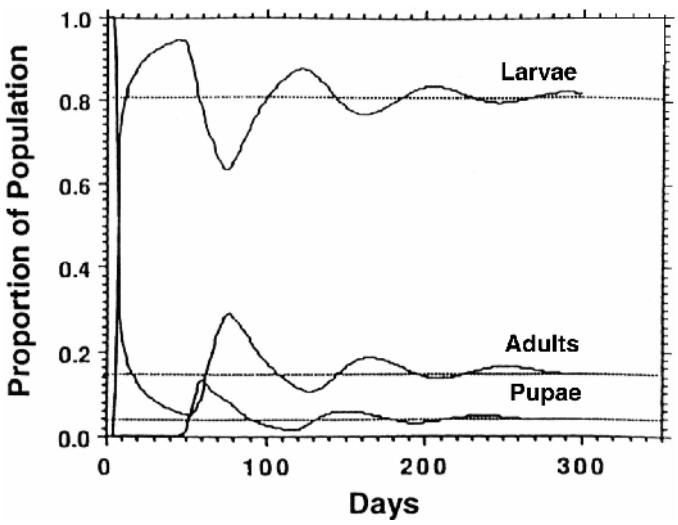

Figure 7.2. Variation over time in the proportion of *Rhyzopertha dominica* in three developmental stages. (Reprinted, with permission, from Hagstrum et al 1990)

monitored. Counting only the adult insects when sampling to estimate insect abundance is generally easier, but in the case of *R. dominica*, less than 15% of the insects in a grain sample unit may be counted. A total count generally requires extracting the immature insects from the grain sample unit or holding the grain sample unit while immature insects develop into adults (see Chapter 2). Computer simulation **models** can provide an alternative to sampling the immature stages by predicting the abundance of each of the developmental stages.

For a short-lived insect such as *Ephestia elutella* (Figure 7.1), adult offspring will **eclose** from the pupal stage over a short time period. A similar peak in adult eclosion can occur during the next generation, but the generations will soon begin to overlap. Long-lived beetle populations will increase more steadily, as shown in Figures 7.3 and 7.4. These insect population trends also can be influenced by the insect pest management methods used, prior insect infestations, immigration, emigration, and diapause.

Functional response equations can be used to connect the models predicting the growth of **natural enemy** populations to the models predicting the growth of the insect pest populations that are their hosts or prey (see Table 22.2). The functional response equation also has been used to predict grain damage by allowing the uninjured grain to take the place of the hosts or prey, and the insect pest to take the place of the natural enemy. Heat-transfer models using weather data to predict the seasonal changes in temperatures at different locations in commodities stored in bulk have been coupled with insect models to predict the spatial variations in insect population growth.

Predictions

Computer simulation models are available to predict the population growth of 14 species of stored-product insect pests and four species of natural enemies (Table 7.3).

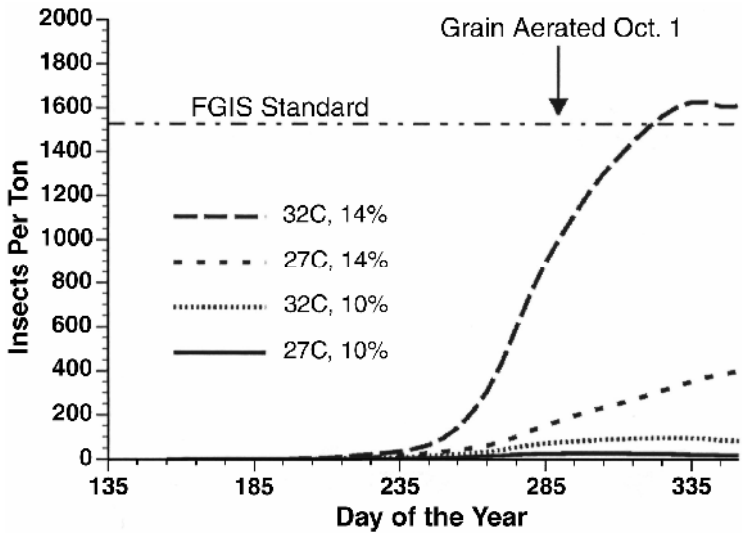

Figure 7.3. Effects of temperature and moisture on the predicted growth of *Rhyzopertha dominica* populations. FGIS = Federal Grain Inspection Service. (Reprinted from Hagstrum et al 1996a, by permission of Routledge/Taylor & Francis Group, LLC; data from Hagstrum and Flinn 1990)

Computer simulations and comparisons of the results of these simulations with the observed insect pest population growth or commodity damage can provide insight during the planning of an insect pest management program into how the ecology of insect pests can be exploited. Computer simulations also can be used directly to forecast insect population growth during the implementation of an insect pest management program. These predictions are likely to be important in making an insect pest management decision because the overall insect population growth rate, damage caused by insects, and economic losses depend upon which insect species are present and their relative abundance. These predictions also allow the variations in the environmental conditions that alter insect population growth rate over time and among locations in a commodity stored in bulk or a facility to be considered in making insect pest management decisions.

The predictions of the computer simulation models comparing the effects of grain temperature and moisture on the population growth of five insect species are shown in Figures 7.3 and 7.4. These models explained 90% or more of the variation between predicted and observed insect population growth rates. The differences in population growth between species tended to be somewhat larger (10- to 150-fold) than those between temperatures and moistures (2- to 10-fold). These models also have been used to predict the effects of harvest date, aeration, fumigation, and residual insecticides. A one-month later harvest (because of differences in latitude) or a one-month delay in fumigation can result in stored-product insect populations that are roughly 5- to 25-fold smaller. Delayed harvest or fumigation reduces the time available for insect populations in stored grain to grow before the grain can be cooled by aeration or winter temperature. Populations are 5- to 25-fold larger for every month that cooling by aeration is delayed. Simulations with a submodel added for the effects of a low-oxygen atmosphere on *Sitophilus oryzae* mortality have been used to predict the effect of low-oxygen atmospheres at different temperatures. Mortality was found to be 99.9% after 15 days of exposure to low-oxygen atmosphere at 29°C and 95.7% after 15 days at 17°C.

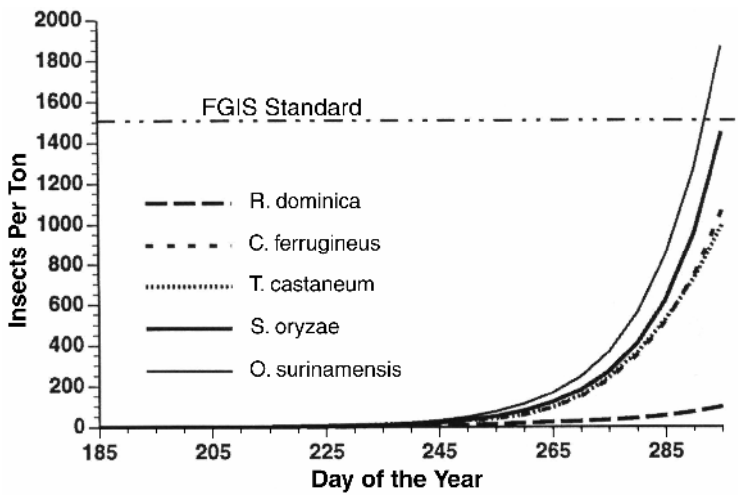

Figure 7.4. Predicted insect population growth of five species at 32°C and 14% moisture. FGIS = Federal Grain Inspection Service. (Reprinted from Hagstrum et al 1996a, by permission of Routledge/Taylor & Francis Group, LLC; data from Hagstrum and Flinn 1990)

Table 7.3. Computer simulation models that predict growth of stored-product insect populations, damage they cause, and effectiveness of insect pest management methods

Simulated attribute or location	Insect species	Source
Aeration	*Cryptolestes ferrugineus*	Arthur and Flinn 2000, Flinn et al 1997
	Sitophilus oryzae	Thorpe et al 1982
	Sitophilus zeamais	Arthur et al 1998, 2001; Maier et al 1996
	Tribolium castaneum	White 1985
	the five species in Figure 7.4	Flinn and Hagstrum 1990b, Hagstrum and Flinn 1990
	four of the five species in Figure 7.4 (Not *Cryptolestes ferrugineus*)	Driscoll et al 2000
Damage	*Prostephanus truncatus*	Holst et al 2000
	Sitophilus zeamais	Holst et al 2000, Maier et al 1996
Elevator	*Rhyzopertha dominica*	Flinn et al 2004a
Food processing plant	*Tribolium castaneum*	Prabhakaran et al 2001
Fumigation	*Tribolium castaneum*	White 1985
	the five species in Figure 7.4	Flinn and Hagstrum 1990b, Hagstrum and Flinn 1990
Host plant resistance	*Sitophilus oryzae*	Baker et al 1991
Hot spots	*Cryptolestes ferrugineus*	Mani et al 2001a,b
Residual insecticide	*Sitophilus oryzae*	Longstaff 1988a
	Tribolium castaneum	White 1985
	the five species in Figure 7.4	Flinn and Hagstrum 1990b, Hagstrum and Flinn 1990
Insecticide resistance	*Sitophilus oryzae*	Longstaff 1988b, Prabhakaran et al 2001, Sinclair and Alder 1985
Low oxygen	*Sitophilus oryzae*	Flinn and Hagstrum 1997
Marketing system	*Rhyzopertha dominica*	Hagstrum and Heid 1988
Parasitoid	*Cephalonomia waterstoni*	Flinn and Hagstrum 1995
	Anisopteromalus calandrae	Smith 1994a
Pathogen	*Nosema whitei*	Onstad and Maddox 1990
Population growth	*Anagasta kuehniella*	Skovgard et al 1999
	Cadra cautella	Throne et al 1998
	Callosobruchus maculatus	Bellows 1982
	Callosobruchus chinensis	Bellows 1982
	Cryptolestes ferrugineus	Hagstrum and Throne 1989, Kawamoto et al 1989
	Cryptolestes pusillus	Throne 1989
	Oryzaephilus surinamensis	Hagstrum and Flinn 1990
	Prostephanus truncatus	Meikle et al 1998a
	Ptinus ocellus	Nuttall 1989

(*continued on next page*)

Table 7.3 (continued)

Simulated attribute or location	Insect species	Source
	Rhyzopertha dominica	Hagstrum 1996, Hagstrum and Throne 1989
	Sitophilus oryzae	Baker et al 1991, Hagstrum and Flinn 1990, Longstaff and Cuff 1984
	Sitophilus zeamais	Maier et al 1996, Meikle et al 1999
	Tribolium castaneum	Hagstrum and Throne 1989
	Tribolium confusum	Hardman 1976, Onstad and Maddox 1990
Predator	*Lyctocoris campestris*	Throne et al 2000b
Temperature	*Cryptolestes ferrugineus*	Flinn et al 1992

The effects of aeration on insect population growth were first simulated for *S. oryzae*. These simulations indicated that the optimal strategy in Australia was to use airflow rates greater than 0.2 $L \cdot sec^{-1}/t$ during the coolest 15% of the night. Simulations of *S. oryzae* populations have shown that aeration should increase the effectiveness of residual insecticides (see Chapter 17) and slow the development of resistance (see Chapter 10). More recently, models for *Oryzaephilus surinamensis*, *R. dominica*, *S. oryzae* and *Tribolium castaneum* were used to predict insect spatial distribution and whether aeration would keep the total insect population below acceptable levels. The model consistently explained 95% of the variation between the predicted and observed population growth for each species in two field studies. For a field study in Australia, the model correctly predicted that the high headspace temperatures would prevent aeration from cooling grain near the surface and, for another study in Indonesia, the model correctly predicted that warming and drying grain near the inlet would result in aeration increasing the insect problem.

Simulations have shown that a combination of autumn aeration to cool maize and chilled aeration in the summer suppressed *Sitophilus zeamais* populations enough at all latitudes in the United States that using residual insecticides or fumigants was unnecessary. These simulations also predicted the grain weight loss caused by insects.

By coupling a heat-transfer model and an insect population-growth **model**, the *Cryptolestes ferrugineus* population growth at different locations in a bin was predicted (see recommended reading by Flinn and Hagstrum). This model was used to simulate the effects of time of aeration, latitude, and bin size. In simulations using aeration controllers to turn on aeration fans when the outside temperatures were suitable for cooling grain, *C. ferrugineus* populations were suppressed better than by traditional aeration starting in November. In these simulations, the fact that harvest at southern latitudes occurred earlier than at more-northern latitudes resulted in higher insect populations in the southern areas before winter temperature could cool the grain. Also, in these simulations, slower natural cooling in large bins than in small bins resulted in higher insect populations in the large bins.

Simulations with a *Tribolium castaneum* population-growth model provided predictions similar to observations in flat storages at Baigin and Mywybilla, Australia. Simulations showed that aeration was ineffective in suppressing populations near the

grain surface because of the high headspace temperatures. Simulations also showed that applying a residual insecticide as wheat was received suppressed insect populations below detectable levels for 14–16 weeks and that reinfestation of wheat by immigrants after fumigation allowed populations to reach detectable levels after 29 weeks of storage. The model has been used by the Queensland Department of Primary Industries to evaluate its insect pest management policies and recommendations at a cost of Aus$2–5 per simulation, and this was considered inexpensive compared with a cost of Aus$100 for many insect pest management methods.

The grain damage models for *Prostephanus truncatus* and *Sitophilus zeamais* may, in combination with insect population-growth models for these two species, be able to forecast the losses for single bins or over a large geographical area. Simulations showed that *P. truncatus* was by far more damaging than *S. zeamais* and that together these two species can account for most of the grain damage in maize stores in West Africa. The percent of grain damage increased much more rapidly than weight loss. Models tended to overpredict densities of both species in maize stores, which may be a result of not including emigration and **natural enemies** in the *P. truncatus* model and natural enemies in the *S. zeamais* model. *S. zeamais* immigrated into stored grain continuously, and simulations with a single immigration of *P. truncatus* into stored grain provided better predictions than simulations with a single immigration of *S. zeamais*.

The population-growth model predicting when and where *Cryptolestes ferrugineus* will produce a **hot spot** in stored grain includes submodels for insect movement, heat production by insects, and heat transfer in the grain. In simulations, the center of the bulk was the most-favorable location for insect reproduction and the most likely place for a hot spot to develop. At an initial grain temperature of 25°C, no hot spots developed in simulations. In simulations with an initial grain temperature of 30°C, insects that were introduced early in the fall produced a hot spot by December. With an initial grain temperature of 35°C, hot spots developed a month earlier in simulations than with an initial grain temperature of 30°C. In simulations with an initial grain temperature of 30°C, a hot spot developed with an initial density of two insects per kilogram of wheat and reached 39°C, but with an initial density of one insect per kilogram, the maximum temperature increase caused by insects was 1°C. Populations of 550 adults per kilogram and 10,200 immature insects per kilogram in the simulations produced a hot spot that reached 35.6°C. In simulations, the likelihood and duration of hot spots increased as the bin diameter increased.

The **pathogen** *Nosema whitei* was the first natural enemy of a stored-product insect pest for which a computer simulation model was developed. Simulations showed that the pathogen could reduce high-density *Tribolium confusum* populations by 90%, but only one temperature was considered and the predictions of the simulations were compared only to laboratory populations. Another computer simulation model for *T. confusum* did include the effects of temperature on insect population growth, and the simulations showed that developmental time was more important than egg production or survival. The densities of the simulated populations of the **predator** *Lyctocoris campestris* and its host, *Plodia interpunctella*, were almost always within the 95% confidence limits of the density estimates for the insect populations in maize stored in Wisconsin, although the population growth predicted by the model may have been slightly slower.

Two of the models predict when **parasitoids** should be released and how many to release. For *Cephalonomia waterstoni*, simulations showed that the timing of a parasitoid release can be more important than the number of parasitoids released.

Parasitoids were most effective in simulations when released as the hosts first become fourth **instars**. Twenty times more parasitoids needed to be released after the 40th day of a *Cryptolestes ferrugineus* infestation to achieve the same suppression as releasing two pairs of parasitoids on the 20th day. For *Anisopteromalus calandrae* at 25°C, simulations found the optimal strategy to be three releases at nine-day intervals starting when 15-day-old host larvae were available. Releasing 10 parasitoids for each *Sitophilus zeamais* adult was optimal. However, the first release reduced the insect pest population by 95.3%, and the two additional releases to reduce population by another 2.5 and 3.4% may not have been cost-effective.

Simulations with the population-growth **model** for *Cryptolestes pusillus* found that even small delays in larval development and small reductions in egg production or survival had a large effect on the future insect population level. Simulations have shown that resistant soft wheat cultivars should reduce the *Sitophilus oryzae* population after 180 days by 20.9% when development is delayed by only 0.7 days. Submodels for insect pest management methods have not been added to the computer simulation models for the population growth of *Callosobruchus chinensis*, *Callosobruchus maculatus, Cryptolestes pusillus*, and *Ptinus ocellus* (formerly *Ptinus tectus*), and their predicted population growth rates have been compared only with those of laboratory populations.

A computer simulation model predicting the population growth of *Rhyzopertha dominica* in bins at an elevator suggested that the immigration rate of insects into the bins at elevators was 50% higher than that on the farms. A model predicting *R. dominica* populations in wheat moving through the marketing system from farms to ports explained 96.5% of the month-to-month variation in insect density. Simulations with a model developed to predict the development of insect resistance to a fumigant in food-processing plants suggested that *Tribolium castaneum* is unlikely to develop resistance to **sulfuryl fluoride**.

Fitting the population growth model for *Anagasta kuehniella* to three years of trapping data from two Danish flour mills showed that the moths realized only 1–3% of their reproductive potential in these mills. Predictions were good in both mills even though the moth population in one mill was 10 times larger that in the other. The model predicted two peaks in moth emergence caused by the delayed **eclosion** of adults because of larval diapause, but including additional variation in the model for the moth developmental times resulted in one peak in adult trap catch similar to that observed in the mills. When cooling mills to outdoor temperatures was simulated, outbreaks were less frequent. Simulations for *Cadra cautella* predicted the times of peak adult densities in four published studies, but additional submodels will be needed for the effects of diapause, **natural enemies,** and insect pest management methods before the model will be able to predict abundance.

Accuracy

Before the predictions of a computer simulation model are used to make insect pest management decisions, the model predictions need to be validated by comparing them to field data. Showing that the peaks in insect population density occur at about the same time as the model predicts or that the changes in insect densities over time are similar to those predicted by the model provides a qualitative validation. For a more quantitative validation, observed insect densities can be regressed against predicted

insect densities; the correlation coefficient of the regression indicates how much of the variation between the observed and predicted insect densities is explained by the regression. The growth of stored-product insect populations is predicted adequately by considering the effects of grain temperature and moisture on insect life history. All but 5–10% of the variation in the insect population growth rates was predicted using these two environmental factors. Diet must explain some of the remaining variation. Another statistical test of the accuracy of the predictions is whether the predicted insect densities are within the 95% confidence limits of the observed insect densities.

A similar approach to model validation can be used for computer simulation models predicting the effectiveness of different insect pest management methods, but the models become more complex. In addition to comparing the observed and predicted insect densities, these models have been incorporated into an expert system for making insect pest management recommendations, and the ability of the expert system to make correct insect pest management recommendations has been validated. When computer simulation models were used as part of an expert system to make insect pest management recommendations on farms without sampling to estimate insect density, 80% of the recommendations were correct. More of the recommendations are likely to be correct when the model uses estimates of insect population density to make recommendations. An expert system, using the insect densities estimated by sampling the grain for 532 bins at elevators in the United States, failed to correctly predict that the grain needed to be fumigated in only two of the 92 high-risk bins (see Chapter 8).

Utilization of insect population growth models

Models predicting stored-product insect population growth and distribution can be used in a variety of ways to develop and implement an insect pest management program. The published results of computer simulations can provide insight into how insect pest management methods work and how various aspects of insect biology, behavior, and ecology influence their efficacy. Adapting models to new situations allows information about insect biology, ecology, and behavior to be fully and most-effectively utilized in managing stored-product insect pests.

When commodities are first stored and the insect infestation levels are so low that estimation of density is difficult, previous estimates of immigration rates into stored commodities might be used in a computer simulation model to forecast insect population growth. Average immigration rates of 13.6 *Cryptolestes ferrugineus* and 6.3 *Rhyzopertha dominica* per day were observed for wheat stored in bins on 12 farms in Kansas. Daily immigration rates for *R. dominica* into the grain bins at elevators in Kansas were slightly (1.5 times) higher. Sampling can be done sometime before the time at which the simulation predicts that insect pest populations will reach unacceptable levels.

Because insect populations often grow roughly 10-fold per generation, it is likely that the insect pest populations will need to be sampled sometime during the second generation. The estimates of insect infestation level from sampling can be used to predict when insect pest management will be needed. With computer simulation models, the effectiveness of several different insect pest management programs in reducing insect pest population growth can be simulated, allowing a manager to choose the most effective. Degree-day models or iterative methods of predicting insect developmental times when the temperature fluctuates also might be used to forecast when insect populations will have completed the first and second generations.

Model predictions also can be used to develop and implement research programs that improve insect pest management. Simulating insect population growth might be useful in identifying high-priority research, finding the most productive experimental design, or doing sensitivity analysis to determine which variables are most important.

Models predicting the growth of insect pest populations in wheat stored on a farm or at an elevator and in bagged rice storage have been validated and put into expert systems so that they can be used by persons with limited training. Similar work needs to be done for other commodities in a variety of storage, processing, and marketing facilities and transportation vehicles so that model predictions can be used in making insect pest management decisions throughout marketing system.

Study questions

1. What are the advantages of each type of predictive model?
2. How do species differences in life history influence population growth?
3. How can model predictions be used in studying or managing stored-product insects?

Recommended readings

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Hagstrum, D. W., and Flinn, P. W. 1990. Simulations comparing insect species differences in response to wheat storage conditions and management practices. J. Econ. Entomol. 83:2469-2475.

Howe, R. W. 1965. A summary of estimates of optimal and minimal conditions for population increase of some stored products insects. J. Stored Prod. Res. 1:177-184.

Stolk, C., van der Werf, W., and van Huis, A. 1999. Models of stored-product pests: Their relevance to biological control in traditional storage in developing countries. Pages 72-87 in: Proc. 7th International Working Conference on Stored Product Protection. (Beijing, PRC.) J. Zuzan, L. Quan, L. Yongsheng, T. Xiachang, and G. Liaghua, Eds. Sichuan Publishing House, Chengdu, Peoples Republic of China.

Throne, J. 1995. Computer modeling of the population dynamics of stored product pests. Pages 169-195 in: Stored-Grain Ecosystem. D. S. Jayas, N. D. G. White, and W. E. Muir, Eds. Marcel Dekker, Inc., New York.

Chapter 8

Decision Aids

Preventive and monitoring-based insect pest management programs require many decisions. The cost-effectiveness of stored-product insect pest management programs will depend upon the quality of these decisions. The five primary questions to be answered in developing a pest management program for stored-product insects are these:

1. Which insect species are present?
2. When and where will insect pest suppression be needed?
3. Which insect pest management method or methods should be used?
4. What options should be used to implement an insect pest management program?
5. Was the insect pest management method used effectively?

Determining when and where insect pest suppression will be needed generally requires information about the current and future severity of an insect infestation and the insect spatial distribution. Sampling and predictive models can provide this information (see Chapters 5 and 7). Careful examination of the insects found in sample units can provide information about which species are present (see Chapter 1 for identification aids). The advantages and disadvantages of each insect pest management method and each of the available options for its implementation need to be considered in developing the most cost-effective insect pest management program (see Chapters 11 through 19). The choice of the best method may depend upon which of the available implementation options are to be used. Sampling also is necessary to determine whether a method was used effectively. An area-wide approach to insect pest management, integration of more than one insect pest management method, and utilization of consultants and expert systems may improve the cost-effectiveness of a pest management program for stored-product insects.

Economics must be considered in answering each of these five questions. With regard to which insect species are present, some species of insect pests can cause greater economic losses than others (see Chapter 1). Using predictive models to determine when and where insect pest management is needed can reduce the cost of sampling and optimize the timing and targeting of insect pest suppression so that it is done most cost-effectively (see Chapters 5 and 7). Some insect pest management methods and options cost more than others (see Chapter 9). Determining whether an insect pest management method was used effectively is important because additional insect suppression may be needed to prevent economic losses when follow-up sampling shows that a method was not used effectively. Decision aids available for answering these questions include sampling information, cost-benefit analysis, consultants, expert systems, and the predictions of computer simulation models.

Monitoring-based insect pest management

Standard storage and **good manufacturing practices** are used to reduce the risk of contamination of raw and processed foods as they move through the marketing system. The food- and feed-processing industries use the **hazard analysis and critical control points** (HACCP) method to identify, monitor, and manage biological, physical, and

chemical hazards. Critical control points in the food-processing plant are identified. Monitoring at these locations is likely to detect most problems. The HACCP program needs to be reevaluated frequently to be sure that it still detects most problems. Monitoring for insect pests is generally not part of HACCP.

Management programs for stored-product insect pests can use both preventive and monitoring-based methods. The preventive methods commonly used for stored commodities include aeration, sanitation, exclusion, inspection of incoming ingredients for insects, insect-resistant packaging, stock rotation, and residual insecticides. These preventive methods often are used without information about the insect infestation level. The main advantage of a preventive insect pest management program is that maintaining very low or zero insect densities can prevent economic losses. Preventive methods often are used on a calendar schedule, which is an advantage for facilities operated for 24 hr a day and seven days a week. The main disadvantages of a preventive insect pest management program is that insect pest suppression might not be done when most effective and might cost more than the economic losses it prevents.

Methods such as fumigation and heat treatment often can be used most cost-effectively in a monitoring-based insect pest management program. Insect monitoring and insect population-growth models provide information about the insect infestation level that can optimize the timing of insect pest suppression so as to maximize the effectiveness and minimize the cost of an insect pest management program. For example, studies sampling grain for insects at **elevators** have shown that, often, fewer than 10% of the concrete bins at an elevator have insect densities that justify fumigation. Fumigating only the bins that require fumigation can reduce the cost of the pest management program for stored-product insects. Fumigating all of the bins at a grain elevator storing 19,048 t (700,000 bushels) of wheat would cost US$14,000. However, when the elevator manager knows that only three out of 30 of these bins are likely to have insect densities of more than two insects per kilogram during the next two months, fumigation of only these three bins is the proper response. This fumigation would cost only US$1,400, which would reduce the cost of fumigation by US$12,600. This savings could more than cover the cost of using cables with sensors for **acoustical detection** of insects or a vacuum probe to sample each bin for insects.

Cost-benefit analysis

In an integrated pest management (IPM) program, the cost of insect pest suppression is justified when it prevents insect pest densities from reaching an economic injury level (EIL). An EIL is the insect pest density at which the economic losses attributed to insects are greater than the cost of the insect pest suppression. The EIL is not fixed but depends upon the cost of the method to be used and the value of the infested commodity. Thus, a less-expensive method of managing insect pests or an increase in the market value of a commodity lowers the EIL. Cost-benefit analysis can be used to ensure that insect pest suppression is done when and where it will be most cost-effective.

The economic threshold (ET) is the insect density at which insect pest populations must be suppressed to prevent them from reaching the EIL. The ET is calculated as a fraction of the EIL. With stored wheat, using an ET of two or more live insects injurious to grain per kilogram of wheat allows the insect densities to be kept below the EIL of sample grade (32 insect-damaged kernels per 100 g of wheat). The ET and the EIL

were developed empirically, but research on the relationship among insect density, the economic losses caused by insects, and the market value of the commodity are needed to fully utilize cost-benefit analysis.

Because residual insecticides are so inexpensive and easy to use compared to other insect pest management methods, cost-benefit analysis can actually favor the use of residual insecticides over other methods, and these insecticides may be used more often as a result of doing cost-benefit analysis. When using cost-benefit analysis, a conscious effort must be made to use a variety of insect pest suppression methods in order to slow the development of insect resistance to residual insecticides and other insect pest management methods.

For subsistence farmers, commercial residual insecticides may be too expensive to use on all of their stored food, but cost-benefit analysis indicates that residual insecticides can be used cost-effectively on the food that is to be stored for a long time or to be sold as a cash crop. Traders in the tropics provide incentives for farmers to deliver quality grain (see recommended reading by Compton et al). In Ghana, visible insect damage of less than 5–6% does not change the market value. As maize becomes scarcer, more damage is tolerated, and the market value increases. Even a twofold increase in the market value is not a sufficient incentive for many farmers to store grain, and most farmers sell their grain soon after harvest.

In the United States, increases in the market value of wheat between one harvest and the next help to cover the cost of storage. Much of the grain is stored at elevators, but the grain stored on farms may be subject to penalties when delivered to an elevator (see recommended reading by Reed et al). Low **test weight** was the primary reason that wheat delivered by farmers to the elevator was discounted. Wheat with low test weight was more likely to be discounted for insects than wheat with a higher test weight. Small lots of grain were less likely to be discounted than large lots because they could be blended with other grain without measurably changing the overall quality.

Combinations of more than one insect pest management method must be more effective than either method alone; if they are not, they are likely to be more expensive and difficult to justify economically. The most important reason for combining more than one method is to improve insect suppression. Integration generally involves using more than one type of stress on insects or using a second method to combat reinfestation because the first method does not provide long-term protection (see recommended readings by Hagstrum and Subramanyam). Combinations of insect pest management methods may be used because different methods are most effective at different times, at different insect densities, or for different insect species. Compatible combinations may be justified as part of a resistance-management program when they replace multiple applications of the same insect pest management method.

Area-wide insect pest management

Area-wide insect pest management programs coordinate insect pest suppression over a large area so as to reduce the overall densities of insect pests and minimize the risk of initial infestation or reinfestation after insect pest suppression. The simplest area-wide insect pest management program might be facility-wide or company-wide. An area-wide insect pest management program might include a flour mill and a nearby grain elevator. Several companies may work together to develop and implement an

area-wide insect pest management program. In many countries, grain is stored in large networks of country and terminal **elevators**. Failure to suppress insects at a few of these elevators may make the grain from these elevators a source of insects that can infest much larger quantities of grain as a result of commingling as grain moves through the grain-marketing system. Area-wide insect pest management is needed because mixing infested and uninfested grain increases the cost of pest management for stored-product insects. Area-wide pest management for stored-product insect pests is also needed as packaged foods are transported from food processors to distribution warehouses to grocery stores and during their storage at each of these locations.

In Australia, the effectiveness of residual insecticides against stored-product insects led to complacency, and sanitation programs were neglected for several years (see recommended reading by Bridgeman and Collins). As a remedy, an area-wide pest management program for stored-product insects was implemented by writing standard operating procedures for sanitation, providing training programs, and having periodic audits of the sanitation programs. Amorphous silica dust was used instead of residual insecticides, and structures were sealed for better fumigation. Amorphous silica dust was also used to treat the structure and to cap the grain to prevent insect entry and hold fumigant longer. This area-wide insect pest management in Australia reduced the percentage of the storage structures that were infested from 60 to 16 and the cost of insect pest management from Aus$1.50 to $0.60/t. Because selection for resistance to insect pest management methods may be greater for area-wide programs that reduce the number of refuges for susceptible individuals, a resistance-management program, as discussed in Chapter 10, is important.

Evaluating the efficacy of insect pest management

Several studies cited in Table 8.1 have shown that insect pest management programs are sometimes ineffective. Efficacy might be influenced by many factors. The effectiveness of many insect pest management methods depends upon insect age; therefore, the age structure of the insect pest population might influence the method's efficacy. The effectiveness of insect pest management methods also differs among insect species, so the species composition of the insect pest population might influence efficacy. The effectiveness of a program might depend upon the environmental conditions before, during, and after implementation and how well the program was implemented. A follow-up evaluation of the efficacy of an insect pest management program is needed to determine whether further insect pest suppression will be needed. Also, finding the reason for the failure of a method might allow the method to be used more effectively the next time. The recommended reading by Slade illustrates such a verification program for the effectiveness of a sanitation program in reducing foodborne-illness-causing pathogens in a food-processing plant.

Residual insecticides provide good protection for grain during the first several months of storage on farms, but these chemicals break down, and infestations of *Cryptolestes ferrugineus*, *Prostephanus truncatus*, *Rhyzopertha dominica*, and *Sitophilus zeamais* in treated grain can reach densities that are as high as those in untreated grain.

Applying a wettable-powder spray of **malathion** to the stacks of bagged **citrus pulp** stored in a warehouse was ineffective in reducing the *Cadra cautella* population. The resistance to malathion of diapausing and nondiapausing larvae had

increased 6- and 7.5-fold, respectively, and no resistance-monitoring program was in place to indicate that another insect pest management method should be used. When the spraying was discontinued, the insect pest population was suppressed by a naturally occurring **parasitoid**, *Habrobracon hebetor*, which had been killed by the residual insecticide in previous years.

In open-top bins at elevators in Australia, psocids became a problem when managers began using fumigation instead of residual insecticides as their primary insect pest management method. *Liposcelis decolor*, *L. bostrychophila*, and *L. entomophila* were the most common of 13 species of psocids found, representing 89% of the total psocid population. *Liposcelis* spp., which survived near the grain surface and on the bin walls above the grain, reached prefumigation infestation levels in a month or two. To pre-

Table 8.1. Studies on the efficacy of stored-product insect pest management methods

Commodity-facility	Insect species	Source
	Farm storage	
Maize in farm bin	*Prostephanus truncatus*	Meikle et al 2002
	Sitophilus zeamais	Meikle et al 2002
Wheat in farm bin	*Cryptolestes ferrugineus*	Reed et al 1990
	Rhyzopertha dominica	Reed et al 1990
	Central storage	
Citrus pulp in warehouse	*Cadra cautella*	Hagstrum and Sharp 1975, Zettler 1977
Grain at elevators	*Liposcelis* spp.	Rees 2003
Peanuts in warehouse	*Cadra cautella*	Hagstrum and Stanley 1979
Rice in bags	*Rhyzopertha dominica*	Mohan et al 1994
	Tribolium castaneum	Hodges et al 1992, 1997
Sorghum in bags	*Rhyzopertha dominica*	Carino and Morallo-Rejesus 1976
	Sitophilus zeamais	Carino and Morallo-Rejesus 1976
Tobacco warehouse	*Lasioderma serricorne*	Minor et al 1983
Wheat at elevators	*Rhyzopertha dominica*	Flinn et al 2003
	Processing facility	
Confectionery factory	*Cadra cautella*	Bowditch and Madden 1996
Flour mill	*Tribolium castaneum*	Campbell et al 2003
	Storage of processed commodities	
Flour warehouses	*Ptinus villiger*	Smallman 1948
	Transportation of processed commodities	
Cornmeal in bags	*Carpophilus pilosellus*	Laudani et al 1966
	Tribolium spp.	Laudani et al 1966
	Retail store	
Pet stores	*Stegobium paniceum*	Nansen et al 2004b
	Sitophilus oryzae	Nansen et al 2004b
	Tribolium castaneum	Nansen et al 2004b

vent this resurgence, the psocids in the headspace that were not killed by the fumigant were killed by automatically dispensing **dichlorvos** daily for a week in the bin headspace.

Although fumigation of peanut warehouses reduced the *C. cautella* population, many insects survived, and the population recovered quickly. Fumigations were ineffective because the warehouse could not be tightly sealed to hold the fumigant for the period necessary to kill all of the pest insects.

Bagged rice is covered with a tarpaulin before fumigation. The area outside the tarpaulin is sprayed with a residual insecticide to kill adult *Rhyzopertha dominica* or *Tribolium castaneum*. This is a cost-effective way to reduce reinfestation of bagged rice by these insects because the cost of spraying is only 8% of the cost of fumigating again. However, spraying a central store only once with a residual insecticide was as effective as respraying at regular intervals. Resampling after six weeks was recommended to be sure that the fumigation was effective.

In the Philippines, *R. dominica* and *S. zeamais* infest sorghum in the field before harvest. Sorghum sprayed with residual insecticide in the field before harvest in the dry season could be safely stored for three months, and that sprayed before harvest in the wet season could be safely stored for two months. Tetrachlorvinphos was more effective than **pirimiphos methyl**, and both were more effective than malathion. A combination of a preharvest residual insecticide spray and storing sorghum in bags treated with residual insecticides was more effective than either alone.

Treating tobacco with 10 ppm **methoprene** was as effective in suppressing *Lasioderma serricorne* as 140 dichlorvos foggings and an annual **phosphine** fumigation. Both insect pest management methods reduced the light-trap catches over a 1.5-year storage period by 99% compared with the trap catches for the untreated control. At grain elevators, fumigations were often not effective enough to prevent a rapid recovery of *R. dominica* populations.

Weekly applications of **pyrethrins** were unnecessary in many areas of a confectionary factory. Adult *C. cautella* continued **eclosing** and reproducing between residual insecticide applications, and the residual insecticide did not kill the immature stages that were hiding in accumulated food residues. Searching for insect-infested food residues near **pheromone** traps with high insect catches and removing these food residues was as effective in suppressing insect infestations as applying the residual insecticide. Samples of *Tribolium castaneum* from the tailings at two flour mills indicated that the timing of fumigations was not always optimal for preventing increases in insect pest populations.

Low winter temperatures in warehouses in Manitoba, Canada, killed most species of the stored-product insect pests, but *Ptinus villiger* survived the winter to cause serious problems in the spring and summer. Residual insecticide treatment of stored-flour warehouses with **DDT** in an oil solution in April reduced the *P. villiger* population by 99% compared with an untreated warehouse, and treating again in June did not improve the results. DDT in a water suspension reduced the insect population by 94%, and **lindane** in an oil solution reduced the population by 96%. Lindane smoke reduced insect the population by only 76% because the loose construction of the warehouses allowed a large portion of the insecticide to escape. Aluminum and magnesium oxides applied as dust reduced the insect population by 83 and 84%, respectively. The number of times a warehouse was swept and the type of broom may have influenced the effectiveness of residual insecticides by removing insecticide residues. Cotton bags

impregnated with DDT and untreated paper bags provided nearly complete protection. *P. villiger* females were able to penetrate cotton bags, but not paper bags, with their ovipositor to lay eggs. However, some larvae were able to chew holes in the paper bags and enter. Although paper bags were more effective than cotton bags, they were not acceptable to the milling industry during the 1940s.

Insect-resistant multiwall paper bags protected cornmeal during shipment from Kankakee, Illinois, to Rio de Janeiro and Santos, Brazil, through the Alabama State Port at Mobile. When the shipment reached Mobile, the cornmeal in 30% of the cotton bags was infested by *Carpophilus pilosellus* and *Tribolium* spp., and so the cornmeal in the cotton bags was fumigated with **methyl bromide**. While the cornmeal in 56% of the conventional cotton bags was infested when it reached Brazil, the cornmeal in only 1% of the insect-resistant paper bags was infested. During shipment, 2.7% of the cotton bags and 4.1% of the paper bags were damaged.

Insect monitoring with traps has shown that a one-time cleaning did not reduce the densities of residual *Stegobium paniceum*, *Sitophilus oryzae*, and *T. castaneum* populations in retail pet stores. Cleaning at regular intervals may reduce the insect pest population more than a one-time cleaning, but residual insecticide applications, stock rotation, and insect-resistant packaging also may be needed in addition to sanitation.

Consultants and expert systems

Private consultants and scouting services have been critical to the implementation of IPM in field and orchard crops. Consultants can facilitate the optimal use of simple insect pest management methods and provide the expertise needed to use more complex methods. Private consulting and inspection services are already used extensively by the food-processing industry (see recommended reading by Gerberg), but they generally have been used less for the management of insect pests infesting raw commodities during storage. The recommended reading by Skinner illustrates how consultants helped farmers protect grain stored on farms. Consultants have an economic incentive to minimize pesticide use, because the more they help a client save money on pesticide application costs through careful monitoring, the more likely they are to keep the client.

Computer programs ("expert systems") that diagnose insect pest problems have the advantage of pooling the knowledge of different experts. Some decision-support expert systems provide recommendations for insect pest management, and others are learning or planning aids. Expert systems have been developed for managing the insect pests of stored grain in several countries (Table 8.2).

With Stored Grain Advisor, computer simulation **models** can be used to forecast the effectiveness of different insect pest management programs primarily for wheat stored on-farm. Another expert system, CanStore, provides similar recommendations. An expert system for central storages of bagged rice uses insect-monitoring data and simple exponential insect population-growth equations to make recommendations (see recommended reading by Hodges et al). PestMan and Grain Pest Advisor-2 compare the costs of different insect pest management methods for stored wheat. PestMan ranks insect pest management recommendations by their cost and provides graphical site plans that allow a manager to quickly find the information about any bin. Grain Management Expert System, developed from PestMan for use in China, has keys for identifying insect and mite pests, predicts insect population growth, keeps insect pest management records, and makes insect pest management recommendations. Integrated

Grain Storage Manager is a new version of Grain Pest Advisor-2 that was developed with input from farmers and storekeepers to better suit their needs.

Stored Grain Advisor Pro was developed from Stored Grain Advisor primarily for wheat stored at elevators. The program uses model predictions to forecast the risk of insect problems based upon the current estimates of insect density, grain temperature, and grain moisture. Risk analysis is presented to the elevator manager on a bin-layout diagram and in a table. The manager is also given insect pest management recommendations and economic analysis for each bin. To evaluate the cost-effectiveness of the software, all of the grain at 28 elevators in Kansas and Oklahoma was sampled to a depth of 13 m (43 ft) every six weeks with a vacuum probe. For the 532 bins sampled, Stored Grain Advisor Pro predicted which bins were at low risk (less than two insects predicted in one to two months), moderate risk (2–10 insects predicted in one to two months), or high risk (more than two insects when sampled and more than 10 insects predicted in one to two months). Stored Grain Advisor Pro correctly predicted that 392 out of the 532 bins were either at low or high risk. For bins with high risk, fumigation was recommended, and for the bins with low risk, sampling again in six weeks was recommended. For the 138 bins found to be at moderate risk, the program predicted higher insect densities than were observed after six weeks. For these bins at moderate risk, the recommendation was to consider fumigation or to sample again after six weeks. For only two out of 92 bins did Stored Grain Advisor Pro fail to predict that the bins were at a high risk and, in both cases, the insect density was high only near the surface, suggesting recent insect immigration into these bins.

Initially, managers often did not follow the recommendations, but after receiving several reports, many of the managers started to do so. Currently, a private company is

Table 8.2. Available expert systems for stored-product insects and their function

Expert system	Country	Function[a]	Source
Stored Grain Advisor	United States	R	Flinn and Hagstrum 1990a
Grain Pest Advisor-2	United Kingdom	R	Wilkin and Mumford 1994
Central bagged-rice storage	Indonesia	R	Hodges et al 1997
PestMan	Australia	R	Longstaff 1997
Grain Management Expert System	China	R	Zonglin et al 1999
Integrated Grain Storage Manager	United Kingdom	R	Knight et al 1999
Stored Grain Advisor Pro	United States	R	Flinn et al 2003a,b
CanStore	Canada	R	On Internet[b]
PestTools	Australia	L	Longstaff 1997
Grain Storage Information System	Canada	L	Mann et al 1997
Computer-Assisted Learning	Indonesia	L	Longstaff 1999
QualiS	France	P	Ndiaye et al 2003
Malting Barley Encyclopedia	Europe	L	Knight and Wilkin 2004

[a] R = recommendation, L = learning aid, P = planning aid.

[b] Mani, S., White, N. D. G., Jayas, D. S., Fields, P. G., Muir, W. E. and Mann, D. 2000. Available at http://res2.agr.ca/winnipeg/storage/pages/cnstr_e.htm.

using Stored Grain Advisor Pro and grain sampling to advise 30 elevators in several states. The company is in its third year of business and continues to expand. Because the number of bins at an elevator that needed to be fumigated varied from none to all of the bins and averaged 10%, insect monitoring to locate these bins was cost effective. The insect monitoring program also improved insect pest management by ensuring that fumigation was done at the time when it would be most effective. Information about current insect infestation levels and forecasts of future insect infestation levels allowed elevator managers to sell first the grain that was most likely to need fumigation if it were kept for another month or two. Taking grain samples from the full depth of each bin also provided grain quality data that could be used by the elevator managers to more profitably market their grain.

Some programs (such as PestTools, Grain Storage Information System, and Computer-Assisted Learning) are primarily learning aids. Teaching users why certain insect pest management actions are more likely to be successful has proved to be better than simply making recommendations. QualiS assists managers in planning for quality maintenance of malting barley, and a supplemental encyclopedia has been developed for malting barley.

Software for Stored Grain Advisor (http://bru.gmprc.ksu.edu/proj/sga), Canstore (http://res2.agr.ca/winnipeg/storage/pages/cnstr_e.htm), and Stored Grain Advisor Pro (http://bru.usgmrl.ksu.edu/proj/sga/sga_pro_reg.asp) is available on the Internet. More information on QualiS is available at http://www.bordeaux.inra.fr/qualigrain/.

Utilization of decision aids

Money spent to sample for insects and suppress insect pest populations reduces profits, and therefore these are economic losses that must be attributed to insects. Sampling for insect pests is justified when the economic losses prevented by having this information exceed the cost of sampling. Insect pest suppression can be done only when the losses attributed to insects are likely to exceed the cost of using an insect pest management method.

The ecology of stored-product insects and thus the insect pest management program that is needed are likely to be unique for each location in the marketing system and for each time that insect pests are managed. Consultants, expert systems, and computer simulation models can assist in selecting the most cost-effective insect pest management program and effectively implementing it. Area-wide pest management programs can be important in reducing the overall numbers of insect pests in the marketing system and eventually lowering the cost of these programs.

Sampling to determine whether insect pest management was effective will become more important as managers depend less on residual insecticides and depend more on integrating several methods. Evaluating the efficacy of insect pest management each time insect pests are managed allows additional insect pest management to be done when necessary and might allow an insect pest management method to be used more effectively the next time.

Study questions

1. What questions need to be answered in planning and implementing a pest management program for stored-product insects and how can each be answered?

2. What are the differences between preventive and monitoring-based insect pest management programs?
3. Why are area-wide approaches, integration of more than one insect pest management method, consultants, and expert systems important to insect pest management?
4. Why is an evaluation of the effectiveness of insect pest management important?

Recommended readings

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Chapter 9

Economics

Market values for raw commodities generally increase during the storage period as the demand increases relative to the supply. Insect pest management is part of the cost of storing commodities until they are needed. For raw commodities, the cost of insect pest management is passed along to the food processor and ultimately to the consumer. For processed commodities, this cost is passed along to the consumer as part of the purchase price.

Comparisons of the relative costs of different insect pest management methods must consider whether a method provides long-term protection and whether it can be used after an insect pest problem is discovered. Residual insecticides that are used as empty-bin sprays or are applied directly onto commodities are inexpensive and can provide good long-term protection in cool, dry environments. However, residual insecticides often must be applied before a manager knows whether the insect populations will reach unacceptable levels. Moving grain is expensive, and moving grain to another bin to apply a residual insecticide greatly increases the cost. On grain, in empty bins, and in food-storage and food-processing facilities, residual insecticides do eventually break down, and reapplication or other insect pest management methods are needed.

Fumigation, aeration, extreme temperatures, or ionizing radiation can be used to suppress an existing infestation, but they have no residual activity for long-term suppression of the insect pest populations. When commodities are used or processed immediately without further storage, no other insect pest management method is needed. However, for commodities stored after these insect pest management methods have been used, natural enemies and insect-resistant packaging can provide long-term protection of the commodities. With a good insect-monitoring program, natural enemies can be used after an insect infestation is discovered; packaging is a method that prevents insects from entering the commodity. The cost of using more than one insect pest management method may need to be considered when long-term suppression is not provided by an insect pest management method.

Cost comparisons for raw commodities

The operating costs of pest management methods for stored-product insects have been estimated in a few cases (Table 9.1). Some of the differences between these studies result from variations in the costs of electricity, labor, equipment, and materials over time and among locations. If the value of a metric ton of commodity is US$100 (all dollars in this chapter are U.S. dollars unless otherwise noted), then spending $0.00033/t on an empty-bin spray represents 0.0003% of the value of the commodity and spending $6.52/t on chilled aeration represents 6.5% of the value of the commodity. In addition to the operating cost shown in Table 9.1, aeration, modified atmospheres, extreme temperatures, and ionizing radiation may require renting or purchasing of equipment.

Using ambient aeration to cool wheat in the autumn costs less than aerating to cool and maintain the moisture content of popcorn. **Phosphine** fumigation of grain stored

Table 9.1. Operating costs of pest management methods for stored-product insects

Method	Commodity	US$/t	Source
	Aeration		
Ambient aeration	Popcorn	5.22	Rulon et al 1999
	Wheat	0.18–0.26	Noyes et al 1991a
Chilled aeration	Popcorn	6.52	Rulon et al 1999
	Biological control		
Parasitoids	Grain	0.14–1.47	Schöller and Flinn 2000
	Empty-bin spray		
Chlorpyrifos-methyl (concrete bin)	Wheat	0.0028	Kenkel et al 1993
Chlorpyrifos-methyl (steel bin)	Wheat	0.0047	Kenkel et al 1993
Cyfluthrin (concrete bin)	Wheat	0.0010	Kenkel et al 1993
Cyfluthrin (steel bin)	Wheat	0.0017	Kenkel et al 1993
Malathion (concrete bin)	Wheat	0.00033	Kenkel et al 1993
Malathion (steel bin)	Wheat	0.00055	Kenkel et al 1993
Methyoxychlor (concrete bin)	Wheat	0.0023	Kenkel et al 1993
Methyoxychlor (steel bin)	Wheat	0.0039	Kenkel et al 1993
	Fumigation		
Carbon dioxide	Wheat	0.36	Kenkel et al 1993
Low oxygen	Raisins	9.66–10.64	Soderstrom et al 1984
Methyl bromide	Raisins	8.39	Soderstrom et al 1984
Phosphine	Raisins	10.76	Soderstrom et al 1984
Phosphine (concrete bins)	Wheat	0.91–1.10	Kenkel et al 1993
Phosphine (contract, steel bins)	Popcorn, wheat	2.41	Rulon et al 1999
Phosphine (in-house, steel bins)	Popcorn, wheat	2.26	Rulon et al 1999
Phosphine (steel bins)	Wheat	0.33	Reed et al 1990
	Wheat	0.43	Kenkel et al 1993
	Protectant		
Chlorpyrifos-methyl	Wheat	0.81	Kenkel et al 1993
	Wheat	0.61	Reed et al 1990
Diatomaceous earth	Wheat	2.30	Subramanyam and Roesli 2000
	Wheat	2.22	Kenkel et al 1993
Malathion	Wheat	0.14	Kenkel et al 1993
	Wheat	0.04	Reed et al 1993
Methyoxychlor	Wheat	0.11	Reed et al 1993
	Radiation		
Electron beam	Wheat	0.3–0.67	Halverson and Nablo 2000
Gamma	Wheat	6.16	Halverson and Nablo 2000
Microwave	Wheat	2.07	Halverson et al 1996
	Wheat flour	2.74	Halverson et al 1996
Radiofrequency	Wheat	1.29	Nelson 1996

in steel bins is less expensive than fumigation of grain stored in concrete bins. Phosphine pellets are probed into the grain stored in steel bins, but to add a fumigant to the grain stored in a concrete bin, the grain is generally turned from one bin to another. The estimated cost for **turning** grain is $0.48–0.67/t. The estimates of Rulon and colleagues in 1999 for phosphine fumigation are higher because they estimated the cost of three fumigations per year. The estimated cost of $0.75/t for a single in-house fumigation or $0.80/t for a single contract fumigation is closer to the $0.43/t estimated by Kenkel and colleagues in 1993. Soderstrom and colleagues in 1984 included in their estimate the cost of covering and sealing the raisins ($6.00/t) before fumigation and the cost of the six fumigations that generally are done each year. The estimated cost of $0.79/t for the fumigant and labor for a single fumigation is closer to other estimates. Excluding the cost of covering and sealing raisins, the cost for a single application of methyl bromide is $0.40/t and that for low-oxygen atmosphere is $0.61–0.77/t.

Applying residual insecticides to grain as protectants costs more than using residual insecticides as empty-bin sprays. The larger surface-to-volume ratio for steel bins compared with that for concrete bins makes the spraying of the walls and floor of empty steel bins cost more per bushel of capacity than spraying empty concrete bins.

The type of residual insecticide used also can influence the cost. In 1993, for 3.8 L of insecticide, **methyoxychlor** cost $17, **malathion** cost $30, **cyfluthrin** cost $45, and **chlorpyrifos-methyl** cost $252.

The manner in which an insect pest management method is implemented can greatly influence the cost (see recommended reading by Beckett and Morton). Heating grain to 60°C in a **spouted bed** and holding it at this temperature for 0.73 min killed 99.9% of the insects and cost AUS$2.72/t. However, the same mortality can be achieved at a cost of AUS$1.87/t by heating the grain to 55°C in a spouted bed and holding it at this temperature for 23.6 min before cooling. This cost comparison does not consider how the grain is cooled after the heat treatment.

Cost comparisons for the food processor

The operating costs for sanitation or packaging are estimated per production unit. For flour mills, the cost of sanitation varied from $0.147 to $0.334 per 45.36 kg (100 lb) of flour milled (see recommended reading by Chowaniec). Packaging materials are generally sold by weight, and the area covered per weight of packaging material purchased is used to calculate the cost of a package (Table 9.2). Packaging materials in 1990 cost from $0.047 to $0.138 per 0.65 m^2 (1,000 $in.^2$). The electricity and labor

Table 9.2. Area covered per weight of packaging material purchased[a]

Material	Number of 0.65-m^2 sheets per 0.45 kg (Number of 1,000-in^2 sheets per lb)
Polyethylene (2 mil)	10.0
Ionomer (2 mil)	14.7
195 K Cello	19.5
Nylon (1 mil, coated)	21.2

[a] Data from Hirsch 1991.

necessary for operating the packaging machines would also be part of the operating cost, and packaging machines require a large capital investment.

No published estimates have been found for the cost of adding insect resistance to a package. Tests to establish the efficacy of a package in providing insect resistance add to the cost of package development. The packaging material and type of sealing needed to make a package insect-resistant may be more expensive. Existing packaging lines may need to be modified to produce packages with improved insect resistance, and this may add to the cost of the packaging. However, the final package will need to serve many functions (see Chapter 13), and separating the cost of insect resistance from that of the other functions is not easy.

For heat treatments of facilities, estimated energy costs for a single heater can be $46.80 per day for generated electricity or $17.60 per day for electricity purchased from a utility company. Where gas heaters are safe to use, energy costs are less. Heating with propane can cost $8.64 per day, and heating with natural gas can cost $5.00 per day. The number of heaters will depend primarily on the size of the building but also may depend upon the number and size of outside windows, doors, and vents from which heat will be lost. Equations are available for making these calculations, and software called Heat Treatment Calculator, which calculates the energy needed to heat a facility, has recently been developed (see recommended reading by Subramanyam).

Calculating equipment cost

The operating cost of a piece of equipment is simply the sum of the costs of the energy, materials, and labor needed to run it. Calculating the cost of purchasing and maintaining or renting equipment is more complex. Also, manufacturers consider this information proprietary and disclose it only to their customers.

According to published data, aeration equipment can cost $3,000 per bin; a small chiller for eight bins can cost $50,000; a low-oxygen generator can cost $87,000 without heat recovery or $112,000 with heat recovery; and a large chiller for 59 bins can cost $150,000. Such equipment is affordable only when used for many years and for large volumes of commodities.

Purchased equipment generally is depreciated over a useful life of 5–15 years, and the cost per unit of commodity is calculated. When depreciating small chilled-aeration equipment over 10 years, the equipment costs are estimated to be $6.26/t. When depreciating a low-oxygen gas generator over 15 years, the equipment costs are estimated to be $0.94/t without heat recovery and $1.21/t with heat recovery. Renting equipment spreads the cost of equipment over several years and gives the rental company the responsibility for maintenance and insurance.

Overall cost

Although the differences in operating and equipment costs per unit of commodity for different insect pest management methods seem small, using a more expensive method can considerably increase the overall cost of an insect pest management program for large quantities of commodity. The cost of replacing phosphine fumigation at grain elevators in the United States with other insect pest management methods was estimated to be more than $14 million.

Utilization of economic information

When using cost-benefit analysis, finding a less-expensive insect pest management method or taking into consideration increases in the market value of the commodity can reduce the level of insect infestation tolerated before an insect pest management method is cost-effective. The costs of electricity, labor, equipment, and materials vary over time and among locations, and the cost of an insect pest management program must be calculated for each location in the marketing system. These costs may need to be reevaluated each time insect pest suppression is needed.

Study questions

1. How big are the differences in the cost per unit of commodity among insect pest management methods, and why should managers be concerned about these differences?
2. What aspects of an insect pest management method or methods need to be considered in determining the total cost of a pest management program for stored-product insects?

Recommended readings

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Chapter 10

Resistance

Insect populations readily adapt to new conditions, including the efforts to manage them with biological, chemical, and physical methods, and this resistance often can be inherited by the next generation. Insect populations become resistant because homozygous susceptible insects are killed, while homozygous resistant and **heterozygous** susceptible-resistant insects survive. Development of resistance is delayed by various kinds of refuges and by heterozygotes that allow some insects with a susceptible gene to survive.

Development of resistance has been most evident when chemical pest management methods are used. Insects that are resistant to one residual insecticide can become resistant more quickly to another with the same mode of action than to one with a different mode of action. However, general resistance mechanisms such as limited penetration, expulsion, and detoxification by mixed-function oxidases, hydrolases, and transferases may be effective for many different residual insecticides. Resistance, in most cases, is irreversible and is not reduced even when a residual insecticide is no longer used.

Although insects have not developed resistance to the less-widely used biological and physical insect pest management methods as quickly as they have to the widely used chemical methods, it is important to recognize that insects are resilient and may have the capacity to develop resistance to any type of insect pest management method. Therefore, resistance management needs to be part of any insect pest management program. Using a second insect pest management method with a different mode of action to kill insects that have become resistant to the first method is the best way to slow the development of resistance.

Resistance mechanisms

Insects may have more than one mechanism of resistance to an insect pest management method (Table 10.1). They can become resistant to *Bacillus thuringiensis* by reducing the binding of toxin to their gut membrane and the rate of activation of toxins by proteolytic enzymes in their gut. Insects can become more tolerant to diatomaceous earth treatments by losing water more slowly, by moving more slowly so as to pick up

Table 10.1. Studies on the resistance mechanisms of stored-product insects

Pest management method	Source
Bacillus thuringiensis	Herrero et al 2001
Diatomaceous earth	Rigaux et al 2001
Juvenile hormone	Dyte 1972
Residual insecticide	Georghiou 1972
Modified atmosphere	Donohaye 1991
Phosphine	Chaudhry 1997

less diatomaceous earth, and by avoiding areas treated with diatomaceous earth. An insecticide-resistant insect may have more of the enzymes (such as mixed-function oxidases, hydrolases, and transferases) that break down residual insecticides than susceptible insects, may take up less of the residual insecticide, and may be able to avoid areas treated with the residual insecticide. An insect that is resistant to **phosphine** may take up less phosphine than a susceptible insect and may be able to actively expel and detoxify phosphine.

Resistance to **juvenile hormone** was first observed as cross-resistance in a strain that was resistant to several residual insecticides. An insect that is resistant to low oxygen can survive longer on anaerobic metabolism than a susceptible insect, and insects resistant to high carbon dioxide may have higher triglyceride reserves that allow them to prevent desiccation longer than susceptible insects can.

Prevalence

Insects that are resistant to residual insecticides have been found in more than 80 countries (see recommended reading by Subramanyam and Hagstrum). Some insects have been shown to be resistant to most of the commonly used residual insecticides and fumigants. All of the species of stored-product insects that have been tested were resistant to some residual insecticides or fumigants. Resistance generally is controlled by a single, semidominant gene. In most cases, insects were less than fivefold resistant, but for some species, resistance has reached two to three orders of magnitude. Cross-resistance to more than one residual insecticide with the same mode of action is common.

Monitoring

Measuring the level of resistance in an insect population may be necessary to determine whether the ineffectiveness of an insect pest management program is the result of insect resistance or something else. Monitoring also can forewarn of future insect pest management failures and help prevent resistant genes from being spread globally. A **diagnostic dose** can be used to detect resistance more quickly than **dose-response lines**. The diagnostic dose must be determined experimentally, but it often will be close to a dose giving 99% mortality. Rapid biochemical methods have been developed to screen for insecticide resistance, but these generally have not been developed for stored-product insects except for cyclodiene resistance in *Tribolium castaneum* (see recommended reading by Andreev et al). Using pheromone-baited sticky traps with different dosages of a residual insecticide may provide a simple and effective means of monitoring insecticide resistance in adult stored-product insect populations (see recommended reading by Haynes et al). Because resistance is generally irreversible, preventive resistance-management programs should be used to delay the onset and spread of resistance.

Biological factors

Biological factors influencing the rate at which insects become resistant include primarily the initial population size, population growth rate, and immigration rate (see recommended reading by Tabashnik). Population size is important because larger populations have greater genetic variability and are more likely to carry resistant

genes. The rate of selection for resistance increases as the population growth rate increases. Reducing the population growth rate by cooling grain is an example of manipulating a biological factor to slow the development of resistance (see Chapter 7). Immigration of susceptible individuals into a population can slow the development of resistance, but immigration rates are generally too low. The additional genetic variation provided by immigrants also can promote the development of resistance.

Operational factors

The operational factors affecting the rate at which insects become resistant can be manipulated more easily than the biological factors (see recommended reading by Tabashnik). Increasing the dose, coverage, application frequency, or persistence of a residual insecticide or a fumigant generally increases the selection pressure and can accelerate the development of resistance. High doses can kill the **heterozygous** susceptible-resistant insects as well as the homozygous susceptible. However, the high cost of this approach may outweigh the benefits. Higher doses are more expensive to apply, are more disruptive to biological control, and may contaminate the environment more than low doses. Fumigants have traditionally been used at doses that kill all of the insects, and therefore resistance to fumigants has been slow to develop. However, the use of **phosphine** without adequate sealing has resulted in insects becoming resistant.

Two residual insecticides with different modes of action can be applied as a mixture, sequentially, in rotation, or in a mosaic pattern. In principle, insects that are resistant to both chemicals are rare, and the second chemical kills all of the insects that are resistant to the first and vice versa. Simulations have shown that mixtures are better than sequential use and that a mosaic application pattern is least effective. However, the assumptions that the two chemicals are equally persistent and that double resistance is rare are often not correct. Integration of biological and physical management methods with chemical management methods may be a better way to manage resistance.

Refuges

Untreated areas provide refuges in which susceptible individuals can survive. Having susceptible individuals to mate with resistant individuals and produce **heterozygotes** that are easier to kill than homozygous resistant individuals slows the development of resistance. However, because of insect mobility, these untreated refuges may need to be quite large. Sometimes the insects in one developmental stage can serve as a refuge for susceptible genes. Internal-feeding stages of *Sitophilus* spp. or *Rhyzopertha dominica* may survive because chemicals do not reach their feeding sites inside the kernel. Also, the egg and pupal stages are more resistant to fumigants than the larval or adult stages because of their lower metabolic rate. These more-resistant developmental stages may act as refuges.

Farm storage

For farms in Australia, factors influencing the development of resistance by stored-grain insects over a 20-year period have been studied using a computer simulation model (see recommended reading by Sinclair and Adler). In simulations, wheat was

harvested and stored during warm weather and sorghum during cool weather. The first ton of grain harvested received 24% of the insects from residual infestation in the combine harvester and was generally discarded or used as animal feed. An additional 35 loads of 10 t each were harvested. The first three of these loads were assumed to have 50, 20, and 6% of the insects from the residual grain in the combine. Insect infestation levels were simulated for 50 g of residual grain in the combine header; the grain stored for marketing, animal feed, and seed; and 300 g of grain spillage on the farm. Although additional feed grain may be purchased and bring resistant or susceptible insects to the farm, in this simulation, there was no migration of insects onto the farm. There was a 0.002 probability of the insects leaving grain residues reaching new residues and probably the same probability for those insects reaching the stored grain as well.

In simulations, insects are removed from the farm as half of the wheat is sold at harvest, and most of the rest is sold over the next two months, with 10% of the wheat remaining on the farm for feed and 20% remaining for seed. All wheat was cleared from the farm before the sorghum harvest. Sorghum is sold over a six-month period. The degree of cleanup of the spilled grain and the efficacy of residual insecticide sprays were varied. Simulations were done using the toxicity and persistence data for **dichlorvos**, **fenitrothion,** and **deltamethrin** with half-lives of 2, 14, and 80 weeks, respectively. Most of the data used to simulate the insect population were for *Sitophilus oryzae*. Grain stored for marketing was fumigated when the insect density reached 20 adults per kilogram of grain; seed stock was fumigated when insects reached a level of 100; and feed stock was fumigated when insects reached a level of 500 adults.

When residual insecticides were not used in simulations, cleaning the combine header was more effective than cleaning up the spilled grain, and cleaning both was even more effective. Prolonged storage of wheat on the farm increased the number of insects that were delivered to the elevator. Cooler weather when sorghum was harvested and stored resulted in lower insect infestations in sorghum than in wheat.

Farm management was kept similar for sprayed and unsprayed farms in simulations, but, in the absence of residual insecticides, sanitation was improved so that the farm population of insects remained at one million. This resulted in deliveries to **elevators** having five adult insects per ton of grain. Residual insecticide sprays were assumed to have an efficacy of 99% in the grain stored for marketing, 70% in the feed stocks, and 50% in the combine header.

On-farm simulation studies showed that the persistence of the residual insecticide used, how much of the grain was sprayed, and the spray schedule determined how rapidly resistance developed. Sensitivity analysis showed that development of resistances was influenced more by the decay rate than by the efficacy of a residual insecticide. Both dichlorvos and deltamethrin allowed resistant insects and some heterozygotes to survive, but the greater persistence of deltamethrin made it better at slowing the development of resistance. The insect infestation level was minimized by spraying everything, but unsprayed refuges for susceptible insects slowed the development of resistance. Introducing 10 heterozygotes into a population of 1,090 adults resulted in complete resistance in seven years. Even after a 20-year simulation using the most severe selection with fenitrothion, the percentage of heterozygous resistant individuals rose to only 0.1%, and there were no homozygous resistant individuals in the population. Not spraying during some years resulted in the development of resistance to fenitrothion.

A survey of *Oryzaephilus surinamensis* resistance to fenitrothion and **pirimiphos-methyl** on 63 Australian farms found that all of the storages with untreated grain were infested, but only 20% of those with treated grain were infested (see recommended reading by Herron et al). Susceptible insect populations were found only on grain with less than 0.8 mg of insecticide per kilogram. Resistant insects were present on some farms with untreated grain, possibly because resistant insects were brought onto the farm with purchased grain or because insecticides had been used in previous years. Sanitation did not affect insect density by itself but increased the efficacy of protectants.

Utilization of a resistance-management program

Using a residual insecticide until it fails and then finding another residual insecticide is not the best way to manage insect resistance. Health and safety concerns limit the kinds of residual insecticides that can be used against stored-product insects, so few residual insecticides are registered for this use. Because use on stored products is a minor use of residual insecticides, compared with their use for public health and field or orchard-crop insect pests, the cost of developing and registering a new residual insecticide for use on stored products is difficult to justify.

On-farm simulation studies showed that the persistence of the residual insecticide used, how much of the grain was sprayed, and the spray schedule determined how rapidly resistance developed. Insect populations readily adapt to new conditions and are likely to eventually become resistant to any insect pest management method. Integrating several insect pest management methods with different modes of action so that insects that are resistant to one method are killed by another method is the best way to manage insect resistance.

Study questions

1. How do insect populations become resistant to an insect pest management method?
2. What is the best way to manage insecticide resistance?
3. What factors are important in determining the rate at which insects become resistant to an insect pest management method?

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Part II

Choosing a Pest Management Method

The advantages, disadvantages, implementation options, and examples of integrating more than one insect pest management method are discussed in this section, to take the reader through the thought process involved in choosing the best method or methods. Chapters 11 through 18 have a similar structure so as to encourage the reader to compare different methods of managing stored-product insects. Table 19.1 provides a comparison of insect pest management methods with respect to each of several types of advantages and disadvantages.

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Chapter 11

Biological Control

Principles

Many stored-product insect pest species have **natural enemies** that reduce their numbers. Effective insect pest management often requires some manipulation, mass-rearing and releasing, or integration of these natural enemies with other insect-pest management methods to prevent stored-product insect pests from reaching unacceptable levels.

Natural enemies of stored-product insect pests include parasitoids, predators, and pathogens. Insects that parasitize stored-product insect pests are mostly in the order Hymenoptera. Hosts on which the parasitoid larvae develop are generally killed and completely consumed. Adults of many species of parasitoids in the families Bethylidae, Braconidae, and Pteromalidae paralyze and feed on the host before laying their eggs externally on it. The ichneumonid *Venturia canescens* deposits eggs internally, and the host larvae are not permanently paralyzed. Development of this parasitoid is delayed on small hosts until the host reaches the final **instar**. Trichogrammatid wasps lay their eggs in host eggs. Predators include several species of Hemiptera in the family Anthocoridae and Coleoptera in the family Histeridae. Species of Acarina (mites) in the families Cheyletidae and Ascidae also prey upon stored-product insects. Pathogens that cause diseases in stored-product insect pests include bacteria, viruses, fungi, protozoa, and rickettsia. Nematodes also are known to attack stored-product insect pests.

Natural enemies of stored-product insect pests are thought to have been spread by commerce along with the insect pest species that are their hosts or prey. The natural enemies are self-perpetuating in tropical climates or in bulk grain storage, warehouses, and food-processing plants in temperate climates, and they can dramatically suppress stored-product insect pest populations.

Advantages

Most pests have natural enemies. The most-important stored-product insect pest species have parasitoids and predators that can be easily mass-reared and released. Pathogens are commercially available for some stored-product insect pest species. Some natural enemies attack a single insect pest species, while others attack several species. Predators tend to attack more species than parasitoids do. *Cephalonomia tarsalis* attacks mainly *Oryzaephilus surinamensis* larvae. *Anisopteromalus calandrae* attacks the larval stage of anobiid pests, the bruchid pests of legumes, and the bostrichid and curculionid pests of cereal grains. *Lariophagus distinguendus* and *Theocolax elegans* also attack the larval stage of bostrichid and curculionid pests that feed inside cereal grain kernels. *Pteromalus cerealellae* has a very broad host range. Several species belonging to the family Trichogrammatidae are important parasitoids of stored-product insect eggs. *L. distinguendus* also is known to parasitize two species of parasitoids, *Habrobracon hebetor* and *Venturia canescens*. Mites of the genera *Blattisocius* and *Cheyletus* attack grain mites and insect eggs or small larvae. *Blattisocius* mites are

carried to new locations on adult stored-product insects as they disperse. *Bacillus thuringiensis* and granulosis viruses generally infect moth larvae.

Natural enemies are good at finding pests. Natural enemies released at a few locations in a facility will disperse and find areas with insects. The abilities of different species of natural enemies to find prey or hosts can be compared using their **functional responses**. Functional responses have been determined for seven natural-enemy species attacking 10 stored-product insect pest species (Table 22.2).

Several species of natural enemies have been found to use chemical cues to find hosts, and many others also may use chemical cues (see Chapter 3). *Cephalonomia waterstoni*, *H. hebetor*, and *V. canescens* follow the chemical trails left by wandering host larvae. *H. hebetor* also will fly upwind in response to the volatiles from an *Anagasta kuehniella* infestation. *Laelius pedatus* and *Lariophagus distinguendus* are attracted to the volatiles produced by their host species. *Teretrius nigrescens* is attracted to the aggregation pheromone of its host, *Prostephanus truncatus. Pteromalus cerealellae* moves upwind in response to volatiles from its host, *Callosobruchus maculatus*.

Natural enemies can be self-perpetuating. Once introduced into a facility, natural enemies are often carried over from one storage season to the next when winter temperatures are warm enough for them to survive. *T. nigrescens* has become well-established since its introduction in Africa during early 1990s (see recommended reading by Borgemeister et al).

Biological control occurs naturally. Natural enemies generally are as widely distributed geographically as their hosts. A 1999–2000 survey in Greece showed that nearly half of 513 samples of grains (wheat, maize, oats, and barley), flours (wheat and maize), legumes, and dried fruits (figs, raisins, and sultanas) from a variety of storage and processing facilities were infested by predacious mites (mainly Acaridae and Cheyletidae) as well as mite or insect pests (see recommended reading by Eliopoulos et al). Scattered records from many countries suggest that parasitoids and insect predators of stored-product insects also are this prevalent.

Several species of naturally occurring parasitoids were abundant in a cull fig warehouse in Fresno, California, and, in the absence of residual insecticide applications, these natural enemy populations were sustained from year to year during a five-year period (see recommended reading by Johnson et al).

Prostephanus truncatus was introduced into East Africa from South America during the late 1970s without its histerid predator, *T. nigrescens*, and into West Africa during the early 1980s. The predator was introduced into Togo, Benin, Ghana, and Kenya during the early 1990s and is now widespread in Africa.

Biological control is effective. Natural enemies can effectively suppress stored-product insect pest populations (see Table 6.5). Natural populations of *Cephalonomia waterstoni* reduced the numbers of *Cryptolestes ferrugineus* infesting wheat by more than 50%; natural populations of *Anisopteromalus calandrae* reduced *Sitophilus zeamais* infesting maize by 0–79%; natural populations of *T. nigrescens* reduced *P. truncatus* infesting maize by 73 and 84%; natural populations of several species of parasitoids reduced *Callosobruchus maculatus* populations by 0–73%; and natural populations of *H. hebetor* reduced *Cadra cautella* infesting peanuts by 26–73%. These parasitoids will increase as the insect pest population increases if they are not killed by other insect pest management methods or business practices (see Chapter 1). Insect pest managers can benefit from monitoring and protecting the natural-enemy populations.

Although **inoculative releases** may not be necessary when sufficient numbers of natural enemies occur naturally, **augmentation** or **inundative releases** of these natural enemies may be necessary to keep insect damage to a commodity within acceptable limits (see recommended reading by Flinn et al). For 163 out of 212 estimates of stored-product insect pest mortality with 13 natural enemy and 19 insect pest species (see Table 6.5), releases of natural enemies reduced the insect pest populations by 70–100%. For 87 of these estimates, insect pest mortality was between 90 and 100%.

Biological control is a low-risk method. The risk of natural enemies themselves contaminating processed commodities is a concern, but their ability to find and greatly reduce residual stored-product insect pest populations is likely to reduce the overall risk of insect contamination.

Biological control is registered for use. The genera of parasitoids and predators registered by the Environmental Protection Agency for use against stored-product insect pests in the United States include *Anisopteromalus*, *Bracon*, *Cephalonomia*, *Dibrachys*, *Dufuriellus*, *Habrocytus*, *Holepyris*, *Laelius*, *Lariophagus, Lytocoris*, *Mesostenus*, *Pteromalus*, *Theocolax*, *Trichogramma*, *Venturia*, and *Xylocoris*.

Pathogens can be used like residual insecticides. The commercially available pathogens are formulated for use as dusts or emulsifiable concentrates and therefore can be applied like residual insecticides. Applying pathogens with the inexpensive equipment used to apply residual insecticides can be a big advantage because managers are already familiar with the equipment.

Resistance is not a problem yet. Because parasitoids and predators are coevolving with their hosts, stored-product insect pests may become resistant to them more slowly than to other insect pest management methods. However, insect pest management programs may interfere with this natural coevolution.

Disadvantages

The shelf life of natural enemies is limited. Care must be taken in shipping parasitoids, predators, and pathogens. They must be kept at a suitable temperature and released or applied as soon as possible. Pathogens can be stored longer than parasitoids or predators. Parasitoids and predators can be held at cool temperatures to better time the releases.

Commodities can be contaminated by natural enemies. Federal regulations in the United States under the Federal Food, Drug and Cosmetic Act do not distinguish filth or insect fragments contributed by stored-product insect pests from those contributed by natural enemies. Therefore, contamination of commodities by natural enemies is just as bad as contamination by insect pests. For raw commodities, sieving and **aspiration** before processing can remove most of the natural enemies. When natural enemies are used for insect pest management in places where packaged foods are stored, contamination of food is unlikely. Generally, the amount of contamination by parasitoids is small compared to the amount of contamination by the stored-product insect pests that they attack.

Correct species and timing are necessary for biological control. Natural enemies often attack only one stored-product insect pest species, and more than one species of natural enemy may need to be released when more than one insect pest species is present. Releasing more than one species of natural enemy may increase the cost of insect pest management. Such costs also may be increased when multiple releases of one or

more natural enemies are necessary. With the proper timing of a release, additional natural enemies often may be unnecessary (see Chapter 7). Natural enemies need to be released while insect pest populations are small because they may not suppress insect pest populations as rapidly as chemical methods. Quality control is necessary in the production of natural enemies so that only the healthy natural enemies are sold and the correct species of natural enemies are released.

Implementation options

For several component parts of the biological control method, a number of options are discussed for the implementation of biological control as part of a pest management program for stored-product insects.

Conservation. Protecting existing populations of natural enemies may be the easiest and least-expensive biological control method. Using only insect pest management methods that will not harm natural enemies is the most critical **conservation** method. **Malathion**-resistant strains of parasitoids have been found and could be used for **inoculative** or **inundative** releases. However, this does not alleviate the problem of residual insecticides reducing the number of hosts that are available for the natural enemies.

Augmentation. Creating conditions that promote the optimal performance of naturally occurring or released natural enemies is another easy and less-expensive biological control method. This generally involves altering the environment to favor the natural enemies or providing food to increase their population growth rate. Aerating to cool grain is an example of modifying the environment to favor parasitoids (see the Integration section of this chapter).

Parasitoids in the families Bethylidae, Braconidae, and Pteromalidae paralyze and feed on host larvae before laying eggs externally on the host. Some of these host larvae crawl away after being stung and before becoming paralyzed. These larvae are suitable for oviposition and parasitoid development when found by other parasitoids. Releasing paralyzed host larvae along with parasitoids increases the parasitoids' effectiveness (see Chapter 6). Sterile host eggs can be provided to increase the effectiveness of Trichogrammatidae.

Species. Knowing which stored-product insect pest species are present may be important in conservation or **augmentation** of natural enemies. For several insect pest species, one or more species of parasitoids, pathogens, and predators are available, and the success of inoculative or inundative releases may depend upon choosing the best species. Because the mortality of insect pest species is highest during the egg and early **instars**, egg parasitoids may be less effective than those attacking other developmental stages. Many of the eggs that are killed by these parasitoids would have died in the egg stage or as young larvae even if they had not been parasitized.

Numbers. The release or application rate is a compromise. Using too low a rate will provide inadequate insect pest suppression and using too high a rate is not cost-effective. A release rate of two parasitoids or predators for each adult host is generally recommended. Often multiple releases of parasitoids have been made at one- to four-week intervals, but this may not be necessary or cost-effective.

Timing. To prevent the damage caused by stored-product insects, natural enemies need to be released while the population density of the insect pests is still low. The timing of the release or application of natural enemies greatly influences their effec-

tiveness. Population growth models for *Cryptolestes ferrugineus* and its parasitoid, *Cephalonomia waterstoni*, have been used to predict when and how many parasitoids should be released (see recommended reading by Flinn and Hagstrum and Chapter 7). When parasitoids or predators are released too early, hosts will not be available, and the natural enemies may die. When parasitoids or predators are not released soon enough, they must be released in larger numbers. Releasing *C. waterstoni* on day 20 reduced the *C. ferrugineus* population by 75% more than releasing the same number of parasitoids on day 40.

Source. *Bacillus thuringiensis* has been registered for use against moth larvae infesting stored products and is commercially available. *Plodia interpunctella* granulosis virus is registered by Agrivir for use in the United States as a crack-and-crevice treatment. Several companies have from time to time marketed parasitoids and predators of stored-product insect pests. If the demand for natural enemies for stored-product insect pests were greater, the companies that produce natural enemies for field and orchard crops might produce these natural enemies.

Autodissemination of pathogens. Inoculation of the stored-product insect pests by attracting them to traps containing pathogens has been studied for *Trogoderma glabrum* and *Plodia interpunctella*. Insects carry the pathogens to their breeding places, and other insects may become infected. Results were better for the *T. glabrum* than for the *P. interpunctella*. The method probably would work better for *P. interpunctella* if the traps attracted females instead of males. Parasitoids and predators may also be vectors for pathogens.

Integration

Packaging. Natural enemies can reduce the number of stored-product insect pests outside packages and thus reduce the chances of packaged commodities becoming infested by insect pests. *Cadra cautella* infestations can be reduced by 97% by releasing *Habrobracon hebetor*, 92% by releasing *Venturia canescens*, and 78% by releasing *Xylocoris flavipes*. These natural enemies have been shown to be effective in delaying the infestation by insects of vulnerable two-ply paper bags and even of more-resistant glued paper boxes when these boxes were damaged.

Aeration. Releasing parasitoids while aerating to cool wheat can provide more-effective insect pest management. Using an aeration controller to aerate during the coolest part of the day, wheat can be cooled soon after it is stored in the summer. Decreasing the grain temperature from 32 to 25°C slowed *Rhyzopertha dominica* development and gave the parasitoid *Theocolax elegans* more time to find hosts (see Chapter 6). The lower temperature evidently did not reduce the ability of the parasitoid to find its hosts.

Utilization of biological control

Natural enemies have been utilized successfully for commodities stored in bulk and to keep the residual stored-product insect populations low in retail stores. The risk of natural enemies themselves contaminating processed commodities is a concern, but their ability to find and greatly reduce residual stored-product insect pest populations may reduce the overall risk of insect contamination. The importance of naturally occurring populations of natural enemies in suppressing the stored-product insect

populations throughout the marketing system is probably grossly underestimated, and this biological control often may be disrupted by standard business practices and efforts to manage stored-product insect pests.

Study questions

1. What is biological control, and how can it be used to suppress stored-product insect pest populations?
2. What are the advantages and disadvantages of using biological control to suppress stored-product insect pest populations, and how is each important in deciding whether to use biological control?
3. What are the advantages and disadvantages of each of the available implementation options for using biological control, and how is each important in deciding whether to use biological control?
4. What other insect pest management methods can be integrated with biological control to suppress stored-product insect pest populations, and why is each of the combinations better than a single method?

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Chapter 12

Aeration

Principles

Aeration involves forced movement of outside air through a bulk-stored commodity to create a uniform temperature throughout the bulk. Cooling by aeration minimizes the growth of insect and mold populations and prevents spoilage and economic losses.

In unaerated grain, air currents remove moisture from the grain. This moisture condenses on the underside of the bin roof or the cooler grain near the surface in the autumn, and this results in the wetting of the surface of stored grain and spoilage. Aeration is particularly important for large bins in which grain otherwise would take a long time to cool (see recommended reading by Flinn et al).

By using an automatic aeration controller, wheat can be cooled sufficiently in temperate climates soon after a summer harvest to slow stored-product insect population growth and keep insects from reaching unacceptable numbers before the grain can be cooled further by autumn and winter temperatures. Reducing grain temperature from 27 to 22°C can halve the insect population growth rate. Cooling also slows the breakdown of residual insecticides so that they are effective in suppressing insect populations for a longer time. For high-value commodities in warm climates or during a warm season, grain **chillers** can be used to aerate and cool commodities stored in bulk.

Some tobacco warehouses have been designed so that they can be cooled by aeration in winter. Fans on the roof pull outside air into the building; the air leaves through gravity-closed vents in the sidewalls.

Advantages

Aeration is effective. Aerating to cool grain slows the growth of the populations of many species of stored-product insect pests. Cooling below 13–20°C can result in close to 100% mortality of some species of stored-product insect pests when these temperatures can be maintained for several months. (*Oryzaephilus surinamensis* and *Sitophilus oryzae* are more cold hardy and may take longer to kill than other species. Also, more insects may survive near the grain surface if it rewarms.) In Oklahoma, cooling by aeration reduced the percentage of grain bins that needed to be fumigated from 30–94% to 20–28%.

Aeration is safe. Aeration is a nontoxic and nonpolluting method of managing stored-product insects. The training and safety precautions that are required by law for using fumigants are not needed for aeration.

Operating cost is low. The electricity to run aeration fans generally costs no more than fumigation. Only simple, inexpensive equipment is needed to monitor the temperature of the exhaust air or the number of hours that an aeration fan has run. Aeration fans may need to be run for 180–300 hr, depending upon the size of the bin and the aeration fan. The cost of electricity can be calculated as 0.75 times the horsepower of the fan motor times the hours that the fan runs times the cost of electricity in kilowatt-hours. Using an automatic aeration controller to run the aeration fans only when

the difference between the outside air temperature and the grain temperature is sufficient to cool the grain can minimize the costs and complexity of aeration.

Resistance is not a problem yet. Insect resistance to cooling by aeration may be slow to develop as long as aeration is not the only insect pest management method that is used on farms and at elevators or other facilities.

Aeration maintains grain quality. Grain quality is maintained by equilibrating grain temperature throughout the grain mass and thus preventing moisture migration. Cooling the grain reduces the growth of insect and mold populations and prevents spoilage and economic losses.

Disadvantages

Aeration provides only short-term protection. Once a facility or bulk grain rewarms, insects can reinfest.

Poor aeration can reduce quality. Poorly managed aeration can cause localized moisture problems, spoilage, and economic loss. Cost-effective aeration requires leveling of the grain surface, correct duct size and layout, and moving a temperature front all the way through the grain.

Capital investment is high. Aeration requires an initial capital investment in perforated ducts or floor, an aeration fan, and an automatic aeration controller. Very large bins may require more than one fan. In some cases, additional ventilation may need to be added to the roof to allow the exhaust air to escape.

Aeration is complex. Using aeration may seem to be more complex than other insect pest management methods because it is less familiar. Properly sized ducts and fans must be purchased. Fan hours must be sufficient to move a cooling front through the grain, but excess fan hours increase the cost of aeration. Automatic aeration controllers can simplify aeration and make it more appealing to insect pest managers. Monitoring grain or exhaust air temperature is the best way to determine when grain cooling is complete.

Aeration can reduce moisture. Cooling grain by aeration can reduce grain moisture by 0.2–1%. This moisture loss reduces the weight of the grain available for sale and thus reduces profit.

Implementation options

For several component parts of the aeration method, a number of options are discussed for the implementation of this method as part of a pest management program for stored-product insects.

Preparing grain for aeration. Fine material, including broken and shrunken kernels and dockage, can plug the air space between the kernels of grain (which makes up 40% of the bulk volume), and increase the time required for aeration and the cost of aeration. Setting the combine to minimize breakage is a first step toward effective aeration. Cleaning grain is the ideal way to increase aeration efficiency, but the loss of marketable commodity may not make cleaning a viable option. Alternatively, grain spreaders can be used to distribute the fines rather than concentrating them in the center of the grain mass. Spreaders also can improve the uniformity of airflow by leveling the grain surface. However, spreaders also may reduce airflow by packing the grain more tightly. Another option is to remove a core of grain from the center of the bin after loading to remove the fines that have built up in the center.

Perforated ducts or full floor. Air-distribution systems are designed to move enough air through the grain as uniformly as possible. Ducts can be rectangular, tubular, or half round. Having the correct size and number of perforations in ducts or floor and the correct size and layout of ducts is necessary to achieve the most-uniform air movement through the grain. Generally, 10–14% of the duct is perforations, and ducts are corrugated for strength. Plastic ducts that are less expensive than metal are used in flat storage. Even with the best sizing and layouts, there may be some areas of the grain with lower airflow. The uniformity of airflow near the surface can be improved by leveling the grain. When grain is peaked, grain in the peak will have lower airflow. Innovations might include a cross-flow of air from side to side in tall bins or systems that direct air along bin walls to keep this grain from rewarming. Spreading plastic sheeting on the grain surface will reduce airflow to the areas under the sheeting and increase airflow to other areas.

Fan selection. Fans are selected to move air through a commodity at a rate usually between 0.022 and 0.67 m^3/min per metric ton (0.025 and 0.75 ft^3/min per bushel) of commodity, and the size of fan needed increases with the volume of the commodity that is being aerated. The amount of air that fans can move decreases as the pressure they are working against increases. This pressure is greater for small grains like wheat and milo than for larger grains like corn and soybeans, and it increases with the depth of the commodity in a bin. Restrictions, turns, and increased length of the duct also increase the pressure against which a fan works.

The airflow vs. pressure relationship for a particular fan is called the "fan performance data." Performance depends on the size, shape, and speed of the impeller and the size of the motor driving it. Performance differs widely among brands and models, even for fans with the same-size motor. Graphs and tables for performance data are available from the manufacturers, and software for choosing a fan that will provide sufficient airflow at expected operating pressure is available at the website www.bae.umn.edu/extens/harvest.html.

Aeration fans are generally 0.5–10 hp and turn at 3,500 rpm. Centrifugal fans are effective at higher pressure and cost more, but they are not as noisy as axial-flow fans. Axial-flow fans can be turned around more easily to reverse the direction of the airflow; centrifugal fans generally are not turned around once installed. Higher airflow can be achieved by using more than one fan in series or at different locations on a bin. Large metal bins and flat storage may have several fans around the base. With multiple fans, it is important that all fans be running so that the air is moved through the commodity and does not take a shortcut through a fan that is not running. Elevators may connect one fan to several bins. Push-pull systems at elevators use one fan at the top and another at bottom. With this push-pull system, it is important that the headspace be sealed so that air is pulled through the commodity and does take a shortcut through headspace openings in the bin.

Push or pull air. Aeration fans can be used to push air up through grain, to pull air down through the grain, or to do both. There are advantages and disadvantages to either method. Pulling cools the grain near the surface first, while pushing cools the grain near the bottom of the bin first. Because insects infest grain near the surface after the grain is stored, cooling the grain near the surface first may be advantageous.

When pushing, warm-humid exhaust air can cause condensation on cool bin walls and roof, and this condensed water may drip onto the surface of the grain. Grain spoilage and sprouting can occur in such wet spots. Additional fans sometimes are used to

remove this moisture from the headspace. The heat from the operation of large fans and from the air being compressed is pushed through grain. The heat of compression can be 2.8°C (5°F). Pushing air may keep the ducts and fans cleaner. When pulling air, fans may need more maintenance because of dust accumulations, and insects may breed in the accumulated grain dust. Pulling air deposits moisture on grain near the bottom, where it is difficult to monitor grain quality changes, and moves hot air from the headspace through the grain.

Airflow rate. Generally, airflow rates are between 0.022 and 0.67 m^3/min per metric ton (0.025 and 0.75 ft^3/min per bushel). Higher airflow rates can be inefficient because the air has less time to remove heat from the grain. The grain through which the air enters is cooled first. The layer of cool grain expands gradually as air removes more heat from the grain. The boundary of the cool-grain layer farthest from air-entry point is called the "cooling front."

Fan hours. The fan hours required to cool grain vary with the size of the fan, the bin diameter, and the depth of grain in the bin. The air removes only a small amount of heat from the grain, and so large volumes of air are required to cool grain. Dry air cools grain with fewer fan hours than moist air because of greater evaporative cooling. Cooling the entire grain mass generally requires 180–300 fan hours.

Automatic aeration controller. Automatic aeration controllers simplify the task of finding air temperatures that are 8°C (15°F) lower than the grain temperature (see recommended readings by Reed). For instance, in Kansas (which is located approximately in the middle of the United States), immediately after the wheat harvest, aeration controllers can be set to turn on the aeration fans whenever the air temperature is below 21°C (70°F). When the hour meter says that the fan has run for 80–100 hr, the first cooling front should be through the grain, and the threshold temperature for turning on the fans is set at 15°C (60°F) for the next 80–100 fan hours. The threshold is then set at 4°C (40°F) for the final 80–100 hr. To compensate for the latitudinal differences in the seasonal temperature changes, these three thresholds may need to be as much as 3°C (5°F) warmer south of Kansas, and as much as 3°C (5°F) cooler north of Kansas. With push aeration, surface-grain temperatures or, with pull aeration, air temperatures near the aeration fans can be measured to confirm that the temperature front is through.

Temperature monitoring equipment. Grain temperatures can be monitored throughout the grain depth using thermocouple cables that are permanently installed in the bin. Grain temperature at the surface can be monitored by pushing a thermocouple into the grain. When using pull aeration, air temperatures can be monitored near the aeration fan.

Chilled aeration. For high-value commodities in warm climates or during warm seasons, grain **chillers** can be used (see recommended reading by Maier). However, chilled aeration requires a larger capital investment or renting of equipment as well as higher operating costs than aerating with ambient air.

Integration

Sanitation. Early aeration can reduce stored-product insect population growth by cooling the grain, but insect populations may still reach unacceptable levels unless the grain storage bins have been cleaned thoroughly to eliminate residual insect infestations.

Utilization of aeration

Aeration has been used most widely and effectively in steel grain bins on farms and at grain elevators. Aeration of grain in the tall concrete bins at grain elevators is more difficult than aeration of grain in flat storages or steel bins, but aeration of grain in tall concrete bins also can be very effective. Aeration has been used to cool raw commodities in warehouses too.

Cooling by aeration alone has been used to effectively suppress stored-product insect populations infesting stored grain in temperate climates. Aeration can begin soon after harvest. The fans are run whenever the outside air is cool enough to reduce grain temperatures. A similar aeration program can be used in the lowland tropics, but other insect pest management methods are likely to be needed as well.

Study questions

1. What is aeration, and how can it be used to suppress stored-product insect pest populations?
2. What are the advantages and disadvantages of using aeration to suppress stored-product insect pest populations, and how is each important in deciding whether to use aeration?
3. What are the advantages and disadvantages of each of the available implementation options for using aeration, and how is each important in deciding whether to use aeration?
4. What other insect pest management methods can be integrated with aeration to suppress stored-product insect pest populations, and why is each of the combinations better than a single method?

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Chapter 13

Sanitation and Exclusion

Principles

Sanitation prevents insect problems by reducing, through routine cleaning, the residual food that is available to insects. Stock rotation can prevent ingredients and products from becoming sources of insect infestation. The design and maintenance of the building, grounds, and equipment can make an insect pest management program more effective by preventing insects from entering a facility and eliminating refuges where food can accumulate and insects can hide. Other important exclusion methods include insect-resistant packaging and the inspection of incoming ingredients for insects.

Frequent removal and proper disposal of residual food accumulations from inside and outside the building and equipment can reduce the survival and reproduction of stored-product insect pests. Thorough cleaning may require disassembly of equipment. Inspections for insects through ports in equipment and incubation of samples of the food being processed may be used to verify the effectiveness of the sanitation and exclusion methods. The time interval between inspections or cleanings and the period required for complete stock rotation should be less than an insect's generation time of four to six weeks so that immature insects do not have time to become adults and reproduce.

Dust collection systems used at terminal elevators and in food-processing plants can reduce the food residues that are available for insects. However, stored-product insects can develop, survive, and reproduce on very small amounts of food residues. Therefore, sanitation alone generally will not eliminate stored-product insect populations. Without intervention, stored-product insect populations will increase over time.

Exclusion through design and maintenance of building, grounds, and equipment includes 1) the placement of outside lights and ornamental plants so as not to attract insects, 2) the screening and sealing of windows, vents, utility lines, and doors so that insects cannot enter a building, 3) sealing cracks and crevices around the bases of equipment and floor-wall junctions, 4) maintaining a vegetation-free barrier zone around the perimeter of a facility, 5) adequate drainage to prevent the accumulation of water on the grounds, 6) proper maintenance of the garbage-disposal area, 7) removal of weeds and mowing of lawns, and 8) maintaining a clutter-free roof.

Inspections for stored-product insects in incoming ingredients and the trucks that deliver them can prevent the introduction of insect infestations into a facility. Stock rotation (first in-first out) is the best way to minimize the storage time for ingredients or products and to remove infested commodities that can be a source of stored-product insects that infest other commodities. Insect-resistant packaging can protect processed foods from insect infestation throughout the marketing system.

Advantages

Sanitation and exclusion are effective. Sanitation and exclusion can reduce the numbers of many species of stored-product insects in storage, processing and marketing facilities, and transportation vehicles and make other insect pest manage-

ment methods more effective (see recommended reading by Reed et al and the section titled "Integration" in this chapter).

Packaging resists insect entry during marketing. Even when their products become infested after leaving the food-processing plant, food processors are still held responsible by the consumer for an insect infestation. An insect-resistant package is the best line of defense that a food processor has against many species of stored-product insects after the product enters the marketing channels for delivery to a distribution warehouse and a retail store.

Sanitation and exclusion are low risk. Sanitation and exclusion methods generally are nontoxic and nonpolluting, leave no residues, and pose no risk for workers and consumers. Dust-collection systems also reduce the risk of dust explosions at elevators and make air healthier for workers to breathe.

Some of the tools are inexpensive. In a facility designed for good dust collection and easy cleaning, only simple tools such as brooms and vacuum cleaners are needed to keep a facility clean. Plastic door strips, air curtains, and window and door screens can be used to prevent insects from entering a facility. Periodic vacuuming and high-pressure water cleaning of raw-commodity storage facilities may reduce the residual food and thus the stored-product insect populations (see recommended reading by Jacobson and Pinniger).

Resistance is not a problem yet. Stored-product insects may have already developed some behavioral resistance to sanitation and exclusion methods, but this has not been studied. The refuge-seeking behavior that reduces their susceptibility to residual insecticides also may reduce their susceptibility to sanitation (see recommended reading by Cox et al). The ability of stored-product insects to find shelter, food, mates, and suitable egg-laying sites, even when these essential resources are rare, makes exclusion difficult (see Chapter 3).

Disadvantages

Sanitation and exclusion require continuous effort. New food residues accumulate every day and must be cleaned up. Also, as a general rule, only about half of the facility and equipment are available for cleaning because of their design. A good sanitation program requires many hours of work and is expensive. For example, approximately 15–20 hr were needed to clean a 9,290-m^2 (100,000-ft^2) retail store. The scheduling of this cleaning also may be a problem when facilities operate 24 hr a day, seven days a week. Maintenance of a building and grounds to exclude insects is an unending challenge. It needs to be done regularly and may require a quick response.

Sanitation and exclusion are labor intensive. Labor costs may be high but they can be reduced by designing buildings and equipment so that they can be cleaned easily.

Sanitation and exclusion require organized effort. Good sanitation and exclusion programs require the coordinated effort of quality assurance, maintenance, and all employees. The sanitation program also may need to be coordinated with the services of contracted insect pest management professionals. Development of a sanitation team and periodic reviews of the sanitation program are essential. Detailed written sanitation procedures and schedules are important. Also, thorough documentation of the completion of each task and any observed problems is important. Although inspections are generally done by plant sanitarians, private consultants, or government inspectors,

the most successful programs are those in which all employees are involved in reporting problems.

Longevity of insects limits effectiveness. Although many stored-product insects may be removed along with the food residues during cleaning, sanitation alone does not remove all of the insects. Many species can survive for several months to a year on the small amount of food residues that cannot be cleaned from cracks and crevices. A residual insecticide applied after cleaning kills some of the insects that were not removed by the sanitation program.

Implementation options

For several component parts of the sanitation and exclusion methods, a number of options are discussed for the implementation of these methods as part of a pest management program for stored-product insects.

Design and maintenance. Good design and maintenance of the building, grounds, and equipment are essential for effective plant sanitation and insect exclusion (see recommended reading by Imholte and Imholte-Tauscher). Building construction materials can be selected and utilized to minimize the accumulation of food and eliminate hiding places for insects. When areas sheltering insects cannot be eliminated, they should be made easily accessible for cleaning. It is important to ensure that the accumulated food in cleaning tools does not become a breeding place for stored-product insect pests. Cleaning tools should be color-coded by location so that a particular color is used at each location to avoid cross-contamination. The grounds should be well maintained and free of flowering plants that attract insects or allow them to breed. A vegetation-free zone around the perimeters of the buildings is particularly important. Equipment must be designed to not permit the buildup of food residues and to make regular inspections and cleaning easy.

Stock rotation. All of the ingredients or processed foods should have dates on their packages to indicate when they were received or packaged. These dates allow the oldest ingredients to be used first and the processed foods that have been stored the longest to be shipped first. Stock rotation is important because the longer ingredients or processed foods are stored, the greater is the chance of stored-product insect infestation and the larger the insect infestation may be.

Packaging. The level of insect resistance depends upon the materials used for packaging, the type of seal, and the package design. *Lasioderma serricorne, Rhyzopertha dominica*, and *Trogoderma variabile* adults and *Plodia interpunctella* larvae often enter packages by chewing a hole in the packaging material, while *Cryptolestes pusillus*, *Oryzaephilus mercator*, *O. surinamensis*, and *Tribolium castaneum* adults generally enter through existing holes or loose seams (see recommended reading by Cline). Adults of *C. pusillus*, *L. serricorne, O. mercator*, and *T. castaneum* are better penetrators than larvae. Food odors emanating from small holes in packaging may cause females to lay eggs near or in these holes (see recommended reading by Mowery et al). Holes too small for adults may allow newly hatched larvae to enter.

Many plastic films or foils provide better insect resistance than paper or cellophane. Polyester and polypropylene provide better protection than polyethylene and polyvinyl chloride. Often multiwall paper packages or laminates of more than one material are used. For cereals, the plastic bags inside paperboard boxes can be heat-sealed, and the

glue pattern for the paperboard boxes can be chosen to maximize insect resistance. Shipping boxes and overwraps can be used to minimize the risk of package damage and stored-product insect infestation during shipping.

In addition to insect resistance, many other factors need to be considered in choosing a package (see recommended reading by Brody). The cost of packaging materials and equipment; the retention of consumer recognition of the product; the space occupied by the packages during shipping and on shelves; the permeability of the packages to water, volatile flavors and aromatic additives; the need for a grease-proofing layer; the need for the package to accommodate a change in atmospheric pressure; and the physical properties such as abrasiveness or brittleness must be considered. Incorporating an insect repellent or vapor barrier into packages could reduce their attractiveness to insects. Methyl salicylate is the first repellent to be approved as a package treatment by the U.S. Environmental Protection Agency and the U.S. Food and Drug Administration. The final package design will be a compromise, and making packages easy to open or able to adjust to changes in atmospheric pressure may reduce their insect resistance.

Inspection. Regular visual inspections by the staff, consultants, third-party auditors, or regulatory agencies are needed to detect insect infestations in food storage, processing, and marketing facilities and transportation vehicles. A visual inspection needs to be systematic and thorough. It might be done as follows in a food processing facility.

Before entering a facility, the exterior of the building is examined for unscreened windows or doors, fan louvers that don't close tightly, lights near doorways, flowering trees and shrubs that attract insects, and vegetation that touches the building. Problems observed outside are used to identify internal areas that need to be checked more closely.

Inside, the inspection should begin in the raw-ingredients storeroom. Broken packages and the seams of ingredient bags are checked for insects or signs of their presence. Vacuum cleaner bags and the bristles of brooms also are checked for insects. A flashlight is shined along the floor-wall junction or along the wall to reveal insects. Off-odors or insect trails in the dust may indicate an insect problem.

When leaving the storage area, the inspection can follow the flow of ingredients from the receiving areas through the production process to where the finished product is packaged and stored, awaiting shipment. Dust accumulations in hard-to-reach areas inside and behind equipment, in electrical boxes, and on I-beams are a true indicator of the quality of a plant's sanitation program. Light fixtures, electrical conduits and boxes, window ledges, and the spaces above hanging ceilings or inside equipment are checked for insects and built-up food residues. Food residues larger than that expected during one day's operation might indicate that a better sanitation program is needed. Sanitation in the packaging areas is not generally as difficult as in processing areas. A systematic inspection can reveal problem areas that need more attention.

Integration

Packaging. Using packaging, sanitation, and exclusion methods together is more effective than using any one of these methods alone. Stored-product insects will eventually find defects or damage in a package that allows them to enter (see recommended reading by Karitas). Using sanitation to reduce insect numbers will

allow packaging to protect a commodity longer. Exclusion limits the number of insects entering a facility, and sanitation reduces the reproduction of those that have already entered.

Residual insecticides. If food residues are not removed before a residual insecticide is applied, they can provide untreated refuges for stored-product insects. **Fenitrothion** has been shown to be less effective against *Cryptolestes ferrugineus*, *Oryzaephilus surinamensis*, and *Sitophilus granarius* when untreated refuges are available (see recommended reading by Cox et al). Insects spend less time outside refuges when the refuges contain food. *C. ferrugineus* spent less time outside refuges at a dosage of 250 mg/m^2 of fenitrothion than at a dosage of 2 mg/m^2. **Malathion** and fenitrothion also were found to be less effective against *Tribolium castaneum* when untreated refuges were available.

Food residues accumulating after a cyfluthrin application were found to be a barrier that prevented insects from contacting the residual insecticide (see recommended reading by Arthur). Also, these food residues may rub the residual insecticide particles off the insects and provide the energy that these insects need to detoxify the residual insecticide and recover from insecticide poisoning.

Utilization of sanitation and exclusion

Sanitation and exclusion generally have been utilized more extensively for processed commodities than for raw commodities because of the stricter standards for processed commodities. For both raw and processed commodities, the mobility, longevity, and ability of stored-product insects to survive and reproduce on small amounts of many different foods result in some insects surviving even the most-effective sanitation program and gaining entry even with the best exclusion program. Therefore, sanitation and exclusion must generally be integrated with other insect pest management methods.

Study questions

1. What are sanitation and exclusion, and how can they be used to suppress stored-product insect pest populations?
2. What are the advantages and disadvantages of using sanitation and exclusion to suppress stored-product insect pest populations, and how is each important in deciding whether to use sanitation or exclusion?
3. What are the advantages and disadvantages of each of the available implementation options for using sanitation and exclusion, and how is each important in deciding whether to use sanitation or exclusion?
4. What other insect pest management methods can be integrated with sanitation and exclusion to suppress stored-product insect pest populations, and why is each of the combinations better than a single method?

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Chapter 14

Extreme Temperatures

Principles

Insects generally do not regulate their body temperature, and so extreme temperatures reduce survival. Lethality depends upon the temperature and the exposure time (see recommended readings by Donahaye et al, Fields, and Mourier and Poulsen). Temperatures over 60°C can cause death in seconds, temperatures between 50 and 60°C in minutes, and temperatures between 43 and 46°C in hours. High temperatures also can cause insects to move around more. Temperatures between 5 and 15°C delay insect development and are eventually lethal after very long exposures. Temperatures between –1 and 3°C can cause death in hours or days, and temperatures below –1°C can cause death more quickly. The efficacy of extreme temperatures for suppression of stored-product insect pests depends upon these extreme temperatures being reached throughout a commodity or facility.

High temperatures have been investigated for stored-product insect pest suppression in several commodities, including cereal grain, cowpeas, and in-shell nuts, as well as in grain bins and food-processing facilities. In tropical countries, solar heating has been recommended for killing insects infesting cowpeas and grain. Many but not all insects are killed during forced hot-air drying. **Fluidized or spouted beds** have been used to spread grain out so that it can be more uniformly heated. Infrared radiation and **dielectric heating** by microwave or radio frequencies have been shown to be effective for in-shell nuts and cereal grains. Large-capacity gas, steam, or electric heaters and fans to circulate hot air can be used to kill stored-product insects in food-processing facilities and grain bins. Typical heating rates for commodity disinfestations are 1–15 degrees C per minute compared to 2–5 degrees C per hour for facility heat treatments. The susceptibility of different stored-product insect species and developmental stages may depend upon the heating rate (see Chapter 6).

Aeration and refrigerated aeration of bulk grain were covered in Chapter 12. Refrigeration is generally cost-effective only for processed foods or high-value raw commodities such as almonds, walnuts, popcorn, or shelled peanuts. However, in areas with cold climates, flour mills have been opened up to cool them down to lethal temperatures during the cold season. For consumers, leaving small quantities of infested commodities in their freezers for one to two weeks will kill stored-product insects.

Oryzaephilus mercator, Tribolium castaneum, and *T. confusum* are the most cold-susceptible species, and *Anagasta kuehniella*, *Ephestia elutella*, *Plodia interpunctella*, *Sitophilus granarius*, and *Trogoderma granarium* are the most cold-tolerant. Studies have shown that the susceptibility of different insect developmental stages depended upon how low the temperature was. The ranking of the susceptibility of insects to high temperatures differed among studies. For *T. confusum* at 44°C, the order of heat tolerance was pupae > eggs > larvae > adults. However, at 50°C, these differences in heat tolerance among stages were not significant.

Advantages

Insects are susceptible to extreme temperatures. Heating facilities to 50°C or more for 28–35 hr was 95–99% effective in suppressing the adults of many stored-product insect species in food-processing facilities (see recommended reading by Roesli et al). However, adult *Tribolium castaneum* populations were more difficult to suppress. Radio-frequency heating of in-shell walnuts to 55°C within 5 min and then holding walnuts in hot air for at least 5 min resulted in 100% mortality of the most-tolerant fifth **instar** *Amyelois transitella*, which infests walnuts in the field (see recommended reading by Wang et al). *A. transitella* is more heat-tolerant than the storage pest, *Plodia interpunctella*, and this treatment should be effective against both species.

In fluidized beds, *Rhyzopertha dominica*, *Sitophilus oryzae*, and *Sitotroga cerealella* are killed by exposing grain to 59°C for 12 min, 62°C for 6 min, or 65°C for 4 min. Empty farm bins also can be disinfested before loading (see recommended reading by Beckett and Qaisrani). All *T. castaneum* were killed during the 10-min period that it took to reach 54°C; 99.99% of *R. dominica* were killed by a 3-hr exposure to 55.2°C or 4-hr exposure to 53.4°C; and 100% of *R. dominica* were killed by the time temperatures reached 60.6°C.

Forced hot-air drying can kill up to 90% of stored-product insects (see recommended reading by Keever et al and Chapter 6), but it requires several hours, and some insects survive because heating generally is not uniform throughout the commodity. Solar heaters constructed of plastic sheeting can heat cowpeas to >57°C and kill all *Callosobruchus maculatus* after a 1-hr exposure (see recommended reading by Ntoukam et al).

Extreme temperatures are safe. Extreme temperatures generally are nontoxic, nonpolluting, and leave no residues that pose a risk to workers and consumers. High temperatures can kill stored-product insects without reducing the germination of seeds or altering the milling properties of grain or the baking quality of the flour milled from heat-treated wheat.

Less sealing is needed. Unlike fumigation, heat treatment does not require gas tightness, although covering vents with plastic sheeting is recommended.

Resistance is not a problem yet. Resistance to high and low temperatures may develop with more-extensive use because insects are known to adapt to extremely low arctic temperatures and extremely high thermal-hot-spring temperatures.

Disadvantages

Facilities need to be closed, and there is no long-term protection. A facility may need to be closed for 24–36 hr to prepare and complete a heat treatment. Building sprinkler systems may need to be shut down or replaced with ones that have a higher temperature threshold, and the fire department should be notified about the plans for a heat treatment. Personnel need to monitor the air temperatures and heater and fan operation during the heat treatment. Extreme temperatures provide no long-term protection, and other insect pest management methods may be needed to prevent reinfestation.

Extreme temperatures can damage buildings and equipment. Extreme temperatures can damage buildings and equipment, and the amount of damage may depend upon the rate of heating or cooling (see recommended reading by Imholte and

Imholte-Tauscher). Materials with low melting points can be damaged by heat. Materials with different coefficients of expansion can separate and cause damage. The effects of the high temperatures used for heat treatment on the equipment and many of the materials used in a food-processing facility (such as paints, caulks, and sifter screens) is unknown. Heat-sensitive equipment (such as computers) should be removed from the building or protected. Opening, cleaning, and closing equipment before heat treatment is a good way to avoid damage.

Capital investment or rental fees are required. Heaters and fans generally must be rented or purchased. Some facilities with steam heat may have sufficient capacity to achieve high temperatures without additional heaters.

Achieving uniform temperatures is difficult. Obtaining and maintaining uniformly high or low temperatures in a building can be nearly impossible. For disinfestations with infrared, microwave, or radio frequencies, commodities are spread into a thin layer. The depth of the penetration of heat into commodities can be a limiting factor for the disinfestations of raw commodities. **Fluidized or spouted beds**, pneumatic conveyors, or rotating drums can be used to spread out grain so that it is more uniformly heated.

Removal of food is necessary. All food products should be removed from a food-processing facility before a heat treatment because food products are poor conductors. They may heat up slowly and thus provide refuges from the heat in which stored-product insects can survive. Food residues, which also may provide refuges, need to be removed by thorough cleaning. Bulk food products will need to be fumigated before they are brought back into a facility to prevent reinfestation.

Implementation options

For several component parts of the extreme-temperature method, a number of options are discussed for the implementation of this method as part of a pest management program for stored-product insects.

Building and equipment design. Heating systems with sufficient capacity for heat treatments should be installed when a facility is built. Buildings and equipment can be designed so that stored-product insects inside equipment and in other inaccessible places are exposed as much as possible to lethal temperatures. Damage to a building and equipment can be reduced by using heat-resistant materials during construction.

Heaters, fans, or compressor. When the building heating system does not have the capacity for heat treatments, the size, number, and location of heaters and fans are important in achieving and maintaining uniform high temperatures sufficient to suppress the stored-product insect population (see Chapter 9). Identifying the rate of heat loss for different sites in the building, particularly windows and doors, will help managers decide where heaters and fans should be placed.

Fluidized or spouted beds created with forced-air heating can be used to disinfest grain (see recommended reading by Evans et al). Infrared radiation and **dielectric heating** with microwaves or radio frequencies can be used to disinfest grain, walnuts, and other commodities (see recommended reading by Nelson). The frequency and energy level selected must kill stored-product insects while minimizing commodity heating. Radio frequencies can penetrate deeper into commodities than microwaves. Intermittent exposure to microwaves was shown to be more effective than continuous exposure for *Plodia interpunctella* and *Tribolium confusum*, so, for some stored-

product insect species, intermittent exposures might be used (see recommended reading by Shayesteh and Barthakur). A compressor of appropriate size needs to be selected for refrigerated aeration of bulk commodities or refrigerated storage.

Exposure time, maximum temperature, and heating rate. For moving commodities, the flow rate determines the time that stored-product insects are exposed to high temperatures. Grain needs to move slowly enough for the insects to be killed but not so slowly as to allow damage to the commodity or to delay commodity shipments more than necessary. Exposure time may be inversely related to the maximum temperature needed. Heating commodities or facilities less and increasing the exposure time is more economical (see Chapter 9). The susceptibility of different developmental stages and insect species may depend upon the heating rate (see Chapter 6). For heat treatments in flour mills, exposure time may vary among locations. A period of 5–12 hr is generally required to heat a facility, and high temperature is maintained for 24–36 hr.

Monitoring. Temperatures need to be monitored throughout a building, using infrared detectors or data loggers to be sure that a uniformly high temperature is achieved and maintained during heat treatments. The efficacy of heat treatment is generally measured using caged insects. The number of insects caught in traps may actually increase during and after a heat treatment because insects move around more. Temperature monitoring is also important when disinfesting raw commodities to ensure efficacy and prevent damage to the commodity.

Integration

Inert dusts. Heat treatment of a building can flush insects out of the equipment and other hiding places. Inert dusts can readily kill these insects in the dry environment (20% rh) created by the heat treatment. Laboratory studies suggest that a combination of heat and inert dusts should kill adult *Tribolium confusum* in less time (13–22 hr vs. 32–38 hrs) and at a lower temperature (41 vs. 46–47°C) than either alone. The reduced operating cost for heaters should more than pay for the inert dust treatment.

Modified atmospheres. In the laboratory, combining high temperatures (38, 40, or 42°C) with high carbon dioxide (60, 90, 95, or 98%) or low oxygen (0.5, 1, 2, or 5%) reduced the times required to kill *T. castaneum* larvae. Shorter exposure times for these combinations of insect pest management methods should make implementation in food-processing and food-storage facilities more practical and less expensive.

Heat and cold. A combination of heat followed by cold treatment (eight days at 10.5°C) also may reduce the overall high-temperature exposure times required for suppression of *Plodia interpunctella* eggs. For the combination of heat and cold, only 6.5 hr at 42°C or 7.7 min at 46°C were required for 99.9% mortality instead of 10.3 hr at 42°C and 34 min at 46°C for high temperature alone or 19.8 days at 0.5°C for low temperature alone.

Utilization of extreme temperatures

Cold storage is economical mainly for high-value raw or processed commodities. High temperatures have been used commercially to disinfest flour mills. Pilot-scale equipment has been tested for using hot-air fluidized beds to disinfest grain and grain **chillers** to reduce insect population growth in raw commodities. Smaller-scale tests

have been done using high temperatures to disinfest other commodities and facilities. The temperatures to which insects are exposed while commodities are dried often are insufficient to completely disinfest the commodities. Simple solar methods have been developed for the disinfestation of commodities by subsistence farmers in tropical countries.

Cold kills insects more slowly than heat. Cold temperatures are often maintained for the duration of storage. Heat treatments do not provide any long-term protection against stored-product insects and must be repeated periodically, or other insect pest management methods must be used.

Study questions

1. What are extreme temperatures, and how can they be used to suppress stored-product insect pest populations?
2. What are the advantages and disadvantages of using extreme temperatures to suppress stored-product insect pest populations, and how is each important in deciding whether to use extreme temperatures?
3. What are the advantages and disadvantages of each of the available implementation options for using extreme temperatures, and how is each important in deciding whether to use extreme temperatures?
4. What other insect pest management methods can be integrated with extreme temperatures to suppress stored-product insect pest populations, and why is each of the combinations better than a single method?

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Chapter 15

Impact and Removal

Principles

Internal and external insects infesting whole grain or other commodities can be killed by impact when a commodity is moved or by using impact machines. Cleaning grain or other raw commodities by hand or by sieving and **aspiration** can remove insects, as can sieving of flour. However, some method of killing the insects in the sievings is necessary to prevent these insects from reinfesting commodities or facilities. Disturbance of insects by tumbling also can reduce the infestation levels of at least one insect species.

At **elevators,** grain is often **turned** from one bin to another to equalize the temperature throughout the grain mass, to increase the homogeneity of the grain quality or to apply fumigants. As grain is initially stored in a bin, turned, or shipped, the insect pest population is reduced by the impact of the kernels against the spouts, conveyors, bin bottom, and other kernels (see Chapter 6). Multiple impacts are more effective than a single impact. Insect mortality is higher when a **pneumatic conveyor** system is used than when a **drag**, **belt, or screw conveyor** is used. Augers tumble grain as it moves through and throw it against the sides. In pneumatic conveyors, there are probably multiple impacts of insects and kernels with other kernels and the sides of ducts.

It is the multiple impacts during tumbling rather than the rotation of the kernels that damages the insects. The fourth instars, prepupae, and pupae of both *Sitophilus granarius* and *S. zeamais* are the stages that are most susceptible to impact. Impact does not delay the development of the survivors of either species. A twice-daily 3.3-m (10.8-ft) drop (kernels reaching a velocity of 6.4 m/sec) throughout their developmental period caused 100% mortality, and a 0.11-m (0.36-ft) drop (kernels reaching a velocity of 1.4 m/sec) caused 34% mortality. Death seems to be caused not because damage to the cuticle increases loss of water but by physical damage to the insects, such as that visible in the pupal stage of *S. granarius* as physical distortion of legs.

Subsistence farmers in tropical countries routinely separate insect-infested kernels from noninfested kernels by hand and feed them to their animals. Tumbling beans every 8 hr over a two-week period reduced the *Acanthoscelides obtectus* populations by 97% (see recommended reading by Quentin et al). Tumbling prevented the young larvae from boring into the seed. In Africa, sieving beans every five days for 50 days gave excellent suppression of *A. obtectus* for another 150 days (see recommended reading by Nahdy). The practicality of subsistence farmers using these tumbling and sieving methods needs to be investigated. A combination of light, heat, and disturbance removed 90% of *Oryzaephilus surinamensis* from tea moving along a conveyor belt (see recommended reading by Robertson). Cleaning and aspirating of farmer stock peanuts removed 95–98% of the insects (see recommended reading by Payne et al).

Impact machines are widely used by the milling industry to remove insects from grain before milling and to kill the insects in flour before bagging and shipping (see recommended reading by Plarre and Reichmuth). Impact machines break open the infested kernels and release the insects. These internal-feeding insects as well as the external-feeding insects are killed by impact and removed by **aspiration**. Impact

machines also could be used at grain elevators to kill insects infesting wheat or those in the cleanings from wheat.

Although some insect species can be removed from bulk commodities by sieving and aspiration, insects cling tightly, and several passes over a sieve or through an aspirator may be necessary to remove most of these insects. Information on the sieve mesh sizes appropriate for separating different species of laboratory-reared insects from commodities is given in Table 2.3. However, field-collected insects may be smaller than laboratory-reared insects, and smaller mesh sizes may be needed to retain them.

Advantages

Many insects can be killed by impact or removed by sieving or aspiration. High mortalities of many species of stored-product insects are possible using **pneumatic conveying** or impact machines. Pneumatic conveying at rates of 19–38 t/hr can kill nearly 100% of the insects, but sometimes mortalities are much lower. Mortality as low as 24% has been reported for immature *Cryptolestes ferrugineus*. Some species are more susceptible than others to pneumatic conveying (*Typhaea stercorea* > *Oryzaephilus surinamensis* > *Trogoderma granarium* > *Tribolium castaneum* > *Rhyzopertha dominica* > *Cryptolestes ferrugineus* > *Sitophilus oryzae* > *S. granarius* > *Sitotroga cerealella*).

Turning barley from one bin to another using conveyor belts and a bucket elevator reduced *C. ferrugineus* populations of eight insects per kilogram by 80% and *Liposcelis bostrychophila* and *L. decolor* populations of 8–58 insects per kilogram by 67%.

Transferring wheat stored on-farm to another bin reduced a *C. ferrugineus* population of 120 adults per kilogram by 83% and a population of 230 larvae per kilogram by 61%. In another study, augering wheat caused 89% mortality of a population of 95 *T. castaneum* adults per kilogram, 94% mortality of a population of 137 *C. ferrugineus* adults per kilogram, and 100% mortality of populations of 17 and 20 larvae per kilogram of the two species. In the same study, pneumatic conveying caused 100% mortality of the larvae and adults of both species.

With a pneumatic conveyor, the mortality of *T. castaneum* populations of 72 and 63 adults per kilogram with a grain flow rate of 3.5 t/hr was 96% at a wheat moisture level of 14% and 79% at a wheat moisture level of 20% (see recommended reading by Paliwal et al). Mortalities at these two moistures were only 2 and 6% higher at a grain flow rate of 5 t/hr. Results were very similar for *C. ferrugineus*.

Commodities are fed into the center of the rotor of an **impact machine** and accelerated by centrifugal force. Insects are killed when they hit the pegs on the rotor. The combinations of rotor velocity and throughput needed to achieve 100% mortality using an impact machine have been shown to be very similar for *O. surinamensis*, *S. granarius*, and *T. castaneum* adults and *Anagasta kuehniella* eggs.

Little published information is available on the effectiveness of sieving or aspiration in removing insects from commodities on a large scale. However, available tests suggest that the results are similar to those for extraction on a small scale (see Chapter 2). Small-scale extraction using a dockage tester removed 84–91% of 25 *C. ferrugineus* adults per kilogram of wheat and 57–81% of 25 larvae per kilogram of wheat. The dockage tester is used in grain grading to simulate a grain cleaner. A centrifugal sieve removed 100% of 50 live and 50 dead *Tribolium confusum* adults from flour. On a larger scale, a multipass aspirator reduced the insect population in a 20-t (750-bushel)

wheat bin by 96–100% from an initial trap catch of 40,129 *Cryptolestes* spp., 30 *R. dominica*, 431 *Sitophilus* spp., and 89 *T. castaneum* (see recommended reading by Kice). The equipment in a cleaning house of a mill was shown to reduce the adult insect population by 80% and the larval population by 86% (see recommended reading by Wanzenried).

Impact is safe. The impact that occurs when grain is moved or in an **impact machine** is a physical method that, unlike a residual insecticide, leaves no residues and poses no toxic risk for workers and consumers. Dropping wheat seven times from a height of 14.1 m (46.3 ft) onto a terrazzo floor did not reduce germination. Three passes through a pneumatic conveyor did not reduce germination.

Operating costs are low. The costs of electricity for operating impact machines, sieves, and aspirators and for maintenance are low. When grain is being received, **turned,** or shipped, the insect mortality caused by impact is an added benefit without additional cost. Cleaning grain may reduce the likelihood of discounts and **hotspots**, increase the storage space available for sound grain, and improve aeration.

Resistance is not a problem yet. Insects are routinely exposed to impact in the marketing channels and may have already developed some resistance. Insects may become resistant to sieving and aspiration by holding on tighter and remaining inside the holes made by insects in the kernels of grain. However, the extent to which insects can develop resistance to impact, sieving, and aspiration has not been fully studied.

Disadvantages

Impact does not provide long-term protection. After killing insects by impact or removing insects by sieving or **aspiration**, commodities can be reinfested by stored-product insects because these methods do not protect against reinfestation.

Impact or removal alters the commodity. Impact as grain is moved and, to a lesser extent, sieved can increase the amount of broken kernels and grain dust. Maize is more susceptible to kernel breakage than wheat. Impact breaks 1 or 2% of the wheat kernels at a velocity of 20.7 m/sec, 4–12% at 28.4 m/sec, and 9–19% at 45.7 m/sec. Impact machines can kill insects without changing the particle size of flour, but they can change the particle size distribution of semolina. Aspiration removes some product along with the contaminant.

Cost may be high. Impact machines, sieving equipment, and aspirators are a capital investment, and **turning** grain just to suppress insect populations is too expensive.

Market for cleanings variable. Grain cleaning has been widely adopted in some countries and might be more widely used in the United States if the market for the cleanings was less variable.

Implementation options

For several component parts of the impact and removal methods, a number of options are discussed for the implementation of these methods as part of a pest management program for stored-product insects.

Settings of the impact machine. Insect mortality and the number of damaged kernels generally increase as the rotor speed of an impact machine is increased from 25 to 65 m/sec and decrease as the throughput of the commodity is increased from 1 to 8 t/hr. The insects freed from the kernels by the **impact machine** can be sieved or aspi-

rated from the grain to minimize the number of insect fragments in flour. The equipment must be set to minimize the breakage of uninfested kernels by impact and the removal of product and uninfested kernels by **aspiration**. Several or larger impact machines can be used to ensure that they do not slow down the milling process. Double rotors also have been used to increase the throughput of a single impact machine.

Type of conveyor. Using pneumatic conveyors causes more insect mortality than using belt, drag, or screw conveyors. Insect mortality increases with the length of the pneumatic conveyor. This may be a concern when samples are being conveyed to the laboratory to determine the number of live insects in a grain sample.

Designing conveying systems so that they increase insect mortality without increasing the breakage of grain could be a cost-effective way to reduce insect infestation levels. Insect mortality is influenced by the impact velocity of the kernels, the type of surface against which the kernels impact, and the angle at which they impact. Starting with a population of 90 *Rhyzopertha dominica* for each of 10 replicates, increasing the impact velocity of the kernels from 9.6 to 20.4 m/sec increased the mortality of pupae from 54 to 93%, that of fourth instars from 36 to 89%, that of third instars from 30 to 87%, and that of second instars from 24 to 83%. At a velocity of 20.4 m/sec, the average mortalities for larvae in the last three instars and pupae decreased from 92% at a zero impact angle to 89% at a 30 or 45° impact angle and 72% at a 60° impact angle. At a velocity of 20.4 m/sec, the average mortalities were 88% when kernels hit a concrete surface, 87% against steel, and 85% against other wheat kernels. The impact surface was less important than the velocity or the angle of impact.

Type of sieving equipment and aspirator. Cleaning grain and sieving flour can be done with a shaker sieve, a rotating sieve, or a centrifugal sieve. A portable multipass **aspirator** also is available for cleaning grain. Farmers and small **elevators** have favored rotary sieves (see recommended reading by Noyes et al). These can be portable and can have more than one screen, and the angle of inclination and speed of rotation can be adjusted easily to optimize efficiency. The mesh size of the sieves must be large enough for the insects to drop through but must hold the commodity. The angle of inclination and the frequency and amplitude of oscillation of shaker sieves can be adjusted for optimal efficiency. The size of the sieving equipment or aspirator will depend on the needed throughput of the commodity. The airflow of the aspirator must be set to remove contaminants without removing more of the commodity than is necessary.

Utilization of impact and removal

Impact machines, **aspiration,** and sieving are routinely used for insect disinfestation in the grain cleaning house of a flour mill, and impact machines are used just before bagging flour. Grain cleaning is done commercially, but disposing of cleanings can be a problem. Cleaning by aspiration and sieving also is used for many other commodities, such as raisins and peanuts. Subsistence farmers in the tropics often separate infested from noninfested commodities by hand.

Impact during grain handling kills many insects, but its importance is often unrecognized. Removal of insects from commodities is effective only when the insects in the cleanings are killed or transported away before they can reinfest the cleaned commodity or infest commodity residues in the facility.

Study questions

1. How can impact and removal be used to suppress stored-product insect pest populations?
2. What are the advantages and disadvantages of using impact and removal to suppress stored-product insect pest populations, and how is each important in deciding whether to use impact or removal?
3. What are the advantages and disadvantages of each of the available implementation options for using impact and removal, and how is each important in deciding whether to use impact or removal?

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Chapter 16

Ionizing Radiation

Principles

Ionizing radiation sterilizes or kills insects by damaging cells and producing free radicals that break chemical bonds. Radiation sensitivity is directly related to cell reproductive activity and inversely related to the degree of cell differentiation. Within a developmental stage, the susceptibility of an insect to ionizing radiation varies greatly with age. The use of nonionizing radiation for stored-product insect pest management is discussed in Chapter 14.

Ionizing radiation that can be used for insect pest management includes gamma rays from cobalt-60 or cesium-137 isotopes, acceleration of electrons from a tungsten filament, and x-rays derived from accelerated electrons. The doses required to kill adult moths tended to be higher than those required to kill adult beetles (1.0 vs. 0.5 kilogray [kGy]). The least-susceptible species of beetles tolerate a six- to seven-times higher dose than the most-susceptible species. Bostrichids, tenebrionids, dermestids, and anobiids are the least susceptible, and bruchids, curculionids, and laemophloeids are the most susceptible. Sterilizing doses vary from 50 Gy for bruchids to 1 kGy for moths. Females are generally sterilized at a lower dose than males.

Advantages

Radiation is effective. Insect mortalities close to 100% and sterility of many species of stored-product insects are possible with ionizing radiation. Although irradiated insects can live for days or weeks, they tend to feed less and do not reproduce.

Operating cost is low. After a large capital investment, the cost per unit of commodity treated with ionizing radiation ranges from US$0.3–6.2/t. Also, irradiation can be done very quickly. Handling rates of 1–400 t/hr have been used in large-scale facilities.

Resistance is not a problem yet. Insect resistance to ionizing radiation may be slower to develop with wider use than resistance to other insect pest management methods. Laboratory studies have shown that neither beetles nor moths developed resistance after 25–30 generations of selection (see recommended reading by Tilton and Brower).

Ionizing radiation has other benefits. Currently, the primary use of food irradiation is to prevent sprouting in potatoes and onions and to reduce microbes in spices and meats.

Ionizing radiation is accepted. The clearance database of the International Consultative Group on Food Radiation (http://www.iaea.org/icgfi/) shows that the use of ionizing radiation for stored-product insect disinfestations is acceptable for one or more cereal grains in 23 countries, for cereal grain products in 16 countries, for legume seeds in 15 countries, for dried fruits in 20 countries, and for one or more of 17 other foods in 20 countries. Overall, the use of ionizing radiation for stored-product insect disinfestations is accepted for at least one food in 31 countries. Seventy facilities in 33 countries have been approved for irradiating food. Most of these facilities use cobalt-60 irradiators and only a few use accelerated electrons.

Although irradiation can alter baking quality, taste, and vitamins for irradiated flour or flour from irradiated wheat, this generally should not be an issue at the dose of 0.5 kGy that is needed for stored-product insect disinfestations. Exceptions might be the most radiation-sensitive vitamins, B_1, B_6, and E, which may be reduced 20–40% at 0.25–1 kGy. A joint committee convened by the FAO, WHO, and International Atomic Energy Agency (IAEA) evaluated the available data in 1980 and concluded that irradiation of any food commodity at an average dose of 10 kGy or less presents no toxicological hazard and requires no further testing.

Disadvantages

Ionizing radiation does not provide long-term protection. Irradiation does not provide long-term protection of commodities against reinfestation by stored-product insects, and other insect pest management methods may be needed to prevent reinfestation.

Mortality is delayed. Insects may live for days or weeks after being treated with ionizing radiation and will still be counted as live insects when found by inspectors.

Precautions are needed for worker safety. Ionizing radiation can be harmful to humans, and sources of radiation must be shielded. Because electron beams can be turned off during maintenance and loading of commodities, accelerated electrons may be safer to use than gamma rays.

Ionizing radiation kills seeds. Seeds are killed at the same doses that kill insects. Therefore, irradiation may not be appropriate for stored-product insect disinfestations of seeds that are to be used for planting or as malting barley.

Ionizing radiation requires a large investment. A cobalt-60, x-ray, or accelerated-electron irradiator facility can cost from 1 to 3 million dollars. Cobalt-60 has a half-life of 5.3 years, and 12% of the source should be replaced each year to maintain the original strength of the radiation. Ionizing radiation is therefore cost-effective for stored-product insect disinfestations only at facilities that handle millions of kilograms of commodities annually.

Moving grain is expensive. Irradiation needs to be done when grain is being received, blended, or shipped because moving grain for the purpose of irradiation is expensive.

Implementation options

For several component parts of the ionizing radiation method, a number of options are discussed for the implementation of this method as part of a pest management program for stored-product insects.

Equipment. Gamma rays and x-rays penetrate deeper (≥50 vs. 1.7–4 cm) into commodities than accelerated electrons, but electron accelerators can irradiate commodities at higher rates (≥10 kGy/sec vs. <10 Gy/sec). X-ray penetration is similar to that of gamma radiation from a cobalt-60 irradiator, but the conversion of accelerated electrons to x-rays is only 2% efficient at 1 million electronvolts (MeV) and 19% efficient at 10 MeV. At 5 MeV, which is the maximum permitted by the Codex Alimentarius Commission, the conversion of accelerated electrons to x-ray is only 4–6%.

Dose. The dose depends on the radiation-absorption characteristics of the commodity, the dose rate, and the duration of exposure. A dose of 0.5 kGy will kill even the most-resistant beetles and the immature stages of moths. Most adult moths will be sterile, and any offspring that are produced will be sterile.

Monitoring. Dosimeters should be placed at several locations in the commodity to be sure that the insects are exposed to an effective dose and that the dose remains within the legal limits. Inventory control is important because irradiated food looks like nonirradiated food. Several detection methods that have been developed for determining whether food has been irradiated can be used to monitor the marketing of irradiated food.

Integration

Nonionizing radiation. Stress on insects from nonionizing radiation such as infrared or microwave radiation is more effective in combination with ionizing radiation than either alone, and the combined treatment can cost less.

Impact. In radiation tests, moving grain with a pneumatic conveyor reduced *Cryptolestes ferrugineus*, *Rhyzopertha dominica*, and *Sitophilus oryzae* adult populations of 22–26 insects per kilogram by 99% and immature insect populations of 8–37 insects per kilogram by 82–96%. Moving grain with a pneumatic conveyor killed some of the insects that were not killed by the irradiation and vice versa.

Utilization of ionizing radiation

Ionizing radiation has been used commercially mainly to prevent sprouting in potatoes and onions and to reduce microbes in spices and meats. However, the use of ionizing radiation for insect disinfestations has been approved in many countries. The survival of insects for a long time after irradiation is a problem because regulations consider these insects to be just like other live insects.

Study questions

1. What is ionizing radiation, and how can it be used to suppress stored-product insect pest populations?
2. What are the advantages and disadvantages of using ionizing radiation to suppress stored-product insect pest populations, and how is each important in deciding whether to use ionizing radiation?
3. What are the advantages and disadvantages of each of the available implementation options for using ionizing radiation, and how is each important in deciding whether to use ionizing radiation?
4. What other insect pest management methods can be integrated with ionizing radiation to suppress stored-product insect pest populations, and why is each of the combinations better than a single method?

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Chapter 17

Residual Insecticides

Principles

Residual insecticides are applied either as a liquid or a dust to specific areas of a processing facility, storage structure, transportation vehicle, or stored commodity to suppress insect pest populations for a period of time ranging from months to a year or more. Residual insecticides also have been applied as a fog, mist, aerosol, or smoke to kill flying insects or exposed crawling insects, but these treatments are not very penetrating and generally do not reach insects in commodities, commodity residues, or the cracks and crevices where insects hide.

The use of natural insecticides and repellents against stored-product insects may date back nearly to the origin of agriculture, and subsistence farmers still use botanicals, vegetable oils, and inert dusts such as clays, ash, and minerals as protectants (see recommended reading by Panagiotakopulu et al). Natural products may be relatively cheaper, safer, and more readily available in the tropics than commercial synthetic residual insecticides (see recommended reading by Lale). Research is needed to identify the active ingredients of the plants used in pest management programs for stored-product insects, to investigate their mode of action, and to develop standardized extraction methods. For most natural insecticides, field research is rare, and studies are needed to improve application methods and to optimize the frequency of application. These plant products need to be made commercially available to farmers and grain merchants in a usable form.

Organophosphate insecticides, *Bacillus thuringiensis*, **spinosad**, **juvenile hormone**, and diatomaceous earth have been recommended for direct application on raw commodities as protectants against stored-product insects. Cereal grain and legume varieties are being developed that have insect-**resistant seed** with toxins such as those of *B. thuringiensis* or alpha-amylase digestive enzyme inhibitor. Organophosphates, **pyrethroids**, and **chlorinated hydrocarbons** have been recommended as empty-bin sprays.

Organophosphates, pyrethroids, chlorinated hydrocarbons, juvenile hormones, diatomaceous earth, and **carbamates** have been recommended for use as crack-and-crevice, spot, or general surface treatments in food-processing facilities. In such facilities, crack-and-crevice, general surface, and spot treatments must be done so that the residual insecticides do not contaminate food or surfaces with which food will come in contact. Most residual insecticides are not registered for use during plant operation. Spot treatments are directed at areas where insects are likely to be found, and these areas should not exceed 0.19 m^2 (2 ft^2). General surface treatments are applied to broad expanses of walls, floors, and overhead surfaces. **Dichlorvos** commonly has been used as a space treatment.

Sublethal effects of low dosages of residual insecticides may result in suppression of an insect pest population greater than that measured by insect mortality alone (Table 22.5). For example, with 50% insect mortality and 50% reduction in egg production, the overall suppression of insect population growth is 75%. Conversely, the release of

fertile eggs, which can develop into adults, by females dying from exposure to carbon dioxide, dichlorvos, or **malathion** reduces the overall level of suppression.

The use of insect repellents and antifeedants (see recommended reading by Nawrot and Harmatha) also has been investigated for the management of stored-product insect pests, but these generally have not been marketed for commercial use. The EPA and FDA have approved the repellent methyl salicylate as a package treatment. Registrations change and vary among countries, so it is important to consult EPA and FDA websites (see Chapter 1), similar agencies in other countries, and product labels for the most recent information.

Advantages

Residual insecticides are quick acting. Residual insecticides can suppress insect populations more quickly than aeration or natural enemies. Botanicals, vegetable oils, inert dusts, and **juvenile hormone** may kill fewer insects or may take longer to kill insects than the chlorinated hydrocarbon, pyrethroid, **carbamate**, and organophosphate insecticides and thus may not suppress insect pest populations as quickly.

Residual insecticides are persistent. At 20°C and 11% moisture, when the insecticide **chlorpyrifos-methyl** is applied to wheat at 6 ppm, it will be above the effective dose for *Sitophilus oryzae* (1.65 ppm) for more than 10 months (see recommended reading by Arthur et al). However, at 35°C and 14% moisture, this insecticide will be above the effective dose for less than two months. Increasing moisture from 11 to 14% shortened the effective life of chlorpyrifos-methyl 1.5-fold, while increasing temperature from 20 to 35°C shortened its effective life three- to fourfold. **Malathion** is less persistent than chlorpyrifos-methyl, and many natural plant products are less persistent than malathion.

Residual insecticides are broad-spectrum. The insect species against which a residual insecticide is effective must be listed on the label, and the list is often quite long. However, many insect species have become resistant to residual insecticides, and mixtures of two or more residual insecticides have been used to overcome the resistance problem.

Residual insecticides have low mammalian toxicity. Only residual insecticides with low mammalian toxicity can be registered for use on stored products. The oral toxicity LD_{50} (i.e., the lethal dose for 50% of the population) for rats is 80 mg/kg for dichlorovos, 88–125 for **lindane**, 900 for **cyfluthrin**, 1,500 for **synergized** pyrethins, 1,000–3,700 for chlorpyrifos-methyl, >5,000 for diatomaceous earth, 6,000 for **methoxychlor,** and >34,600 for **methoprene**.

Residual insecticides are inexpensive. Organophosphate insecticides generally cost only US$0.1–0.8/t of commodity. Insect growth regulators cost three to four times more. Treating empty bins costs US$0.0003–0.005/t of storage capacity. The labor costs more than the chemicals when residual insecticides are used for crack-and-crevice, surface, or spot applications.

Residual insecticides are easy to apply. Residual insecticides can be applied with little training and simple, inexpensive equipment. However, the effective use of residual insecticides depends upon careful and accurate calibration of the application equipment so that the correct dose is applied. This calibration may require bioassay or residue analysis to confirm that the application rate is correct. When insect-resistant

seed becomes commercially available, stored-product insect pests may be managed even more easily by selecting the most-appropriate resistant variety for planting.

Disadvantages

Residual insecticides are used preventively. For raw commodities, the decision to use a residual insecticide as a protectant often needs to be made before a manager knows whether the insect population will reach an unacceptable level. Residual insecticides need to be applied when a commodity is received because moving the commodity to apply the residual insecticide later is too expensive.

Residual insecticides break down. The rate of residual insecticide breakdown after the application to surfaces or commodities increases as temperature and moisture increase. Poor storage conditions, dockage in grain, and dust on treated surfaces may reduce the effectiveness of residual insecticides. Some residual insecticides break down faster on alkaline surfaces such as concrete.

Residual insecticides leave residues. Laws prescribe maximum residue tolerances for residual insecticides, and food can be seized when residues exceed the established tolerances. The residue tolerances for residual insecticide on raw commodities are higher than those on processed foods. For example, the residue tolerance for **chlorpyrifos-methyl** is 6 ppm on whole wheat and 2 ppm in flour. International residue tolerances have been developed for many residual insecticides. Insecticide residues on commodities may prohibit their importation into some countries.

Residual insecticides are poisons. Many residual insecticides are neurotoxins and must be used safely. Inhalation of inert dusts can cause health problems. Botanicals, vegetable oils, and **juvenile hormones** are considered relatively safer for mammals.

Residual insecticides may kill natural enemies. **Natural enemies** often are more susceptible to residual insecticides than pest insects are, and these insecticides also kill their host or prey, depleting their food supply. Even some of the residual insecticides that can be used more safely because of their low mammalian toxicity (such as diatomaceous earth and vegetable oils) may still kill insect parasitoids and predators.

Registration costs are high. In the United States, the time from the discovery of a residual insecticide to its registration as a new **carbamate**, **chlorinated hydrocarbon**, **organophosphate**, or **pyrethroid** insecticide may be 8–12 years, with an estimated cost of US$40–80 million (see recommended reading by Arthur). Residual insecticides with low mammalian toxicity, such as **juvenile hormones**, and those that are environmentally benign, such as **spinosad**, can be commercialized in less than eight years, with an estimated cost of US$2–3 million. Although the seed varieties developed in traditional breeding programs are not regulated, transgenic insect-**resistant seed** must be shown to be safe. Regulatory approval for transgenic seed may require three to five years and cost millions of dollars.

Resistance is a problem. Resistance to many residual insecticides is widespread. Insects that have become resistant to one residual insecticide can often more easily develop resistance to another residual insecticide with the same mode of action. The higher doses needed to kill these resistant insects cannot be used because they will cause residues to exceed the maximum legal tolerances.

Residual insecticides have other problems. **Juvenile hormones** extend the period of larval feeding, and additional feeding may increase the damage to stored com-

modities caused by insects. Some inert dusts are abrasive to milling equipment. Inert dusts reduce the flowability of grain and alter **test weight**. Also, some residual insecticides may be less effective because they repel insects.

Implementation options

For several component parts of the residual insecticide method, a number of options are discussed for the implementation of this method as part of a pest management program for stored-product insects.

Choosing a residual insecticide. Differences in the effectiveness of residual insecticides against different stages and species of insect pests, their persistence, tolerances for their residues, and their cost should be considered in selecting a registered residual insecticide. For example, **chlorpyrifos-methyl** kills many species of beetles but is less effective against *Rhyzopertha dominica*. Also, each residual insecticide is registered for certain commodities or applications. Chlorpyrifos-methyl was registered for use on barley, oats, rice, wheat, and sorghum, and **pirimiphos-methyl** is currently registered in the United States for use on maize, popcorn, and sorghum. **Cyfluthrin** is registered for use as a crack-and-crevice, surface, and spot treatment in food storage or processing facilities and as an empty-bin spray, but it is not registered for use on commodities as a protectant in the United States.

Mixture. Combinations of more than one residual insecticide have been used to deal with differences in the susceptibility of different insect species. **Organophosphates** have been combined with **pyrethroids, methoprene**, or other organophosphates to increase their effectiveness.

Dosage. Recommendations for each formulation and use are based on insect susceptibility and the maximum residue tolerance. Even with the best calibration and application methods, the actual amount of residual insecticide deposited on the commodity may be less than 70–80% of the calculated rate. Residual insecticides are typically applied at rates of 1–6 ppm. Vegetable oils are applied at 10 ml/kg, and botanicals are applied at 200–300 g/kg.

Formulation. Residual insecticides are often sold as emulsifiable concentrates, suspended concentrates (flowables) with insecticide particles already suspended in a liquid, and wettable or soluble powders. They generally have 20–80% active ingredients and are diluted with water to 1 or 2% before application. Wettable powders and suspended concentrates are better than emulsifiable concentrates on brick, concrete, timber, or sacking because the carrier with the residual insecticides remains on the surface. However, wettable powders can block the sprayer nozzle, settle out of the suspension, and leave a noticeable white powder on dark surfaces. Concrete can be painted with silicone paint to prevent its alkaline pH from hydrolyzing a residual insecticide. Oil (rather than water) formulations, need to be used around electrical wires, junction boxes, or outlets.

Application method. Liquids are more economical and cleaner than dusts, and their application can be controlled better. Wheat flour, clay, talc, boric acid, and silicone dioxide are used as carriers in dust formulations. Dusts can be applied as slurry for cleaner applications. However, inert dusts are less effective when applied as slurry. Residual insecticides can be applied to grain as a spray or drip as it is moved with an auger or on a **belt conveyor**. Aeration fans have been used to apply inert dusts to empty bins. In food storage and processing facilities, crack-and-crevice, surface, and

spot applications of residual insecticide are used. Residual insecticides dissolved or suspended in odorless kerosene or heavier technical white oil solvent can be applied as an aerosol, mist, or fog. These space treatments are not penetrating like fumigants, and they mainly kill flying insects and those on the surface of the commodity or other surfaces.

Treating part of the commodity. Only the surface can be treated by applying residual insecticide to the last grain that is put into a bin or by top dressing with residual insecticide and raking it into the grain. Inert dust can be applied at a rate of 1.8 kg/92.9 m^2 (4 lb/1,000 ft^2) of grain to the last grain put into a bin so that only the top 30–61 cm (1–2 ft) is treated because a large portion of the insect infestation will be in this grain. Likewise, 1.8 kg (4 lb) of Dipel (*Bacillus thuringensis*) can be applied as a top dressing to the top 10 cm (4 in.) of each 46.5 m^2 (500 ft^2) of grain to kill the larvae of stored-product moths, which generally infest only this part of the grain.

The application method may result in only part of the grain being treated with a residual insecticide. Dripping or spraying **malathion** on the grain as it is augered into a bin is likely to be effective even if the grain is not treated uniformly (see recommended reading by Minett). Malathion was shown to be effective against *Rhyzopertha dominica*, *Sitophilus oryzae*, and *Tribolium confusum* when 1% of the grain was treated with the full recommended dose.

Finally, protecting some grain with a residual insecticide may be more cost-effective than treating other grain. Subsistence farmers may treat only the grain that will be stored for a long time or will be traded and not the grain that is stored for only a short time for their own use. For 300-kg (662-lb) traditional mud storage bins in Ghana, treating only the bottom 25 cm (63.5 in.) and the top 10 cm (25.4 in.) of grain, and withdrawing first the grain from between these two layers through a side port, provided good protection against *R. dominica* and *Prostephanus truncatus*, reducing their populations by 97–98% (see recommended reading by Hodges et al). However, the reductions for the more-mobile *Sitophilus* spp. and *Tribolium castaneum* were only 12 and 22%, respectively.

Integration

Aeration. Computer simulations have shown that cooling grain by aeration when using residual insecticides as protectants can improve insect pest suppression. Cooling slows both the insect population growth rate and the rate at which the residual insecticide degrades and loses its effectiveness. Using residual insecticides and aeration together also can increase the effectiveness of some **pyrethroids** and **chlorinated hydrocarbons** because they become more effective as the temperature decreases.

Oil. When **pirimiphos-methyl** is applied to maize in 1 ml of coconut, peanut, or soybean oil per kilogram of grain, 82–85% *Sitophilus zeamais* mortality can be achieved with 1/16th of the recommended dose (see recommended reading by Obeng-Ofori and Amiteye). Only half the recommended dose of pirimiphos-methyl in 10 ml of peanut, rapeseed, or sunflower oil per kilogram of grain killed 90–100% of the *S. granarius* infesting wheat. The oil may distribute the residual insecticide more evenly, and insects may pick up the residual insecticide more readily when it is combined with these vegetable oils. Treatments were effective for up to 60 and 90 days, respectively, in these two studies. Although treatment of grain with peanut, rapeseed, or sunflower

oil reduced seed viability and water adsorption, particle size after milling was unaffected. The insecticide-oil mixtures may be particularly important where residual insecticides are expensive and in short supply.

Pheromone. Treating a small area with a combination of a residual insecticide and an attractant may be as effective as treating a large area (see recommended reading by Nansen and Phillips). At a density of one pair of *Plodia interpunctella* per 11.3 m^3 (39.9 ft^3), a combination of sex **pheromone** and 6% **permethrin** reduced the moth population by 75%, but this attracticide was less effective at higher insect densities. Sex pheromones that attract males may be less effective than those that attract females. Killing females can prevent their reproduction, but because males mate more than once, killing males may only delay mating and reproduction by the females. Lures that attract both sexes may be the most effective. For some stored-product insect species, water, food odors, and aggregation pheromones attract both sexes, but these attractants generally are less effective than sex pheromones.

Utilization of residual insecticides

Residual insecticides are inexpensive, broad-spectrum, and easy to use. They provide long-term protection and are widely used directly on raw commodities and in storage and processing facilities. The law requires that residual insecticides be used according to label instructions. Residual insecticides are often used to prevent insect problems, and many insect species have become resistant. The best ways to slow the development of resistance include using residual insecticides only when absolutely needed, using them correctly, and using them in combination with other pest management methods that have different modes of action. An insect pest management method with a different mode of action should kill the insects that have become resistant to a residual insecticide.

Study questions

1. What are residual insecticides, and how can they be used to suppress stored-product insect pest populations?
2. What are the advantages and disadvantages of using residual insecticides to suppress stored-product insect pest populations, and how is each important in deciding whether to use residual insecticides?
3. What are the advantages and disadvantages of each of the available implementation options for using residual insecticides, and how is each important in deciding whether to use residual insecticides?
4. What other insect pest management methods can be integrated with residual insecticides to suppress stored-product insect pest populations, and why is each of the combinations better than a single method?

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Chapter 18

Fumigants and Modified Atmospheres

Principles

Fumigants are toxic gases that penetrate into commodities. Maintaining an adequate concentration of a fumigant for sufficient time kills most insect species. Modifying the oxygen or carbon dioxide levels in air and maintaining these modified atmospheres for sufficient time also can kill insects. Hermetic sealing of storage structures so that oxygen is depleted and the carbon dioxide is increased by the respiration of microorganisms, seeds, and insects has been used for at least 2,500 years.

Popular liquid fumigants such as **carbon disulfide** and **ethylene dibromide** are no longer registered for general use in the United States, and **methyl bromide** is scheduled to be phased out by the year 2005 because of its ozone-depleting properties. **Phosphine** is currently the most widely used fumigant for stored commodities. **Sulfuryl fluoride** (sold commercially as ProFume) has recently been registered for postharvest use. The toxicities of 11 fumigants are compared in Table 22.3. *Sitophilus granarius* is more resistant to **carbon tetrachloride**, **chloropicrin**, ethylene dichloride, and **hydrogen cyanide**, while *Tribolium confusum* is more resistant to **carbon disulfide**, ethylene oxide, methyl bromide, and sulfuryl fluoride.

Modified atmospheres (<1% oxygen or >35% carbon dioxide) act more slowly than methyl bromide or sulfuryl fluoride but as fast as phosphine. Modified atmospheres are more expensive to use than other fumigants. Sublethal effects of low dosages of fumigants and modified atmospheres also may be important in managing stored-product insect pests (Table 22.5).

Advantages

Fumigants can be used responsively. Most of the pest management methods that are used for stored-product insects are preventive. Because fumigants work quickly and are effective against most insect species, they can be used in response to discovering an insect problem. Fumigations are sometimes done on a calendar schedule but can be used only when a sampling program indicates that the insect pest population is likely to reach an unacceptable level.

Fumigants are penetrating. Fumigants are volatile gases that can penetrate into bulk commodities by diffusion. However, diffusion is slow, and the natural air currents within a commodity may be important in distributing the fumigant. Fans and ducts have been used to recirculate fumigant to distribute it more evenly. Fumigants that are heavier than air tend to move down into the commodity by gravity. Carbon dioxide is heavier than air and is sometimes mixed with fumigants to help distribute them. **Sorption** into commodity can reduce the fumigant concentration in the air. Phosphine concentration in air may be reduced 20% per day by sorption. The volatility of fumigants makes it difficult to hold the required dose for sufficient time to kill insects in structures that are not sealed sufficiently.

Fumigants leave little residue. Because of the volatility of fumigants, their residues on commodities are generally less problematic than those of residual insec-

ticides. However, because of the sorption of fumigants by commodities and the odor of fumigants, aeration is needed after fumigation to reduce the fumigant concentration to acceptable levels in a commodity, storage structure, or building.

Fumigants are inexpensive. While the fumigant needed for a ton of grain costs only US$0.3–0.4, labor costs for applying the fumigant, sealing a structure, and aerating to remove the fumigant increase the cost. These labor costs and the cost of electricity when grain needs to be moved to apply the fumigant increase the overall cost of a fumigation to US$0.9–1.1/t of grain. Moving grain results in shrinkage and damage that typically average an additional US$0.28/t of grain.

Fumigant application is simple. Applying fumigants can be as simple as opening the valves of high-pressure cylinders, dropping pellets into moving grain, or probing them into bulk grain. Automatic dispensers are available for adding pellets to moving grain. Calculating the appropriate dose can be more difficult. Also, heaters may be needed in the line supplying methyl bromide to the area being fumigated to ensure its evaporation, and fans may be needed to distribute this fumigant so that sorption into the commodities is not excessively high at the place where fumigant enters.

Disadvantages

Fumigants do not provide long-term protection. Commodities are unprotected after the volatile fumigant is cleared, and the fumigated commodities can be reinfested by stored-product insects.

Fumigants must be used carefully. Fumigants and modified atmospheres need to be used with care because both can be lethal to humans. Also, phosphine is corrosive to copper, silver, and gold. It can be highly flammable or even explosive at 1.79% in air (17,900 ppm). Recently, 2% phosphine has been marketed in a cylinder with 98% carbon dioxide (ECO_2Fume) to reduce the flammability and to apply it as a gas rather than a solid. Mixtures of liquid fumigants such as **carbon tetrachloride** and **carbon disulfide** (80:20) were used to reduce flammability.

Compliance with safety regulations can be expensive. Before aluminum or magnesium phosphide can be applied, users in the United States are now required to prepare a comprehensive fumigation management plan for the site (see recommended reading by Walter). Fumigant and modified-atmosphere concentrations need to be monitored; respirators may need to be used; and applicators must be sure that the fumigant does not leak into adjacent structures. Structures being fumigated and those with modified atmospheres need to have placards indicating that they are unsafe to enter.

Fumigants work better at warm temperatures. The effectiveness of fumigants generally increases as insect metabolic rates increase with temperature. Phosphine is not released from pellets below 4.5°C (40.1°F), and methyl bromide must be above 3.6°C (38.5°F) to reach its boiling point. Phosphine fumigations at temperatures below 15°C (59°F) are less likely to be effective because of the slower release of phosphine gas from the pellets, greater sorption of the phosphine by the commodity, lower insect susceptibility to phosphine, and slower development of insects from the more-phosphine-resistant egg or pupal stages to the more-phosphine-susceptible larval and adult stages.

Resistance is becoming a problem. With adequate sealing, fumigant concentration, and exposure time, even the insects with resistance genes can be killed. However, insect resistance to phosphine has developed at an alarming rate because this fumigant

is often used without adequate sealing and the required dose is not maintained long enough to kill the insects. Exposure times long enough for insects to develop from the more-phosphine-resistant egg or pupal stages into the more-phosphine-susceptible larval and adult stages can improve the effectiveness of fumigation (see recommended reading by Hole et al). However, such long exposure times may be impractical.

Implementation options

For several component parts of the fumigation method, a number of options are discussed for the implementation of this method as part of a pest management program for stored-product insects.

Fumigant. In the United States in recent years, **phosphine** and methyl bromide have been the primary fumigants available for stored-product insect management. **Sulfuryl fluoride** has been registered only recently for postharvest use. The liquid fumigant **chloropicrin** can be used for empty bins. The use of low oxygen or high carbon dioxide has been limited by the high cost, the better sealing that is required, and the long exposure time required for killing insects. When fumigating, it is important that the fumigant does not damage the product. Methyl bromide is phytotoxic and can reduce the germination of some seeds. Phosphine can darken some fruits or vegetables, reducing their market value. Internationally, carbonyl sulfide, cyanogen, ethyl formate, methyl isothiocyanate, **methyl iodide**, and propylene oxide are being considered for postharvest use. Odor can be a problem for carbonyl sulfide; cyanogen is phytotoxic and reduces the germination of seeds; ethyl formate is explosive, flammable, and corrosive to metals; methyl isothiocyanate is highly sorbed by grain; methyl iodide is as effective against insects as methyl bromide but is more expensive to synthesize; and propylene oxide is flammable but can be used near foods because it is detoxified in the stomachs of vertebrates.

Dosage. The recommended dosage of a fumigant is given as the product of concentration × time. High doses of fumigant generally can be used for a shorter time than low doses. However, high doses of phosphine and low doses of **hydrogen cyanide** can cause **narcosis** in insects and reduce insect susceptibility. **Sorption** of a fumigant by a commodity may increase the dosage necessary for killing insects. Sorption is inversely proportional to temperature, so more fumigant sorbs into cold product. The dose of phosphine used for wheat in the state of Kansas is 11–13 pellets/t (300–360 pellets per 1,000 bushels) of grain storage capacity. Each pellet releases 0.2 g of phosphine, and the permitted application rates range from 750 to 3,600 ppm (1–5 mg/L). The dose is based on the total volume of the storage structure being fumigated and not on the volume of grain that is stored.

In 64 published studies, for all of the insect species studied except *Trogoderma* spp., the relationship between phosphine concentration and the exposure time required for 100% mortality of all susceptible individuals is hyperbolic and not linear, i.e., 10,000 ppm (13.9 mg/L) for 1.5 days, 1,200 ppm (1.67 mg/L) for two days, 1,000 ppm (1.39 mg/L) for eight days, 200 ppm (0.28 mg/L) for 10 days, 35 ppm (0.049 mg/L) for 20 days, and 10 ppm (0.014 mg/L) for 30 days (see recommended reading by Annis). A method called Siroflo was developed in Australia to maintain a low dose of phosphine for a long time. Phosphine (2%) mixed with carbon dioxide or nitrogen (98%) is gradually added from cylinders to replace the phosphine that escapes.

The effectiveness of modified atmospheres varies with temperature, insect species, and developmental stage. For modified atmospheres, the exposure times required for 95% mortality are longer at 14–17°C (5–28 days) than at 20–29°C (1–16 days). Also, the exposure times for internal-feeding insect species such as *Rhyzopertha dominica* and *Sitophilus oryzae* tend to be longer than those for external-feeding species such as *Cadra cautella*, *Oryzaephilus surinamensis*, *Tribolium castaneum*, and *Trogoderma glabrum*.

Formulation. Liquid fumigants are packaged in sealed cans, and methyl bromide is packaged in high-pressure cylinders. Phosphine can be purchased in high-pressure cylinders and in sealed cans or pouches as pellets, tablets, ropes, blankets, or sachets. Phosphine that is sold in sealed cans or pouches is released by reacting with atmospheric moisture, leaving a claylike dust. Manufacturers recommend disposing of this dust by stirring in water.

Air with low oxygen concentration can be generated at a site by specially designed equipment, and nitrogen or carbon dioxide can be delivered by tanker truck. Gases can be purchased in high-pressure cylinders for treatments in small chambers. The treatment time for high carbon dioxide can be substantially reduced using specially designed high-pressure chambers. Dry ice can be used as a source of carbon dioxide and has the advantage of releasing this gas over time. The effectiveness of carbon dioxide is reduced less than that of a low-oxygen atmosphere by dilution with the outside air resulting from insufficient sealing.

Sealing. The cost of sealing new structures is not as high as that for retro-sealing older structures (see recommended reading by Newman). Pressure relief valves are needed to allow well-sealed storages to adjust to changes in the internal pressure due to daily temperature changes, changing barometric pressure, the effects of wind, and air displacement during the filling and emptying of the storage. Small cracks can be sealed using silicone caulking, acrylic-based paints, polyurethane foam, or gaskets. These materials have largely replaced bitumen and butyl mastics. Large openings such as bin hatches, vents, aeration ducts, and spouts generally are sealed temporarily by taping gas-proof sheeting over them.

Stacks of bagged grain may be covered with gas-proof sheeting using sand- or water-filled bags 10 cm (4 in.) in diameter to hold the sheeting in place. Heavier, plastic-coated nylon fabric may be used outdoors because it is less likely to be torn by the wind than polyethylene sheeting. Gas-proof sheeting may be needed under the stacks of bags when the floor is porous, allowing fumigant to leak out. Gas-proof sheets and sand bags may also be used to cover the surface of grain in bins.

Storage structures can be tested for gas-tightness by using a blower to raise the internal pressure. With a pressure drop from 500 to 250 Pa in 5 min, sealing is satisfactory. Smoke generators can be used to find the leaks in a structure. Leakage may be greater on a windy day.

Application method. Liquid fumigants can be applied from outside the bin by using a hand pump or by opening and inverting cans so that the opening is 15 cm (6 in.) below the grain surface. High-pressure gas cylinders are opened in a large structure, or fumigant is piped into a smaller structure. After the initial purge of the commodity with a fumigant, more fumigant can be added to replace that lost as a result of leakage. In the United States, solid formulations of phosphine may be placed on the surface or probed into grain. However, the laws in some countries prohibit contact between the phosphine carrier and the grain and require recovery of the carrier after fumigation.

Small fans can be used in storage or processing structures (or on ships during transit) to more evenly distribute the fumigant and improve efficacy. Closed-loop fumigation eliminates the expense incurred when grain stored at an elevator in a concrete bin is turned from one bin to another while fumigant is added (see recommended reading by Noyes and Kenkel). The closed-loop fumigation method also may encourage managers to fumigate individual bins when fumigation is most needed instead of fumigating all bins when the manager has time to move all the grain at an elevator for the purpose of blending. After an initial capital investment in the recirculation fan and pipes, and their installation, the operating costs for closed-loop fumigation are very low. An equation is available for calculating the recirculation rate required to adequately distribute carbon dioxide in a grain bin (see recommended reading by Navarro et al). An in-transit agreement with the buyer may be needed when commodities are to be fumigated while being transported.

Vacuum chambers were developed to increase the rate of penetration of a fumigant into a commodity and to reduce the time required (1.5–4 hr instead of 12–24 hr) for fumigation with hydrogen cyanide. Vacuum fumigation has been used extensively in quarantine programs. Vacuum chambers have more recently been used with methyl bromide but cannot be used with phosphine because it is unstable at reduced pressure.

Monitoring. Colorimetric systems, halide detectors, thermal conductivity instruments, and infrared detectors are available for monitoring the concentrations of fumigants inside and outside commodities and structures to ensure worker safety and the efficacy of insect suppression. Colorimetric systems and thermal conductivity instruments are used to monitor oxygen and carbon dioxide concentrations.

Aeration or recapture. The rate at which a fumigant is removed from bulk commodities and facilities by aeration may need to be adjusted to keep from exceeding allowable concentrations in the surrounding air. Technology can be developed so that fumigants such as methyl bromide can be recaptured using activated carbon or zeolite (hydrated silicate of calcium or aluminum), absorbed onto liquids using alkali or organic amines, or condensed. Activated carbon absorbs 30% by weight; zeolite, 95%; and a combination of absorption by carbon and condensation by refrigeration, 98%. Fumigants can be reused by heating the absorbents to release them, or they can be destroyed by combustion, ozone, or catalytic destruction. However, if recapture of fumigants is necessary, this may make fumigation more expensive than alternative pest management methods for stored-product insects.

Integration

Aeration. Because fumigants are volatile and provide no protection against reinvasion by insects after the fumigant has escaped, aerating to cool grain after fumigation can be very effective in preventing further insect problems.

Packaging. Insect-resistant packaging also can provide the long-term protection that is not provided by the fumigant. Fumigants reduce the number of insects and thus reduce the number of insects entering packages.

Stress. Lower phosphine fumigant concentrations (65–100 ppm) can be used effectively when insects are stressed by heat (32–37°C) and carbon dioxide (4–6%), which increase insect respiratory rate. Lower phosphine concentrations should reduce the overall cost of fumigation, the fumigant residues on commodities, and possibly the corrosion of metals by the fumigant.

Impact. The pupal stage is most susceptible to impact and least susceptible to fumigants. Impact will kill some of the insects not killed by fumigation and vice versa.

Utilization of fumigants and modified atmospheres

Like residual insecticides, fumigants are inexpensive, are widely used commercially, and must be used according to label instructions. Modified atmospheres have not been used commercially as widely as fumigants have. Unlike residual insecticides, fumigants penetrate into the commodities, generally leave little residue after aeration, and provide no long-term protection. Resistance to fumigants has been slow to develop because the recommended dosages and exposure times generally have killed all of the insects. However, phosphine, the fumigant that currently is most widely used, must be held for longer times than the previously used fumigants, and insufficient sealing has resulted in the development of resistance by insects.

Study questions

1. What are fumigants and modified atmospheres, and how can they be used to suppress stored-product insect pest populations?
2. What are the advantages and disadvantages of using fumigation and modified atmospheres to suppress stored-product insect pest populations, and how is each important in deciding whether to use fumigation or a modified atmosphere?
3. What are the advantages and disadvantages of each of the available implementation options for using fumigation or modified atmospheres, and how is each important in deciding whether to use fumigation or a modified atmosphere?
4. What other insect pest management methods can be integrated with fumigation or modified atmospheres to suppress stored-product insect pest populations, and why is each of the combinations better than a single method?

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Chapter 19

Conclusions

The first chapter provided an overview of the relative importance of different stored-product insect species and the types of economic losses that can be attributed to them in different parts of the marketing system. Each of the chapters that follow builds upon this information.

Alphitobius diaperinus or *Alphitobius* spp., *Cadra cautella*, *Lasioderma serricorne*, *Oryzaephilus surinamensis, Plodia interpunctella, Rhyzopertha dominica*, and *Tribolium castaneum* have been shown by 12 studies to have a broad host and geographical range (see Chapter 1). *Ahasverus advena*, *Lasioderma serricorne*, *Oryzaephilus surinamensis, Plodia interpunctella, Rhyzopertha dominica*, *Tribolium castaneum,* and *Typhaea stercorea* have been found to be part of the residual insect populations in storage, processing, and retail facilities and in transportation vehicles (see Chapter 4). *Cadra cautella* has been found to be part of the residual insect infestation in storage and processing facilities and transportation vehicles but not in retail stores. Most of these insect species are rapidly capable of causing extensive damage, but *Alphitobius diaperinus*, *Ahasverus advena*, and *Typhaea stercorea* are not capable of significantly damaging stored commodities. These three insect species cause economic losses mainly as contaminants of stored commodities. *Lasioderma serricorne* can cause significant damage to stored commodities. The host ranges of *L. serricorne*, *P. interpunctella*, and *T. castaneum* are given in Table 1.2. Insect species such as *Callosobruchus maculatus*, *Prostephanus truncatus*, *Sitophilus zeamais*, and *Trogoderma granarium* also are rapidly capable of causing extensive damage, but they have narrower host and geographical ranges.

The recent spread of three species of stored-product insect pests and one species of predator has been documented by published studies—in more detail than the studies listed in Table 1.3 have documented the spread of other species of stored-product insects by commerce. *Prostephanus truncatus* was introduced into Tanzania in the late 1970s and Togo in the early 1980s and, since its introduction, has spread to 14 other African countries (see Chapter 1). A predator of this species, *Teretrius nigrescens*, was introduced in 1991 in Togo and has established and spread. The predator was later released in Benin, Ghana, Kenya, Malawi, and Zambia.

Trogoderma granarium was introduced in California before 1946 and spread to 16 counties in California, five in Arizona, and three in New Mexico before being discovered in 1953 (see Chapter 1). By 1966, it had been eradicated in the United States. However, 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.

Before 1900, *Cynaeus angustus* was found breeding in decomposing plant material in the southwestern United States (see Chapter 3). From 1900 to the early 1970s, it spread across the United States and became a pest of several cereal grains. In 1964, it was intercepted in a shipment of tobacco from Georgia to Dublin, Ireland. These examples of the spread of stored-product insects illustrate the importance of area-wide insect pest management programs for stored-product insects.

The cost of the weight loss caused by stored-product insects has been better quantified in the published literature than the reductions in market value caused by insect contamination and the cost of pest management programs for stored-product insects. However, these economic losses from weight loss may be much smaller than those from reduced market value and the expenditures on pest management programs for stored-product insects.

Ecology, sampling, cost-benefit analysis, and pest management programs for stored-product insects are likely to be unique for each location in the marketing system and for each time that stored-product insect pests are managed. Current information on stored-product insects and their environment is generally needed to maximize the cost-effectiveness of programs for their management. Using current information about stored-product insect pests and their environment to make insect pest management decisions will move stored-product entomologists away from the spray and count approach advocated during the industrial age toward information-based insect pest management programs more appropriate for the information age. Examining business practices to be sure that they favor effective insect pest management programs as much as possible may result in cost-effective ways to improve these programs.

Correct identification of insects is very important because the effectiveness of insect pest management methods differs among species. Also, knowing which insect species are present allows the published information about those species to be used to design and implement a study, a sampling program, or an insect pest management program. The second chapter introduced entomological techniques that will become increasingly important as greater emphasis is given to using residual insecticides and fumigants more effectively and integrating residual insecticides and fumigants with other insect pest management methods to better manage insect resistance to pest management methods.

Insect pest management is applied insect ecology. Chapters 3–5 emphasized the spatial aspects of stored-product insect ecology and Chapters 6 and 7 emphasized the temporal aspects. Because of the complexity of insect ecology, computer simulation models can be useful in fully employing the information about both the spatial and the temporal aspects of this ecology to develop and implement the most cost-effective sampling and pest management programs for stored-product insects.

The mobility of stored-product insects makes excluding them from a facility and from bulk or packaged commodities difficult. Once they enter, their mobility, longevity, and ability to survive and reproduce on small amounts of many different types of foods make them hard to manage. Some insects in inaccessible areas of bins, warehouses, food-processing facilities, transportation vehicles, and retail stores may not be killed by an insect pest management method. Their mobility results in the surviving insects quickly reinfesting the areas in which an insect pest management method was successful. The observed spatial distribution pattern of insect populations is a result of their moving to find essential resources.

Conversely, insect mobility also can facilitate insect pest management by increasing the effectiveness of residual insecticides and traps. Knowledge of stored-product insect mobility can be used to improve insect pest management in at least three ways. First, knowledge of insect mobility can be used to predict insect spatial distribution. Second, it can be used to convert trap catch to absolute estimates of insect population density. Third, it can be used to manipulate insect spatial distribution so as to improve insect pest suppression. Many environmental factors influence insect movement; an insect's

physiological state is important in determining its response to these environmental factors; and insects respond to combinations of environmental factors rather than to individual environmental factors. Given this complexity, fully utilizing this information in a stored-product insect pest management program is not easy.

Knowing the sources of an insect infestation is important in making insect pest management decisions. When grain is infested in the field, a program that prevents infestation before harvest may be the most effective way to manage stored-product insect pests. Growing a variety of maize that has a tight husk can reduce insect infestation before harvest and insect infestation of unhusked maize during storage. In some cases, there may be more than one source population. Infested commodities can be the most important source because they can produce the largest number of insects. When stored commodities are not infested, then insects from commodity residues become the primary source of new insect infestations. Limited insect population growth on wild hosts may make this the least significant source of infestation in most cases. Some of the insects entering a facility from outside may be insects that have previously left that facility and are reentering, or they may be insects breeding on commodities spilled outside.

Locating and eliminating source populations can be one of the least-expensive and most-productive components of an insect pest management program. Exclusion, inspection of incoming commodities for insects, rotation of stock, and sanitation are important methods of minimizing the number and size of source populations. Storage, processing, and marketing facilities and transportation vehicles can be designed to make excluding, finding, and removing source populations easier.

Knowledge of how environmental factors influence the life histories of stored-product insects should allow the manager to consider the variation in life histories among locations within bulk commodities, among locations in a facility, among geographical locations, and over time when planning a study, a sampling program, or a pest management program for stored-product insects. A large number of interactions among environmental factors (temperature, moisture, diet, natural enemies, handling. and processing) and the components of insect life histories (developmental time, mortality, egg production, longevity, and diapause) often need to be considered when developing and implementing a pest management program.

While information on insect mobility and life histories has been used to develop spatiotemporal computer simulation **models** for stored raw commodities (see Chapter 7), similar models have not been developed for processed commodities. The processing, storage, transportation, and retail habitats in which processed commodities are found often may be structurally more complex than the habitats in which raw commodities are found. A modular approach may be needed to develop predictive models for these parts of the marketing system. The study of the movement of *Tribolium castaneum* among patches of residual commodities and its reproduction in these commodity residues (see Chapter 3) is a simple example of the type of information needed for each modular part of the marketing system. Developing data for the commonly found modules (such a floor area with a pallet, with a piece of equipment, or with retail store shelving) would allow these modules to be incorporated into a computer simulation model in such a way as to predict the activities of the insects in a facility over space and time. Estimates of the rate at which insects leave a module would provide estimates of the rate at which insects enter adjacent modules.

In making an insect pest management decision, a manager's objective is to classify a stored-product insect population as being above or below an insect density threshold

at which insect pest suppression is required. Taking too many sample units wastes money, while too few or unrepresentative sample units can result in incorrect pest management decisions and in economic losses. Fewer sample units generally are required to classify an insect population than to estimate the actual insect density. When an insect pest management program is ineffective, follow-up sampling is needed to discover whether additional insect pest suppression is needed. Also, finding the reason for the ineffectiveness may allow an insect pest management method to be used more successfully the next time.

While traps can often detect stored-product insect pests at lower densities than other insect-sampling methods, they may not provide reliable information about insect densities. The example in Chapter 5 of trap catches in grain bins declining as the weather cools because of low insect mobility at cooler temperatures even though the insect populations are still increasing illustrates the importance of converting trap catches to absolute insect densities. Trap catch is influenced by environmental factors such as temperature, residual food, and air movement and by the physiological states of the insect pests that influence their mobility. Because the environment and the physiological states of the insect pests generally change over time, trap efficiency can change over time. Converting trap catch to absolute insect density can adjust for this variation in trap efficiency and allow managers to better classify insect pest populations as being above or below an insect density threshold at which insect pest suppression is required.

Chapters 8 and 9 considered the decision aids that are useful in developing and implementing a pest management program for stored-product insects; Chapter 10 discussed resistance management; and Chapters 11 through 18 dealt with choosing an insect pest management method or methods. Decision aids include sampling information, cost-benefit analysis, consultants, expert systems, and the predictions from computer simulation models. The economics of insect pest management (Chapter 9) is important when using cost-benefit analysis. A standard calendar-based preventive pest management program for stored-product insects sometimes can be ineffective (see Table 8.1), but this may not be apparent without follow-up sampling to evaluate the efficacy of the program.

Resistance and cross-resistance to residual insecticides are widespread among stored-product insects. Insufficient sealing has resulted in stored-product insects becoming resistant to some fumigants. Insect resistance to these and other insect pest management methods needs to be managed so that insect resistance will develop more slowly. Biological factors such as immigration and operational factors such as persistence can both increase and decrease the rate at which insects develop resistance (see Chapter 10). The best ways to slow the development of insect resistance to any particular insect pest management method are to use it only when absolutely needed, use it correctly, and use it in combination with another insect pest management method that has a different mode of action and will kill the insects that have become resistant to another method.

Some general characteristics of pest management methods for stored-product insects may be useful in selecting a method or methods. Biological control, fumigation, and heat treatment of a facility penetrate into places where insects hide. A good sanitation program can discover and eliminate many insect infestations and make other insect pest management methods more effective. Residual insecticides and insect-resistant packaging are the primary methods that provide long-term protection against

stored-product insects. However, residual insecticides lose their effectiveness over time, and stored-product insects may eventually penetrate some of the insect-resistant packages. Refrigerated storage, cooling commodities by aeration, and use of **natural enemies** can provide long-term protection in some situations. Refrigeration is used primarily for high-value commodities, and cooling by aeration is most effective during cool seasons of the year and in geographical areas with cool climates. Natural enemies can be self-perpetuating, but their effectiveness often is reduced by standard business practices and other insect pest management methods.

A good way to choose the best pest management method or methods for stored-product insects is to compare their advantages and disadvantages across the available methods (Table 19.1). The quick suppression of stored-product insect populations by residual insecticides and fumigants gives the impression that they are more effective than nonchemical insect pest management methods. However, because of incomplete coverage, fumigant leakage, **sorption,** and the breakdown of residual insecticides, chemical methods often are not any more effective than the available nonchemical insect pest management methods. Stored-product insect pest mortalities approaching 100% are possible with natural enemies, aeration, extreme temperatures, pneumatic conveying, impact machines, and ionizing radiation. Removal of stored-product insects from grain or other raw commodities by sieving and **aspiration**, and from flour by sieving also can approach 100%.

Most of the insect pest management methods used for stored-product insects are broad spectrum, killing most stored-product insect species (including the natural enemies). Parasitoids generally have a narrow spectrum, each species killing only one or a few stored-product insect pest species. Predators often attack a larger number of stored-product insect pest species than parasitoids.

Low risk to workers and consumers is an advantage for stored-product insect pest management methods. However, most of these methods have some risk. For biological control, residual insecticides, impact, removal by sieving or aspiration, high temperatures, and ionizing radiation, these risks include contamination or reduced quality of the commodity. Poorly managing aeration can reduce quality when the temperature and moisture fronts are not moved completely through the grain bulk. Worker safety is an issue when using residual insecticides, fumigants, and ionizing radiation.

Operating costs are low for all of the insect pest management methods listed in Table 19.1. The last four methods require a capital investment or renting of equipment. The capital investment for using ionizing radiation or extreme temperatures is larger than that for aeration or impact and removal. Methods requiring a high capital investment are more likely to be cost-effective at facilities handling large volumes of commodities. On-site production of modified atmosphere and grain cleaning also require a capital investment, but this equipment can be portable so that it can be moved among sites. For residual insecticides and fumigants, the cost of registration and compliance with regulations is high. Sanitation is very labor-intensive, and labor costs can be high. Building and equipment designs that make cleaning more effective may reduce these labor costs. Biological control and impact may provide cost-free suppression of stored-product insect pests on an ongoing basis, but there is little information on the magnitude of their contribution at any location in the marketing system.

Complexity can be a disadvantage because complex methods are more difficult to use. However, complexity can be an advantage because it increases the number of

Table 19.1. Comparison of insect pest management methods with respect to their advantages or disadvantages

	Sanitation and exclusion	Biological control	Fumigant	Residual insecticide	Aeration	Tempera-ture	Ionizing radiation	Impact and removal
				Advantages				
Protection	Packaging gives long-term protection, broad-spectrum	Finds pests, self-perpetuating	Penetrating, quick-acting, broad-spectrum	Long-term protection, quick-acting, broad-spectrum	Reduces pest reproduction, long-term, broad-spectrum	Penetrating, can be long-term, broad-spectrum	High insect mortality, broad-spectrum	High insect mortality or removal, broad-spectrum
Risk	Low risk	Low risk	Low residue	Mammalian toxicity low	Low risk	Low risk		Low risk
Cost	Primary tools inexpensive	Naturally occurring, registered for use	Low cost	Low cost	Operating cost low	Scaling is less extensive and critical than for fumigation	Low operating cost	Low operating cost
Complexity	Simple tools	Pathogens sprayed like residual insecticides	Application simple	Application simple	Aeration controllers can simplify			
Insect resistance	Not a problem yet	Not a problem yet			Not a problem yet	Not a problem yet	Not a problem yet	Not a problem yet

	Sanitation and exclusion	Biological control	Fumigant	Residual insecticide	Aeration	Tempera-ture	Ionizing radiation	Impact and removal
				Disadvantages				
Protection	Cleaning and exclusion are ongoing	Limited shelf life, narrow-spectrum	Short-term	Preventive, loses effectiveness	Short-term	Short-term	Short-term, delayed pest mortality	Short-term
Risk		Contamina-tion of commodity	Worker safety measures needed	Residue on commodity, toxic to mammals, kills parasitoids and predators	Moving front through grain is required	Damage to building, equipment, and com-modity; reduces throughput	Worker safety measures required, kills seeds	Reduces quality of commodity
Cost	High labor cost		Compliance regulations expensive	High registration cost	Capital investment	Capital investment or rental fees	High capital investment	Equipment is a capital investment
Complexity	Must be well coordinated	Using parasitoids and predators is complex			Monitoring fan hours or temperature is important	Hard to achieve uniform temperature	Monitoring dosage is important	Balance insect mortality or removal with loss of commodity
Insect resistance			Problem	Problem				

ways in which an insect pest management method can be used and may allow insect pest management to be done more cost-effectively. Using even the methods that are considered simple to use can be complex when done correctly. Consultants, expert systems, and computer simulation **models** may be needed to deal with this complexity. Buildings and equipment that are easy to clean and suitable for heat treatment, aeration capability, packaging, stock rotation, biological control, and resistance management require long-term planning. The cost of large equipment such as packaging, grain cleaning, and impact machines; dust collection systems; aeration capability; gamma-ray, accelerated electron, or x-ray irradiators; and on-site generators of gases for modified atmospheres may need to be justified by long-term use.

Careful integration of more than one insect pest management method can make pest management for stored-product insects more effective without increasing the cost. Many of the effective combinations of methods that have been investigated involve the use of multiple stresses (extreme temperatures, impact, ionizing radiation, modified atmosphere, fumigant, and inert dust). Designing facilities so as to prevent insects from entering and to eliminate hiding places inside, inspection of incoming ingredients for insects, and stock rotation can make sanitation more effective. Removing residual food may increase the effectiveness of residual insecticides. Insect-resistant packaging can be integrated with sanitation, biological control, fumigation, and other pest management methods for stored-product insects to provide long-term protection.

Using insect sex **pheromones** to reduce insect mating (see Chapter 3), for mass trapping (see Chapter 3), and as attracticides (see Chapter 17) may be more compatible with use of **natural enemies** than other insect pest management methods. Some parasitoids are more effective when grain has been cooled by aeration. A combination of cleaning grain storage bins and aeration is more effective than either alone. Delaying fumigation until aeration can be used to prevent reinfestation can eliminate the need for a second fumigation. Cooling by aeration slows the breakdown of residual insecticides, and some **pyrethroids** and **chlorinated hydrocarbons** are more effective at low temperatures. Formulating residual insecticides in oil may reduce the amount needed because insects pick up more.

Computer simulation **models** can be used to compare the effectiveness of different pest management methods for stored-product insects or combinations of insect pest management methods. These models also can be used to evaluate the effectiveness of different implementation options and to optimize the timing of pest management programs for stored-product insects. Currently, computer simulation models are available primarily for insect pests of stored grain, but in the future, such models will be useful in making insect pest management decisions throughout the marketing system. Insect monitoring programs will be important in optimizing the timing of stored-product insect pest suppression and verifying that insect pest management was effective. Monitoring and predicting insect population growth allow commodities with the greatest risk of future insect problems to be marketed first. This reduces the cost of pest management programs for stored-product insects and slows selection for insect resistance to insect pest management methods.

Part III

Resources and Exercises

Chapters 20 and 21 list and discuss many of the published books, reviews, and conference proceedings that are available on stored-product entomology. In Chapter 22, expanded explanations are provided for some of the terms used in the book. These terms are printed in bold type throughout the book. The sampling exercise in Chapter 23 illustrates how the accuracy of estimating insect density increases with the number of sample units examined. Chapter 24 discusses a computer program that simulates stored-product insect population growth and how it can be modified for different insect species, insect pest management methods, and types of facilities or transportation vehicles.

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Chapter 20

Books and Reviews

R. T. Cotton wrote a book on stored-product entomology, first published in 1941, reprinted in 1950 and 1952, revised in 1956, and reprinted again in 1963. He covered the management of stored-product insect pests in raw grain during storage and grain products in processing facilities. Emphasis was placed on the monitoring and prevention of stored-product insect problems. Fumigants, heat treatments, wood ash dusts, **synergised pyrethrins**, **malathion**, and sanitation were discussed as the available stored-product insect pest management tools. A book on stored-product entomology by J. W. Munro was published in 1966.

Between 1954 and 1992, the book *Storage of Cereal Grains and Their Products* was updated four times, and the topics changed a little with each edition. J. A. Anderson and A. W. Alcock edited the first edition in 1954, C. M. Christensen the next two editions in 1974 and 1982, and D. B. Sauer the most recent edition in 1992. F. Osuji wrote a book in 1985 about stored-product insects in the tropics. D. Rees, in 2004, provided a brief introduction to stored-product entomology, inspection methods, and sampling of stored-product insect populations and descriptions of stored-product insect biology and insect geographical distribution, along with taxonomic keys for many stored-product insect species. H. A. U. Monro wrote a manual of fumigation for insect pests in 1961; the manual was reprinted in 1964, and Monro revised it in 1969. E. J. Bond updated this fumigation manual in 1984. These books were major expansions of Cotton's book. Monro also wrote a book in 1951 discussing the stored-product insects found during the inspection of cargo ships in Canada and the management of these insects. Books by Johnson in 1902 and Blodgett in 1978 provide some interesting insights into the development of fumigation for stored-product insect pests.

More recent books have expanded the range of topics covered and provided updates of the available information. Some of these books have emphasized the problems with stored-product insects infesting raw commodities (Sinha and Muir 1973, Sinha and Watters 1985, Perez-Mendosa 1993, Jayas et al 1995, Krischik et al 1995, Golob et al 2002, Hill 2002, Reed 2006), while others have emphasized the stored-product insect problems during and after processing (American Institute of Baking 1979, Baur 1984, Mills and Pedersen 1990, Gorham 1991, Mueller 1998, Hui et al 2003, Heaps 2006). Books edited by Subramanyam and Hagstrum (1996, 2000) emphasized the use of integrated pest management for stored-product insects and alternatives to pesticides for stored-product insect pest management programs. Rees et al (1993) published an index that cross-references, by insect species and method, the literature published mostly between 1980 and 1991 on methods other than conventional pesticides for protecting stored products against insect pests. These methods include modified atmospheres, botanicals, insect growth regulators, minerals, **pheromones,** and biological control.

Other recent books have provided more in-depth coverage of specific topics. Snelson (1987) provides an extensive review of the literature on the residual insecticides used to manage stored-product insect pests. The effort to replace the fumigant **methyl bromide** is documented by Bell et al (1996). Golob and Webley (1980) and Golob et al (1999) summarize the literature on traditional botanical and mineral protectants for stored grain. Ryan (1995) discusses the biology and suppression of the

stored-product insect pests of stored tobacco. Dick (1987) describes the management of the stored-product insect pests of peanuts and Prakash et al (1987) the management of stored-product insect pests of rice. Sokoloff's three volumes review the literature on the morphology, biology, and genetics of *Tribolium* spp. Hill (1990) discusses grain grades and standards, and Hui et al (1986) and Vetter (1996) discuss food laws. Imholte and Imholte-Tauscher in 1999 wrote about building and equipment designs that improve stored-product insect exclusion and sanitation programs. Other books by Navarro and Calderon in 1982 and Navarro and Noyes in 2002 cover grain aeration.

In addition to these books, several journal volumes have been devoted to reviewing the biology, ecology, and management of stored-product insect pests. In 1984, volume 48 of the journal *Tropical Stored Product Information* contained a series of review papers on several stored-product insect pest management methods (**resistant seeds**, **pheromones**, **natural enemies**, and sterile insects) and the role of biological methods in integrated pest management. In 1991, volume 32, issue 1 of the journal *CEIBA* featured a review of the research on *Prostephanus truncatus*. In 1997, volume 33, issue 1 of the *Journal of Stored Product Research* was devoted to reviewing several ecologically safe alternatives for managing stored-product insect pests (insect growth regulators, botanicals, pheromones, low temperature, inert dusts, and natural enemies). In 2002, volume 7, issues 2 and 4 of *Integrated Pest Management Reviews* contained literature reviews that covered the taxonomy, biology, ecology, detection, monitoring, and pest management methods for *Prostephanus truncatus*, as well as the economic losses caused by this insect.

Between 1974 and 2000, a series of literature reviews for stored-product insects were published in the *Journal of Plant Disease and Protection* (81:409-423, 82:236-254, 83:462-491, 85:617-636, 86:584-617, 87:667-699, 88:550-568, 89:534-554, 90:538-558, 91:305-324, 92:535-555, 93:425-445, 94:649-668, 95:651-669, 97:90-113, 98:547-562, 100:91-107, 101:321-335, 102:540-557, 104:296-313, and 107:93-105). Except for the last six of these reviews, which were published in English, the reviews were published in German. During several years before 1974, abstracts of several research papers on stored-product insects were published each year in each of several issues of the *Journal of Plant Disease and Protection*. In addition to books, the following list includes recent literature reviews for several species of stored-product insects.

Abreu, J. M., Williams, R. N., and Rude, P. A. 1982. Revised bibliography of the almond moth (tropical warehouse moth), *Ephestia cautella* (Walker) (Lepidoptera: Phycitidae). Trop. Stored Prod. Inf. 44:15-36.

American Institute of Baking. 1979. Basic Food Plant Sanitation Manual. The Institute, Manhattan, KS.

Anderson, J. A., and Alcock, A. W., Eds. 1954. Storage of Cereal Grains and Their Products, 1st ed. American Association of Cereal Chemists, St. Paul, MN.

Ashworth, J. R. 1993. The biology of *Ephestia elutella*. J. Stored Prod. Res. 29:199-205.

Ashworth, J. R. 1993. The biology of *Lasioderma serricorne*. J. Stored Prod. Res. 29:291-303.

Baur, F. J. 1984. Insect Management for Food Storage and Processing, 1st ed. American Association of Cereal Chemists, St. Paul, MN.

Bell, C. H., Price, N., and Chakrabarti, B. 1996. The Methyl Bromide Issue. John Wiley & Sons, New York.

Blodgett, F. E. 1978. The Essential Truth About Fumigants. The Lowell Press, Kansas City, MO.

Bond, E. J. 1984. Manual of Fumigation for Insect Control. Plant Production and Protection Paper 54. Food and Agriculture Organization (FAO) of the United Nations, Rome.

Christensen, C. M. 1974. Storage of Cereal Grains and Their Products, 2nd ed. American Association of Cereal Chemists, St. Paul, MN.

Christensen, C. M. 1982. Storage of Cereal Grains and Their Products, 3rd ed. American Association of Cereal Chemists, St. Paul, MN.

Cotton, R. T. 1941. Insect Pests of Stored Grain and Grain Products, 1st ed. Burgess Publishing Co., Minneapolis, MN.

Cotton, R. T. 1963. Insect pests of Stored Grain and Grain Products: Identification, Habits and Methods of Control. Burgess Publishing Co., Minneapolis, MN.

Dick, K. M. 1987. Pest Management in Stored Groundnuts. Inf. Bull. 22. International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India.

Golob, P., and Webley, D. J. 1980. The Use of Plants and Minerals as Traditional Protectants of Stored Products. Pub. G138. Natural Resources Institute, Kent, U.K.

Golob, P., Moss, C., Dales, M., Fidgen, A., Evans, J., and Gudrups, I. 1999. The Use of Spices and Medicinals as Bioactive Protectants for Grains. Agricultural Services Bull. 137. Food and Agriculture Organization of United Nations, Rome.

Golob, P., Farrell, G., and Orchard, J. E. 2002. Crop Post-Harvest: Science and Technology. Blackwell Science Ltd., Oxford, U.K.

Gorham, J. R. 1991. Ecology and Management of Food-Industry Pests. Food and Drug Administration Tech. Bull. 4. Association of Official Analytical Chemists, Arlington, VA.

Heaps, J. W., Ed. 2006. Insect Management for Food Storage and Processing, 2nd ed. AACC International, St Paul, MN.

Hill, D. S. 2002. Pests of Stored Foodstuffs and Their Control. Kluwer Academic Publishers, Boston.

Hill, L. D. 1990. Grain Grades and Standards: Historical Issues Shaping the Future. University of Illinois Press, Urbana.

Hui, Y. H. 1986. United States Food Laws, Regulations and Standards. John Wiley & Sons, New York.

Hui, Y. H., Bruinsma, B. L., Gorham, J. R., Nip, W., Tong, P. S., and Ventresca, P. 2002. Food Plant Sanitation. Marcel Dekker, Inc., New York.

Imholte, T. J., and Imholte-Tauscher, T. K. 1999. Engineering for Food Safety and Sanitation. Technical Institute of Food Safety, Crystal, MN.

Jayas, D. S., White, N. D. G., and Muir, W. E. 1995. Stored-Grain Ecosystem. Marcel Dekker, Inc., New York.

Johnson, W. G. 1902. Fumigation Methods, a Practical Treatise for Farmers, Fruit Growers, Nurserymen, Gardeners, Florists, Millers, Grain Dealers, Transportation Companies, College and Experiment Station Workers, etc. Orange Judd Company, New York.

Krischik, V., Cuperus, G., and Galliart, D. 1995. Stored Product Management. Circ. E-912. Cooperative Extension Service, Oklahoma State University, Stillwater.

Longstaff, B. C. 1981. Biology of the grain pest species of the genus *Sitophilus* (Coleoptera: Curculionidae): A critical review. Prot. Ecol. 2:83-130.

Mills, R., and Pedersen, J. 1990. A Flour Mill Sanitation Manual. American Association of Cereal Chemists, St. Paul, MN.

Monro, H. A. U. 1951. Insect Pests in Cargo Ships. Pub. 855. Canadian Department of Agriculture, Ottawa.
Monro, H. A. U. 1961. Manual of Fumigation for Insect Control. Agric. Studies Pub. 56. Food and Agriculture Organization of United Nations, Rome.
Monro, H. A. U. 1969. Manual of Fumigation for Insect Control, 2nd ed. Agric. Studies Pub. 79. Food and Agriculture Organization of United Nations, Rome.
Mueller, D. 1998. Stored Product Protection—A Period of Transition. Insects Limited, Inc., Indianapolis, IN.
Multon, J. L. 1988. Preservation and Storage of Grains, Seeds and Their By-Products: Cereals, Oilseeds, Pulses and Animal Feed. Lavoisier Publishing Inc., New York.
Munro, J. W. 1966. Pests of Stored Products. The Rentokil Library, Hutchinson, London.
Navarro, S., and Calderon, M. 1982. Aeration of Grain in Subtropical Climates. Agricultural Services Bull. 52. Food and Agriculture Organization of United Nations, Rome.
Navarro, S., and Noyes, R. 2002. The Mechanics and Physics of Modern Grain Aeration Management. CRC Press, New York.
Osuji, F. 1985. Outlines of Stored Products Entomology for the Tropics. Fourth Dimension Publishers, Enugu, Nigeria.
Perez-Mendosa, J. 1993. Insectos de Granos Almacenados: Biologia, Danos, Detecion y Combate. Centro de Investigacion Regional del Centro Campo Experimental Bajio, Celaya, Gto., Mexico.
Prakash, A., Rao, J., Pasalu, I. C., and Mathur, K. C. 1987. Rice Storage and Insect Pest Management. B. R. Publishing Corp., Delhi, India.
Reed, C. R. 2006. Managing Stored Grain to Preserve Quality and Value. AACC International, St. Paul, MN.
Rees, D. 2004. Insects of Stored Products. Manson Publishing, London.
Rees, D., Dales, M. J., and Golob, P. 1993. Alternative Methods for the Control of Stored-Product Insect Pests: A Bibliographic Database. Natural Resources Institute, Chatham, United Kingdom.
Ryan, L. 1995. Post-harvest Tobacco Infestation Control. Chapman & Hall, London.
Sauer, D. B. 1992. Storage of Cereal Grains and Their Products, 4th ed. American Association of Cereal Chemists, St. Paul, MN.
Sinha, R. N., and Muir, W. E. 1973. Grain Storage: Part of a system. AVI Publishing Co., Inc., Westport, CT.
Sinha, R. N., and Watters, F. L. 1985. Insect Pests of Flour Mills, Grain Elevators, and Feed Mills and Their Control. Canadian Government Publishing Centre, Ottawa, Canada.
Snelson, J. T. 1987. Grain Protectants. Monograph 3. Australian Centre for International Agricultural Research, Canberra, Australia.
Sokoloff, A. 1972. The Biology of *Tribolium* with Special Emphasis on Genetic Aspects, Volume 1. Oxford University Press, New York.
Sokoloff, A. 1974. The Biology of *Tribolium* with Special Emphasis on Genetic Aspects, Volume 2. Oxford University Press, New York.
Sokoloff, A. 1977. The Biology of *Tribolium* with Special Emphasis on Genetic Aspects, Volume 3. Oxford University Press, New York.
Subramanyam, B., and Hagstrum, D. W. 1996. Integrated Management of Insects in Stored Products, Marcel Dekker, Inc., New York.

Subramanyam, B. and Hagstrum, D. W. 2000. Alternatives to Pesticides in Stored-Product IPM. Kluwer Academic Publishers, New York.

Throne, J. E. 1986. A bibliography of maize weevil, *Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae). ARS-58. U.S. Dept. of Agriculture, Agricultural Research Service, Washington, DC.

Throne, J. E. 1987. A bibliography of the rusty grain beetle, *Cryptolestes ferrugineus* (Stephens) (Coleoptera: Cucujidae). ARS-67. U.S. Dept. of Agriculture, Agricultural Research Service, Washington, DC.

Throne, J. E. 1988. A bibliography of the flat grain beetle, *Cryptolestes pusillus* (Schönherr) (Coleoptera: Cucujidae). ARS-70. U.S. Dept. of Agriculture, Agricultural Research Service, Washington, DC.

Vetter, J. L. 1996. Food Laws and Regulations. American Institute of Baking, Manhattan, KS.

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Chapter 21

Conference Proceedings

Two international meetings dealing primarily with stored-product entomology are each held every three to five years. The first of eight International Working Conferences was held in 1975, and the first of seven Controlled Atmosphere Conferences was held in 1980. In 1984, they were both held the same year, and since then they have been scheduled one to three years apart.

International Working Conferences

The first three meetings were called International Working Conference of Stored-Product Entomology, and then the name was changed to International Working Conference of Stored-Product Protection to include disciplines outside of entomology. The range of subjects covered has been expanded over the years.

All of the International Working Conferences have included sessions on insect biology, chemical pest management methods, and physical pest management methods; during the fifth and subsequent working conferences, a session on biological pest-management methods was added. During the third conference, there was a session on the identification of pest problems, and sampling was added as a regular session during the fifth and several subsequent conferences. This followed a workshop on trapping technology for monitoring stored-product insects that was held in 1989 at the Entomological Society of America meeting in San Antonio, Texas (1990, J. Kansas Entomol. Soc. 63:464-558). Integrated pest management was included with insect biology at the first and second conferences, extended at the third conference, and held as a separate session at the sixth. A session on microorganisms and rodents was held at the second conference, sessions on microflora and mycotoxins at the fourth through seventh conferences, on biology and control of rodents and birds at the fifth conference, and on food safety (including mycotoxins and regulatory issues) at the eighth. A session on engineering was added at the fourth and several subsequent conferences. At the eighth, biology, detection, and biological pest management methods were covered in one session and chemical and physical pest management methods in another. There also have been sessions on tropical entomology (first, second, fourth, and fifth), sanitation in the food industry (fifth), **modeling** (fifth), expert systems (sixth), information transfer and adoption (seventh), quarantine (sixth and seventh), economics and conservation (fifth), stored-product quality (sixth and seventh), the future of stored-product protection (eighth), and processing and applications—including the use of computers and engineering (eighth). The proceedings for the first through fifth and the seventh International Working Conferences were published by the organizing committee, and some of these can be purchased from its secretary/treasurer, James E. Throne (throne@gmprc.ksu.edu).

Controlled Atmosphere conferences

By the second meeting, the Controlled Atmosphere conference had become the Controlled Atmosphere and Fumigation (CAF) conference. All of the meetings have included sessions on application methods and insect response, and all except the third

and seventh included a session on the preservation of commodity quality. Sessions were held at the second through the sixth meetings on sealing and gas-tightness, and at the second and the fourth through sixth on integration. All except the third, fifth, and seventh meetings have included a session on microbial response. Regulations and insect resistance (1993, 1997, 2001, and 2004), and sampling and trapping (1997 and 2001) were added more recently. There also have been sessions on natural airtight storage (1980), bunker storage (1984), physical pest management methods (1984), chemical pest management methods (1984), sealed storage of bag stacks (1990), fumigation under increased pressure (2001), methyl bromide replacements (2004), and international collaboration (2004). The proceedings for the 2004 CAF conference will be distributed to the participants on a compact disk (CD).

Voluntary association of organizations

The Group for Assistance on Systems Relating to Grain After-Harvest (GASGA), a voluntary association consisting of eight organizations in 1986 (five by 1998), conducts research and field projects, provides training, and sponsors workshops on grain and other major food commodities for the postharvest sector in developing countries. It sponsored a seminar on the appropriate use of pesticides in developing countries in 1981, a workshop on *Prostephanus truncatus* in 1984, and one on fumigation in 1986. Subsequent conferences sponsored by GASGA have not included as much on stored-product insect pests. The eight organizations of GASGA in 1984 were the following:

1. Commonwealth Scientific and Industrial Research Organization (CSIRO), Canberra, Australia, http://www.ento.csiro.au/
2. United Nations Food and Agriculture Organization (FAO), Rome, Italy, http://www.fao.org/
3. Deutsche Gesellschaft fur Technische Zusammenarbeit, GmbH (GTZ), Eschborn, Federal Republic of Germany, http://www.gtz.de/home/english
4. International Development Research Centre (IDRC), Ottawa, Canada, http://www.idrc.ca
5. Institut de Recherches Agronomiques Tropicales et de Cultures Vivrieres (IRAT), Paris, France, http://www.cirad.fr/fr/index.php
6. Koninklijk Instituut voor de Tropen (KIT), Amsterdam, The Netherlands
7. Food and Feed Grain Institute (FFGI) of Kansas State University (KSU), Manhattan, Kansas, USA, http://www.ksu.edu/ffgi/
8. Tropical Development and Research Institute (TDRI), London, U.K., http://www.nri.org/

By 1998, The Australian Centre for International Agricultural Research (ACIAR), Canberra, Australia, had replaced CSIRO; IRAT was replaced by Centre de Cooperation International en Recherche Agronomique pour le Developpement (CIRAD), Montpellier, France; and TDRI was replaced by The Natural Resources Institute (NRI), Chatham, England. IDRC, KIT, and FFGI are no longer members.

The following list includes the proceedings for the international conferences, as well as for some of the more-local or regional conferences. They are listed in date order.

Anonymous. 1975. Proc. 1st International Working Conference on Stored-Product Entomology (Savannah, GA).

Anonymous. 1976. Proc. Joint United States-Japan Seminar on Stored Product Insects (Manhattan, KS).

Anonymous. 1979. Proc. 2nd International Working Conference on Stored-Product Entomology (Ibadan, Nigeria).

Shejbal, J., Ed. 1980. Proc. [1st] International Symposium on Controlled Atmosphere Storage of Grains. Elsevier, New York.

Anonymous. 1981. GASGA Seminar on the Appropriate Use of Pesticides for the Control of Stored Product Pests in Developing Countries. Tropical Development and Research Institute, Slough, U.K.

Williams, P., and Amos, T. G., Eds. 1981. First Australian Stored Grain Pest Control Conference (Melbourne, Victoria, Australia).

Anonymous. 1984. GASGA Workshop on the Larger Grain Borer, *Prostephanus truncatus*. Deutsche Gesellschaft fur Technische Zusammenarbeit, Eschborn, Germany.

Mills, R. B., Wright, V. F., and Pedersen, J. R., Eds. 1984. Proc. 3rd International Working Conference on Stored Product Entomology (Manhattan, KS).

Ripp, B. E., Banks, H. J., Calverley, D. J., Jay, E. G., and Navarro, S., Eds. 1984. Proc. [2nd] International Symposium on Practical Aspects of Controlled Atmosphere and Fumigation in Grain Storages. Elsevier, New York.

Champ, B. R., and Highley, E. 1986. Pesticides and Humid Tropical Grain Storage System: Proceedings of an International Seminar (Manila, Philippines). Proc. series No. 14. Australian Centre for International Agricultural Research, Canberra.

Anonymous. 1986. GASGA Seminar on Fumigation Technology in Developing Countries. Tropical Development and Research Institute, London, U.K.

Donahaye, E., and Navarro, S., Eds. 1987. Proc. 4th International Working Conference on Stored-Product Protection (Tel Aviv, Israel). Wallach Press, Jerusalem, Israel.

Champ, B. R., Highley, E., and Banks, H. J. 1990. Proc. [3rd] International Conference on Fumigation and Controlled Atmosphere Storage of Grain. Proc. series No. 25. Australian Centre for International Agricultural Research, Canberra.

Fluerat-Lessard, F., and Ducom, P., Eds. 1991. Proc. 5th International Working Conference on Stored-Product Entomology (Bordeaux, France). Imprimerie Médocaine, Blanquefort Cedex, France.

Navarro, S., and Donahaye, E. J., Eds. 1993. Proc. [4th] International Conference on Controlled Atmosphere and Fumigation in Grain Storages. Caspit Press Ltd., Jerusalem.

Highley, E., Wright, E. J., Banks, H. J., and Champ, B. R., Eds. 1994. Proc. 6th International Working Conference on Stored-Product Protection (Canberra, Australia). CAB International, Wallingford, U.K.

Donahaye, E. J., Navarro, S., and Varnava, A., Eds. 1997. Proc. [5th] International Conference on Controlled Atmosphere and Fumigation in Stored Products. Printco Ltd., Nicosia, Cyprus.

Adler, C., and Schoeller, M., Eds. 1998. Integrated Protection of Stored Products. Pub. 21. International Organization for Biological and Integrated Control, Dijon, Cedex, France.

Zuzan, J., Quan, L., Yongsheng, L., Xiachang, T., and Liaghua, G., Eds. 1999. Proc. 7th International Working Conference on Stored Product Protection. Sichuan Publishing House, Chengdu, Peoples Republic of China.

Donahaye, E. J., Navarro, S., and Leesch, J., Eds. 2001. Proc. [6th] International Conference on Controlled Atmosphere and Fumigation in Stored Products. Executive Printing Services, Clovis, CA.

Credland, P. F., Armitage, D. M., Bell, C. H., Cogan, P. M., and Highley, E., Eds. 2003. Advances in Stored Product Protection. Proc. 8th International Working Conference on Stored Product Protection (York, U.K.). CAB International, Wallingford, U.K.

Chapter 22

Terminology

Acclimation—Prior exposure to gradually decreasing or increasing temperatures can make insects two- to 20-fold more tolerant to cold or heat, respectively. Acclimation to cold generally requires weeks to reach full protective capacity, but rapid cold hardening can occur after 1–2 hr of exposure to 0–5°C. Cold tolerance is lost quickly. Heat acclimation is typically acquired more rapidly and lost more slowly than cold tolerance.

Acoustical detection—Acoustical detection is an indirect method of sampling bulk-stored grain for stored-product insects by monitoring insect-produced sounds instead of directly counting the number of insects in the grain sample. Equipment for detection of stored-grain insect sounds in grain samples has been marketed by several companies, including Sonometrics in the United States and a company in France that makes the commercial product SITO DETECT. For a short time, Pestcon Systems, Inc., Des Moines, IA, marketed a probe for listening to insects without removing grain and a 250-g cup for detecting insects in grain samples collected by releasing grain from the bottom of elevator bins. Systelia (www.systelia.fr) is currently marketing detection equipment for insects in grain samples and in bins of bulk-stored grain.

Adults of stored-product beetles moving on the outside of the grain kernels produce 40–70 times more sound than larvae feeding inside the grain. The number of insect sounds detected varies with the size of the insect. Adult *Sitophilus oryzae* and *Tribolium castaneum* are equally detectable and much more readily detected than *Cryptolestes ferrugineus* or *Oryzaephilus surinamensis*. The size and detectability of *Rhyzopertha dominica* is intermediate. Moth larvae are bigger than beetle larvae and produce more sounds.

A problem with acoustical detection of insects in grain sample units is that insect sounds must be distinguished from grain settling and other sounds. A vibrator can be used to settle the grain and reduce the time during which grain-settling sounds are produced. Computer software has been developed to distinguish between insect sounds that occur more than once at a location in a grain sample unit and other sounds that do not. Ultrasounds produced by *Callosobruchus maculatus* larvae feeding inside cowpeas or *S. oryzae* larvae feeding inside maize kernels can be detected too. Detecting ultrasounds reduces the problem of background sounds because ultrasound is not very penetrating, but this limits the size of the cowpea or grain sample unit in which an insect can be detected. A sound-dampening box also can be used to reduce the number of background sounds.

A better solution may be to mount acoustical sensors on cables permanently installed within the grain mass. After an initial period of grain settling, there are few grain-settling sounds to be mistaken for insects, and other background sounds are not detected because the grain is a very good sound insulator. The sound insulating properties of grain also limit the distance over which the sounds made by insects can travel. The sensors can detect insects up to 10–15 cm (4–6 in.) away. Amplifying the analog signal from the sensor at each sensor location and converting this analog signal to a digital signal for transmission to the computer reduces the electrical noise but does not greatly increase the distance at which insects can be detected.

In on-farm grain storage bins, continuous monitoring using acoustical sensors on cables detected insects three to 28 days earlier than taking grain sample units in front of each sensor. The frequency of insect detection with acoustical sensors was well correlated with the estimated insect densities over a range of zero to 17 insects per kilogram of grain. Acoustical sensors in the top half of each bin could provide a cost-effective early warning system. For an elevator, a computer in the main office could monitor all of the grain storage bins and give the managers a list of bins with grain that needs to be sold or fumigated. By networking computers, individual lots of grain could be followed as they move through the marketing system.

Aggregation—Insect spatial distribution can be random, aggregated, or uniform. With random distribution, there is an equal probability of an insect occupying any point in space, and the variance is equal to the mean number of insects per sample unit. With a uniform distribution, insects are evenly spaced and the variance is less than the mean. With an aggregated distribution, the variance is larger than the mean. Comparing the degree of spatial aggregation, clumping, clustering, or contagion of an insect population at different times, of populations of same species at different places, or of populations of different species can help the observer to understand their ecology. The degree of aggregation in spatial distribution may be a response to local variation in environmental conditions in a habitat; an avoidance of other individuals; or a response to sex pheromones, aggregation pheromones, food odor, or visual cues.

Several statistical methods use the observed frequency distribution of the number of insects per sample unit or the relationship between the mean and variance to describe the degree of aggregation. These methods include the variance-mean ratio, the negative binomial parameter k, Lloyd's indices of mean crowding and patchiness, b of Taylor's power law, and Morisita's indices of dispersion. None of the indices provides insight into why insects are aggregating, and the indices may mistake for aggregation the more rapid increase in variance as the mean insect density increases (see Chapter 5). Geostatistical analysis can provide more insight into why insects are aggregating. The spatial distributions of different insect species or insect populations at different times or places can be compared using geostatistics, as can the relationship between an environmental factor and insect distribution.

Aspiration—Aspirators have been used for many years to separate insects and other contaminants from grain and other commodities by using differences in their size, density, and shape. Falling objects increase in speed until they reach their terminal velocity. The size, density, and shape of objects determine the extent to which air resistance slows their fall. If the velocity of an airstream is greater than the terminal velocity of an object in that airstream, the object will be lifted. Aspirators are set to remove as much of the contaminant and as little of the usable product as possible. Multiple-pass aspirators can remove 90–99.6% of contaminants. However, living insects cling to grain and are not easily removed.

Augmentation (see **Natural enemies**)

Belt conveyor (see **Elevator**)

Berlese funnel—The Berlese or Tullgren funnel has been used to extract *Cryptolestes ferrugineus* from grain samples by slowly heating the samples from the top so that the insects move down and through a screen holding the grain and are directed by a funnel into a collection jar. A 60 or 100-W incandescent light bulb fixed 5–7 cm (12.7–17.8 in.) above the surface of a 0.15-, 0.3-, or 1-kg grain sample has been used to heat the sample. Insect recovery varies with the sample unit size, the grain moisture, and the developmental stage of the insects. A 33.3-degree C temperature gradient was achieved with a 0.3-kg 16%-moisture wheat sample at an initial rate of 5 degrees C per 2.6 hr. The maximum temperature at the bottom of the sample was 39.2°C. Insects were collected in water or in 70% ethyl alcohol in the collection jar. Another study showed that the adults and fourth **instar** insects moved more rapidly, and more of these insects were recovered than the slower-moving, younger larvae. The maximum numbers of second instar were recovered during the first 2–4 hr, of third instar during the first 4–5 hr, and of fourth instar during the first 0–2 hr. The percentages of the larvae that died inside the kernels after 6 hr on the Berlese funnel were 15 for second instar, 20 for third, and 15 for fourth.

Bioresmethrin (see **Pyrethroids**)

Bulk density (see **Test weight**)

Carbamate—The first insecticidal carbamates were discovered in 1947. This class of residual insecticide originated in 1864, when the use of the beans of the plant *Physostigma venenosum* for "trial by ordeal" in West Africa was investigated. When suspects forced to eat the beans survived, they were considered innocent. (The innocent may have been more likely to eat the beans rapidly and vomit them up.) The toxicity of beans was due to carbamic acid, which inhibits cholinesterase, an important neurotransmitter in insects and humans. Propoxur (Baygon) and bendiocarb (Ficam) are registered in the United States for use as crack-and-crevice or spot treatments in food storage and processing facilities. Carbaryl is very effective against *Rhyzopertha dominica* but not very effective against many other species of stored-product insects.

Carbaryl (see **Carbamate**)

Carbon disulfide—Carbon disulfide (CS_2) was first found to be effective against stored-product insects in 1856. Initially, it was not widely used because of its cost. Carbon disulfide is a liquid-type fumigant sold in metal cans or drums. It penetrates well and does not reduce seed germination, but large doses are required to kill insects. (For comparative data on the toxicity of this fumigant, see **Phosphine**.) The vapor of carbon disulfide is 2.6 times heavier than air. It is very toxic to humans, can be absorbed through the skin, and ignites spontaneously at about 100°C. Persons working in concentrations above 20 ppm should wear a respirator with an organic vapor canister. Inhalation of high concentrations results in unconsciousness and death from respiratory failure. An 80:20 mixture (by volume) of **carbon tetrachloride** and carbon disulfide generally is used to reduce flammability. This fumigant can no longer be used for stored products in the United States.

Carbon tetrachloride—Carbon tetrachloride (CCl_4) was first used as a fumigant for stored-product insects in 1910. It can be used alone as a fumigant but is not very toxic to stored-product insects, and high doses or prolonged exposure periods are required. (For comparative data on the toxicity of this fumigant, see **Phosphine**.) At the recommended dosage, it does not affect the germination of seeds. This liquid-type fumigant is generally used to reduce the flammability of other liquid fumigants such as acrylonitrile, **carbon disulfide**, and ethylene dichloride. Carbon tetrachloride is 5.3 times heavier than air and also aids in the distribution of some other liquid fumigants. This fumigant can no longer be used for stored products in the United States.

Chiller—Grain chillers, used to cool commodities by aeration, force ambient air over a bank of refrigeration coils and then reheat the air to reduce the relative humidity. Reheating is generally done with the heat from the condenser of the refrigeration equipment. A German engineer in 1917 may have been the first to propose grain chilling, which has been used most extensively in Europe. Grain chilling was not studied in the United States until the late 1950s. At least seven major commercial manufacturers sell grain chillers. The largest chilling units of the leading manufacturers have similar capacities. Compressors for refrigeration range from 107–130 kW. With an airflow rate of 16,500 m^3/hr at 2,000 Pa of static pressure, the average grain chilling capacity is about 350 t per day.

Chlorinated hydrocarbons—This class of residual insecticide includes lindane, which was the first synthetic insecticide widely used as a grain protectant, and methoxychlor. Lindane, which is benzene hexachloride, was discovered in 1942. It is persistent, lasting two to five years, and is penetrating, leaving residues in flour and milled rice, although much of the residue is lost in cooking. Another chlorinated hydrocarbon, DDT, was first made in 1874, but its insecticidal properties were not discovered until 1939, and its use as an insecticide was patented in 1942. Methoxychlor is a modification of DDT with lower vertebrate toxicity. The modes of action of chlorinated hydrocarbons are not known, but symptoms suggest that they are neurotoxins. Both lindane and methoxychlor are registered in the United States for use as seed-grain protectants. Lindane is registered for spraying empty bins that will be used to store seed grain. Methoxychlor is registered for use as a spray or dust in empty bins and as a crack-and-crevice spray in food storage and processing facilities.

Chloropicrin—Chloropicrin (CCl_3NO_2) was used as a tear gas in World War I and was first used as a fumigant for stored-product insects in 1917. It is a liquid-type fumigant, nonflammable but corrosive to metals and paints. Because it is 5.68 times heavier than air, it is often applied to grain by opening and inverting cans at the surface. It is highly toxic to stored-product insects (for comparative data on its toxicity, see **Phosphine**) and plants and is difficult to remove from commodities but leaves no residue after aeration. Treated grain can be unpleasant to handle until aeration is complete. Because it is a powerful tear gas at 1 ppm, it is used as a warning agent in other fumigants.

Chlorpyrifos-methyl—Chlorpyrifos-methyl (Reldan) is a broad-spectrum **organophosphate** insecticide with low mammalian toxicity. It is effective against stored-product insects other than *Rhyzopertha dominica*. It was registered in the United States

for use as a dust or spray to treat barley, oats, rice, sorghum, and wheat at 6 ppm. It persists on grain for several months. Some of the recommendations are 0.47 L (0.5 pints) per 11.3 L (3 gallons) of water at a rate of 3.8 L (1 gallon) per 60–116 m^2 (650–1,250 ft^2) of empty bin; 0.34 L per 27 t (11.5 ounces per 1,000 bushels) of wheat; and 4.5 kg (10 pounds) of 3% chlorpyrifos-methyl dust per 27 t (1,000 bushels) of wheat. More than 90% of the residues are removed with the wheat bran during milling, and cooking destroys more than half of the residues that remain in the flour.

Citrus pulp—The peel, pulp, and seed by-products of making frozen citrus juice concentrates were once a disposal problem. Since 1932, citrus pulp has been dried, stored in bags, and sold as cattle feed.

Conservation of natural enemies (see **Natural enemies**)

Cuticle—This outer layer covers the surface of an insect, including foregut and hindgut. The cuticle functions as a skeleton for muscle attachment and to protect insects from dehydration. It includes the cuticle-producing epidermal cells and various glands and sense organs. Below a waxy water-proof layer, the noncellular cuticle is composed mainly of chitin and proteins. The cuticle must be replaced periodically by **molting** to allow an insect larvae or nymph to grow. A cross-linking of chitin to proteins causes the cuticle to harden again after the insect has expanded to its larger size.

Cyfluthrin—Cyfluthrin (Tempo) is a synthetic **pyrethroid** insecticide that was first registered in the United States in 1987. It is a contact and stomach poison. The label specifies application rates of 9.5 and 19.0 g/94 m^2. Reapplication can be made at 10-day intervals. For *Cadra cautella*, *Plodia interpunctella*, *Prostephanus truncatus*, *Tribolium castaneum*, and *T. confusum*, but not for *Rhyzopertha dominica,* the effectiveness of cyfluthrin is inversely related to temperature.

DDT (see **Chlorinated hydrocarbons**)

Defect action level (DAL)—In the United States, the Food and Drug Administration (FDA) establishes maximum levels for unavoidable filth in food processed under **good manufacturing practices** and uses these DAL levels to decide whether to recommend regulatory action (Table 22.1). The DALs for many processed foods specify the allowable number of insects, number of insect fragments, or percentage of commodity with defects. The DALs are reviewed periodically, and changes are made or new products are added to the list as needed. It is illegal to blend food with a higher DAL with similar food with a lower DAL. The FDA has legal authority to prevent delivery of adulterated food across state lines by going to court to seize the food exceeding the DAL, to seek to prohibit its shipment or sale, or to criminally prosecute the persons adulterating food.

Deep-bin cup (see **Trier**)

Degree-day—The degree-day method is used to forecast the emergence of larvae from eggs, the pupation of larvae, or the **eclosion** of adults from pupae. Insects are expected to develop only between a lower temperature threshold, below which the developmental

Table 22.1. Defect action levels (DALs) for insect infestation of various types of stored products

Commodity	Defect action level
	Dried fruit
Dates, whole	Average of 5% or more dates by count are rejects (moldy, dead insects, insect excreta, sour, dirty, and/or worthless) as determined by macroscopic sequential examination
Prunes, dried and dehydrated, low-moisture	Average of a minimum of 10 subsamples is 5% or more prunes by count are rejects (insect-infested, moldy or decomposed, dirty, and/or otherwise unfit)
	Grains
Cornmeal	Average of one or more whole insects (or equivalent) per 50 g OR Average of 25 or more insect fragments per 25 g
Wheat	Average of 32 or more insect-damaged kernels per 100 g
	Grain products
Macaroni and noodle products	Average of 225 insect fragments or more per 225 g in six or more subsamples
Wheat flour	Average of 75 or more insect fragments per 50 g
	Legume seeds
Peanut butter	Average of 30 or more insect fragments per 100 g
Peanuts, shelled	Average of 5% or more kernels by count are rejects (insect-infested, moldy, rancid, otherwise decomposed, and dirty) OR Average of 20 or more whole insects or equivalent in 100-lb bag siftings
Peanuts, unshelled	Average of 10% or more peanuts by count are rejects (insect-infested, moldy, rancid, otherwise decomposed, and dirty)
Peas and beans, dried	Average of 5% or more by count insect-infested and/or insect-damaged by storage insects in a minimum of 12 subsamples
	Nuts
Almonds	At or in excess of 5% unshelled or shelled nuts are rejects (insect-infested, rancid, moldy, gummy, and shriveled or empty shells) as determined by macroscopic examination.
Pecans	At or in excess of 10% unshelled or 5% shelled nuts are rejects (insect-infested, rancid, moldy, gummy, and shriveled or empty shells) as determined by macroscopic examination.
Pistachios	At or in excess of 10% unshelled or 5% shelled nuts are rejects (insect-infested, rancid, moldy, gummy, and shriveled or empty shells) as determined by macroscopic examination
Walnuts	At or in excess of 10% unshelled or 5% shelled nuts are rejects (insect-infested, rancid, moldy, gummy, and shriveled or empty shells) as determined by macroscopic examination
	Spices
Cinnamon, ground	Average of 400 or more insect fragments per 50 g
Curry powder	Average of 100 or more insect fragments per 25 g
Nutmeg, ground	Average of 100 or more insect fragments per 10 g

(*continued on next page*)

Table 22.1 (continued)

Commodity	Defect action level
Oregano, ground	Average of 1,250 or more insect fragments per 10 g
Oregano, crushed	Average of 300 or more insect fragments per 10 g
Paprika, ground	Average of more than 75 insect fragments per 25 g
Pepper, ground	Average of 475 or more insect fragments per 50 g
Sage, ground	Average of 200 or more insect fragments per 10 g
Sesame seeds	Average of 5% or more seeds by weight are insect-infested or damaged
Thyme, ground	Average of 925 or more insect fragments per 10 g

rate is assumed to be zero, and an upper threshold, above which insect mortality is assumed to be 100%. For stored-product insects, the lower temperature threshold has ranged from 8.8 to 18.3°C and the upper temperature threshold from 31.6 to 40°C. In the marketing system, daily temperature fluctuations are assumed to follow a sine wave, and the degree-days are calculated by summing over time the difference between hourly temperatures and the lower temperature threshold. The number of degree-days observed under field conditions is compared with the number of degree-days required for the completion of insect development at constant temperatures under laboratory conditions. When the accumulated number of degree-days in the field reaches the number required to complete development under laboratory conditions, development is expected to be complete.

Deltamethrin (see **Pyrethroids**)

Diagnostic dose—The diagnostic dose, at which susceptible insects die but the **heterozygous** and homozygous resistant insects survive, initially is determined using a **dose-response line**. The number of insects surviving at the diagnostic dose then can be used to estimate the insecticide resistance level more quickly and with fewer insects than with a dose-response line. Test kits can be prepared for quickly detecting insecticide resistance in the field. The level of insecticide resistance that can be detected increases as the number of insects tested increases. The numbers of insects (n) that need to be tested to detect insecticide resistance can be calculated as

$$n = \frac{log_{10}(1-P)}{log_{10}(1-F)} , \qquad (1)$$

where P is the probability of detecting at least one resistant individual and F is the minimum frequency of insecticide resistance in the insect population that can be detected.

Dichlorvos—Dichlorvos is an **organophosphate** insecticide that is registered in the United States for space treatments because it has a vapor pressure that is 1,000 times greater than other organophosphate insecticides at room temperature. Sometimes known as DDVP, it was introduced about 1955. Residues in flour milled from treated grain degrade quickly and are completely destroyed by cooking.

Dielectric heating—The chemical composition and molecular structure of materials determine their behavior in an electric field (i.e., their dielectric properties). Different materials have different dielectric properties and therefore absorb energy from radiofrequencies (1–100 megahertz) or microwaves (1–30 gigahertz) and convert it to heat at different rates. Dielectric heating generally increases with moisture content. Selective heating of insects can occur because insects contain higher moisture than a commodity. Infested material is exposed to radiofrequencies by passing it between two electrodes that produce an electric field; alternatively, microwaves are directed into an infested commodity. The effectiveness of dielectric heating also depends on how fast the surrounding commodity conducts heat away from the insects.

Dose-response lines—Pesticide resistance in field populations of stored-product insects can be determined by exposing insects to a series of doses of a residual insecticide and recording the mortality of insects at each dose. Offspring of field-collected insects may need to be reared in the laboratory to have enough insects for the dose-mortality test. Residual insecticide may be applied topically to each insect, or a known number of insects may be exposed to filter paper or a commodity treated with residual insecticide. A control group of insects under the same environmental conditions is used to determine the natural mortality in the absence of the residual insecticide. Insect mortality caused by the residual insecticide is corrected for natural mortality using Abbott's formula,

$$\text{Corrected mortality} = \frac{\text{Treatment mortality} - \text{Control mortality}}{1 - \text{Control mortality}}, \qquad (2)$$

where corrected mortality, control mortality and treatment mortality are the proportions of dead insects. When the control mortality exceeds 10%, the reason for this high mortality should be determined. The probit of the corrected mortality is regressed against the logarithm to the base 10 of the corresponding dose of the residual insecticide. The level of resistance is determined by comparing this regression line for the field strain with that for a susceptible laboratory strain.

Drag conveyor (see **Elevator**)

Eclosion—Eclosion is the emergence of an adult from the pupal stage or the hatching of a larva from the egg.

Electrophoresis—Electrophoresis is a relatively simple method for separation and identification of organic chemicals. For example, samples from the guts of larvae or adults of the predator *Teretrius nigrescens* were placed at one edge of a polyacrylamide or cellulose acetate gel, and a voltage was applied to move chemicals along the gel. Each gel was stained for esterases, and the pattern of bands was used to identify the prey species. For the predators captured in pheromone traps, specific prey proteins were identified for only 2%, compared with 13% for the predators from maize stores. Predators from maize stores may have eaten more recently than those captured in traps. Prey species could be identified by electrophoresis only within a 20-hr period after consumption. An antibody method might allow identification of prey species for up to a week, but an antibody must be prepared for each of the prey species.

Elevator—In the United States, an elevator is a facility for storing large volumes of grain. Elevators get their name from the bucket elevators that are used to move the grain from an underground receiving pit to the top of the facility, where it is weighed and distributed to different storage bins. A series of buckets on a vertical belt pick up grain at the bottom and dump it at the top. In addition to storing grain, elevators also sort, clean, size, dry, and fumigate grain. In small elevators, a distributor may direct grain to one of several storage bins. At larger elevators, an open belt or enclosed drag or screw conveyor moves the grain horizontally to different storage bins, or pneumatic conveyors may be used. Grain shipped from an elevator is discharged at the bottom of the storage bins onto a conveyor and again elevated and weighed before being loaded onto a truck, railcar, barge, or ship. Much of the grain is first received at a country elevator and later shipped to a terminal elevator. Terminal elevators in the United States are often larger than country elevators and have storage capacities of 5,405–540,540 metric tons (200,000 to 20 million bushels) of grain.

Ellis cup—The Ellis cup is a hand scoop used to sample grain on a moving conveyer belt. Samples are generally taken from the center and each side of the belt.

Enzyme-linked immunosorbent assay (ELISA)—This type of assay is used extensively for clinical diagnostics, and, more recently, ELISA methods have been developed to detect insects, pesticides, and aflatoxins in food. Antibodies for the protein myosin are produced by injecting a rabbit with myosin purified from cricket femur. To determine whether wheat is infested by insects, any myosin extracted from a 200-g ground sample of wheat with a dilute salt solution is allowed to react with the antibody. Colorimetric changes in adsorption at 414 nm are used to quantify the amount of myosin. ELISA can detect nanogram quantities of myosin from 17 stored-product insect species. Larvae in the second to fourth **instars**, pupae, and adults of *Sitophilus granarius* can be detected, but not eggs or first instar. A first instar *S. granarius* contains 0.08 ng of myosin, second instar 2 ng, third instar 5 ng, fourth instar 9 ng, pupa 2 ng, and adult 6.6 ng. Calibration curves can be used to estimate the number of insects in a grain sample when the age structure is known.

Ethylene dibromide—Ethylene dibromide ($C_2H_4Br_2$) was found to be toxic to insects in 1925, but it did not become widely used at that time because of its high cost. It is a liquid-type fumigant, nonflammable and 6.5 times heavier than air. It is one of the more-toxic fumigants to insects (for comparative data on its toxicity, see **Phosphine**), and insects remain moribund for many days before dying. It doesn't appear to effect germination of many cereal and vegetable seeds, but seeds of high oil content such as soy, flax, sesame, and groundnuts need prompt postfumigation aeration. A respirator fitted with an organic vapor canister should be worn when working with this fumigant. Ethylene dibromide has been used to fumigate grain and fresh fruits and vegetables and for spot fumigations in flour mills and food-processing plants, but it can no longer be used for stored products in the United States.

Fenitrothion—Fenitrothion is a broad-spectrum **organophosphate** insecticide with low mammalian toxicity. It is not fully effective against *Rhyzopertha dominica*. This residual insecticide has been used in several countries but is not registered for use in the United States against stored-product insects. It is not covered by patents, and the

composition varies among manufacturers. Applications of 5–10 mg/kg can provide protection for nine to 12 months. There is minimal penetration into the grain, so all but 10% of the insecticide is removed by milling and all but 1–2% by cooking.

Fenvalerate (see **Pyrethroids**)

Fluidized or spouted bed—These are terms used for methods of drying grain. Heat transfer by conduction is slow because commodities are good insulators. Heat can be transferred more quickly by moving hot air through a commodity or by using an airflow rate of 1.6 m/sec to separate kernels from one another, creating a fluidized bed (kernels floating in the air). The commodity also can be air cooled more quickly after heating to prevent damage using the fluidized bed. A spouted bed is a variation of the fluidized bed in which air enters through a nozzle, above which the grain is fluidized. The grain eventually circulates into areas of lower air velocity and leaves the spouted bed. Spouted beds work better for maize because the larger size of maize kernels makes them more difficult to fluidize.

Functional response—The number of attacks per parasitoid or predator generally increases at a decreasing rate as the density of host or prey increases. This functional response of natural enemies to host or prey density is described by the equation

$$N_a = N_i\left(1 - \exp\frac{-aTP_i}{1 + aT_h N_i}\right), \tag{3}$$

where N_a is the number of hosts attacked, N_i is the number of host or prey available, a is the instantaneous search rate, T is the total time for searching, P_i is the number of parasitoids or predators, and T_h is the handling time. Handling time is the interval between the time that a **natural enemy** encounters a host or prey and the time it begins its search again. Handling time alone may limit the attack rate at high host or prey densities, but the number of eggs that parasitoids can lay or satiation of predators may be limiting. The coefficients a and T_h are estimated by using a nonlinear least-squares method to fit the functional response equation to the data.

The functional response of natural enemies to host or prey densities provides a measure of their effectiveness in finding and suppressing insect pests. Functional responses have been studied for seven natural enemies and 10 species of host or prey on five commodities (Table 22.2). The column labeled "Maximum" gives the largest number of hosts or prey attacked per female per day (ranging from 3.2 to 43) and the host or prey density at which that occurred is given in parentheses, except for *Theocolax*, for which the tests were run and the results reported for 12 hr. Host or prey were eggs or small larvae for *Uscana* and *Xylocoris* and mature larvae for the other natural enemies. *Xylocoris* attacked young larvae of *Rhyzopertha dominica* inside wheat kernels as well as eggs of this species. Temperatures were 27–35°C, and the amount of commodity ranged from 100 grains of rice to 3.3 kg of wheat, except that no commodity was used for *Xylocoris* preying on *Sitotroga cerealella* and *Tribolium castaneum*. Functional responses were determined for *Anisopteromalus calandrae* on five species, *Xylocoris flavipes* on five, *Lyctocoris campestris* on three, and *Lariophagus distinguendus* on two. The functional responses were determined for two species of natural enemies attacking each of six species of host or prey and for three species

Table 22.2. Pests and their natural enemies for which functional response data have been collected

Insect pest species	Natural enemy species	Commodity	Maximum[a]	Source
Callosobruchus chinensis	*Anisopteromalus calandrae*	adzuki bean	18 (180)	Shin et al 1994
Callosobruchus chinensis	*Lariophagus distinguendus*	adzuki bean	8 (120)	Shin et al 1994
Callosobruchus maculatus	*Ansiopteromalus calandrae*	cowpea	14 (50)	Heong 1982
Callosobruchus maculatus	*Uscana lariophaga*	cowpea	43 (109)	van Alebeek et al 1996
Cryptolestes ferrugineus	*Cephalonomia waterstoni*	wheat	6.3 (100)	Flinn and Hagstum 1991
Oryzaephilus surinamensis	*Lyctocoris campestris*	maize	5 (40)	Parajulee et al 1994
Oryzaephilus surinamensis	*Xylocoris flavipes*	wheat	12.4 (30)	Donnelly and Phillips 2001
Plodia interpunctella	*Lyctocoris campestris*	maize	7.5 (40)	Parajulee et al 1994
Plodia interpunctella	*Xylocoris flavipes*	wheat	37.7 (300)	Donnelly and Phillips 2001
Rhyzopertha dominica	*Anisopteromalus calandrae*	wheat	13 (32)	Menon et al 2002
Rhyzopertha dominica	*Theocolax elegans*	wheat	6 (50)[b]	Flinn and Hagstrum 2002
Rhyzopertha dominica	*Xylocoris flavipes*	wheat	18.6 (200)	Donnelly and Phillips 2001
Sitophilus oryzae	*Lariophagus distinguendus*	rice	21 (70)	Hong and Ryoo 1991, Shin et al 1994
Sitophilus oryzae	*Anisopteromalus calandrae*	rice	25 (80)	Shin et al 1994
Sitophilus zeamais	*Anisopteromalus calandrae*	maize	9 (100)	Smith 1994b
Sitotroga cerealella	*Xylocoris flavipes*	no commodity	3.7 (8)	LeCato and Arbogast 1979
Tribolium castaneum	*Lyctocoris campestris*	maize	3.2 (40)	Parajulee et al 1994
Tribolium castaneum	*Xylocoris flavipes*	no commodity	11 (50)	Donnelly and Phillips 2001

[a] Largest number of hosts or prey attacked per female per day, with host or prey density at which that occurs in parentheses.

attacking *R. dominica*. For *Cryptolestes ferrugineus*, *R. dominica*, *Sitophilus oryzae*, and *S. zeamais*, the attack rate was highest at 30 or 35°C and decreased by two- to six-fold at 20°C.

Good manufacturing practices (GMP)—In the United States, the Food and Drug Administration has regulations for the manufacturing, processing, packing, and holding of human foods under sanitary conditions, which are called "current good manufacturing practices." These were first proposed in 1968 and approved in 1969. They cover the responsibilities of the plant management for disease control, personal hygiene, and training of employees; design, construction, and maintenance of the plant and grounds; cleanliness of the equipment and utensils; coding of lots so that they can be recalled if contamination is discovered; quality control; and record keeping. The ultimate goal of the good manufacturing practices is to produce food that is safe and wholesome and to protect the consumer from hazards associated with food production, distribution, and consumption.

Hazard Analysis and Critical Control Points (HACCP)—This is a monitoring-based food safety and quality-control program that prevents poisonous and deleterious substances from being present in the food. Hazards unique to each step in the food processing are identified (hazard analysis, HA), and monitoring for these hazards is done at specific manufacturing points (critical control points, CCP). CCP are points in the food-production process at which there is a high probability that improper control of food production may result in a hazard injurious or lethal to humans or animals. Manuals are written specifying the monitoring procedures; the critical limits for each hazard; the corrective actions required when microbial, chemical, or other contamination or other quality problems reach these critical limits; and the required records. Procedures for verifying that the HACCP program is working correctly also are required.

Heterozygote—An insect with two different genes for a trait is heterozygous, and one with two of the same gene is homozygous. If the trait is insecticide resistance, one gene may confer susceptibility and the other may confer resistance. If the resistance gene is dominant, the heterozygous insects will not be killed by a residual insecticide, but if the resistance gene is recessive, the heterozygous insects will die.

Hot spots—Localized grain heating can be caused by grain and fungal respiration when moisture is greater than 15% or by very high densities of *Cryptolestes ferrugineus* in drier grain (see Chapter 7). Heat production increases as the initial grain temperature increases from 15 to 35°C or grain moisture increases from 12 to 18%. At 30°C, densities of 900 *Rhyzopertha dominica*, *Sitophilus granarius*, *Sitophilus oryzae*, *Tribolium castaneum*, or *Tribolium confusum* per 200 g of wheat can raise the grain temperature by 2.6–5.9 degrees C over a 10-hr period. Heat production declines, and insects emigrate from hot spots when the temperature exceeds 38.5°C. In grain storage bins at **elevators**, thermocouples on cables are used to detect hot spots, and grain is **turned** to another bin to break up a hotspot.

Hydrogen cyanide—Hydrogen cyanide or hydrocyanic acid (HCN) was first used as a fumigant to manage insects in 1854. It is one of the fumigants most toxic to insects (for comparative data on its toxicity, see **Phosphine**.), but if an effective dose is not obtained quickly, **narcosis** can result. Being readily **sorbed**, it may not penetrate well.

Sorption is completely reversible for dry commodities. HCN is soluble in water, where it forms a weak acid, and it is lighter than air (0.9 times the weight of air). Because of its water solubility, it cannot be used with fresh fruits and vegetables. It does not reduce the germination of dry seed. The flammability limits of HCN in air are between 6 and 41% by volume and well above recommended dosages of up to 1.5% (16 g/m^3). However, at the beginning of a fumigation, near the release point, flammability may be a concern. When HCN is stored as liquid without a stabilizer, it can decompose and explode the container. A respirator should be used because HCN causes unconsciousness with a few breaths and death in a few minutes. This fumigant can no longer be used for stored products in the United States.

Impact machines—These centrifugal machines have two disks connected by pegs. Whole grain or flour is fed in at the center, and rotation of the disks accelerates it toward the edge. Multiple impacts with pegs and housing are more effective than a single impact, and so there may be two or more offset rows of pegs. Machines were first developed during the 1940s to break up particles during milling but were soon found to be effective in killing stored-product insects. They are also known as entoleters, pin mills, or infestation destroyers.

Inoculative releases (see **Natural enemies**)

Instar (see **Molt**)

Inundative releases (see **Natural enemies**)

Juvenile hormones—Juvenile hormones (JH) produced by insects prevent normal **metamorphosis** and **molting**, but they are not stable enough to be used for insect pest management. In at least several orders of insects, JH also are necessary for yolk formation by females and the development of accessory glands by males. Eggs treated with JH may fail to hatch or may produce inviable larvae. JH are unique to insects and should affect only insects. JH mimics, which would be more stable than natural JH, were needed for insect pest management. The more-stable JH mimic methoprene was discovered in 1973, fenoxycarb in 1981, and pyriproxyfen in 1984. While preventing normal development and **eclosion** of adults, these JH mimics do not kill adult insects and do cause larvae to feed longer, reach a larger size, and cause more damage. Also, when larvae can find untreated food, they resume normal development. JH mimics have been tested and shown to be effective on *Cadra cautella, Oryzaephilus surinamensis, Plodia interpunctella, Rhyzopertha dominica, Sitophilus oryzae*, and *Tribolium castaneum*. Methoprene is registered in the United States as a protectant for grain; an empty-bin spray; and a crack-and-crevice, surface, and spot treatment in food storage and processing facilities. Hydroprene (Gentrol) is registered for crack-and-crevice, surface, and spot treatments in food storage and processing facilities.

Lindane (see **Chlorinated hydrocarbons**)

Machine vision—Many industries use machine vision and pattern recognition methods for quality control inspections. One of the studies cited in Table 2.2 used statistical analysis of a digital color image of the sievings from an insect-infested 3-kg wheat

sample to sort 8 × 8 pixel subimages into insect and non-insect categories. Red, green, and blue images were analyzed to improve insect recognition, and subimages were analyzed to more effectively utilize the computer to make extensive calculations. Another machine vision study used a bar-shaped template to recognize the insects.

Malathion—Malathion is an **organophosphate** insecticide that is still registered for use in the United States after more than 40 years of use as a grain protectant, empty-bin spray, and crack-and-crevice treatment in food storage and processing facilities, even though many species of stored-product insect pests are now resistant. Malathion is registered for use as a dust or spray. Relatively little of the malathion deposited on grain penetrates, and 95% is removed or destroyed before reaching the consumer.

Mark-recapture (see **Release-recapture**)

Metamorphosis—Metamorphosis is a series of changes that occur in insects as they develop from egg to adult stages. Insects with complete metamorphosis have larval and pupal stages, while insects with incomplete metamorphosis have nymphal stages. The orders Coleoptera, Lepidoptera, and Hymenoptera listed in Table 1.1 have complete metamorphosis. The insects in the order Hemiptera and the psocids are examples of insects associated with stored products that have incomplete metamorphosis.

Methoprene (see **Juvenile hormone**)

Methoxychlor (see **Chlorinated hydrocarbons**)

Methyl bromide—In 1932, while using methyl bromide (CH_3Br) to reduce the flammability of liquid fumigants, researchers found methyl bromide to be more effective against insects than the liquid fumigants were. Methyl bromide is a nonflammable, nonexplosive fumigant widely used for plant quarantine and food-processing facilities. It is not as toxic as some other commonly used fumigants. (For comparative data on the toxicity of this fumigant, see **Phosphine**). It penetrates well, being 3.27 times heavier than air, and leaves residues only in the parts-per-million (ppm) range after aeration. However, methyl bromide can react chemically with a commodity so that it will not desorb, which can be a problem. Currently, methyl bromide is scheduled to be phased out by the year 2005 in the United States because it destroys the stratospheric ozone layer.

Methyl iodide—Methyl iodide (CH_3I), or iodomethane, is used for soil fumigation and is being considered for use with stored products.

Microwave radar—A microwave radar system was developed recently to detect hidden infestations of termites. Through a Doppler effect, the frequency of the radar reflected is slightly higher than the emitted frequency when an insect moves toward the receiver and slightly lower when it moves away. Microwave radar operates over a distance of <1–2 m (3.3–6.6 ft); high-moisture commodities can interfere with insect detection; and shielding to minimize background activity may be needed. Fifty adult *Oryzaephilus surinamensis* could be consistently detected in boxes of cornmeal mix and flour mix. In boxes with five *Tribolium castaneum* or 10–20 *O. surinamensis*,

insect infestations could be detected but with less certainty. Readings exceeded baseline in 2% of cornmeal boxes that were not infested and 12% of uninfested flour boxes.

Models—The most recent computer simulation models that have been developed to forecast stored-product insect population growth have at least four components (see Chapter 24). Equations describing the relationship between the rate of insect development, grain temperature, and grain moisture are used instead of degree-days to predict egg-to-adult developmental times. The distributed-delay method is used to simulate the variation between individual insects in developmental times. An array is used to keep track of adult age by moving them to the next element each day. Adult survival time is determined either by the number of elements in the array or an equation describing adult survivorship. Equations describing the relationship among age, temperature, and egg production are used to predict the number of eggs laid each day.

Molt—Molting or ecdysis is the process of shedding the old **cuticle** as an insect enters the next instar, or developmental stage. Insects of the orders Lepidoptera, Coleoptera, and Hymenoptera have complete metamorphosis and go through three morphologically distinct immature stages, i.e., egg, larva, and pupa. The larval stage of stored-product insects commonly has three to seven instars, but there may be more. The instars are referred to by number, with the first instar occurring between egg hatch and the first larval molt. Orders Psocoptera, Hemiptera, and Acarina have incomplete metamorphosis, going through the egg and several morphologically similar nymphal stages before becoming adults.

Narcosis—Narcosis is a state of stupor or arrested activity. Low doses of **hydrogen cyanide** and high doses of **phosphine** can paralyze insects and thus reduce their susceptibility to these and other fumigants. The maximum recommended dosage of hydrogen cyanide should be reached as quickly as possible to prevent narcosis. Monitoring the concentration of phosphine may be necessary to avoid high dosages that cause narcosis and to compensate for losses from leakage and **sorption**. Some fumigants should not be used together. Narcosis caused by hydrogen cyanide can protect insects from **methyl bromide**, but the narcosis caused by phosphine does not.

Natural enemies—Parasitoids, predators, and pathogens are natural enemies that kill stored-product insect pests. Such natural suppression is prevalent, but its impact on stored-product insect pests rarely has been measured. To date, 58 species of insects have been studied as natural enemies of 79 species of stored-product insect pests. Large-scale tests have been done on the efficacy of *Theocolax elegans* against *Rhyzopertha dominica*; *Anisopteromalus calandrae* against *Sitophilus zeamais*; *Cephalonomia waterstoni* against *Cryptolestes ferrugineus*; *Holepryis sylvanidis* against *Oryzaephilus mercator*; *Dinarmus basalis*, *Eupelmus vuilleti*, and *Uscana lariophaga* against *Callosobruchus maculatus*; and *Habrobracon hebetor*, *Trichogramma* spp., and *Xylocoris flavipes* against *Cadra cautella* and *Plodia interpunctella*. In the United States, all of these parasitoids and predators except those attacking cowpea weevils have been exempted from the requirements of a tolerance for residue by the Environmental Protection Agency (EPA).

Parasitoid larvae generally feed on only one host during their development, while immature and adult predators often attack many prey. Because these natural enemies have been spread worldwide along with their stored-product host or prey, classical biological control (importing parasitoids into areas where only the host or prey has been introduced) generally is not needed. The largest full-scale study has been for the predator, *Teretrius nigrescens*, against introduced *Prostephanus truncatus* in Africa. This is an example of classical biological control. Because natural enemies can be found associated with stored-product insect pests in most situations, conservation of natural enemies can be an important component of an insect pest management program. Conservation of natural enemies may be simply not fumigating when the natural enemies are abundant enough to suppress the insect pest population. Natural enemies can be self-perpetuating and provide long-term suppression. However, after fumigation, immigrants and the surviving insect pests can cause a rapid recovery of the insect pest population because the natural enemies have been killed.

Augmentation of natural enemies can improve their effectiveness. Providing diapausing or sterilized hosts is an example of augmentation. If some species of natural enemies are not present, inoculative releases of small numbers of these species may be sufficient because many parasitoids can complete two generations for each host generation and suppress the insect pest population. When necessary, damage can be minimized by inundative releases of large numbers of mass-reared natural enemies, but many of them may die for lack of host or prey when the releases are too large. Applying pathogens in the same manner that residual insecticides are applied is an example of an inundative release.

Near-infrared spectroscopy (NIRS)—NIRS is routinely used in grain quality laboratories to measure several grain quality characteristics such as oil and protein content. NIRS can identify stored-product insects to species because the **cuticle** of each species has a unique chemical composition. This unique chemical composition causes molecules to vibrate at unique frequencies and to absorb near-infrared energy at these frequencies and overtones of these frequencies. Absorption spectra were measured from 400 to 700 nm and analyzed using partial least squares regression and a type of principal component analysis.

Nuclear magnetic resonance (NMR)—Organic chemists commonly use NMR spectroscopy for structural analysis of chemicals. The sample is placed in a magnetic field and irradiated with low-power radiofrequency. At certain frequencies, atomic nuclei within the sample will absorb the radiation and enter an excited state. After a time, the nuclei will re-emit the radiation. How much radiation is re-emitted, when re-emitted radiation is recorded, and the peak area of this curve are directly proportional to the number of absorbing nuclei. An uninfested wheat kernel gives a broad, shallow peak, and an insect-infested wheat kernel gives a sharp peak, whose area decreases as the kernel is consumed. The decrease in area is related to the size of the insect.

Organophosphates—Organophosphate insecticides, derived from work on nerve gases during World War II, are the largest class of insecticides. Like **carbamates**, they are inhibitors of the neurotransmitter, cholinesterase. This class includes **dichlorvos,** which has been registered in the United States for space treatments; **malathion**, **chlorpyrifos-methyl,** and pirimiphos-methyl (Actellic), which have been registered as

protectants in the United States; and acephate, diazinon, and chlorpyrifos (Dursban), which have been registered for crack-and-crevice treatments in food storage and processing facilities in the United States. Diazinon also has been registered for spot treatments.

Parasitoids (see **Natural enemies**)

Pathogens (see **Natural enemies**)

Pelican sampler—A pelican sampler is a leather pouch on the end of a pole used to sample free-falling grain as it is being loaded or unloaded. Ideally, the pelican is moved through the grain stream rapidly enough that it is not full until it is completely through the grain stream.

Permethrin (see **Pyrethroids**)

Pheromone—Sex pheromones are chemical signals released by one sex to attract the other sex of the same species for purposes of mating. They can be long-distance attractants and can be detected at very low concentrations. Female of the families Pyralidae, Gelechiidae, Tineidae, Anobiidae, and Dermestidae and males or females of the family Bruchidae release sex pheromones. Adults of species belonging to these families generally live only a few days or weeks.

Aggregation pheromones, which attract both sexes, are generally released by males of the long-lived beetles of the families Bostrichidae, Curculionidae, Laemophloeidae, Silvanidae, and Tenebrionidae. Many studies indicate that feeding is necessary for the production of aggregation pheromones. Aggregation pheromones often work best when food odors also are present. Some species utilize both sex and aggregation pheromones.

Pheromones have been identified for 46 species of stored-product beetles and moths (Table 1.1). Most of these pheromones have been synthesized, and pheromones or parts of pheromone for 25 insect species have been commercially available as lures for traps, for use with residual insecticides as attracticides, and to suppress mating by permeating the atmosphere.

Specificity is due to pheromones having multiple compounds or isomers. Therefore, for the best results when they are used as lures in traps, the pheromone components must be released in the proper ratio and at the proper time of day or season. Slow, near-constant pheromone release rates can be achieved for several weeks by incorporating pheromones into a rubber or plastic septa or releasing them from a reservoir through semipermeable membranes. These formulations also slow the degradation of pheromones. Devices that spray a precise dose of pheromone at preset time intervals also have been used to reduce mating by permeating the atmosphere with pheromones.

Phosphine—Phosphine, or hydrogen phosphide (H_3P), was first used against *Sitophilus granarius* in 1936. It is a highly poisonous and flammable gas that is only 1.2 times heavier than air. Phosphine formulations may have a strong carbide, garlic, or ammonium odor. Phosphine is practically insoluble in water, fats, and oils and has little reaction with most commodities.

Table 22.3. Concentration × time products (LD_{99}[a] in mg/L × hours) for several fumigants against two species of stored-product insect pests with exposure of 5 hr at 25°C[b]

Fumigant	*Sitophilus granarius*	*Tribolium confusum*
Acrylonitrile	11.0	19.5
Carbon disulfide	325.0	560.0
Carbon tetrachloride	4,495.0	2,025.0
Chloropicrin	150.0	57.5
Ethylene dibromide	34.5	31.0
Ethylene dichloride	1,230.0	365.0
Ethylene oxide	36.0	127.5
Hydrogen cyanide	80.0	8.5
Methyl bromide	28.0	64.0
Phosphine	1.0	0.5
Sulfuryl fluoride	17.5	55.0

[a] Lethal dose for 99% of the population.
[b] Data from Monro 1969.

Table 22.3 compares the toxicity of phosphine with that of several other fumigants. Phosphine penetrates well but kills insects slowly (at least three days) by interrupting their respiration. An insect's spiracles do not need to be open, but oxygen must be present for phosphine to work. High dosages can cause **narcosis** and reduce insect mortality. Larval and adult stages are more susceptible than egg and pupal stages. Holding fumigant long enough for the eggs to hatch and the adults to **eclose** from pupae improves the effectiveness of this fumigant. Phosphine does not appear to affect germination or the milling qualities of the grain.

Methods were developed in Germany in the 1940s for safely using this fumigant for grain. Aluminum phosphide in moisture-permeable paper packets (sachets) is inserted into the grain or dropped on the grain surface at regular intervals. Gloves should be worn to prevent contact with the fumigant during application. Atmospheric moisture liberates phosphine from aluminum phosphide. Subsequently, aluminum phosphide was compressed into tablets with ammonium carbamate to slow its release and make the fumigant less combustible. Pellets, another formulation, are one fifth the size of the tablets. Magnesium phosphide formulations also are available; these release phosphine at lower temperatures and moistures than aluminum phosphide formulations.

Tablets can be thrown by hand or automatically dispensed into a moving grain stream. Tablets, packaged 30 per hermetically sealed tube, have a long shelf life but should be stored in a cool, dry, well-ventilated place. They release phosphine over a 36-hr period at 25°C. A more recent formulation is sold as 2% phosphine plus 98% carbon dioxide gas (ECO_2Fume) in a high-pressure gas cylinder. Phosphine apparently leaves only parts-per-billion residues in grain after aeration. Applicators should monitor phosphine concentrations and carry a respirator for use if needed.

Photoperiod—These natural day-night changes in light intensity and seasonal changes in day length influence stored-product insect physiology, behavior, and ecology (Table 22.4). Changes in light intensity either directly initiate periods of feeding, diapause, **eclosion**, locomotion, **pheromone** release, mating, or egg laying, or they entrain an internal endoge-

Table 22.4. Influences of photoperiod on stored-product insect life histories and behavior[a]

Species	Influences	Source
Acanthoscelides obtectus	development, mortality, egg laying	Stamopoulos 1989
Amyelois transitella	pheromone release, mating	Landolt and Curtis 1982
Anagasta kuehniella	eclosion, larval movement	Giebultowicz and Cymborowski 1976
	eclosion	Moriarty 1959
	egg laying	Bell 1981
	development, mortality, egg laying	Cymborowski and Giebultowicz 1976
	sperm activity	Thorson and Riemann 1977
	pheromone release-response	Traynier 1970
Cadra cautella	eclosion, mating, egg laying	Steele 1970
	egg laying	Bell 1981, Hagstrum and Tomblin 1973
	egg laying, adult movement	Madrid and Sinha 1983
Callosobruchus maculatus	polymorphism	Utida 1969
Callosobruchus subinnotatus	mating, egg laying	Mbata et al 1997
Corcyra cephalonica	egg laying	Bell 1981
	pheromone response	Singh and Sidhu 1975
Ephestia elutella	egg laying	Bell 1981
Gnatocerus cornutus	development	Savvidou and Bell 1994
Habrobracon hebetor	diapause	Zinovjeva 1992
	oocyte maturation	Lum and Flaherty 1973
Oryzaephilus mercator	development, mortality, egg laying	Okiwelu et al 1998
Plodia interpunctella	egg laying	Bell 1981, Lovitt and Soderstrom 1973, Lum and Flaherty 1970, Mbata 1985
	larval movement, pupation, eclosion, adult movement	Arai 1979
	movement, egg laying	Madrid and Sinha 1983
	pheromone release	Nordlund and Brady 1974a,b
Rhyzopertha dominica	development, egg laying	Aslam et al 1994
	pheromone release	Bashir et al 2003
Sitotroga cerealella	mortality, egg laying	Ismail et al 1988
Sitophilus granarius	susceptibility insecticide	von Reinhardt and Esther 1971
Tenebrio molitor	development	Tyshchenko and Ba 1986
Tribolium castaneum	pheromone production-response	Abdel-Kader et al 1987
Trogoderma glabrum	pheromone release-response, concealment	Shapas and Burkholder 1978
	pheromone release	Hammack and Burkholder 1976
	pheromone release-response, mating	Vick et al 1973

(*continued on next page*)

Table 22.4 (continued)

Species	Influences	Source
Trogoderma granarium	development, egg laying	Odeyemi and Hassan 1993
	pheromone release-response	Hammack and Burkholder 1981
Trogoderma inclusum	pheromone release-response, concealment	Shapas and Burkholder 1978
	pheromone release-response, mating	Vick et al 1973
Trogoderma variabile	pheromone release-response, concealment	Shapas and Burkholder 1978
Uscana lariophaga	parasitization	Van Huis and Appiah 1995

[a] See Bell 1994 for a review of studies on photoperiodic initiation and termination of diapause and Table 3.2 for studies on photoperiodic regulation of stored-product insect mobility.

nous biorhythm for these activities. Photoperiods consist of a photophase (day) and scotophase (night), which are often abbreviated (e.g., 16L:8D for 16 hr of light and 8 hr of dark). Insects active during the photophase are diurnal, and those active during the scotophase are nocturnal. The transitions in light intensity between night and day (dawn) or day and night (dusk) are twilight. Insect activity is said to be "crepuscular" when the insect is active at both dawn and dusk. Because the earth's axis is tilted 23.5°, day length varies with latitude (0–24 hr) and season of the year. Photoperiods in the temperate regions vary from long days (16L:8D) during the summer to short days (8L:16D) during the winter.

The majority of the research on the influence of photoperiod on stored-product insects has focused on the times of release and response to pheromones, mating, egg laying, mobility, and diapause. With dusk at 17:00–18:00 hr, *Cadra cautella* adults eclosed from the pupal stage between 15:00 and 16:00 hr, released pheromone and mated between 17:00 and 18:00 hr, and laid eggs primarily at dusk, but there may be another smaller egg-laying peak at dawn. The time at which females lay eggs also can be determined by thermoperiod. Temperatures falling 0.15 and 0.3 degrees C per hour in continuous light also resulted in egg laying by *C. cautella*.

For six stored-product insect species, photoperiod influenced their developmental times by as much as several days. For four insect species, it influenced the number of eggs laid and their mortality. In some cases, this simply may be a result of longer light or dark periods, which allow insects to feed or lay eggs over a longer period of time. For two species of pyralid moths, continuous light reduced the fertility of males, delayed egg laying by females, and reduced the number of eggs laid. Photoperiod also influenced the timing of the wandering of mature moth larvae, adult movement and concealment, pupation, parasitization, diapause, polymorphism, and susceptibility to residual insecticides.

Pneumatic conveyor (see **Elevator**)

Predator (see **Natural enemies**)

Pirimiphos-methyl (see **Organophosphates**)

Probe trap—The probe trap is a cylindrical tube with downward-slanting perforations (outside to inside) in the upper section, through which insects drop into the trap. Probe traps are pushed into grain to monitor stored-product insect populations. The lower section of the trap is separated from the upper section by a funnel that helps to keep insects from escaping from the insect collection vial below. These traps have a pointed tip for easy insertion into the grain. The first probe traps were made of brass, but they were later made of plastic to reduce cost and were sold commercially. Traps with various sizes and numbers of holes have been tested to see whether trap efficiency could be improved. Also, traps with upward-slanting perforations have been shown to reduce the amount of trash falling into the trap without reducing its efficiency. Less trash makes the counting of insects easier. A commercial coating (Fluon) may be put on the rim of the collection vial, and a killing agent or food may be added to the insect-collection vial to reduce the number of insects escaping. Baiting traps with pheromone (or the moisture and pheromone produced by the insects collected in the trap) may increase trap catch. Quinones produced by *Tribolium* spp. may reduce the number of captures. In some cases, light-sensitive diodes have been added to the funnel to remotely monitor the number and species of insects caught.

Pyrethrins—Pyrethrins are botanical insecticides extracted from pyrethrum, an oil from the flowers of *Tanacetum cinerariaefolium* (formerly in the genera *Pyrethrum* and then *Chrysanthemum*), which has been used for over 170 years to suppress insect pest populations. The major insecticidal components of pyrethrum are two alcohols (pyrethrolone and cinerolone) and two acids (chrysanthemic and pyrethric) that combine to form four esters. Pyrethrins have remarkably low mammalian toxicity and almost instantaneous knockdown of insects. Pyrethrins and synthetic **pyrethroids** are flushing agents that cause insects to move rapidly and come out of their hiding places. Many of the insects that are rapidly immobilized by pyrethrins recover after several hours. The **synergist** piperonyl butoxide is added to prevent detoxification of pyrethrins and insect recovery. Pyrethrins are not very stable in humid or well-lighted environments, and piperonyl butoxide also is an antioxidant that prevents degradation.

Pyrethroids—This class of residual insecticides includes the natural botanical **pyrethrins** and the more-stable synthetic versions of pyrethrin, including allethrin, bioresmethrin, **cyfluthrin**, deltamethrin, fenvalerate (Pyrid), lambda-cyhalothrin, permethrin, and resmethrin. Allethrin is an ester of chrysanthemic acid and allethrolone. It is quite similar to the pyrethrins, but resmethrin, permethrin, fenvalerate, deltamethrin, cyhalthrin, and cyfluthrin have more extensive changes. Resmethrin is an isomeric mix, and bioresmethrin is one of the *trans* isomers. Permethrin was developed to be degraded less by light. The residues of bioresmethrin are destroyed by cooking, but those of permethrin and fenvalerate are not.

Several of the synthetic pyrethroids are very effective against *Rhyzopertha dominica* at 1 or 2 mg/kg and have been used in combination with **organophosphates** that are not effective against this species. **Synergized** pyrethrins are registered as grain protectants and empty-bin sprays, and cyfluthrin is registered as an empty-bin spray in the United States. Allethrin is registered for use with a synergist as a spray or aerosol, and cyfluthrin, fenvalerate, lambda-cyhalothrin, and resmethrin are registered for use as crack-and-crevice or spot treatments in food storage and processing facilities in the

United States. Cyfluthrin and fenvalerate also are registered for use as general surface treatments in these facilities.

Release-recapture—Marking, releasing, and recapturing insects is a way of estimating insect population density from the ratio of marked to unmarked insects caught. An alternative to releasing insects is to use an equal number of self-marking and capture traps and to assume that the probability of being marked is equal to the probability of being captured. The accuracy of estimates depends upon insect survival, behavior, and capture rate not being affected by marking; the marked insects becoming completely mixed with the general insect population; and the population size not changing as a result of immigration, emigration, birth, or death while the estimates are being made.

Resistant seed—Seeds may be resistant to insects because females do not lay eggs on these seeds or because the seeds are unsuitable for the development of insect larvae. Resistance may be due to physical barriers or biochemical content. Germ plasm with significant resistance to stored-grain insects is not available to plant breeders. Transgenic introduction of biochemical resistance may be an alternative. Six possibilities have been investigated: 1) alpha-amylase digestive enzyme inhibitor in pea seed against bruchid beetles, 2) *Bacillus thuringiensis* endotoxin in maize seed against *Plodia interpunctella*, 3) avidin from chicken eggs in maize seed against several species of stored-product beetles, 4) the cysteine proteinase inhibitor oryzacystatin from rice in oilseed rape against the cabbage seedpod weevil, *Ceutorhynchus assimilis* (Paykull), 5) amylase-subtilisin inhibitor from barley in rice against *Cryptolestes pusillus*, and 6) barley trypsin inhibitor CMe in wheat against the migratory grasshopper, *Melanoplus sanguinipes* (Fabricius). Other candidates for transgenic introduction of seed resistance include immunoglobulins, lectins, chitinases, cholesterol esterases, vegetative insecticidal proteins, and peroxidases that have been expressed in plants. Seed resistance provides an easy way to apply residual insecticides, but, as with other residual insecticides, a good resistance management plan will be needed to maintain the usefulness of resistant seed as a stored-product insect pest management tool.

Screw conveyor (see **Elevator**)

Sorption—Gases are held on the surfaces of solids by weak intermolecular forces (adsorption) or within a solid by capillary forces (absorption). Some gases are sorbed more in commodities with a high water content, while others are sorbed more in those with a high lipid content. The gases may be removed from the solid (desorption) by aerating to reduce the concentration of the gas in the air around the solid. However, some gases react with the solid to form a new chemical, do not desorb, and leave permanent residues. The rate of sorption of water vapors by a commodity often differs from the rate of desorption.

Spinosad—Spinosad is a bacterial fermentation product that is currently registered as a residual insecticide on more than 250 crops in more than 60 countries. It is effective as a stomach and contact poison against insects and has low mammalian toxicity. Spinosad has been fully labeled in the United States for use on stored wheat, maize, sorghum, barley, oats, rice, millet, and birdseed at 1 ppm (1 mg/kg) with a tolerance of 1.5 ppm. It is effective against many stored-product insect species: *Rhyzopertha*

dominica at 0.1 mg/kg and *Cryptolestes ferrugineus*, *C. pusillus*, *Plodia interpunctella*, *Sitophilus oryzae*, and *S. zeamais* at 1 mg/kg. *Oryzaephilus surinamensis* and *Tribolium castaneum* are less susceptible than other stored-product insect species. Larvae of these species are more susceptible than adults. The predator *Xylocoris flavipes* survived on spinosad-treated wheat, but the parasitoids *Anisopteromalus calandrae*, *Habrobracon hebetor*, and *Theocolax elegans* were killed. Spinosad degrades quickly in sunlight, but in farm bins, applications of 0.1–6 mg/kg are stable for one to two years.

Spouted bed (see **Fluidized or spouted bed**)

Sublethal effects—Low dosages of residual insecticides, fumigants, and modified atmospheres may have sublethal effects on several aspects of stored-product insect pest biology (Table 22.5). The sublethal effects most commonly studied were those affecting insect reproduction. The reproductive period often was shortened; fewer eggs were laid or eggs were laid sooner; and fertility was sometimes lower. For *Tribolium castaneum*, **dichlorvos** and **malathion** delayed reproduction, and the surviving females produced as many or more offspring than the controls. Of concern to pest management programs for stored-product insects may be the release of fertile eggs, which develop into adults, by *Cadra cautella* or *Plodia interpunctella* females dying from exposure to carbon dioxide, dichlorvos, or malathion. Sublethal doses of **phosphine** did not change the number of the eggs laid by *Sitophilus granarius*. **Juvenile hormones** reduced mating by *P. interpunctella* and reproduction by *Lasioderma serricorne*. **DDT** caused *Sitophilus granarius* to be attracted to light instead of moving away, and it increased the quinone production and reduced the metabolic rate of *Tribolium confusum*. **Carbon disulfide** and **methyl bromide** increased the developmental time of *T. confusum*. **Sulfuryl fluoride** increased the developmental time of *Lasioderma serricorne* eggs, and the developmental time of eggs depended upon the fumigant dosage. This may be important in determining when to fumigate again to kill the larvae hatching from the more-resistant egg stage. An 80:20 mixture of **carbon tetrachloride** and carbon disulfide at first increased the respiration of *T. confusum* adults and then caused below-normal respiration.

Sulfuryl fluoride—Sulfuryl fluoride (SO_2F_2) was first reported as a fumigant in 1957. It is a volatile, nonflammable gas 2.9 times heavier than air that is currently being sold for postharvest use as the commercial product ProFume in compressed gas cylinders. **Sorption** is similar to that of methyl bromide. Sulfuryl fluoride has little or no effect on the germination of weed and crop seeds, but it is injurious to green plants, vegetables, fruits, and tubers. It has no objectionable color, odor, or corrosive reaction with photographic supplies, metals, paper, leather, rubber, plastics, or cloth. For some stored-product insect pest species, it is more toxic than methyl bromide for larvae, pupae, and adults and equally toxic for eggs. (For comparative data on the toxicity of this fumigant, see **Phosphine**.) Exposure to 35 g/m^3 for 1 hr was effective against *Anagasta kuehniella*, *Plodia interpunctella*, *Sitophilus granarius*, *Stegobium paniceum*, *Tenebrio molitor*, *Tribolium confusum*, and *Trogoderma versicolor*. The eggs are the stage most tolerant to sulfuryl fluoride, possibly because it does not penetrate the eggshell layers well.

Table 22.5. Sublethal effects of a low dosage of residual insecticides, fumigants, and modified atmospheres on stored-product insects

Species	Chemical	Influence[a]	Source
Anagasta kuehniella	carbon dioxide	R	Press and Flaherty 1973
Attagenus unicolor	dichlorvos	R	Zettler and LeCato 1974b
	malathion	R	Zettler and LeCato 1974b
Cadra cautella	avermectins	R	Lum and Halliday 1989
	carbon dioxide	R	Press and Flaherty 1973
	dichlorvos, malathion	R	Yadav 1977
Callosobruchus chinensis	diazinon	R	Dutt and Roy 1984
	dimethoate	R	Dutt and Roy 1984
	fenitrothion	R	Dutt and Roy 1984
	fenthion	R	Dutt and Roy 1984
	methyl demeton	R	Dutt and Roy 1984
Lasioderma serricorne	juvenile hormone	R	Marzke et al 1977
	pyrethrum	R	Tenhet 1947
	sulfuryl fluoride	D	Su and Scheffrahn 1990
Plodia interpunctella	carbon dioxide	R	Flaherty et al 1973, Lum et al 1973, Press and Flaherty 1973
	dichlorvos	R	Lum et al 1973
	juvenile hormone	M	Oberlander et al 1975
	malathion	R	Lovitt and Soderstrom 1973
Sitophilus granarius	carbon disulfide	R	El-Nahal and El-Halfawy 1973a
	DDT	L	Barlow 1968
	phosphine	R	Reynolds et al 1967
	phosphine	T	Bond and Upitis 1973
	pyrethrins	R	El-Nahal and El-Halfawy 1973c
Sitophilus oryzae	carbon disulfide	R	El-Nahal and El-Halfawy 1973a
	pyrethrins	M	Boles 1974
	pyrethrins	R	Boles 1971
	pyrethrins	R	Chadwick 1962
	pyrethrins	R	El-Nahal and El-Halfawy 1973c
Tenebroides mauritanicus	phosphine	T	Bond and Upitis 1973
Tribolium castaneum	80 CCl_4:20 CS_2	Resp.	Carlson 1968
	permethrin	R	Hodges and Meik 1986
	phosphine	T	Hobbs and Bond 1989
Tribolium confusum	carbon disulfide	D	El-Nahal and El-Halfawy 1973a
	carbon disulfide	R	El-Nahal and El-Halfawy 1973a
	DDT	R	Loschiavo 1955, Taher and Cutkomp 1983
	dichlorvos	R	Zettler and LeCato 1974a
	ethylene dibromide	R	Loschiavo 1960
	lindane	R	Taher and Cutkomp 1983

(*continued on next page*)

Table 22.5 (continued)

Species	Chemical	Influence[a]	Source
	malathion	R	Zettler and LeCato 1974a
	methyl bromide	D, R	El-Nahal and El-Halfawy 1973b
	phosphine	T	Bond and Upitis 1973
	pyrethrins	Resist.	Cline et al 1984
	pyrethrins	Repel.	Cline et al 1984
	sodium fluoride	R	Johansson and Johansson 1972

[a] R = reproduction, M = mating, L = light response, D = development, T = tolerance, Resp. = respiration, Resist. = resistance, Repel. = repellency.

Synergist—In terms of insect pest management, a synergist is a chemical that is inactive or negligibly active as a residual insecticide but increases the toxicity of residual insecticides. When the synergist piperonyl butoxide is added to **pyrethrins** in a ratio between 1:5 and 1:10, only a quarter or less of the normal amount of pyrethrin is needed, and the cost of applying this residual insecticide is reduced. The maximum residue tolerance for piperonyl butoxide on cereal and cereal products is 20 mg/kg. Piperonyl butoxide also is a synergist for **carbamate** and **organophosphate** insecticides. It synergizes in part by inhibiting the oxidative breakdown of residual insecticides by mixed-function oxidases. Other synergists include sesame oil and sulfoxide.

Test weight—Test weight, or bulk density, is the amount of grain that will flow into a standard volume without packing. It is measured by filling a 1-L (2,150.42-in.^{3}) cup, leveling the grain by moving a wooden stick across the cup, and then weighing the cup full of grain. The accepted weight per bushel in the United States is 60 lb for wheat and soybeans; 56 lb for maize, rye, and flax; 48 lb for barley; and 32 lb for oats. Test weight tends to decrease as moisture content or dustiness increases.

Trier—Triers, probes, or spears are used to remove a sample from commodities in bags, storage bins, or transportation vehicles. Triers for bags are generally shorter (15 cm to 1 m) and of smaller diameter (12 mm) than those used for bulk commodities so as to damage the bags as little as possible. Bag triers may be as simple as a pointed hollow tube with an opening on one side that is pushed horizontally into a bag with the open side down and then turned to allow a grain sample to pour in and come out through the handle. More elaborate triers are double-walled tubes with openings at intervals along their lengths. After the trier is inserted vertically into a bulk commodity or horizontally into bags, the inner tube is turned to align the holes in the two tubes so that the commodity can fill the trier. The inner tube is turned to close the trier again before it is withdrawn. The inner tubes of some triers are compartmented, and the sample is dumped through the same holes used to take the sample. With an uncompartmented inner tube, the sample can be dumped through a hole in the handle. Some uncompartmented triers are made so that the bottom holes open before the top holes because otherwise, when the trier is used vertically, more grain would enter through the top holes than through the bottom holes.

Triers of 1.5, 1.8, or 2.4 m in length are used to take samples from trucks; triers of 3.0 m are used to take samples from hopper trucks or railcars; and triers of 3.6 m are used to take samples from barges and ships. Another type of grain probe, the deep-bin cup, can take roughly 250-g grain samples from deep within a grain mass because of its small size. The deep-bin cup, like the trier, is a metal tube with a pointed tip. Metal rods attached to the cap are used to push the deep-bin cup into the grain. A number of 4-ft sections of rods can be screwed together to push the cup deeper. After the deep-bin cup is pushed to the depth from which a grain sample is to be taken, pulling up on the rods opens the cap and allows a grain sample to flow into the tube. The cap is attached to the sample container by a metal loop so that the rods also can be used to pull the deep-bin cup with the grain sample out of the grain mass.

Vacuum probes, with the opening at the tip, use suction to take the grain samples. Because the grain is removed as the probe is pushed into the grain, it is possible to take samples from even deeper in the grain mass than with a deep-bin cup. Vacuum probes on remote-controlled mechanical arms are used at **elevators** to sample grain in trucks. A video camera may be used to allow the operator to position the probe at the desired place for taking the grain sample, and the sample may be moved pneumatically to the location where the grain grading is done.

Turning—Movement of grain from one storage bin to another is called "turning." Grain is turned at **elevators** to cool it, to fumigate it, to break up a hot spot, and to blend grain from different bins to obtain a more uniform grain quality. Blending also can be done by discharging grain from several storage bins onto the conveyor belt when shipping grain. Turning can cost US$0.48–0.67 per ton (US$0.013–0.018 per bushel).

Vacuum probe (see **Trier**)

X-ray—A sample of grain is spread out in a single layer and x-rayed. The developmental times of seven species of stored-product insects developing inside kernels have been determined using radiographs (see Table 2.4). Fifty percent of eggs, 75% of first instar, 87% of second and third instar, 96% of fourth instar, 100% of prepupae, and 99% of pupae and adults of *Sitophilus granarius* were recognized on radiographs. Radiographs have been digitized so that the number of insect-infested kernels can be determined using **machine vision** and pattern recognition. For *S. granarius*, machine vision recognized 6% of second instar, 12% of third instar, 72% of fourth instar, 85% of prepupae, 47% of pupae, and 77% of adults. For *S. zeamais*, machine vision recognized 5% of first and second instar, 17% of third instar, 51% of fourth instar, 22% of prepupae, 36% of pupae, and 53% of adults. This higher recognition for the *S. granarius* may be a result of its larger size. The widths of *S. zeamais* feeding chambers averaged 69–75% of those of *S. granarius*. Machine vision generally was not quite as good as human recognition.

Sampling Exercise

The objective of this exercise is to improve your understanding of the relationship between insect density and the difficulty of estimating insect density.

A low-density population (Figure 23.1 with a mean of 0.2 insects per sample unit) and a high-density population (Figure 23.2 with a mean of 2.0 insects per sample unit) are to be sampled by selecting a random coordinate from Figure 23.3 and entering into Figure 23.4 the insect density for the sample unit at that grid coordinate. The running average is calculated by dividing the cumulative sum of the number of insects in the sample units by the number of sample units taken. Coordinates are selected by following a row, a column, or a diagonal until the running average equals the actual insect density (0.2 or 2.0).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1						3															3
2				2													2				
3					1						3										
4											2			4							
5	2	1																			
6		1											4				3				
7			5								1										
8																			2		
9				5									1								
10																				2	
11																					
12								2					3								
13	1										1										
14						1				7				7			4			2	
15	3		2								5										
16												1									
17																					
18																					
19			1			1								1							
20																					
21															4						
22	1				1		1														
23											1										
24														4					1		
25																		6			
26										1					6						
27													4			5		2	3		
28																					
29							2												5	2	
30																			3		
31						1															

Figure 23.1. Example of a tabulation of a low-density insect population, showing number of insect in each sampling unit.

The exercise can be repeated by starting at a different place in the table, or selecting a different row, column, or diagonal to follow. If you have not estimated the actual insect density by the time that you have finished one row, column, or diagonal, then start another. You will find that many more sample units are generally required to accurately estimate the mean for the low-density insect population than are required to accurately estimate the mean for the high-density insect population.

You should be able to tell whether you are sampling from a low-density or a high-density insect population well before you have estimated the actual insect density. In practice, only enough sample units are taken to estimate insect populations within ±20% of the actual mean. The exercise also can be used for presence-absence sampling by entering only 0 or 1 instead of the number of insects and calculating the cumulative fraction of the sample units with insects. The insect density for each fraction of sample units with insects can be determined using Figure 5.1. The exercise could also be used to try a sequential sampling plan, using Figure 5.4.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	1	4	1	1		3		1	4	1	1	1	3	1	1	2	2	2		1	3
2	5		2	3		1			1		2	1		1		2		1	4	4	
3	10	5				1	3		2		1	2	1		6	4	2			2	
4				1		1	3	1	1	1		1		1	3			1	1		1
5	2	3		2	3			1		4			1	1	3	3	8		6	12	
6			2	3	1	2	2	3	1	1		4		1					3		1
7		2	2	2		3	5	4	1	2		6	1	4	2	1				3	
8		1	2	1	1	1		1	5					3	1	3	1	1	2	1	
9	3	1					2		1	1	2		2	4		6	2	4	2	5	16
10		1		6	1		1	1	3	8	3	2		1			4	2	3	9	5
11		4		2	11		1		11	1	5	5	1	7		4		5	3	1	2
12	6	2		2	7	3	2	2	1		1	11		4	2	2			5		21
13	7			1	1		2		1		2			2				4	2		
14	3	11	1	3	3			1			1		1			2		8	2	1	5
15	3	8	1	2		3	1	3	5	4	1	1			1	5	5		1	11	1
16		1	2	2	8	2	5	2				1	4		3		1	10	1		2
17		3	5		1		4		1		15	7				1	1	1	5		2
18	3		1			21		3	5	5	1				1	4		3	1	4	
19	1	1		1	4	4	1	7	15	4	1	4	2	5	2		2				6
20					1			3	13			1	2	9		5		6	4	1	
21		1		2		2	1	7	3	7	1	1	1	1	2	1	5	7		1	1
22	1		1		1				1	2	1			10	4	4	3		1		2
23	1		1					13	8	1	1	16			1	1	1		1	7	
24	4	1	3		1		7		2	1		3				2	3	1	13	1	4
25	1	5	1	2	3	8		1		2			1	4	2	1	1	1	1	7	9
26				2	2		2	2	2	1		3		3	2			4	4	2	2
27	12	1	1	2		2	1	1		1	1	1	5		2		2			6	
28	2	1	1		1	3	6	4	8		1		1		7	3	6	5	1		2
29			2	4		2	2	1	3	5	2	3		3	1		1	1	2	1	2
30					1		1	1	8		4		1	2		1		2	4		1
31	1	1	4	1	3		1	9		7		4		1			1	1	1	1	

Figure 23.2. Example of a tabulation of a high-density insect population, showing the number of insects in each sampling unit.

D1	J17	T15	G21	J14	L24	N2	H10	D30	U4
U27	T28	B10	T23	U31	F20	D31	N23	B17	R7
C9	A2	I4	A11	C21	K19	B22	F19	M16	N22
E26	G29	I22	T22	P8	Q30	U5	T27	K23	A19
P24	F22	D17	U17	N24	J3	G13	E30	S27	N7
T17	M9	N15	M30	J14	F21	C2	G30	D15	U11
E1	V28	H29	P4	O22	E18	H17	M4	O10	N18
B31	C3	J23	P30	H11	E6	T21	K15	P23	I29
D12	F9	U6	N8	O26	F4	L6	F25	D6	T12
R15	H6	U18	L27	A28	O13	F7	E10	K24	I23
U12	F9	H31	K17	G20	V26	E15	E11	F5	C18
L5	T18	F5	U28	M31	P7	O29	I2	F10	F10
N9	G15	S19	D7	I6	M20	A29	L17	L22	O15
A18	D29	S21	T5	J30	E8	G3	Q29	Q18	F11
T9	G7	J27	G22	G5	N21	P18	K9	R27	K21
M29	K25	L3	U19	L7	N16	L14	I3	A12	L10
U25	L4	J7	K31	Q23	G25	R28	A30	N31	B1
P25	G24	R1	M8	G19	C28	O14	G12	I24	I25
C4	T26	H9	R21	M14	S31	F28	N27	L19	T29
H19	I15	S16	H8	U8	C23	J15	O18	L12	U26

Figure 23.3. Random coordinates for sampling exercise.

Calculation of Estimated Insect Density

Sample number	Sample location	Number of insects	Cumulative sum	Running average
1	_____	_____	_____	_____
2	_____	_____	_____	_____
3	_____	_____	_____	_____
4	_____	_____	_____	_____
5	_____	_____	_____	_____
6	_____	_____	_____	_____
7	_____	_____	_____	_____
8	_____	_____	_____	_____
9	_____	_____	_____	_____
10	_____	_____	_____	_____
11	_____	_____	_____	_____
12	_____	_____	_____	_____
13	_____	_____	_____	_____
14	_____	_____	_____	_____
15	_____	_____	_____	_____
16	_____	_____	_____	_____
17	_____	_____	_____	_____
18	_____	_____	_____	_____
19	_____	_____	_____	_____
20	_____	_____	_____	_____
21	_____	_____	_____	_____
22	_____	_____	_____	_____
23	_____	_____	_____	_____
24	_____	_____	_____	_____
25	_____	_____	_____	_____
26	_____	_____	_____	_____
27	_____	_____	_____	_____
28	_____	_____	_____	_____
29	_____	_____	_____	_____
30	_____	_____	_____	_____
31	_____	_____	_____	_____

Figure 23.4. Worksheet for recording data and calculating estimated insect density.

Chapter 24

Insect Population Growth Model

The objective of this chapter is to explain the computer program that has been used in many of the recent studies cited in Table 7.3 to simulate the population growth of stored-product insects. The simplified FORTRAN program given below was used in Baker et al in 1991 to simulate the growth of *Sitophilus oryzae* populations at 25°C. The computer program code can be downloaded from http://bru.gmprc.ksu.edu/proj/PopGrow. With this program, the growth of *S. oryzae* populations at 25°C can be simulated. Developmental times, egg production, and adult longevities can be changed to simulate the population growth of this or other insect species at different temperatures. With knowledge of the FORTRAN computer programming language, the program can be modified to simulate the effects of changing temperature, age-specific egg production, and various insect pest management methods on insect population growth.

The program begins by defining the dimensions of the arrays and setting them to zero. The DATA DT /.1/ statement indicates that the program will be run 10 times during each day. The array for immature insects (RI) has 159 values; that for adult males (RAM) has 255 values; that for preoviposition adult females (RPAF) has 10 values; that for young adult females (RYAF) has 272 values; and that for old adult females (ROAF) has 105 values. Old adults are no longer laying eggs. The lengths of the array will need to be modified for different insect species.

Next, the program reads 10 entries from a file called SOINPUT. For *S. oryzae* at 25°C, IJDATE=1, LJDATE=112, RIN(1)=0, RIN(2)=2, RIN(3)=1, RIN(4)=1, RIN(5)=0, TEMPFN=SOTEMPS, IPRINT=2, and OUTFN=SOOUT were used. The input file has only one of these numbers or file names on each line. The first two numbers indicate that the program will start on day 1 and run for 112 days. LJDATE can be changed for longer or shorter simulations. (RIN(I), I=1,5) reads the next five numbers, indicating that the initial numbers of insects at the beginning of a simulation are 0 immatures, 2 adult males, 1 preoviposition adult female, 1 young adult female, and 0 old adult female. These are entered as an input statement so that the program will not need to be recompiled to change the initial numbers of insects. The data file TEMPFN has one temperature on each line and requires one temperature for each day of the simulation. Aeration can be simulated using an appropriate SOTEMPS file or equations predicting the temperature changes due to aeration. IPRINT and OUTFN specify the type of format and the name of the output file. The number of days (NUMDAY) that the simulation will run is calculated. Line 2770 gives the format of the output file.

The initial values of the delays due to immature developmental times (DEL) that are used in the subroutine DELLVF are set before beginning the main loop of the program. DELP carries over the value of DEL to the next iteration. Developmental times and thus the values of DEL differ among insect species. Care must be taken in changing DEL so that the program is not unstable (see the next to the last paragraph). JDATE is calculated so that the simulation begins at time zero. On each pass through the main loop, 1 is added to JDATE to advance the simulation to the next day. The DO5700 I=1,NUMDAY statement and 5700 CONTINUE tell the program to run from day 0 to day NUMDAY, which in this case is day 112.

Within the main loop, the DO5200 J=1,10 statement and 5200 CONTINUE tell the program to do 10 iterations each day. At the beginning of each of the iterations, the number of insects in each age class is calculated. There are several DO loops within this DO loop that request that calculations be made for each of the five age classes, i.e., DO3000, DO3500, DO3700, DO5100. CALL CALC and CALL DELLVF run the subroutines and bring in new values for the variables or arrays listed in the CALL statement during each of the iterations. DELLVF stands for distributed delay with storage losses and variable time delay. Starting at line 3800, the RIN arrays for age classes are processed in the reverse order so that the insects can be moved to the next age class before setting CARRY equal to RIN. CARRY is set equal to RIN so that the insects are not lost but carried over to the next iteration when the temperature is too cold for the insect to develop (NODEV=1). Mortality can be imposed on the insects in CARRY in the DO5100 M=1,5 loop. Before starting the next iteration, adults are distributed in a 1:1 sex ratio.

For simplicity, there is only one immature stage (RI), but additional arrays can be added to simulate egg, larval, and pupal stages separately. For *S. oryzae* at 25°C, EGGNEW calculates female egg production as a fraction of their total 384 eggs. The TOTEGGS=384 could be dropped and EGGNEW could be calculated by substituting an equation describing egg production over a range of temperatures (TEMP(I)). These equations are available for the several stored-product insect species in the publications cited in Table 7.3.

SZ is the total number of insects in each stage at the end of each of the iterations. After completing the 10 iterations for each day, ENDSZ (1) totals the number of immatures, ENDSZ (2) the number of males, ENDSZ (3) the number of females, and ENDSZ (4) the number of eggs so that they can be written to an output file.

The subroutines determine how rapidly insects move through the age classes representing immature development and adult longevity. In the CALC subroutine, IF statements check whether the temperature is suitable for insect development. For simplicity, XDEL for immatures is equal to the developmental time of *S. oryzae* in days at 25°C. XDEL for adult *S. oryzae* is equal to the time spent in that age class at 25°C. However, XDEL for immatures can be calculated using an equation predicting the developmental times over a range of temperatures (TEMP). These equations are available for many stored-product insect species in the publications cited in Table 7.3. Mortality due to fumigation and residual insecticides also can be included in the CALC subroutine by changing the value of SURV or adding equations describing the dose-response relationship.

The subroutine DELLVF simulates individual variation in the time that insects remain in an age class and imposes mortality. Calculation of R(I) moves insects through arrays representing immature developmental time and adult longevity. The shape of the curve describing the number of individuals leaving a stage over time is determined by K, which is calculated as mean developmental time divided by variance. K for each age class was determined by first calculating a K for each temperature for which data are available and then taking the average of the Ks over these temperatures. To ensure stability, K should be less than mean/(2*DT), where DT is the time step in the program. With a time step of 0.1 days, K should not exceed mean*5.

Some of the publications cited in Table 7.3 use the distributed delay (subroutine DELLVF) for immatures but not for adult insects. Their adult array is set up like RYAF. However, a one-day time step is used, and adults are moved through the adult array within the main loop but outside the loop for doing 10 iterations per day. This makes using an equation that includes age-specific egg production easier.

```
C*********************************************************************
C****** FORTRAN Program Simulating Insect Population Growth ******
C*********************************************************************
C
C*********************************************************************
C INITIALIZE VARIABLES
C*********************************************************************
C
      CHARACTER*72 TEMPFN,OUTFN
      DIMENSION CARRY(5),DEL(5),DELP(5),ENDSZ(4),NODEV(5),RYAF(272)
     2,RAM(255),ROAF(105),RPAF(10),RI(159),RIN(5),SURV(5),SZ(5),
     2,TEMP(366)
      DATA DT /.1/
C
C*** SET ARRAYS EQUAL TO 0  ****************************************
C
      DO30 I=1,5
      RIN( )=0.
      SZ( )=0.
   30 CARRY(I)=0.
      LOGNEW=0.
C
C***    SET THE INTERNAL RATES FOR DELIVF EQUAL TO 0    *************
C
      DO40 I=1,159
   40 RI(I)=0.
      DO70 I=1,255
   70 RAM(I)=0.
      DO75 I=1,10
   75 RPAF(I)=0.
      DO80 I=1,272
   80 RYAF(I)=0.
      DO90 I=1,105
   90 ROAF(I)=0.
C
C*********************************************************************
C INPUT BLOCK
C*********************************************************************
C
C ***    READ THE INPUT FILE   ***************************************
C
      OPEN(UNIT=8,file='SC INPUT')
      READ(8,*,END=400)IJDATE,LJDATE,(RIN(I),I=1,5),TEMPFN,IPRINT,OUTFN
  400 CLOSE(8)
C
C ***  CALCULATE THE NUMBER OF DAYS THE PROGRAM WILL RUN   ************
C
      NUMDAY=LJDATE-IJDATE 1
C
C ***  READ THE TEMPERATURES   ****************************************
C
      OPEN(UNIT=7,file=TEMPFN)
      READ(7,*,END=500)(TEMP(I), =1,NUMDAY)
  500 CLOSE(7)
C
C ***    WRITE HEADINGS TO OUTPUT FILE   ****************************
C
```

```
      OPEN(UNIT=6,file='SOOUTPUT')
C
C **DON'T WRITE OUT READINGS IF NOT WRITING OUTPUT TO A FILE **
C
      IF(IPRINT.EQ.1)GOTO 2800
      OPEN(UNIT=7,file=OUTFN)
      WRITE(7,2770)
 2770 FORMAT('DAY',3X,'TEMP',8X,'TVMS',6X,' VALES',7X,' EFMS',6X,'EGGS
     2,')
C
C*****************************************************************
C MAIN LOOP
C*****************************************************************
C
C MODEL RUNS FROM 8 AM TO 8 AM - OUTPUT FOR DAY 1 IS NUMBER OF
C       INSECTS PRESENT AT 8 AM THE NEXT DAY.
C
 2800 CONTINUE
C*** SET INITIAL DELAYS ***************************************
      DEL(1)=36.
      DEL(2)=116.
      DEL(3)=2.
      DEL(4)=98.
      DEL(5)=21.
 2900 JDATE=IJDATE-1
C
C***    BEGIN THE MAIN LOOP    ***********************************
C
      DO5700 I=1,NUMDAY
      JDATE=JDATE-1
      EGGOUT=0.
C
C***    BEGIN THE DAILY TIME-STEP LOOP    **************************
      DO5200 J=1,10
C
C***    CALCULATE DELAY INPUT RATES - NUMBER GOING INTO    *****
C***    EACH STAGE AT BEGINNING OF EACH DT.    *********************
C
      CARRY(1)=CARRY(1)+EGGNEW
      EGGNEW=0.
      DO3000 K=1,5
      RIN(K)=RIN(K)+CARRY(K)
 3000 CARRY(K)=0.
C
C***    CALCULATE INITIAL VALUES FOR DERIVE    ********************
C
      DO3500 K=1,5
      IF(RIN(K).EQ.0..AND.SZ(K).EQ.0.)GOTO3500
      CALL CALC(RIN(K),TEMP(I),NODEV(K),DEL(K),SURV(K),K)
 3500 CONTINUE
      IF(I.NE.1)GOTO3800
C
C***    SET DELP DEL DURING FIRST RUN    **************************
C
      DO3700 L=1,5
 3700 DELP(L)=DEL(L)
C
```

```
C***    CALL DELLVF FOR EACH STAGE    ****************************
C
 3800 IF(RIN(5).EQ.0..AND.SZ(5).EQ.0.)GOTO4000
C***  CALL DELLVF FOR OLD ADULT FEMALES    ************************
      CALL DELLVF(RIN(5),ROAF,SZ(5),SURV(5),DEL(5),DELP(5),DT,108
     2,DEADAF,NODEV(5))
      IF(NODEV(5).LQ.1)GO_03900
      RIN(5)=0.
      GOTO4000
C**   IF NO DEVELOPMENT, SAVE THE NUMBER OF INSECTS INPUT  ***
C**    TO THIS STAGE DURING THIS DT.   ****************************
 3900 CARRY(5)=RIN(5)
      RIN(5)=0.
 4000  F(RIN(4).EQ.0..AND.SZ(4).EQ.0.)GOTO4200
C***  CALL DELLVF FOR YOUNG ADULT FEMALES ************************
      CALL DELLVF(RIN(4),RYAF,SZ(4),SURV(4),DEL(4),DELP(4),DT,272
     2,RIN(5),NODEV(4))
      IF(NODEV(4).EQ.1)GOTO4100
      RIN(4)=0.
C**    OVIPOSITION    ***********************************************
      TOTEGGS=384.
      EGGNLW=(SZ(4)*(TOTEGGS*DT/DEL(4)))
      GOTO4200
C**    IF NO DEVELOPMENT, SAVE THE NUMBER OF INSECTS INPUT   **
C**   TO THIS STAGE DURING THIS DT.   ****************************
 4100 CARRY(4)=RIN(4)
      RIN(4)=0.
 4200 IF(RIN(3).EQ.0..AND.SZ(3).EQ.0)GOTO4400
C***  CALL DELLVF FOR PREOVIPOSITION ADULT FEMALES   **************
      CALL DELLVF(RIN(3),RPAF,SZ(3),SURV(3),DEL(3),DELP(3),DT,10
     2,RIN(4),NODEV(3))
      IF(NODEV(3).LQ.1)GO_04300
      RIN(3)=0.
      GOTO4400
 4300 CARRY(3) RIN(3)
      RIN(3)=0.
 4400 IF(RIN(2).EQ.0..AND.SZ(2).EQ.0.)GOTO4600
C***  CALL DELLVF FOR ADULT MALES   ******************************
      CALL DELLVF(RIN(2),RAM,SZ(2),SURV(2),DEL(2),DELP(2),DT,255
     2,DEADAM,NODEV(2))
      IF(NODEV(2).EQ.1)GOTO4500
      RIN(2)=0.
      GOTO4600
 4500 CARRY(2)=RIN(2)
      RIN(2) 0.
 4600 IF(RIN(1).EQ.0..AND.SZ(1).EQ.0.)GOTO5000
C***  CALL DELLVF FOR IMMATURES     ******************************
      CALL DELLVF(RIN(1),RI   ,SZ(1),SURV(1),DEL(1),DELP(1),DT,159
     2,EXPHAR,NODEV(1))
      IF(NODEV(1).EQ.1)GOTO4700
      RIN(1)=0.
C**    DISTRIBUTE EMERGING ADULTS AT 1:1 SEX RATIO    *************
      RIN(2)=EXPHAR*.5
      RIN(3)=EXPHAR*.5
      GOTO5000
 4700 CARRY(1)=RIN(1)
      RIN(1)=0.
```

```
C
C***    MORTALITY WHEN NODEV 1 AT BEGINNING OF RUN    **************
C
 3000 DO5100 M 1,5
      IF(SZ(M).NE.0..OR.CARRY(M).EQ.0.)GOTO5100
      IF(M.EQ.1)CARRY(1)=CARRY(1)*1.
      IF(M.EQ.2)CARRY(2)=CARRY(2)*1.
      IF(M.EQ.3)CARRY(3)=CARRY(3)*1.
      IF(M.EQ.4)CARRY(4)=CARRY(4)*1.
      IF(M.EQ.5)CARRY(5)=CARRY(5)*1.
 5100 CONTINUE
C
C***    SUM NO. EGGS LAID OVER A DAY    ****************************
C
      EGGOUT=EGGOUT-EGGNEW
 5200 CONTINUE
C
C*** SUM THE NUMBER OF INSECTS IN EACH STAGE AT END OF DAY *********
C
      ENDSZ(1)=EGGNEW-SZ(1)+CARRY(1)
      ENDSZ(2)=SZ(2)+CARRY(2)
      ENDSZ(3)=SZ(3)+SZ(4)+SZ(5)+CARRY(3)+CARRY(4)+CARRY(5)
      ENDSZ(4)=EGGOUT
C
C***    WRITE OUT NUMBER IN EACH STAGE    ************************
C
      JTEMP=NINT(TEMP(I))
      WRITE(6,3630)JDATE,JTEMP,(ENDSZ(M),M 1,4)
      IF(IPRINT.EQ.1)GOTO5700
      WRITE(7,3600)JDATE,JTEMP,(ENDSZ(M),M 1,4)
 5700 CONTINUE
 3600 FORMAT(I3,I7,4(3X,F9.0))
 3630 FORMAT(I3,I7,4(3X,E15.5))
      CLOSE(7)
      CLOSE(6)
C
C*********************************************************************
C END MAIN LOOP
C*********************************************************************
C
10000 CONTINUE
      END
C
C*********************************************************************
      SUBROUTINE CALC(RIN,TEMP,NODEV,DEL,SX,ISTAGE)
C*********************************************************************
C
      DATA DT/.1/
      NODEV=0
      RIN=RIN/DT
      TK=TEMP+273.15
C
C***CALCULATE DELAY TIME*************************************
C
C **IMMATURES*****************************************************
      IF(ISTAGE.NE.1)GOTO120
      IF(TEMP.GT.30.0)GOTO10
```

```
      IF(TEMP.GE.21.0)GOTO20
   10 NODEV=1
      XDEL=36.
      GOTO220
   20 DEL=36.
      GOTO210
C**ADULT MALE*****************************************************
  120 IF(ISTAGE.NE.2)GOTO150
      IF(TEMP.GT.30.0)GOTO130
      IF(TEMP.GE.21.)GOTO140
  130 NODEV=1
      XDEL=116.06
      GOTO220
  140 DEL 116.06
      GOTO210
C ** PREOVIPOSITION ADULT FEMALE*******************************
  150 IF(ISTAGE.NE.3)GOTO175
      IF(TEMP.GT.30.)GOTO160
      IF(TEMP.GE.21.0)GOTO170
  160 NODEV=1
      XDEL=113.
      GOTO220
  170 DEL=2.0
      GOTO210
C**YOUNG ADULT FEMALE*****************************************
  175 IF(ISTAGE.NE.4)GOTO180
      IF(TEMP.GT.30.)GOTO176
      IF(TEMP.GE.21.0)GOTO177
  176 NODEV=1
      XDEL=98.
      GOTO220
  177 DEL=98.
      GOTO210
C ** OLD ADULT FEMALE ****************************************
  180 IF(ISTAGE.NE.5)GOTO230
      IF(TEMP.GT.30.0)GOTO190
      IF(TEMP.GE.21.0)GOTO200
  190 NODEV=21.
      XDEL=113.
      GOTO220
  200 DEL 21.
      GOTO210
C
C***SURV VAL*****************************************************
C
  210 IF(ISTAGE.EQ.1)SURV=1.
      IF(ISTAGE.EQ.2)SURV=1.
      IF(ISTAGE.EQ.3)SURV=1.
      IF(ISTAGE.EQ.4)SURV=1.
      IF(ISTAGE.EQ.5)SURV=1.
      S=ALOG(SURV)/DEL
      SX=AMIN1(EXP(S*DT),1.)
      GOTO230
  220 RTN=RTN*DT
      SX=1.-((1./XDEL)*DT)
  230 RETURN
      END
```

```
C
C*****************************************************************
      SUBROUTINE DELLV2(RIN,R,STRG,S,DLL,DELP,DT,K,DELL,NODEV)
C*****************************************************************
C
      DIMENSION R(1)
      FK=FLOAT(K)
      IF(NODEV.EQ.1)GOTO20
      B=1.0 (DELL-DELP)/(FK*DT)
      A=FK*DT/DLL
      DELP=DELL
      KM1=K-1
      DO10 I=1,KM1
C UPDATE INTERNAL RATES
      R(I)=R(I)+A*(R(I+1)-R(I)*B)
   10 CONTINUE
      R(K)=R(K)+A*(RIN-B*R(K))
   20 STRG=0.
      DO30 I=1,K
C SURVIVAL RATE
      R(I)=R(I)*S
C SET SMALL RATES TO ZERO TO PREVENT UNDERFLOW
      IF(R(I).LT.1E-20)R(I)=0.
C CALCULATE STORAGE
      STRG=STRG+R(I)*DELL/FK
   30 CONTINUE
      IF(NODEV.EQ.1)GOTO40
      DLL=R(1)/10.
   40 RETURN
      END
```

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