Chapter 1
Importance of Stored Product Insects

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Introduction

With the continuous development of human civilization over the last 10,000 years or so, methods to produce food and other materials and to store them for future use have developed enormously. Moreover, significant population growth over the last few centuries aligned with increasing life expectancy and industrialisation has led to the gradual loss of arable land to make way for housing, industries and transportation network. To feed the world's bulging population, food security has become one of the most important priorities for both the developed as well as developing nations across the globe. The concept of food security emerged only in the 1970–90s due to the deepening of global food crisis, specifically affecting the poor in the under developed world. At the World Food Summit of 1996, issues of famine, hunger and food crisis were extensively examined and the behaviour of potentially vulnerable and affected people was identified as a critical aspect, based on which the initial focus, was on the volume and stability of food supplies. Food security was defined in the 1996 World Food Summit (FAO 1996) as: 'availability at all times of adequate world food supplies of basic foodstuffs to sustain a steady expansion of food consumption and to offset fluctuations in production and prices'. The leaders attending the conference also solemnly proclaimed that 'every man, woman and child has the inalienable right to be free from hunger and malnutrition in order to develop their physical and mental faculties'. The universal understanding now is that, apart from targeting to produce more food, we must protect what we produce.

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Grain has been a major source of food for humans since the beginning of agriculture and settled communities. Archaeological evidences suggest that grain was grown and stored in bulk at least 7000 years ago, much before the great civilizations of the Orient and Mesopotamia (Roberts 1976). Ancient Egyptian records indicated storage of grains in pits lined with straw during 2000 B.C. (Lee 1960), and archaeological remnants in India showed communal granaries comprised of mud-brick houses in 2500 B.C. (Mellart 1961). Effects of colonisation, international trade and industrialisation have resulted in many advances in storage structures since these descriptions from the ancient history. Although the old mud-brick structures are still in practice in several parts of Africa, now we have large structures of steel and concrete for storing commodities in most of the developed countries (Reed 1992). Several commodities are being stored, that may include but not limited to durable food and materials for livelihood such as grain (cereals, pulses, oilseed and nuts), dried tubers, dried fruits, herbs and spices; dried fish and meat products; museum and herbarium artefacts and hides skins and wool.

The storage environment, with rich sources of food as described above, is a very attractive place for a range of insects to thrive, and show preference for the stored commodities over their previous natural habitats. The threat to biosecurity of stored food, specifically the grain and its products from insect infestations has been a well-established phenomenon. A recent forecast estimated that the food production would need to increase by 60% to feed an estimated global population of 10.5 billion in 2050 (Alexandratos and Bruinsma 2012). To meet this demand and to ensure future global food security, apart from increasing production and improving distribution; a major focus should be on reducing post-harvest food losses.

A significant proportion of the post-harvest losses occur due to infestations from insect pests. Of the 32 taxonomic Orders of insects, species belonging to only three Orders, Coleoptera (beetles), Lepidoptera (moths) and Psocoptera (psocids) are considered as pests of stored commodities. In addition, a few species belonging to the Orders Hemiptera (bugs) and Hymenoptera (wasps) are also being reported to be associated with stored commodities, but only as predators or parasites of the species belonging to the three major orders mentioned here (Rees 2004; Heaps 2006) Most of the stored products pests are considered as opportunists; several beetles (Coleoptera) were initially recorded under the bark of trees; several moths (Lepidoptera) were supposedly originated from dead and ripening fruits; whereas several psocids (Psocoptera) were originated from leaf litters (Rees 2004). A rare exception is the granary weevil *Sitophilus granarius* (L.) (Coleoptera: Curculionidae), which is the only species that has never been detected outside the storage environment (Plarre 2010). The oldest record of storage pests associated with human beings goes back to ancient Egypt, where *Tribolium confusum* Jacquelin du Val (Coleoptera: Tenebrionidae), *Oryzaephilus surinamensis* (L.) (Coleoptera: Silvanidae) and *S. granarius* (Coleoptera: Curculionidae) were reported (Rees 2004).

In the recent past, there have been comprehensive books and chapters written on the classification, identification and general biology of major pests of stored commodities and their management (e.g. Rees 2004; Hagstrum et al. 2012). The aim of this chapter is to highlight the importance of the storage pests affecting the durable commodities. Apart from a brief listing of major stored product pests, we aim to, broadly, discuss their economic impact. Unless there is an absolute need, our focus will be on published reports from the last decade.

Overview of Insect Pest Species Associated with Stored Products

Stored product pests can be defined as organisms that are injurious to stored commodities of all types including grains, pulses, fruits, seeds and plant and animal materials (Hill 2002). The impact can be in the simplest form of physical damage to the commodity and can extend to a broader sense of economic loss in terms of quality and market access. Due to its global importance as a major stored commodity, grain will constitute a significant part of the discussion in this chapter. Rees (2004) has given a comprehensive account of all stored product pests along with their host range, distribution and life cycles. We provide an overview of insects in stored products under the following six categories: pests of grain and their products; pest of dried fruits and nuts; pests of durable herbs, spices, tobacco and pet food products; pests of dried fish and other animal products; predators and parasitoids; and scavengers and foragers.

Pests of Grain and Grain Products

Pests of grain and grain products constitute the major group of insects occurring in the stored product environment. They are further categorised into primary and secondary pests. Primary pests attack whole grain and are capable of penetrating an undamaged seed coat and pod to feed on the embryo, endosperm or cotyledons. Secondary pests feed on grain products or grain that has already been damaged by the primary pests or as a result of harvesting, handling and transporting. The primary pests typically have a narrow range of food preferences such as cereals and pulses. The secondary pests, however, have a wide host range including damaged whole grains, milled products such as flour and processed and manufactured food products such as breakfast cereals, chocolates and compound animal foods. There is a distinct difference in the life cycle of pests belonging to these two categories. The life cycle of a primary pest involves lodging of the eggs inside or on the outer coat of grain, followed by development within the grain, making the immature stages difficult to detect. Because the entire life cycle (egg, larva and pupa) often takes place inside the kernel these primary pests are also called as internal feeders. In contrast, the eggs of secondary pests are laid in a scattered manner in or near the food source where the developing larvae can easily be seen. As the entire life cycle takes place outside the whole grain, the secondary pests are called as external feeders. Due to the major difference in life cycles, damage to whole grain by primary pests is very distinctive in form and pest recognition is easier compared to the secondary pests.

Major Primary Pests

The major primary pests of cereals include the beetles of the genus *Sitophilus* [the rice weevil *S. oryzae* (L.), the maize weevil *S. zeamais* Motschulsky, the granary weevil *S. granarius* (L.)], the borers [the lesser grain borer *Rhyzopertha dominica* (F.) and the larger grain borer *Prostephanus truncatus* (Horn)] and the Angoumois grain moth *Sitotroga cerealella* (Olivier).

The major primary pests of legumes (peas, beans, grams etc.) are bruchids including the bean weevil *Acanthoscelides obtectus* (Say), the cowpea weevils belonging to the genus *Callosobruchus* [*C. maculatus* (F.), *C. chinensis* (L.) and *C. analis* (F.) and *C. phaseoli* (Gyllenhal)], the groundnut bruchids *Caryedon serratus* (Olivier) and the Mexican bean weevil *Zabrotes subfasciatus* (Boheman).

Major Secondary Pests

The major secondary pests include two species of *Tribolium*, the rust red flour beetle *T. castaneum* (Herbst) and *T. confusum*; a group of *Cryptolestes* species [the rusty grain beetle *C. ferrugineus* (Stephens) and flat grain beetles *C. pusillus* (Schönherr) and *C. pussilloides* (Steel and Howe)]; two *Trogoderma* species [the Khapra beetle *T. granarium* Everts and the warehouse beetle *T. variabile* Ballion]; the saw-toothed grain beetle *O. surinamensis*; the warehouse moth *Cadra cautella* (Walker); the rice moth *Corcyra cephalonica* (Stainton); the Indian meal moth *Plodia interpunctella* (Hübner) and a group of *Liposcelis* psocid species [*L. bostrychophila* Badonnel, *L. entomophila* (Enderlien), *L. decolor* (Pearman) and *L. paeta* Pearman].

Pests of Dried Fruits and Nuts

Major insect pests under this category include the dried fruit beetle *Carpophilus hemipterus* (L.) and several moths including the Indian meal moth *P. interpunctella*, almond moth *C. cautella* (Walker), tobacco moth *Ephestia elutella* (Walker) and the raisin moth *Cadra figulilella* (Gregson).

Pests of Durable Herbs, Spices, Tobacco and Pet Food Products

Key pests under this category include the cigarette beetle *Lasioderma serricorne* (F.), the drugstore beetle *Stegobium paniceum* (L.), the carpet beetles *Trogoderma glabrum* (Herbst) and *Trogoderma ornatum* (Say), the lesser mealworm *Alphitobius diaperinus* (Panzer) and the clothes moth *Tineola bisselliella* (Hummel).

Pests of Dried Fish and Other Animal Products

Species particularly belonging to the genus *Dermestes* called hide beetles (*D. maculatus* Degeer, *D. frishii* Kugelann) and the red legged ham beetle *Necrobia rifipes* (Degeer) are considered as major pests of stored dried fish, hides, skins and other dried animal products such as processed meat and cheese.

Predators and Parasitoids

The predators include mainly the bugs such as the stack bug *Lyctocoris campestris* (F.), the cereal bugs *Xylocoris* species, and the assassin bugs *Amphibolus venator* (Klug) and *Peregrinator biannulipes* (Montrouzier). These insects do not damage the commodities, but prey on other insects, which can be an advantage from pest management point of view. However, their presence can be considered as a contamination issue and a health issue because they may also irritate the storage workers.

Parasitoids that are associated with stored products are mostly wasps that attack the juvenile stages of beetle and moth pests that are already in the commodity, and do not feed on the commodity. The major parasitic wasps include *Trichogramma* species; *Habrobracon* species and *Venturia canescens* (Gravenhorst) parasitising several moth species; *Anisopteromalus calandrae* (Howard) parasitising several beetles and moth species; *Uscan* species parasitising eggs of bruchids; and *Choetospila elegans* Westwood parasitising several beetle pests.

Scavengers and Foragers

These are insects that occur in stored products but don’t feed directly on them. They rather feed on the residues or the dead bodies of insects and other animals. Some of the notable scavengers include cockroaches, earwigs and silverfish.

Implications from Insect Infestations

Economic Implications from Quantitative Loss Due to Physical Damage

The term ‘post-harvest loss’ (PHL) is being used over last two decades in relation to both quantitative and qualitative food loss in the post-harvest system (de Lucia and Assennato 1994; Hodges et al. 2011). A significant quantitative loss can occur to the stored products due to physical damage caused as a result of direct consumption by primary pests followed by a series of invasions from a range of secondary pests. A cumulative weight loss of up to 56.9% of wheat was reported as a result of feeding by *R. dominica* over a period of 2 months (Rao and Wilbur 1972). Few reports are also available from laboratory evaluations on the direct physical damage caused to grain by psocids. McFarlane (1982) estimated a weight loss of 5% and of milled rice as a direct result of heavy infestations of *L. bostrychophila* over a 6-month period, whereas Kücerová (2002) measured an average weight loss of 9.7% of broken wheat kernels due to infestations from the same species over a 3 months period. Weight loss was 0.17% during the 4 months of storage from a stable infestation of 4000 psocids/kg. In a recent study, it was revealed that although weight loss due to *L. entomophila* and *L. paeta* infestations was low in intact kernels (0.2 and 0.4%, respectively) compared with damaged wheat seeds (8.5 and 3.3%, respectively), germination in intact kernels was reduced by 32% by *L. paeta* infestation (Gautam et al. 2013).

In terms of post-harvest losses during storage, there were species-specific reports available from several countries in the sub-Saharan Africa. *C. maculatus*, alone was found to be responsible for up to 24% losses in stored pulses in Nigeria (Tapondjou et al. 2002); whereas about 23% losses were recorded in stored maize due to combined infestations of *S. zeamais* and *P. truncatus* in Benin (Meikle et al. 2002).

Physical damage to grain during post-harvest handling such as threshing, drying and transporting make the grain vulnerable to rapid and extensive damage and decay by insects and mould (Rowley 1984). The most common methods to measure weight loss assessment include the standard volume weight, thousand-grain mass and count and weigh methods (Reed 1986). Our discussion, however, will be focussed on reported losses irrespective of the methods used to measure them. Although figures on actual economic damage are difficult to obtain due to the ‘commercial in confidence’ nature of the information, we present here the published reports.

A comprehensive review of the assessment of losses caused by insects to stored food commodities was undertaken way back in 1955 (Parkin 1956). According to that review, the annual losses to grains as a direct result of insect infestations from major stored grain pests in the USA over a decade (1951–60) was 325 million bushels, valued at $454.8M (USDA 1965). It is noted that the currency values reported here and elsewhere in the text are at the time of the respective reporting period, it may vary significantly if calculated at the present time. Moreover, a further loss of $8.8M incurred due to insect infestations in processed cereal products (USDA 1965). We have seen similar figures on post-harvest losses due to insects even after 30 years after that report, where the losses in the USA were estimated to be $500M per year during 1990 (Herein and Meronuck 1991). In contrast, based on a study over 1961–71, Bourne (1977) reported the losses arising from insect infestation in stored grain in central storage and handling systems in Australia to be insignificant. Although there has been no recent report from Australia on the current losses from insect infestations in stored post-harvest commodities, research in the USA has estimated that in developed countries, the average annual losses may go to 10% (Mason and McDonald 2012).

For the Indian subcontinent, the annual losses of grain during storage are estimated at $1B (INR 50B) (Singh 2010; Nagpal and Kumar 2012), and losses due to insect problems alone are estimated around $364M (INR 17B) (Boxall 2001). In the developing countries, the estimated losses are being reported to be up to 20% by several authors (Mason and McDonald 2012). In sub-Saharan Africa, the losses are reported to be around $4B annually (World Bank and FAO 2011).

In a recent study, Abass et al. (2014) assessed the post-harvest handling practices and food losses in a maize-based farming system in semi-arid areas of Central and Northern Tanzania during two harvest seasons in 2012. Based on the major crop maize, these researchers have estimated the quantitative post-harvest losses during storage to be 15–25%, mostly attributed to damages caused by the larger grain borer, *P. truncatus*), the grain weevil *S. granarius* and, the lesser grain borer *R. dominica*.

Among the range of pests, *S. zeamais* is considered as the most destructive in stored maize grain in tropical and subtropical regions worldwide and causes grain yield losses of 15–30% in developing countries (Bergvinson 2001). In sub-Saharan Africa, *S. zeamais* along with *P. truncatus* is reported as the major pests of stored maize and significantly impact household food security in the smallholder sector (Vowotor et al. 2005).

Effect on Quality

Serious biological deterioration of stored commodities, specifically grain can occur between the initial storage period and first processing as a direct result of activities from insects and related fungi (Fleurat-Lessard 2002). The effect of insect activities in grain mass can be multifold so far as quality is concerned. The grain loses value and receives a lower grading due to simple contamination from dead insect bodies, waste products, frass and dusts as a result of insect activities (Fleurat-Lessard 2002). The insect feeding activities can also add to the fatty acid content of the grain and leave high quantities of uric acid that lead to grain rancidity (Mason and McDonald 2012).

Significant effect on seed germination due to direct feeding by insects has been well demonstrated. In Brazil, Santos et al. (1990) showed that the presence of *S. zeamais* and *S. cerealella* in maize grains led to a reduction in germination with increasing developmental stage of the insects. In Nigeria, Okiwelu et al. (1987) recorded high level of moisture, combined with a decrease in germination ability of maize due to infestation by *S. zeamais*, while Mbata (1994) showed that infestation of bambara groundnuts (*Vigna subterranea*) with *C. subinnotatus* reduced seed viability and increased free fatty acids and peroxides, which are indices used in measuring biochemical deterioration. In a recent study, Keskin and Ozkaya (2013) revealed that infestation from *S. granarius* had significantly reduced thiamine and riboflavin contents in wheat over a period of 6 months storage. Sudesh et al. (1996) found that infestation of wheat, maize and sorghum grains with single or mixed populations of *T. granarium* and *R. dominica* resulted in substantial reductions in the contents of total lipids, phospholipids, galactolipids, and polar and nonpolar lipids, while Kumar et al. (1996) recorded a substantial reduction in starch in parboiled cassava chips due to infestation with *S. oryzae* and *R. dominica* as compared to the uninfested chips.

Apart from the quality affected by the devouring of grain by both adults and immatures of the pests, the effect of quality can be severely affected by secondary infestation from a range of fungi. The presence of insects raises the product temperature, due to their feeding activity, resulting in 'hot spots', sometimes reaching up to 57 °C (Mills 1989). These spots, in turn, lead to concentrating of humidity within the product, thus stimulating seed deterioration and further fungal activity. Fungal infestation results in change in colour, taste, smell, reduction in nutritional value, increase in free fatty acids (FFA) and reduction of germination ability (Sauer et al. 1992). Preferential attack of the embryo by *Eurotium* species, can result in 50–100% reduction in germination, reduced amino acid contents of the grain that leads to loss of the characteristic grain odour and flavour (Sauer et al. 1992). In a heavily infested grain bulk, the natural odour is replaced with a musty or mouldy odour. Mixing of off-odour grain with a good batch of grain fails to mask the off-odour and it can be expensive to overcome this problem through the use of ozone (Mendez et al. 2003).

Several species of *Aspergillus* and *Penicillium* are associated with mycotoxins (e.g. aflatoxins in groundnuts, sorghum and rice, and orchratoxin A in corn, oats and barley) that can inflict major health hazards to human and animals (Sauer et al. 1992) (see Sect. 'Work Place Health and Safety Implications', below for more).

Work Place Health and Safety Implications

Infestation of insects in grain mass can indirectly lead to several workplace health and safety issues, particularly to those handling grain from harvest to storage and transport.

Although psocids are considered as one of the smallest among all stored product insects, they have emerged as a major concern in the stored grain environment in recent years and in large infestations, they can have significant health and safety impacts (Nayak et al. 2014). In severe infestation situations, psocids have been reported to have swarm over storage walkways, ladders, etc., making them slippery and exposing workers to risk of injury (Rajendran 1994; Jiang et al. 2008). Psocids have also been implicated in the development of allergic conditions in workers caused by transmission of microorganisms (Turner et al. 1996) and may be responsible for transmission of bacterial diseases (Obr 1978), although there is no direct evidence for this. There have been reported cases of delusory parasitosis caused by psocids (Turner 1987). Lis et al. (2011) highlighted the serious health hazard of defensive secretions produced by *T. castaneum* and *T. confusum*. Through a literature review, they have reported the carcinogenic effects of benzoquinones, secreted by these two stored product pests.

As mentioned in the preceding section, elevation in heat and moisture in the grain mass due to insect feeding encourages the development of several species of fungi. Mycotoxins are metabolites that are produced by these fungi can cause several animal and human health problems. A flatoxin from *Aspergillus* is of the greatest concern due to its high carcinogenic properties, and therefore, it is being regulated in the grain trade across the globe (CAST 1989). In several developing countries, high intake of aflatoxins was shown to have a positive link with high incidences of primary liver cancer and hepatitis B in human populations (CAST 1989). Moreover, in animals, aflatoxin was shown to cause acute or chronic diseases in poultry, swine, cattle and many other farm animals (CAST 1989).

Rejection by Consumers and Loss of Market

The consumer preference for safe and clean food that is free from insects and chemical residues has taken an unprecedented momentum over the last few decades. In a comprehensive review recently, Stejskal et al. (2015) have highlighted the filth contamination of flour and pest risk trends in stored food and feed products in Europe based on reported cases in the past 80 years. The two demanding aspects of safe and clean food of the consumer can be conflicting. Several contact insecticides that have been used by industry to provide long-term protection from a range of pests leave residues that attract a lower price and restrict markets. Fumigations help in disinfesting stored commodities only and it is difficult to provide long-term protection from insects without applying contact pesticides. Moreover, increasing pressure from environmental movements has seen the phase out of several treatments including one of the most effective fumigants, methyl bromide (Johnson et al. 2012).

To have a competitive edge and meet the consumer preference for insect-free grain, Australia has adopted a ‘Nil tolerance’ policy for live insects in grain destined for international markets, and this principle is recently being implemented at the domestic market (GTA 2017). Currently, this policy applies to all life stages of 12 pest species comprising beetles, moths and psocids. In the USA, strict laws are also in place limiting the number of permissible live insects in commodities and insect-damaged kernels (IDKs), both of which can incur losses in the market. U.S. Department of Agriculture rejects a grain consignment for sale for human consumption, if two or more live insects are detected in a kilogram of grain sample (Adam and Alexander 2012). This issue can be overcome through fumigation to kill the live insects, but at a cost that reduces the value of the consignment. Discounts are also imposed at the time of sale if grain bulk is detected with more than 32 IDKs in a 100 g sample.

Even if exporting countries try to maintain the 'insect-free' status of their grain consignments, sometimes, due to the failure of the phytosanitary measures, live insects are detected at the importing ports that can lead to rejection of the whole shipment of grain or can incur a demurrage cost along with costs for disinfestation. In 2007, Egypt rejected a US$84M load of US soft red wheat due to detection of live insects (Farm Futures 2007).

Strict legislations and regulations are also in place at the international level to restrict the movement of certain pests that are considered exotic to some countries. Quarantine regulations have been imposed on such insect pests and standardised phytosanitary certifications have been developed to restrict their movements for global trading of grain and processed commodities (Tyler and Hodges 2002). Notable among the quarantine pests is the Khapra beetle, *T. granarium* (Stibick 2007). This pest is notorious for its destructive nature and so far reported on 96 commodities across the globe. Due to its high level of tolerance to major treatments including fumigant methyl bromide, in the USA, the cost of its eradication in the 1950s was estimated to be US$8.4M (Klassen 1959).

Costs Associated with Pest and Resistance Management and Research

Since the realisation of the importance of the insect pests in stored commodities and their economic implications, there have been ongoing efforts to develop new treatments and pest management strategies to reduce their impact. Post-harvest storage environments across the globe have witnessed the emergence and demise of several contact insecticides and fumigants over the last century. Typically a fumigant gas is used as a disinfestant to control pest populations in an already infested grain bulk, whereas contact insecticides are being used as residual treatments of freshly harvested uninfested grain for protecting it from insect attacks, hence these treatments are named as 'grain protectants'. Apart from these major treatments, there are several other aspects of pest management that include hygiene, aeration cooling, drying and controlled atmospheres. There is a significant literature available on the history of different pest management options developed and used in the stored grain systems across the world (see Chapter 'Insect Pest Management in Stored Grain' by Daglish et al.).

The cost associated with managing a pest infestation varies greatly depending on the treatment used. We cite a few examples here on the economics of the current pest management practices in developed countries. In Australia, the current costs for a range of pest management options calculated in Australian dollars per tonne of grain stored (incorporating labour and materials) are: on-farm hygiene (AU$0.23/t), an aeration cooling system (AU$0.91/t), aeration drying (AU$17.21/t), phosphine (AU$0.35/t), sulfuryl fluoride (AU$4.00), silo bags (AU$4.00/t), and a protectant treatment of chlorpyrifos-methyl, s-methoprene and spinosad (AU$3.40/t) (GRDC 2017). Adam and Alexander (2012) outlined a comprehensive account of economics around the integrated pest management (IPM) decisions that are currently being practiced in the USA. These authors, calculated the cost components of sampling for live insects to be approximately at US$0.40/t including the cost of amotorised equipment and labour required to separate and count insects. They have also undertaken a costing for fumigation with turning to be approximately at US $1.20/t (Adam and Alexander 2012).

It is important to note here that the estimated cost of discovery, development and registration to bring a new pesticide to the market for use by industry exceeds US $180M and may take 8 to 10 years (Whitford et al. 2017), and the stored products is likely to be a small market for new pesticides. Development of resistance in target pest species to a particular chemical, therefore, can be a very costly affair, both in terms of losing the market for that product and developing an alternative. Even if there have been several contact insecticides and fumigants introduced to the storage systems across the world, resistance in key pest species have been a regular phenomenon (Nayak et al. 2015). In the last two decades, a major emphasis has been given to the management of resistance in key pest species across the globe to enhance the longevity of established products (Nayak et al. 2015). In the following paragraphs, we will cite few examples to highlight the costs associated with pest and resistance management and related research.

Recently, an AU$30M research initiative was launched under the umbrella of Cooperative Research Centre for National Plant Biosecurity (CRCNPB) to protect Australia's post-harvest grain (approximate annual value of AU$9B) (CRCNPB 2007). Over a 5 year period (2007–12), the CRCNPB brought together the skills of industry, government and scientific institutions in a unified national approach to develop new technologies, training and biosecurity safeguards. Key CRCNPB partners included federal and state governments, universities, three major bulk grain-handling companies, and the Grains Research and Development Corporation (representing grain growers). A significant portion of the AU$30M was allocated to the development of new phosphine fumigation protocols to manage strongly resistant genotypes in key pest species; development of alternatives such as nitrogen and sulfuryl fluoride, and other research to underpin an integrated approach for pest and resistance management for growers and bulk grain handlers. A follow-up initiative, the Plant Biosecurity Cooperative Research Centre (2012–18), invested approximately AU$42M over a 5 year period focused on the development and adoption of new technologies and tools to protect the post-harvest grain from major pests. A significant part of the investment was allocated towards an ongoing national monitoring programme for pests to key fumigant phosphine (PBCRC 2012).

In 2014, with USAID support of US$8.2M, several universities in the USA formed a unique consortium called 'Feed the Future Innovation Lab for the Reduction of Post-harvest Loss' (KSU 2014). A major goal of this initiative is to improve storage conditions and pest management practices in developing countries including Ethiopia, Ghana, Guatemala and Bangladesh.

The high cost of research investments to tackle insect problems in the grain storages in Australasia region and the benefits from such investments have been well demonstrated in a report from the Australian Centre for International Agricultural Research (ACIAR) (Francisco et al. 2009). As part of the regional cooperation and development programmes, ACIAR supported a series of four research projects during 1983–2005 on developing best practices in use of pesticides for protection of post-harvest grain in the tropical areas of Australia, the Philippines, Malaysia, Thailand and China (Francisco et al. 2009) The main aim of these projects was to use grain protectants in combination and in rotation at lowest effective dose rates to mitigate the serious resistance problem in several pest species to the organophosphate malathion. At the time of an impact assessment undertaken in 2007, the total investment in these projects was AU$9.6M. The adoption of pest management technologies developed through these projects had resulted in a reduction of losses in stored paddy in the Philippines from 9.5 to 4.8% per year (Francisco et al. 2009).

Conclusion

In this chapter, we attempted to give an overview of the importance of stored products insects that highlighted their economic implications in terms of quantitative loss, the effect on quality and consumer and market sensitivity. The impact of insect pests on post-harvest losses contributes significantly towards the overall food loss of approximately 1.3B tonnes of food every year across the world (FAO-World Bank 2010). We also tried to demonstrate the costs involved in research and development towards managing them to emphasise the indirect costs associated with these pests. To conclude, we will outline several approaches that we suggest would help in reducing the impact of stored product pests, specifically in the stored grain environment.

Across the globe, most of the post-harvest grain that is stored in traditional storage structures are vulnerable to insect infestations and mould growth, specifically during long-term storage. The first step in protecting post-harvest grain is the availability of modern storage systems that are sealable (airtight), to be suitable for using fumigants; currently, a common method used for disinfestation of bulk grain. In Australia, sealable silos are currently being sold through adherence to a legalised standard AS2628 (GRDC 2014). Silos meeting this standard pass a 5-minute half-life pressure testing, ensuring a high level of air-tightness. Investing in such type of storage structures would play a critical role in reducing post-harvest losses and preserving grain quality, which in turn would yield in increased revenue in the long term. For farmers and small holders of grain in Africa, there are new modern small storage options (from 20 to 3000 kg capacity) available including UV-stabilised polypropylene bags, small metal silo bins and hermetic bags (FAO 2014).

Early detection of pests through regular monitoring of their populations in and around storages and diagnosis of their resistance towards different treatments are critical components for implementation of appropriate strategies to manage them and preventing their spread. In Australia, a national monitoring programme is in place since last three decades that helps in early detection and management of strongly phosphine resistant stored grain pests across both on farms and bulk handling storages (Nayak et al. 2017). Development of alternatives to traditional pesticides and biorational approaches to disinfest and protect grain are also being promoted recently as ways to address consumer demand for insect and residue free grain and processed food. In a recent review Phillips and Throne (2010) highlighted the importance of biorational tools in stored commodity pest management that include sanitation, management of temperature in stored grain, use of natural enemies of storage pests, computer-assisted decision-making system for pest control and insect sampling. In Australia, recently sulfuryl fluoride has been developed as a suitable alternative to phosphine (Nayak et al. 2016) to manage strongly phosphine resistant populations of rusty grain beetle *C. ferrugineus*, that has recently become a major problem in the bulk grain storages (Nayak et al. 2013). Binary combinations of currently registered products with a new biopesticide spinosad (Daglish 2008) are being used by industry as a way to mitigate multiple resistances to grain protectants in major stored grain pests in Australia; whereas a method is in place for early detection of resistance to spinosad in its target pest *R. dominica* (Nayak and Daglish 2017).

While we are developing modern pest and resistance management strategies that are aimed at meeting the cost-benefit expectations and market access requirements, the role of extension specialists cannot be ignored. In Australia, a well-established national grain storage extension team works as an interface between the researchers and end-users, specifically the growers. This network facilitates extension programmes to growers across the country that include bulletins, fact sheets, on-site demonstrations and workshops emphasising the benefits of adoption of best pest and resistance management practices along the post-harvest grain value chain.

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