

# **Grain Protectants**

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G.P.O. Box 1571, Canberra, A.C.T. 2601

Snelson, J.T. 1987. Grain protectants. ACIAR Monograph No. 3, x + 448 p.

ISBN 0949511 34 X

Typeset and laid out by Canberra Publishing and Printing Co., Fyshwick, ACT.  
Printed by Ruskin Press, Melbourne  
Cover design: Ingrid Slamer

# Grain Protectants

**J.T. Snelson**

*Published in collaboration with the  
Department of Primary Industry  
by the*

**Australian Centre for International Agricultural Research  
Canberra 1987**

## About the author

**J.T. Snelson's** career in agricultural chemistry has spanned the 40 years during which the various grain protectants have progressed from the status of experimental compounds showing some promise to a suite of extremely effective chemicals in widespread use.

Mr Snelson has been a key player in international activity to develop a rigorous code of practice for the safe and effective use of grain protectants, stimulated by a commitment to help in reducing the devastation that insect pests can cause to stored foodstuffs, and by the serious impact that these losses have on people in the developing countries of the world.

Mr Snelson was, from 1969 to 1986, a member of both the FAO Panel of Experts on Pesticide Residues in Food and the Environment and the FAO/WHO Joint Meeting of Experts on Pesticide Residues, and has held office on numerous other national and international committees and working parties concerned with maximising the benefits of pesticide use. He was for many years chairman of the Australian Wheat Board Working Party on Grain Protectants and, from 1967 to 1983, was Australian delegate to the UN Codex Committee on Pesticide Residues.

Although Mr Snelson retired as Pesticides Coordinator in the Australian Department of Primary Industry in 1986, he is still actively involved in pesticide matters as a consultant. In recognition of his service to agriculture, he has been appointed a Member of the Order of Australia, one of the highest honours that can be bestowed on a citizen of Australia.



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# FOREWORD

The Department of Primary Industry and the Australian Centre for International Agricultural Research (ACIAR) are delighted to be associated in the publication of Mr J.T. Snelson's monograph 'Grain Protectants'.

The Department's responsibility for administering the Export (Grain) Regulations has brought it into a close working relationship with those people and organisations responsible for the production, storage, transport, inspection and marketing of all types of grain, and thus into an involvement with the control of stored-product pests. The importance of the wealth of scientific information on effective, efficient and acceptable procedures for controlling stored-product pests is therefore well understood.

The problems involved in providing Australia's international trading partners with high quality grain, free from insect pests, their damage, excreta and fragments have received high priority at all levels of government, industry and private enterprise. Innovative measures that are now regarded as mileposts in grain storage technology gradually evolved until they reduced these problems to manageable proportions. There is no doubt that the dedication, determination and co-operation of a relative few key personnel in the grain trade, grain storage industry, research organisations, government and chemical industry have been mainly responsible for the high levels of freedom from stored-product pests for which Australian grain is now recognised.

During the period 1967-1986 when Jack Snelson served as Commonwealth Pesticides Co-ordinator in the Department of Primary Industry he was intimately involved in all aspects of the efforts to eliminate stored-product pests from commercial grain handled in and exported from Australia. For 13 years he served as Chairman of the Australian Wheat Board Working Party on Grain Protectants where he made a substantial contribution in co-operation with all who served to ensure the success of its research and development.

Mr Snelson was a member of the FAO Panel of Experts on Pesticide Residues in Food and the Environment and the Joint FAO/WHO Meeting of Experts on Pesticide Residues for 17 years. During this period he was responsible for evaluating much of the scientific data on residues of grain protectant insecticides and, with his colleagues, for establishing recommendations for international maximum residue limits for these insecticides in food. He served in a similar capacity on the corresponding Australian body, the Pesticides and Agricultural Chemicals Committee of the National Health and Medical Research Council.

As Australian delegate to the Codex Committee on Pesticide Residues between 1967 and 1985, Mr Snelson found that many officials concerned with food inspection and food laws in both industrialised and developing countries had not had the opportunity to consider the need to use grain protectant insecticides to protect world food supplies or to gain an insight into the nutritional, social and economic consequences of stored-product pests. He recognised the difficulty which administrators and scientists faced because the extensive scientific literature was fragmented, and realised that few had had the chance of considering the many data relating to the biological activity of grain protectants, their properties and fate, and the safety of residues remaining in prepared foods.

In 1978 he began the task of reviewing and summarising the literature in his spare time. However, the volume of information to be handled and work pressure saw this activity shelved until just before his retirement in February 1986. Even so, it has taken almost 12 months of meticulous work to collect, collate and review the more than 2300 publications which form the basis of this monograph.

The Department was pleased to encourage and assist by providing word processing and library facilities, and it is a pleasure to see how these have been put to such good effect.

ACIAR's decision to publish 'Grain Protectants' is in accord with the Australian Government's support for the greater and more effective utilisation of Australia's scientific research and technology capability to assist the economic and social advancement of our Asian-Pacific neighbours.

In important areas of science and technology, particularly in aspects of agriculture, Australia has developed unique capabilities. In particular, we have succeeded in applying many of the principles developed in relation to temperate agriculture to the solution of problems of the tropics.

The subject matter of this monograph is a good example of this. It should enable developing countries to apply the scientific information and practical experience gained in Australia and elsewhere to resolve many of their own problems in the confident knowledge that the safety and acceptability of the control measures have been carefully and independently evaluated and approved. It also draws attention to the fine work of scientists in many countries who have devoted their talents to finding ways of safely eliminating losses and difficulties due to stored-product pests and provides encouragement to apply modern scientific discoveries in solving age-old problems.

The book is published as part of the activities of the ACIAR Grain Storage Research Program, which aims to enhance the capacity of developing countries to identify and overcome constraints to the safe storage of grain, thereby decreasing losses through spoilage. Ensuring correct use of suitable grain protectants is central to this aim.

We are sure that this monograph will serve the needs of scientists, grain storage technologists, the grain trade and administrators concerned with grain handling, food standards and consumer safety now and for many years to come.

It should also bring about a better understanding of the problems which face peoples living in those regions where temperatures and/or humidities are high and where insect pests present serious problems to those producing, storing and handling grain. The realisation that these problems can be brought under control by simple measures which have proven effective, convenient, economical and safe should bring forward the day when the world no longer has to produce food merely to replace what has been damaged or devoured by hungry pests.

If this can happen the work of the author and all those scientists whose labours made this monograph possible will not have been in vain.

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Secretary  
Department of Primary Industry  
Canberra

**J.R. McWilliam**  
Director  
ACIAR  
Canberra  
March 1987

# Preface

Grains, such as wheat, rice, corn, millet etc., and legumes, such as beans, lentils and peas, form a large part of the diet of the world's population. These products are stored as dry seeds and form the only real reserve of food. However, all of them are subject to attack by a variety of insects that cause great damage and loss of nutritious foods, and thus give rise to one of the causes of malnutrition in many lands. **Subrahmanyam (1962)** indicated that the world's total food could be increased by 25–30% if we could avoid post-harvest losses of our food. **Bakal (1963)**, in his *Mathematics of Hunger*, estimated the annual food losses due to rats, insects and fungi at 33 million tonnes, enough seed foods to feed the population of the United States of America for 1 year. Why does the world continue to tolerate the feeding of enormous populations of insects at the expense of hungry and starving people?

The Food and Agriculture Organization of the United Nations (FAO) pointed out in 1973 that world food supplies no longer provided an adequate buffer against crop failure and starvation; food supplies for millions of people depend almost entirely on each year's harvest. At least 10% of harvested food crops are destroyed by pests in storage, and losses of 30% are currently common in large areas of the world (**Hall 1970**), especially in some of the tropical and sub-tropical areas where the need for increased food is greatest. In some of these regions, a certain amount of insect infestation in grains and other food products is accepted as normal but in many developed countries strict control of stored-product insects is dictated not only by economic necessity but also by strict government standards concerning permissible contamination.

The inadequate supply of food in developing countries has long been recognised as one of the major problems that needs attention because a population that is not well fed is prone to deficiency diseases, more susceptible to infectious diseases and does not have the energy to work hard. Both multi-lateral and bi-lateral organisations have recognised this problem and have devoted a large proportion of their aid efforts to increasing the production of food. However, increasing the production of food is not the real goal of these activities. The real goal is to put more food regularly into the mouths of the people and this requires not only the production of more food but also moving that food through the delivery system all the way to the point of consumption. Most attempts to increase the world food supply have failed to recognise that the food must be delivered to the ultimate consumer through the

post-harvest system without significant loss. **Bourne (1977)** in his excellent review *Post-Harvest Food Losses — the Neglected Dimension in Increasing the World Food Supply* drew attention to the critical position and proposed a series of practical measures for bringing about the necessary improvement.

The attention of the world was drawn to the problem of post-harvest food losses by the US Secretary of State, Dr Henry Kissinger, at the World Food Conference that was held in November 1974 in Rome. In his keynote address at the opening session of the World Food Conference, Secretary Kissinger said:

Another major priority must be to reduce losses from inadequate storage, transport and pest control. Tragically, as much as 10% of the country's food production is often lost after harvesting because of pests that attack grain in sub-standard storage facilities. Better methods of safe storage must be taught and spread as widely as possible. Existing pesticides must be made more generally available. Many of these techniques are simple and inexpensive; investment in these areas could have a rapid and substantial impact on the world's food supply.

The attention of the political world was again drawn to the problem of post-harvest food losses by Dr Kissinger in an address presented at the Seventh Special Session of the UN General Assembly on 1 September 1975 in New York. In this address, Dr Kissinger said:

Another priority in the poorest countries must be to reduce the tragic waste of losses after harvest from inadequate storage, transportation and pest control. There are often simple and inexpensive techniques to resolve these problems. Investment in such areas as better storage and pesticides can have a rapid and substantial impact on the world's food supply; indeed, the savings could match the total of the food aid being given around the world. Therefore, we urge that the Food and Agriculture Organization, in conjunction with the UN Development Program and the World Bank, set a goal of cutting in half these post-harvest losses by 1985, and develop a comprehensive program to this end.

This challenge from Dr Kissinger was taken up by the UN General Assembly in that Session and on 19 September 1975 one of the resolutions of the UN General Assembly was:

The further reduction of the post-harvest food losses in developing countries should be undertaken as a matter of priority, with a view to reaching at least a

50% reduction by 1985. All countries and competent international organisations should co-operate financially and technically in the effort to achieve this objective.

This resolution has drawn the attention of the highest levels of government around the world to the problem of post-harvest food losses.

A recommendation to use or not to use pesticides at the small farm level is an important one, as it affects many people. It is estimated that over 100 million farms are less than 5 ha in size and of these over 50 million are less than 1 ha (the President of the World Bank quoted in **Brader 1979**).

As long as the farming practices and varieties grown remain 'traditional', food losses on the small farm are probably of little importance. There is at present ample evidence that storage losses may increase considerably when traditional farming is changed, so a modernisation of agricultural production makes changes in storage practices unavoidable. The financial means of each individual are very limited. Sophisticated storage methods are mostly out of reach. With insecticides, storage losses can be prevented at relatively low cost. The distribution of insecticides and the organisation of the extension of their use poses, however, seemingly insoluble problems.

**De Las Casas (1984)** described FAO's Program on Prevention of Food Losses which began with a request of the Director-General of FAO in 1975 for a survey of the position in member countries. Responses were received from 51 countries. Most of the reports concerned losses of durables and the need to reduce them, but surprisingly enough, despite the high losses reported from many countries, there was no indication of steps being taken to bring about their reduction. Insects were clearly identified as the most important cause of loss in all types of storage, followed by fungi and rodents. The report regarding the various countries reflected a general unawareness of the cause/effect relationship of losses. The magnitude of such losses was generally not well known.

A call for international action was made in 1975 at the 7th Special Session of the United Nations General Assembly, where a resolution was passed calling upon member states to reduce post-harvest food losses by 50% by 1985. It was clearly stated that countries should commit themselves fully to food loss reduction by establishing a national policy and implementing an effective plan of action. FAO has been the leader within the UN system. Its Action Program for the Prevention of Food Losses (PFL) was approved by the 19th Session of the FAO Conference, in November 1977. This action program, as formulated in 1976, identified three major constraints to post-harvest loss prevention in the developing world:

1. lack of information concerning the magnitude of the losses, their nature, causes and the most effective techniques for reducing or preventing them;
2. lack of infrastructure for the implementation of loss prevention measures;

3. lack of investment in food loss prevention.

In formulating the FAO Action Program for the Prevention of Food Losses certain priorities have been set in order to achieve a significant impact within a relatively short time. Thus, in its initial phase, the program has concentrated on reducing post-harvest losses in food grains, roots and tubers, since these foods constitute the staple foods of developing countries. The basic purpose of the program is to assist the countries in planning and implementing national food loss reduction programs. Direct action projects have been implemented to improve storage structures and design, construct and manage pilot warehouses, provide small-scale grain dryers, improve processing facilities, organise activities on quality control and pest management, improve rodent control and carry out training at all levels and in all aspects of the post-production system.

PFL direct action projects carry out activities in five main areas:

1. food loss assessment surveys, which are considered as the basis for action programs for food loss reduction;
2. provision of practical assistance to governments to combat losses at various stages in the post-harvest food system;
3. training and building up national capabilities;
4. establishing national focal points for food loss reduction programs;
5. strengthening research, development and information programs.

At the end of December 1982, the number of projects had reached 108, with a total allocation of \$US34.2 million. Of these projects, 88 were either completed or had reached the state of generating some outputs. The regional distribution of PFL activities shows 30% in Africa, 29% in Asia and the Pacific, 19% in Latin America and the Caribbean, and 14% in the Near East and North Africa.

PFL activities are restricted to staple foods: cereals (rice, maize, wheat, sorghum and millet), pulses and roots and tubers. Pest control activities were carried out by 46 of the 88 completed projects. In most of them, pest control activities have proved to be acceptable, but it has been concluded that this particular component needs to be reviewed. A review of the pest management practices and an evaluation of their adequacy, an assessment of the validity of experimental trials and interpretation of resulting data are now being carried out. The aim is to obtain guidelines for more effective preventative sanitation practices, more economical and safer pest management action and more efficient training instruction, which will be used by the PFL projects.

In the light of the experience gained, many remedial measures have already been incorporated in subsequent projects. For example, more attention has been devoted to the socio-economic analysis of post-harvest practices, pest management and quality control, the right approach

to technology transfer, as well as the economic viability and social acceptance of the proposed new technology. Experience to date indicates the need to broaden the scope

of overall activities, to include expertise on farm management and economics, food quality, home economics, training and extension.

## Acknowledgments

The realisation that there was such a wealth of valuable information about simple, safe, effective and economical measures for preventing the loss of enormous quantities of valuable foodstuffs and that this was not known to or accessible by those needing to put such information to good use prompted me to attempt to make it more readily available. I commenced the task for presentation at the Second International Working Conference on Stored-Product Entomology held in Ibadan, Nigeria in September 1978. I did manage to prepare about 300 pages of manuscript at that time but this did not cover more than a small fraction of the available literature and I therefore resigned myself to a much more extensive exercise.

The large volume of information becoming available since then and the need to explore many issues in greater depth has greatly extended the task and I am sorry that my many friends who have been awaiting this monograph for several years have had to get along without it. However, in spite of the long development period, I trust that the final outcome will be even more useful than it would have been a few years earlier.

I am grateful to my wife Eva for the sacrifice she made so that I could continue the work rather than attend to urgent tasks around the home and for our family. I appreciate the encouragement of colleagues, friends and professional associates in Australia and overseas. The support of the Executive of the Department of Primary Industry in allowing me to devote myself full time to the work for three months before my retirement is gratefully acknowledged.

Most especially I want to acknowledge the dedication of several ladies of the Word Processing Centre of the Department of Primary Industry who skilfully transcribed the whole of the text from my taped dictation. Without

such help there would have been no way for me to complete the task. Their patience and skill has made a wonderful contribution.

Dr Jim Desmarchelier reviewed the manuscript and I acknowledge his comments and encouragement. The scientists in industry who reviewed the chapters on the insecticides developed by their companies have helped to keep the facts and my interpretation in line with their considerable experience. I appreciate their help and also permission to quote many reports which have not been published. I trust that they will feel that the final presentation does justice to the extensive database available on these insecticides.

To my long-standing associates on the Codex Committee on Pesticide Residues, the FAO Panel of Experts on Pesticide Residues in Food and the Environment and the Joint FAO/WHO Meeting on Pesticide Residues I extend thanks for sharing knowledge, experience and concerns. I trust you will find the answers you need to all your questions on grain protectant insecticides.

And to those who are devoting their skills, knowledge and experience to the task of bringing the benefits of scientific development to improve the health, nutrition and economic well-being of those whose agriculture and industry is still in great need of development I express the hope that this monograph will save you time, effort and money and that you will be able to adapt much of the experience that it represents to resolve problems of your part of the world.

Finally, I wish to acknowledge the support of ACIAR, which, by agreeing to publish this monograph, has brought the enterprise to fruition.

**J.T. Snelson**

# 1. Importance of Stored-Product Pests

That insects are a major cause of loss in stored grains and seeds, as well as in many other kinds of stored food products, should be too well recognised to need emphasis here. They not only consume these materials but also contaminate them with insect fragments, feces, webbing, ill-smelling metabolic products and with a variety of microflora; they therefore constitute a major sanitation and quality control problem.

Many of these most important insects and mites found in grain throughout the world have originated from the Old World. Ships, trucks, trains and planes have facilitated their distribution throughout the grain growing and grain handling regions of the world. Once established in a granary, insects can damage stored grain by feeding on it, lowering germination, spoiling its appearance, lowering its milling quality, producing off-odours, causing it to heat and by creating conditions favourable to the growth of moulds.

The insects and mites that attack stored grain have features which distinguish them from those found on growing crops. Most are small, light-avoiding pests capable of hiding in cracks and crevices, and of producing several generations a year. They have become specialised for feeding on dried animal and vegetable matter. Some may survive on foods that contain as little as 1% water, although the species that live on grain usually require not less than 8% water. Some can also tolerate extremes of temperature; indeed, these are the insect pests with which we are chiefly concerned since those that cannot survive the conditions under which grain is stored are not likely to give us trouble (Watters 1959b).

Before crops were cultivated by man, the weevils and Angoumois grain moth (*Sitotroga cerealella*) occurred naturally in seeds on wild plants or in seeds gathered by rodents, ants and other seed harvesting animals (Linsley 1944). Certain species were fungus feeders or scavengers; several were wood borers or lived under loose, dead bark; others inhabited nests of social insects and birds. When man began to store grain, these insects readily moved from their original native habitat to man-made stores. These pests have been carried by commerce to all parts of the world. In the days of the sailing vessels, grain and other dry foods swarmed with insects at the end of long voyages.

Today, several hundred species of insects and mites are associated in one way or another with stored grains and their products. Fortunately, only a few cause serious damage to seeds or cereal products in good condition. Some feed on the fungi growing on spoiled grain or on

other dried vegetable materials. Others are predators or parasites that attack the true grain pests. Environmental conditions in various parts of the world are not equally favourable for the development of all insect species, and those species that are injurious in some areas barely exist in others.

Cotton and Good (1937) listed the species found in stored grain and processed cereal products in four categories.

1. *Major pests* comprise those species responsible for most of the insect damage to stored grain and cereal products. They are particularly well adapted to life in the stringent environment imposed by a bin of grain.
2. *Minor pests* include an appreciably larger group that may become damaging locally and occasionally may approach the status of major pests. Frequently, large populations develop in grain or in cereal products going out of condition because of high moisture and poor sanitation. Certain species *Ptinus villiger* and *Ahasverus advena*, are indicators of high-moisture grain; when they occur in abundance in a grain mass, spoilage from moulds probably has occurred.
3. *Incidental pests* are those insects that stray into an unscreened or open-doored processing plant or into open-doored box cars being loaded or standing in the railroad yards. They include houseflies, roaches, moths, or other insects that might have been attracted to lights, odours or shelter — in fact any insect that happens to alight on or crawl into grain or grain products. Usually these insects are ignored by grain handlers and food processors, but when a moth or beetle accidentally gets into a package of cake mix or breakfast food, it suddenly becomes a major pest to the householder who opens the package.
4. *Parasites and predators* of grain-infesting insects frequently are found in bins of infested grain, where they are as unwanted by grain handlers as are the major pests.

Lists of stored-product pests, categorised by Cotton and Wilbur (1974), are given in Tables 1.1 and 1.2.

Bauer (1984a) has provided useful data on important behavioural aspects of the more important stored-product pests in the form of a table which makes it easy to compare vital features of different species and thus deduce why some are much more pestiferous than others.

Singh *et al.* (1978) have edited a universal review of

**Table 1.1.** Alphabetical list of the major insect pests of stored grain (Cotton and Wilbur 1974)

Scientific Name	Common Name	Family
<i>Acarus siro</i> L.	Grain mite	Acaridae
<i>Anagasta kuehniella</i> (Zeller)	Mediterranean flour moth	Phycitidae
<i>Cadra cautella</i> (Walker)	Almond moth	Phycitidae
<i>Cryptolestes ferrugineus</i> (Stephens)	Rusty grain beetle	Cucujidae
<i>Cryptolestes pusillus</i> (Schönherr)	Flat grain beetle	Cucujidae
<i>Cryptolestes turcicus</i> (Grouv.)	Flour-mill beetle	Cucujidae
<i>Ephestia elutella</i> (Hübner)	Tobacco moth	Phycitidae
<i>Oryzaephilus surinamensis</i> (L.)	Saw-toothed grain beetle	Cucujidae
<i>Oryzaephilus mercator</i> (Fauv.)	Merchant grain beetle	Cucujidae
<i>Plodia interpunctella</i> (Hübner)	Indian-meal moth	Phycitidae
<i>Rhyzopertha dominica</i> (F.)	Lesser grain borer	Bostrichidae
<i>Sitophilus granarius</i> (L.)	Granary weevil	Curculionidae
<i>Sitophilus oryzae</i> (L.)	Rice weevil	Curculionidae
<i>Sitophilus zeamais</i> Motschulsky	Maize weevil	Curculionidae
<i>Sitotroga cerealella</i> (Olivier)	Angoumois grain moth	Gelechiidae
<i>Tenebroides mauritanicus</i> (L.)	Cadelle	Ostomatidae
<i>Tribolium castaneum</i> (Herbst)	Red flour beetle	Tenebrionidae
<i>Tribolium confusum</i> Duval	Confused flour beetle	Tenebrionidae
<i>Trogoderma granarium</i> Everts	Khapra beetle	Dermestidae

grain legume entomology involving contributions from over 20 individual countries concerning grain legume pest complexes.

Newly harvested, uninfested grain in farm storage may become infested from many sources, including hold-over infested grain, cracks, crevices, cadelle tunnels and

**Table 1.2.** Alphabetical list of the minor pests most frequently encountered in stored grain (Cotton and Wilbur 1974)

Scientific Name	Common Name	Family
<i>Ahasverus advena</i> (Waltl.)	Foreign grain beetle	Cucujidae
<i>Alphitobius diaperinus</i> (Panzer)	Lesser mealworm	Tenebrionidae
<i>Araecerus fasciculatus</i> (DeGeer)	Coffee-bean weevil	Platystomidae
<i>Attagenus piceus</i> (Olivier)	Black carpet beetle	Dermestidae
<i>Carpophilus dimidiatus</i> (F.)	Corn sap beetle	Nitidulidae
<i>Carpophilus hemipterus</i> (L.)	Dried fruit beetle	Nitidulidae
<i>Caulophilus oryzae</i> (Gyllenhal)	Broad-nosed grain beetle	Curculionidae
<i>Corcyra cephalonica</i> (Staint.)	Rice moth	Galleriidae
<i>Cynaesus augustus</i> (LeConte)	Larger black flour beetle	Tenebrionidae
<i>Gnathocerus cornutus</i> (F.)	Broad-horned flour beetle	Tenebrionidae
<i>Lasioderma serricorne</i> (F.)	Cigarette beetle	Anobiidae
<i>Latheticus oryzae</i> (Waterhouse)	Long-headed flour beetle	Tenebrionidae
<i>Liposcelis</i> spp.	Psocids	Psocoptera
<i>Palorus ratzeburgi</i> (Wissmann)	Small-eyed flour beetle	Tenebrionidae
<i>Palorus subdepressus</i> (Wollaston)	Depressed flour beetle	Tenebrionidae
<i>Ptinus claviceps</i> (Panzer)	Brown spider beetle	Ptinidae
<i>Ptinus villiger</i> (Reitter)	Hairy spider beetle	Ptinidae
<i>Prostephanus truncatus</i> (Horn)	Larger grain borer	Bostrichidae
<i>Stegobium paniceum</i> (L.)	Drugstore beetle	Anobiidae
<i>Tenebrio molitor</i> (L.)	Yellow mealworm	Tenebrionidae
<i>Tenebrio obscurus</i> (F.)	Dark mealworm	Tenebrionidae
<i>Tribolium audax</i> (Halstead)	Black flour beetle	Tenebrionidae
<i>Trogoderma</i> spp.	Grain-feeding dermestids	Dermestidae
<i>Typhaea stercorea</i> (L.)	Hairy fungus beetle	Mycetophagidae

double-wall construction in bins or other parts of the granary, whether empty or occupied; accumulation of waste or spilled grain in or under the granary or machinery and implements, or in empty grain and feed sacks; imported feeds or seeds from infested sources, especially elevator sweepings; migration by flight from nearby infested sources; and, in many regions, field-infested grain.

**Sinclair and Haddrell (1985)** conducted 3 surveys to determine the extent of migration in a grain farming area by 4 stored-products beetles: *Tribolium castaneum* and *Rhyzopertha dominica* were found to be the predominant migrants being active in the field from early spring to late autumn. There was no clear relationship of catch with nearby infestations, except over short distances. Average density of beetles during flight peaks was estimated to be about 52 per 100 m<sup>3</sup>. These insects represent a serious potential for reinfestation of stored grain.

In commercial and government storage, uninfested grain becomes contaminated from infested grain or wastes on the premises unless exceptionally favourable sanitation procedures have been followed. Many of the older elevators, especially those of the wooden crib type, are difficult to disinfest. Much commercial grain received from farm storage is infested. Grains shipped in wooden box cars is almost certain to become infested during shipment. Insects capable of flight migrate in all directions from feed mills that process infested grain.

**Bauer (1984)** edited a valuable monograph on insect management for food storage and processing which starts off by demonstrating that losses due to insects in food storage, transportation and processing in the United States run 'in the low billions of dollars' annually. It quotes the report of the Council of Environmental Quality on Integrated Pest Management by Dale R. Bottrill of December 1979 as an authority for the statement that the post-harvest loss due to insects in the US is 6% of the value of all foods marketed.

Insects are attracted to damp grain. If leaks occur and portions of a bin of grain become damp, insects will be found there in greater abundance than in dry areas. Surface grain that is cooler than the bulk of grain may become damp as a result of translocation of water from the interior of the grain mass. Whenever a bulk of grain has parts with different temperatures, moisture moves from the warmest to the cooler parts. When heating by insects occurs beneath the surface grain and outside temperatures are low, the temperature gradient is very steep. Water movement may be so excessive that considerable rotting of the surface grain will result. Damp surface grain may attract scavenger and fungus-feeding insects and their presence serves as a certain indicator of high-moisture grain.

In most developing countries 70–80% of all the staple produce never leaves the farm on which it was grown and many factors affect farm-stored produce. Of these, damage due to insects, rodents and fungi is probably the

main cause of loss in quality and quantity of the food stored.

Insect infestations result in contamination by entire insects or parts thereof. Infestations may include eggs, egg shells and egg cases, larvae and cast-larval exoskeletons, pupae and pupal cases and cocoons, and mature insects. Internal-feeding weevils and *Sitotroga* larvae deposit their excreta or fecal pellets inside the kernels; *Rhyzopertha* push excreta along with some starch particles out of the kernel through the entrance hole and leave excreta/starch accumulations as dockage in the infested area (**Cotton and Wilbur 1974**). In addition to the flour consumed, the flour beetles secrete a pungent, irritating liquid consisting of ethylquinone, toluquinone and methylquinone from certain abdominal and thoracic odoriferous glands. Contamination from large populations of flour beetles turns the flour pink.

**Freeman and Turtle (1947)** stated that flour infested with mites has a particularly objectionable smell. When such flour is used for bread making, the bread has a sour taste, poor colour and may not rise adequately.

Larvae of *Plodia interpunctella* and certain other moths spin silken webs over their foods, so that their presence in cereal products ruins much more than the amount eaten. Frequently a thick carpet of webbing may cover the surface of stored grain infested by such moths. Older millers recall that, when *Plodia* infested their mills, the webbing would tie moving mill parts so tightly during the weekend shutdown that it had to be removed to get the machinery into operation again (**Cotton and Wilbur 1974**).

When insects feed on grain, the breakdown of the grain starches during insect metabolism results in heat, moisture and energy as end products. Lowering of the grade of grain as a result of damaged kernels and of off-colour and off-odours may cause a substantial price decrease (**Cotton and Wilbur 1974**).

Storage fungi are recognised as a major cause of spoilage in stored grain and seeds; insects and mites are frequently responsible for their distribution and development. Grain-infesting insects carry fungus spores into the grain and may increase the moisture content of the grain sufficiently so that the spores can develop. **Christensen and Kaufmann (1969)** summed up the situation by stating that at least some of the common grain-infesting insects regularly carry into the grain they infest a large load of inoculum of storage fungi, and, as they develop in the grain, provide conditions favourable to the development of these fungi. These authors stated that what appears to be an insect problem may be an insect-plus-storage-mould problem.

Apart from losses caused by moulds, storage fungi produce an unknown number of toxic chemicals, some of which are carcinogenic, such as aflatoxins and okratoxin and many of which are suspected as causing serious diseases in livestock.

Of great significance is the possible distribution of such

harmful bacteria as *Salmonella*, *Streptococcus*, and *Escherichia coli* by grain-infesting insects. **Husted et al. (1969)**, found that *Sitophilus oryzae* retained *Salmonella montevideo* internally and externally after being in contaminated wheat for 7 days, and for at least 5 weeks after being in contaminated wheat for 14 and 21 days.

The role of insects in promoting, spreading and intensifying the development of mycotoxins in stored grain has not been adequately researched. **Ragunathan et al. (1974)** showed that there was a close association between storage fungi and *Sitophilus oryzae*. The fungi were mainly those responsible for producing mycotoxins. The incidence of infection of the insects ranged from 20% to 100%, the fungi being carried in the alimentary canal of the insect along with the food and excreta. Weevils collected in the field at the time of corn harvest carried *Aspergillus flavus*.

**Senappa et al. (1979)** reported that dried Indian peppers (*Capsicum annum*) containing *Aspergillus flavus* and aflatoxin had been subjected to insect infestation before storage and the small number of infested pods had become completely filled with aspergilli. These pods showed no surface growth of mould, but during storage the incidence of aspergillus-loaded pods increased, depending on insect infestation and relative humidity.

**Phillips and Burkholder (1984)** have reviewed the literature on health hazards of insects and mites in food. The fact that stored-product insects can and do cause illness in humans is well known to entomologists but less so to the food industry. These illnesses range from mechanical irritations of skin, eyes and upper respiratory tract due to the abundance of insect fragments following on even modest levels of infestation to serious allergic reactions induced by the foreign protein of the anatomical structures of pests and the poison glands of insect bodies.

Tapeworm diseases, including dwarf tapeworm and rat tapeworm, are transmitted from rodents to man by cockroaches and meal worms as well as by fleas (**Scott 1962**). Such enteric bacterial and protozoal diseases as typhoid, diarrhoea and dysentery are transmitted mechanically from man to man by cockroaches and other stored-food pests. Various intestinal infestations such as intestinal acariasis, intestinal myiasis and canthariasis result from the ingestion of live stored-food mites, from stored-food flies, and from yellow meal worms and other stored-food beetles. A severe dermatitis known as grain itch, grocer's itch, vanillism, or other names, is caused by bites of stored-food mites. In addition, some persons are allergic to mill dust containing fragments and fecal pellets of stored-food insects (**Cotton and Wilbur 1974**).

Insects render unfit for human consumption much more grain and grain products than they eat, because every infestation contaminates its host product with insect fragments and excreta. Excreta from flour beetles and most other major insect pests of cereal products are deposited directly into the product and cannot be removed.

Most persons have a natural revulsion to all forms of filth in their food. The thought that they may be eating insect fragments and excreta affects the aesthetic sensitivities of most people, but when such filth is actually observed it may have serious effects. The public wants to believe that the cereal products it is using are as free of insect filth as possible. If there were to be a statement on a package of flour to the effect that 'this flour contains fewer than 10 insect fragments per 100 g', it would have an adverse effect on the consumer, even though such a low count represents a major achievement over the past 20 years.

Flour infested with insects is generally rejected for aesthetic and assumed health reasons, without consideration of any undesirable effects, which may be produced by secretions and excretions of the insects, and which may affect the baking qualities and taste of the product. **Smith et al. (1971)** reviewed the work of many authors and showed that cereals infested with *Tribolium* spp. give rise to persistent and disagreeable odours in bread. They have pointed out that the presence of *Tribolium* spp. in flour affected the odour, taste and colour of bread, considerably reducing the volume of the loaf and destroying the texture.

**Smith et al. (1971)** referred to a number of studies of the nature and properties of these insect secretions, which are predominantly quinones. Numerous authors have pointed out that these quinone secretions of *Tribolium* spp. may be important carcinogens since they produce carcinoma in mice. They also showed that whilst bread prepared from flour infested with *Tenebrio*, *Trogoderma* and *Oryzaephilus* spp. showed no changes from the control bread with regard to most quality criteria, the presence of a characteristic, low intensity, taste and/or odour was identified. Bread prepared from flour previously infested with *Tribolium* disclosed a variety of property changes and a distinct offensive taste and odour. These effects were observed notwithstanding the fact that the insects and their body fragments were separated from the flour by sifting, prior to making the bread.

**Storey et al. (1984b)**, reporting the outcome of a survey of over 8000 farm storages across 27 states of the USA indicated that 1 or more live, stored-product insect species were found in 25.1% of the wheat, 56.4% of the oats and 79.7% of the corn samples obtained. The average number of insects per 1000 g in the infested samples was 26 for corn, 39 for oats and 105 for wheat. Insect species that prefer high moisture and which feed on moulds were found in 28.8% of the corn samples. The incidence of insects generally increased with increased grain moisture and average test weights per bushel were lower in infested grain than in uninfested grain. The incidence of insects and the composition of insect populations within each commodity did not vary significantly with the length of time the grain had been in storage.

**Sinclair (1982)** conducted 3 surveys between 1977 and

1979 on about 60 farms on the Darling Downs, Queensland. Farms in this area would be considered to be well above average in the application of management practices. Although predominantly grain producing farms, no commercial grain would be held on the farms. The mean amounts of grain per farm, estimated visually, were 950 kg of bulk and bagged stocks, 270 kg of grain spills, 165 kg in farm machinery and 75 kg in other residues. The mean farm populations of the 4 major pest species combined was estimated at 360 000 adults, of which about 88% were in bulk and bagged stocks. The insect populations peaked in late autumn and reached a minimum in early summer.

During the past decade concerted efforts have been made to expand the production capability of the major staple food and feed grains, to the point of self-sufficiency or even export, both of which would markedly reduce the burgeoning foreign exchange deficits that are presently being experienced in many developing countries. Increasing areas are being brought under irrigation, and existing and new irrigation areas are being more intensively managed, through the utilisation of high-yielding varieties, in a multi-cropping system (**Russell 1980**). **Pomeranz (1982)** stated that 'increased crop productivity is the key to feeding the world's expanding population', and this becomes more evident with the realisation of the disproportionate increase in population that is occurring in the developing world, compared with the industrialised nations. Multi-cropping, simply translated, means that at least one crop is grown during the monsoon season, creating problems and difficulties in harvesting, threshing, drying and storing, resulting in rapid biological deterioration. In addition, the high-yielding varieties are easily shattered, generally softer and, when harvested, tend to have a wider range of kernel maturity than the traditional non-improved varieties. The dichotomy that exists in enhancing productivity utilising high yielding varieties is in the associated problems that are now so prevalent in the post-production system. Traditional systems of storage and handling are now inappropriate, and their shortcomings are accentuated more with the high-yielding varieties than they are with the traditional varieties. One of the most challenging problems of the 1980s will be to reduce losses caused by pests, especially insects, during the food production, storage and processing operations. Without exception, greater benefits would be derived if more intensive efforts were directed towards conservation and quality maintenance of what has already been produced, rather than on energy-expensive methods to produce more. The challenge facing the Association of South East Asian Nations (ASEAN) has been clearly documented by **Semple (1985)**.

**Arthur N. Hibbs (1968)**, a former president of the Association of Operative Millers, in an address to a conference sponsored by his organisation, sharply defined the sanitation problems of the grain-storage and cereal-processing industries:

We all have our common goal, regardless of our affiliation, to do the best possible job in the field of sanitation. Today, as never before, the citizens of this nation, as well as foreign countries, are keenly aware of proper sanitation and pest control. Not only are they aware of it, but they demand it. And this is true no matter what industry we serve or service. Because of the enormous publicity given to sanitation standards and the use of certain chemicals to control pests, we are faced with a far more sophisticated and educated customer for our end products. And, I might add a much more critical customer, too.

If the information now available were utilised, most of the damage and loss due to insects could be prevented.

**Golob (1984)** pointed out that the average small farmer has very little cash. Consequently, improvements in his agricultural practices must be cheap if they are to be acceptable. There are 3 main ways in which improvements could be made to the existing small-holder storage system. These are:

1. improve the storage qualities of the varieties of produce grown;
2. improve the structure of the food store;
3. use protectants to control insect pest damage.

Plant breeders have begun to introduce into their programs factors which will enhance resistance to attack by storage insect pests. Losses can be reduced by improving the structure that the smallholder uses. In several countries the need to do this has led to the development of highly durable but complicated structures which have commonly proved too expensive for the farmer to purchase or build. Even small-farm stores can be made rodent-proof and it is generally easier to do this than to kill rodents once they have entered. Drying rates after harvest can be improved by storing freshly harvested produce in a structure which takes full advantage of prevailing wind. Improved means of access to the grain which avoids damage to the storage structure or its weather-proofness contributes greatly to improving the quality of stored grains. These modifications are simple to implement and of little or no cost. They enable the farmer to keep the produce in good condition during storage. In order to produce a recommendation acceptable to the farmer for the application of grain protectants, the cost proposed must be low to be seen as economical. The costs and benefits, however, change with the duration of the storage period and with the variety of grain stored. Since the development of the insect population only becomes significant during the final stages of storage, the damage to the farmer's grain becomes significant at the end of the storage period.

**Greening (1979a)** produced evidence of the dispersal of grain insects in commerce over quite large distances and from different climatic regions. This was particularly noticeable in the case of dispersal of resistant strains from bulk grain storages to stock-feed mills and produce stores

and later to farms. These examples should serve as a warning of the ease with which insect pests may enter regions where they have not previously been found.

**Joffe (1958)** described additional problems of protecting stored grain from insects under tropical conditions. Loss of quality takes priority over loss of quantity in temperate areas. Loss of quantity is of primary concern in tropical countries where insects have a near optimum environment most of the year.

In the main, storage practices in the tropics have evolved through traditional methods which depend on physical factors such as natural drying, storage and preservation in simple structures. There is little or only ineffective provision for the prevention of reinfestation, and the preservation of quality. Traditional methods include little or no use of insecticides. Hence, in many parts of the developing world, storage practices involve traditional structures such as simple wooden platforms, storage baskets, timber tripods, vertical or horizontal poles or racks, varieties of cribs made from wooden or grass materials, pots or other earthen containers, gourds and other types of granaries. The structures and practices are largely ineffective in the prevention of deterioration of stored agricultural produce. Under such conditions, **Taylor (1974)** indicated that losses due to insect infestation, biodeterioration, microorganisms and rodent damage are considerable. Until recently very limited inputs of pesticides for safe disinfestation of produce were used but recent developments which combined improvements in the design of cribs and storage bins with the wise use of pesticides such as lindane, malathion, pirimiphos-methyl and synthetic pyrethroids show great promise for the future. In particular, successes that have been achieved in incorporating these grain disinfestation and protection methods into traditional storage practices in Nigeria, Kenya, Zambia and many other countries in tropical Africa are now beginning to have a major impact on the reduction of losses at the farm level and therefore on the economy and nutrition of the small farmer.

The present trends in agricultural production patterns and systems and a displacement of populations from rural

to urban areas seems to indicate that in the remaining years of this century decreasing percentages of human populations are likely to be directly involved in farming; small farms are likely to give way to medium scale and large farms; and the storage of agricultural produce is likely to evolve along the lines of greater co-ordination and co-operation in the use of modern techniques of disinfestation and storage. Already in many developing countries, the percentages of agricultural workers are going down from 60–70% of the total working force to 40–50% and greater efforts are going into the organisation of co-ordinated and centralised storage systems which would receive surplus agricultural produce and utilise modern techniques of storage to ensure their preservation and release into the marketing channels as and when necessary. Although this trend is likely to continue and be strengthened in the immediate future, it must be realised that it would depend on a fundamental understanding of the role of the farmer, small or large scale, in the first stage of handling and disinfestation necessary to ensure that produce delivered to medium and long-term storage depots does not constitute foci of infestation and deterioration of the bulk of stored items. In other words, clear guidelines which now form the basis of on-farm disinfestation and handling of agricultural produce should be retained and strengthened and the inputs necessary for their observance ensured at the farm level.

The rest of this century will be crucial in the efforts of man to expand and improve agricultural production and protection in order to feed the population at a level compatible with modern and acceptable concepts of social and economic welfare. The intensification of agricultural production must be matched by the pursuit and application of modern storage technologies if the gains to be realised by such intensification are to be maintained so that they reach the consumer. Tropical storage entomology has many of the answers in terms of developed technology, organisation and relevant research. If this is put to work we may yet avert a possible food crisis before the end of this century and indeed close the food and nutrition gap and strengthen the economies of the developing countries of the tropical world.