Section: Around the World of Stored-Product Protection

Research on stored product protection in Australia: a review of past, present and future directions

Collins, P.J.*#
Agri-Science Queensland, DEEDI, 80 Meiers road Indooroopilly, Qld, 4068 Australia, Cooperative Research Centre for National Plant Biosecurity, LPO Box 5012, Bruce, ACT 2617, Australia

* Corresponding author
# Presenting author

DOI: 10.5073/jka.2010.425.101

Abstract

Since its beginning, research into the protection of stored grain in Australia has been driven by market access, in particular, the need to provide insect free grain to overseas customers

Research began in 1917 when a bumper harvest coincided with disruption of shipping due the First World War and resulted in the unprecedented accumulation of wheat stocks, which were subject to catastrophic attack by 'weevil plagues'. Initial experiments were of insect life cycles and reproductive rate. This was followed by trials of heat and mechanical disinfestation and fumigation, and preventative methods such as admixture or surface treatment with lime, sand or mineral dusts, and hermetic storage. These technologies continued to be developed into the 1950s along with aeration cooling. In addition, ground-breaking research on mathematical descriptions of grain beetle life tables was published.

The admixture of malathion to bulk grain in the 1960s allowed, for the first time, the export of insect-free grain. However, in less than ten years, resistance in target pests had become so serious that alternatives were desperately required. In response, research began on the development of new grain protectants and alternatives such as controlled atmospheres, manipulation of grain temperature, new ways of using phosphine and the development of new fumigants.

Since the mid-1990s, pest management has become dependent on use of phosphine and maintaining susceptibility to this chemical has become a priority. The greatest problem now facing the Australian grain industry is resistance to phosphine fumigant in target insect pests. Our current short-term priority is the control of phosphine resistance outbreaks, while our more strategic research is aimed at gaining a fundamental understanding of fumigant behaviour in grain storages, the movement and colonisation of grain by insect pests and the mechanisms of selection in insect populations – information that will underpin the development of long-term resistance management.

Keywords: research industry collaboration, phosphine resistance, non-chemical technology, insect ecology, controlled atmosphere

1. Introduction

1.1. Preamble

Good morning ladies and gentlemen. I wish to thank the organising committee for this invitation to speak at this the 10th International Working Conference on Stored Product Protection. The topic of my presentation is: "Research on stored product protection in Australia: a review of past, present and future directions".

Australia has a rich history of research achievement in stored products protection and I could easily fill my allotted time describing it to you. However, I think the purpose of a conference like this is to learn from each other and have the opportunity to discuss the latest research developments and for that reason, I think it will be more interesting for you to hear about the research that is happening now and about our future directions than it would be for me to cover old ground. In addition, a "Brief history of entomological problems of wheat storage in Australia" written by Jan van Graver and Bob Winks (van Graver and Winks, 1996) has already been published in the 6th proceedings of this conference series. That paper provides an excellent summary of the problems encountered in Australia and the role that research played in solving those problems. On the other hand, I am not going to ignore previous research. I will present some highlights of past research and briefly describe the environmental and economic characteristics that have set the direction of research undertaken in Australia.

1.2. Background

Research into the protection of stored products in Australia has largely been concerned with the protection of whole cereal grains, particularly wheat, stored in bulk. Wheat is our major crop and our major export grain. On average, about 60% of total grain production, including wheat, is exported and Australia is one of the world's largest wheat exporters as well as being a major barley supplier. To compete successfully in the international marketplace, exporters must provide as high a quality product as possible. A major aspect of quality is absence of live insect contamination. In recent years, the domestic market has grown in importance mainly due to the increasing demand for animal feed with this sector requiring the same level of quality as the export market.

Wheat production in Australia faces a number of problems not shared by its international competitors. Our soils are infertile and even with the advantages of modern agriculture, yields are relatively low at around 1-2 tonne/hectare. In addition, rainfall is highly variable and unreliable, a situation now more unstable because of the vicissitudes accompanying global warming. These factors produce a crop that can vary dramatically in both quantity and quality from year to year. Grain in Australia is grown in a warm temperate to sub-tropical environment. Wheat and barley are sown in winter, grown in spring and harvested at the beginning of summer. This means that the temperature of the grain is about 30^{o}C when it is brought into storage and it is then stored through the hottest part of the year. In some regions, harvest coincides with very low relative humilities but in others it occurs in stormy weather when humidity is high. These conditions favour the growth of insect pest populations and result in high pest pressure on the crop from the very beginning of the storage period.

The seriousness of the threat of loss of markets and the high cost of remedial action if insect infestations are detected in foreign ports has motivated the grain industry from the beginning of export marketing to seek help from scientists to protect its grain from insect infestation. In addition, the size and importance of the industry to the Australian economy has ensured that governments have facilitated its development wherever possible.

Close collaboration between farmers, grain handlers, government agencies and researchers is a characteristic of stored products research in Australia. This partnership has involved a substantial investment in research by industry. This investment, and government policy supporting industry development, has set the direction of research to focus on the development of practical, cost-effective solutions to industry problems.

2. Past

2.1. The beginning

Stored products research commenced in Australia in August 1917 with the formation of the Wheat Weevil Committee in South Australia (Winterbottom, 1922). This committee was established in response to the catastrophic 'weevil plague' that appeared in April 1917 and which was seriously threatened the wheat producing areas of New South Wales, Victoria and South Australia. The Wheat Weevil Committee consisted of state government scientists and representatives of the farming, milling and grain storage sectors.

In 1915, Australia produced a record wheat harvest of 179,065,703 bushels (4,873,332 t) almost double any previous harvest. Until this time, surpluses were shipped overseas as quickly as possible and because of this policy there was no provision for the long term storage of grain. However, due to the outbreak of World War I, shipping had been severely curtailed and storage of the backlog of grain became a serious problem. Moreover, the next two years also produced bumper harvests resulting in an unprecedented accumulation of wheat stocks. At the end of 1916, half the crop from the 1915 harvest was still in storage, at end of 1917 the whole of the 1916 crop was still in stock, at the end of 1918 the whole of the 1917 crop and half of the 1916 harvest was still held and a similar situation occurred in 1919. This problem was most severe in the State of South Australia.

At that time, all wheat in Australia was stored in bags and there were no silos for the storage of bulk grain. Wheat was received from farmers at railway stations or ports in bags which were built into huge stacks. In most locations, the stacks were built in the open and a roof of galvanised iron was laid on top of the bags and in some cases the sides of the bag stack were protected from the weather with curtains of hessian. The Wheat Weevil Committee recognised that storage of grain in bulk would greatly improve insect control, however, that option was not available and they focused on the urgent problem of controlling the ‘weevil plague’.

The Committee undertook experiments and trials on basic insect biology but the emphasis was on testing and developing a range of disinfestation treatments. This research is discussed in detail by Winterbottom (1922) and included (using modern terminology) heat disinfestation, fumigants (hydrocyanic acid and carbon bisulphide), hermetic seal/controlled atmosphere, admixture of lime and fine sand (unsuccessful and successful, respectively), and mechanical cleaning treatments. Of these, the Committee recommended use of controlled atmosphere for long term storage and heat disinfestation plus cleaning before export supported by thorough grain hygiene practices.

Although a large number of insect species were collected from infested bag-stacks, the major pest was identified as Calandra (Sitophilus) oryzae (L.). This species was observed to be the initial coloniser with infestations of Rhyzopertha dominica (F.) occurring once S. oryzae populations had become established. Laboratory experiments demonstrated that S. oryzae in wheat held in sealed containers were killed and that the likely reason was carbon dioxide poisoning. To trial this technique, a gas mixture of 10-15% (nominally 20%) CO2 with the balance mainly N2, generated by burning coke, was applied for 3 days to bag-stacks encased in malthoid (bitumen impregnated felt sheets). The trials were successful and the method was used on 3.7 million bags to the end of 1919. In a large percentage of bag stacks it was found that it was unnecessary to add gas to the storage as there was enough CO2 generated naturally to control insects if the bag-stack was sealed. A number of sterilisation plants, equipped with steam and direct heat disinfestation equipment, were built close to ports following laboratory experiments and pilot trials demonstrating the efficacy of this technique. These plants were used to clean and disinfest 63 million bushels of wheat before export.

Normal shipping resumed in 1919 and grain held in storage could be exported. The 1919-20 harvest was small and the grain storage emergency was over. However, the response to the weevil plague set the characteristics of stored products research in Australia: close collaboration between government, industry and researchers with an emphasis on practical, cost-effective solutions.

2.2. The concept of ‘grain protection’

Until about 1960, insect infestation was managed by turning grain to equalise temperature, the rigorous application of hygiene procedures and the use of fumigants to eliminate insect infestations when detected. Aeration cooling had also been introduced, with a significant proportion of central storages being fitted with this technology. By this time, the grain industry had converted almost completely from bag to bulk handling. In 1960, the concept of ‘grain protection’ was introduced whereby a residual chemical was applied to the grain whether infestations had been detected or not (Bailey,1978). Experience revealed that the best time to apply the ‘protectant’ chemical was when grain was received from the farm into country storages (Van Graver and Winks, 1996). Maldison was the most successful protectant chemical and by the mid 1960s its use was widespread producing a dramatic fall in the incidence of insect infestation (Bailey, 1978).

However, ‘the golden age of malathion’ could not last and resistance was detected in several pest species, firstly in *Tribolium castaneum* (Herbst) in 1968 (Champ and Campbell-Brown, 1970), and then in S. oryzae in about 1970 and in R. dominica in 1972. By the mid 1970s, resistance had become a serious challenge to the effective control of insect pests in many regions in Australia.

The grain industry was able to respond quickly to the emergence of malathion resistance, developing an Integrated Plan for Pest Control in 1971, revised in 1974 (Anonymous, 1974). The industry committee consisted of representatives from exporters, the Australian government, researchers, and the respective state storage and handling organisations. The widespread emergence of commercially significant resistance stimulated the search for effective alternative protectants and renewed interest in non-chemical alternatives including expansion of the use of aeration, and research into controlled atmosphere and thermal disinfestation techniques. The development of alternative protectants was seen at the time as the short term, stop gap solution while fumigation and non-chemical technologies were regarded as the way forward for insect pest management in the long term (Bailey, 1978).

2.3. Development of protectants and establishment of the National Working Party on Grain Protectants (now Protection)

The Working Party on Grain Protectants (WPGP) was established in 1973 with the sole responsibility of developing new protectants (Murray, 2003). However, it changed its name to the National Working Party on Grain Protection (NWPGP) about ten years ago as its work broadened to include fumigation and other chemical and non-chemical strategies. The Working Party was formed because of a failure of the private sector to provide alternative protectants. The world market for these is quite small and few manufacturers are interested in this area. Core representation on the Working Party has included the bulk handling companies, marketing organisations, Flour Millers Council and researchers. In the past 20 years, these have been joined by a range of stakeholders including the farmer research funding organisation (Grains Research and Development Corporation), down-stream industry groups representing the meat, dairy and pork industries, stockfeed manufacturers, brewers and maltsters, pulse and oilseed grain organisations, the Australian Pesticide and Veterinary Medicines Authority, industry standards groups, and most recently, due to the de-regulation of export marketing, a range of exporting companies.

Candidate pesticides usually begin life as pesticides developed for other uses. Crucially, appropriate toxicology and animal transfer data must be available before these materials are considered for development. The role of the Working Party participants is to generate the entomological and residue data required for Australian conditions, particularly efficacy against known chemical resistance. In collaboration with the chemical company concerned, each candidate progresses through several stages including laboratory assessment, pilot-scale field trials and full-scale industrial evaluation which includes milling trials to determine residue distribution in processed fractions and finished products. Working Party representatives liaise with food standards and regulatory authorities to ensure that all trials meet legal requirements. When a candidate meets industry requirements, it is the responsibility of the manufacturer/seller to provide all other data required by the regulatory authority for registration. It is industry policy that new grain protectants or fumigants will not be used commercially until they have Australian and international (Codex Alimentarius Commission) maximum residue limits. In addition, exporters must consider customer requirements before approving the use of new compounds on their commodity.

The following gain protectants have been developed, with most being registered in Australia, through the NWPGP program: Spinosad, Chlorpyrifos-methyl, Pirimiphos-methyl, Fenitrothion, Dichlorvos, Methacrifos, Bioresmethrin, Deltamethrin, Phenothrin, Cypermethrin, Permethrin, Methoprene, Pyrethrins, Piperonyl butoxide, Fenvalerate and Carbaryl, and many other chemicals have been evaluated.

Because of its wide industry representation, the modern role of the NWPGP has been expanded to include entomology and resistance management, insect infestation trends, grain protectants, fumigants, physical controls, pesticide residue violations, market requirements, application technology, extension, and relevant national and international regulatory requirements.

2.4. Non-chemical technologies

Aeration – Research demonstrated that aeration technology could be beneficial many regions of Australia (Bailey, 1968; Sutherland, 1968) and during the 1960s and 1970s the technology was deployed to about 30% of central storages in eastern Australia. However, these systems have been mostly dismantled as the technology was difficult to integrate with use of protectants in the first instance and then fumigation with phosphine. The cost of power also made the technology uncompetitive with chemical treatments. Aeration, however, is now seeing a renaissance for use on-farm. It was believed that this technology would be restricted to southern areas of Australia but the development of effective control systems that track ambient conditions and turn fans on only when the coolest and driest air is available, has extended its potential.

Controlled atmosphere - Extensive trials have demonstrated the feasibility of using nitrogen or carbon dioxide to protect and disinfest grain (Ripp, 1983). Except for two special cases, the treatment of organic grain with carbon dioxide and the use of nitrogen on a large scale to treat grain at the Newcastle export terminal, this technology has not generally been adopted. The principal limitation is the cost of obtaining or producing the controlled atmosphere. However, cheaper pressure swing absorbance technology to extract nitrogen gas from air has now become available making this technology much more cost effective. Trials with the new equipment will commence in 2010-11.

Heat disinfestation - Extensive experimental work was undertaken to determine the temperature and exposure times required to kill insects in grain and at the same time leave grain quality unaffected (Banks, 1988). A large 'spouted bed' heat disinfestation system was trialled at a sub-terminal in southern Australia. Continuous spouted bed disinfestation systems have also been developed for use on-farm (Qaisrani and Beckett, 2003). Despite successfully disinfesting grain, the technology has not been adopted because of the capital and running costs of the equipment.

2.5. Fumigation with phosphine

Concerns over resistance to grain protectants and the preference of markets for residue free grain motivated a move away from the use of grain protectants to widespread use of fumigants, notably phosphine. This occurred first in Western Australia (WA) where a program of sealing all storages was commenced in the early 1980s using specifications already developed for sealing storages for use with gas technologies (Banks and Annis, 1980). This program enabled WA to fumigate grain with phosphine cheaply and effectively so that all from WA is residue free. Sealing programs developed more slowly in eastern Australia. Many grain storages, particularly vertical silos, were quite old and could not be economically sealed. During the 1980s, an innovative method of applying phosphine was developed called Siroflo® that allowed these 'leaky' storages to be fumigated (Winks and Russell, 1997). Siroflo is the application of phosphine gas, under controlled release from a cylinder. The gas is applied to the bottom of a silo under a slight pressure which forces it to move up the silo. The gas is applied at quite low concentrations for relatively long periods of time. This technology enabled grain handlers to decrease their reliance on protectants in eastern Australia.

2.6. New fumigants

The phase out of methyl bromide under the Montreal Protocol agreement motivated a search for a cost-effective alternative fumigant. Carbonyl sulphide was developed (Desmarchelier,1994) and is now under consideration for registration in Australia. This gas is effective against a range of insect pests but it requires a longer time for complete mortality of target pests than methyl bromide, however, it is quicker to act than phosphine. Ethyl formate as a mixture in CO2 has been registered for use on grain in Australia but it has seen only limited use. Sulfuryl fluoride is currently under evaluation and development for Australian conditions.

2.7. Overseas research

A feature of Australian research has been the collaboration of many of our scientists in international projects, particularly in Asia. These have mostly been managed through ACIAR, the Australian Centre for International Agricultural Research, and have involved development of grain protectants, phosphine resistance, controlled atmosphere fumigation and grain drying.

3. Present

Most research into grain protection in Australia is now managed through the Cooperative Research Centre for National Plant Biosecurity (CRCNPB, www.crcplantbiosecurity.co.au). In 2006, the major industry funders of research in Australia, the Grains Research and Development Corporation, representing farmers; and our largest grain companies: CBH, ABB Grain (now Viterra) and GrainCorp formed a consortium to submit a bid to the Australian government for financial support to join the CRCNPB. (The CRC program is an Australian government initiative to encourage end-user driven research partnerships between publicly funded researchers and end-users to address clearly articulated, major challenges that require medium to long-term collaborative efforts. Awards are made on a competitive basis). The bid was based on the threat to the Australian industry of the phosphine resistance problem. The bid was successful and a new CRCNPB research program, Post Harvest Integrity, commenced on 1 July 2007. In addition to extra funding, the advantages for the industry of joining the CRCNPB include centralised professional management of research and access to many potential research providers, not just those specialising in stored products. The CRCNPB also has a strong commitment to the delivery and adoption of its research outputs.

Since the mid-1990s, pest management has become dependent on the use of phosphine. This fumigant provides the industry with a cost-effective, multi-commodity, residue-free treatment, compatible with grain handling logistics that is accepted by markets. Although a number of alternative chemical and non-chemical grain treatments have been developed and have and will have limited and specialised applications, for the majority of situations, none can match the combined attributes of phosphine.

Strong resistance to phosphine was first detected in 1997 in *R. dominica*, and then in *T. castaneum*, *Oryzaephilus surinamensis* (L.) in 2000, in *Cryptolestes ferrugineus* (Stephens) in 2007 and most recently in *S. oryzae* in 2009. Frequencies of Strong resistance generally remain low and we believe that this is because the resistance is mediated by two incompletely recessive genes which both need to be homozygous in an individual insect before Strong resistance is expressed. This lag has provided the industry with a window of opportunity to react in a strategic way to resistance development and undertake a research program that will provide the information needed to manage this resistance.

The greatest problem now facing the Australian grain industry is resistance to phosphine and prolonging the effective life of this fumigant is our current research priority. The project portfolio reflects the urgent necessity of being able to control of phosphine resistance outbreaks now, balanced by the need to generate information that will provide the scientific basis for the development of a long-term resistance management strategy.

3.1. Combating resistance outbreaks

The evolution of Strong resistance in *C. ferrugineus* is our greatest challenge since this resistance is several times greater than in any other species. Our response provides an example of active resistance management. In less than 12 months, and in close collaboration with industry partner GrainCorp, the project team produced a rapid resistance diagnosis test, researched and trialled new phosphine fumigation protocols and developed a successful eradication plan based on the use of protectants and scorched earth sanitation procedures.

3.2. Resistance monitoring and management

It is impossible to respond to control failures and resistance development without information and Australia has had the benefit of a national resistance monitoring program for some years. This program has been re-invigorated with a review of statistical procedures and related sampling and testing methods. In 2010, this project is being expanded to focus further on the interaction of biological, environmental and pest management factors to understand how these lead to the development of resistance.

The extensive data collected during previous resistance monitoring is being analysed in an attempt to link management and other factors to the development of resistance. Insects collected in recent monitoring have been frozen and resistance gene typing of these insects will be undertaken using molecular techniques. In addition, neutral marker technology will be used to address the key question of how important gene flow is in the development of resistance, i.e. is each outbreak of resistance selected individually or is resistance due to insect movement from one site to another?

In collaboration with industry, detailed trials are underway at a large central storage complex and on-farm to evaluate the contribution of our key resistance management recommendations, avoidance of under-dosing, minimising the number to fumigations and implementation of thorough hygiene practices.

Mathematical modelling of resistance to phosphine is under development. So far, the model has demonstrated that a 2-gene resistance is necessary for realistic portrayal of observed data. A two-gene model gives substantially different predictions of resistance development in fumigated populations than a single-gene model. This was the first step in developing mathematical modelling to provide simulation capacity to examine the influence of various ecological, genetic and fumigation factors on the emergence of resistance.

3.3. Resistance genetics

An important initiative is the development of a molecular resistance diagnostic. This will provide the 'break-through' tool needed to undertake more fundamental analysis of the processes involved in the development of resistance. Availability of a resistance diagnostic will also greatly enhance resistance monitoring programs and ecological research. The aim is to identify the resistance genes so that they can be used universally as markers for resistance. At time of writing, two major areas containing resistance genes have been identified on each of the genomes of the major pest species *R. dominica* and *T. castaneum*. We now have a candidate list of about 100 genes for each species. A genome for *T. castaneum* is under development elsewhere but as there is no genome for *R. dominica*, a transcriptome library (based on expressed RNA sequences) is being developed. Fine scale mapping of genes that the two species have in common is now being undertaken based on the assumption that resistance is conserved between the two species. We are also undertaking functional annotation of gene expression under phosphine exposure to identify genes that respond. It is anticipated that the diagnostic for at least one species will be available by the end of 2010.

Once the genes for resistance are identified they will be validated by comparing resistance diagnoses of insects collected during resistance surveys with traditional bioassay methods used to in resistance monitoring programs. In addition, identification of the genes will allow insight into the toxic action of phosphine. Genomic sequencing of *R. dominca* will be continued to produce a partial gene assembly in regions of the identified resistance genes and undertake a functional characterization of those genes. This may lead to the discovery of weaknesses that could be exploited to manage resistance.

3.4. The grain – fumigant interface, modelling gas flow in storages

Rapid, even application of fumigant to all parts of a grain store is fundamental to effective pest management and avoidance of under-dosing and the risk of selection for resistance. Surprisingly little is known of the behaviour of fumigants in grain storages, however. The physical and chemical interaction of fumigants with grain (sorption) is the key factor influencing behaviour of these gases, which in turn affects their movement in silos and their efficacy against insects.

Sorption phenomena are being modelled from the unique perspective of the grain as a carrier of sorption surfaces. This, and the determination of a dispersion coefficient which allows the definition of key parameters, are crucial information facilitating the development of more complex, predictive 3-dimensional flow modelling now being undertaken. Another factor investigated was the phenomenon of interrupted doses of phosphine caused by the diurnal flow of gas inside silos. Recent field trials reveal that interrupted dosing is a feature of fumigation even in fan-forced silos. Research showed that phosphine toxicity was cumulative and despite periods of low exposure, insects did not have time to recover from intoxication.

In other current work, project collaborators are measuring phosphine gas flow in industry storages and using this information to develop three dimensional models to predict fumigant movement under a wide range of conditions. The project team is using novel advanced solution techniques to quantify the fluid dynamics of gas movement in porous media. The model will simultaneously account for the varying multiple natural forces that drive gas flow in sealed and ‘leaky’ storages. This information will be used to improve fumigant application.

3.5. Storage Integrity

To be effective, fumigation with phosphine or any other gas must be undertaken in well-sealed storages so that the gas has enough time to penetrate the grain and exert a toxic effect on target pests. A corner-stone resistance management tactic is the avoidance of under-dosing, which allows the survival of heterozygotes. This means that storages must be able to hold gas at the appropriate concentration and time period and importantly, the gas must be as evenly distributed as possible to eliminate pockets of under-dosing.

Most grain storages in Australia were not designed for fumigation and have been retro-sealed to do this. However, in many cases the existing technology is failing to maintain adequate sealing standards. The aim of this project is to research better sealing technologies and techniques and to develop industry standards for the construction of new storages and the renovation of existing storages to a standard required to maintain effective fumigations. These need to be not only suitable for phosphine fumigation but also must meet the likely future requirements of a range of alternatives to phosphine.

Researchers are also investigating the safety and effectiveness of passive and active phosphine application systems for farm storages.

3.6. Insect pest ecology

Effective resistance management strategies rely on an understanding of the ecology of insect pests. Research has been initiated on the ecology of two major pest species *R. dominica* and *T. castaneum* and the project team is focusing on answering a number of key questions:

- What are the ecological processes responsible for the patterns of insect abundance in the rural and natural environments?
- What are the rates of insect movement in the natural environment and colonisation of grain storages?
- What is the impact of grain handling and transport on insect populations and selection for resistance?
- What are the key habitats and sources of infestation by stored grain beetles?
- What is the relative importance of various refuges where insects are not under selection for resistance?

In the first part of this work, a range of methodologies have been developed or evaluated including field trapping techniques using baits and pheromones, trap liquids for preserving DNA, neutral DNA markers for relatedness studies, and laboratory apparatus for studying emigration from small grain bulks.

Trapping studies in farming regions in southern Queensland and southern NSW have revealed that *R. dominica* are widely distributed away from grain storages while *T. castaneum* are aggregated around silos. Further work shows that R. dominica females have mated before leaving silos, that both sexes typically live for 3 months at 25°C, and that females captured in this way are capable of producing several hundred adult progeny during this time without further mating. In addition, resistance testing showed that there is no difference in resistance gene frequencies between insects caught near silos and those collected in paddocks. Preliminary population genetics analysis of *T. castaneum* trapped at a Queensland grain depot during 2009 suggests that the population structure at this site was stable with no temporal variation.

3.7. Alternatives to phosphine

Nitrogen - Controlled atmosphere technologies, although well developed in Australia, have seen only limited adoption since the Second World War. However, the availability of substantially cheaper pressure swing absorbance (PSA) equipment that can cost-effectively supply a large amount of nitrogen gas provides the opportunity to re-visit this technology. Laboratory experiments are currently underway to determine optimal use of N2 enriched atmosphere in relation to low O2 and CO2 concentrations. The objective is to determine the most cost-effective concentration regime and exposure periods for control of insects. In addition, a problem with N2 treatments is that air will de-sorb from grain for a period after the N2 has been added, potentially compromising its efficacy. Laboratory studies will be undertaken on various grain types to determine air desorption rates in N2 atmospheres. Exposure to N2 atmospheres is known to affect quality of some specialised grain types such as malting barley and oilseeds. Laboratory experiments will be undertaken to delineate the limitations of N2 atmospheres in relation to these grain types.

Field trials of laboratory-developed protocols will be undertaken using a commercially available PSA N2 generator. Further development of the generator will be undertaken to increase its efficiency in collaboration with the manufacturer. In addition, research will be undertaken with the aim of shortening fumigation time and targeting regions in storages that may not receive adequate concentrations of N2. The feasibility of augmenting the technology by strategic addition of other gases will be explored. This technology cannot replace phosphine but can be used at strategic points to provide an alternative to phosphine.

Sulfuryl fluoride, the availability of an alternative fumigant to eliminate phosphine-resistant populations would greatly enhance management of this resistance. DOW Agri-Science has registered sulfuryl fluoride as a grain fumigant in Australia. However, there is little information on the use of this material to fumigate large grain storages, particularly sheds and plastic covered bunkers. Research has commenced to understand the concentration-time efficacy profiles of this chemical against major insect pests of grain at lower concentrations and longer time periods. These data will be used to develop fumigation protocols for use against resistant insect populations.

3.8. Grain knowledge networks

New technologies to manage phosphine resistance will only be as effective as the ability and willingness of individuals within the grains industry to change behaviour and practices (theirs and others') as necessary to implement them. Recommended strategies to manage resistance often compete with other standard practices and market imperatives within the grains industry, and it is perhaps not surprising that, despite some industry investment in, and progress made by, awareness and extension activities in previous years, actual behaviour change in this area has been slow.

This project aims to develop an effective change management strategy for the grains industry to improve its phosphine resistance management outcomes. This project is using a multi-disciplinary approach (based on social science, economic and market research) to find opportunities to achieve practice change and to develop a national change management program to improve phosphine resistance outcomes. Applying change management to the issue of phosphine resistance, it follows, will involve achieving a high level of understanding of individuals' knowledge, practices and motivations in order to implement and test transitional strategies to drive practice change across the industry. This project will combine a better understanding of the grain industry's knowledge network with improved knowledge transfer strategies in the area of phosphine resistance to build a strong evidence-based framework for a national phosphine resistance management strategy post-2010.

3.9. Bio-sensor based detection of insects

There would be many advantages in being able to detect insects and quantify insect infestation in bulk grain without basing population estimates on sampling. However, an effective system has remained elusive. Insect detection technology has included measurement of carbon dioxide, adult trapping, sensing insect noise, measurement of pheromones, sensing specific volatile chemicals, and measuring colour changes of samples. In-situ detection using electronic instrumentation has not been successful due to the characteristic of bulk grain to rapidly attenuate electric, magnetic, acoustic, or thermal energy as it passes through the grain (within 100 mm). Techniques to detect the immature stages of species that exist with grain kernels that are most likely to survive fumigation treatments (eggs, pupae) have not been achieved.

The aim of this proejct is to utilize olfactory receptors from *Tribolium casteneum* to identify biologically active molecules, such as pheromones, that are released by insects during colonization and infestation of grain. The first phase of the project is to isolate genes for olfactory receptors that are capable of detecting the unique olfactory signatures of stored-grain insect pests. The second phase is to express the olfactory receptors in cells and develop assays aimed at determining interaction of the beetle receptor and their unique chemical ligands. The olfactory receptor genes of *T. castaneum* that express detection capability for specific volatile chemicals exhibited by stored product insects (e.g. pheromones) will be used as the genome of *Tribolium* is known and functional genes identified.

3.10. Diagnostics for market access sensitive organisms

Australia is free of two major pest organisms important in the international trade of grain: Khapra beetle, *Trogoderma granarium* Everts, and Karnal Bunt, *Tilletia indica*, and it is important that effective tools are available for Australia to continue to claim area freedom from these pests

The aim of work with *T. indica* is to develop an internationally recognised, highly sensitive, detection system for that will enable direct diagnosis from a few spores and which does not involve time-consuming and labour intensive germination of spores required under the current standard method. The method has been developed and is now undergoing validation.

With increasing amounts of international trade, it is likely that an incursion of *T. granarium* will occur at some time in Australia. Therefore, it is important that rapid and accurate diagnostic methods are available for this insect so that eradication processes can be implemented. Trogoderma is a large genus and there are several Australian species that can be superficially mistaken for *T. granarium*, although they are not pests of stored products. This project is comparing Australian species with international material to develop reliable morphological and molecular diagnostics as well as internationally recognised expertise in identification of these insects.

3.11. Sampling strategies

There is a range of testing and sampling activities being carried out on grain whenever it is delivered, transported and prepared at port for export. The aim of this project is to capture and convert these data to maximise the power of detection and to develop flexible and statistically robust systems to calibrate and improve sampling strategies. The first part of the proejct has been to develop a statistical model of insect infestation as grain moves from farm to export terminal. Research now under way includes evaluation of current supply chain sampling with a view to identifying at-risk elements to improved sampling strategies to maximise detection and analyses.

If any reader would like more information about any of these projects, please contact me and I will forward your enquiry to the appropriate project leader.

4. Future

From its beginning in August 1917, stored products research has responded to essentially the same environmental and economic drivers as it does now. Research has been needed to develop cost-effective techniques and technologies that will ensure that our grain production, whether it is destined for international or domestic markets, is maintained at the highest quality standard, in particular, free from insect contamination.

The greatest changes that have occurred have been in the marketing of grain. Since the Second World War, the storage, handling and transport of grain and both domestic and export marketing had been heavily regulated. However, in 1989 restrictions on storage, handling and transport and domestic marketing of grain were lifted. The major outcome of this change was to diversify this sector and in particular, provide an opportunity for farmers to market grain themselves. It also caused the state owned grain storage and handling organisations to begin the process of consolidation and privatisation. In 2008, the ‘single desk’ assigned to the Australian Wheat Board for export marketing of wheat was abolished and more than 20 export licences have now been granted for the export of bulk wheat. The export of wheat in containers had been de-regulated several years earlier. Australia is now an open market for grain. We are yet to fully see the outcome of these changes.

Despite the dramatic economic changes that have occurred the biological and environmental fundamentals have not changed and the partnership between industry, government and research has continued and will do so for the foreseeable future. The current partnership is managed by the Cooperative Research Centre for National Plant Biosecurity and this will continue for another decade.

The high pressure on the system from insect infestation will always remain and for this reason industry will require research to develop cost-effective solutions to meet market demands for insect free grain. Deregulation has encouraged diversification and innovation in production and marketing and this presents many new challenges and opportunities to researchers. Although use of phosphine will continue to be the dominant disinfestation tool, diversification of grain handling and marketing provides the opportunity for the diversification of insect control tools for specialised uses and industry sectors. The threat and reality of insect resistance to phosphine is also a significant driver. It is likely that alternative fumigants including sulfuryl fluoride, carbonyl sulphide (if registered) and ethyl formate, and controlled atmosphere technology will see greater use. As mentioned previously, farmers are investing in aeration cooling and are often early adopters of new technology as it becomes available. Research into the ecology and population dynamics of grain pests is giving us insights that are invaluable in managing these insects and continuing this research will be a priority for the future. Probably the most innovative technologies and research tools will result from molecular and genomic research on the insects themselves. The enhanced insect detection systems and population dynamics tools mentioned here are only two of the potential array of innovations of the future.

In conclusion, the serious threat that insect infestation poses to market access for Australian grain will ensure a continuation of the partnership between researchers and the grain industry in the development of cost-effective solutions in grain protection.

Acknowledgment

I thank the Cooperative Research Centre for National Plant Biosecurity for supporting my attendance at this conference.

References

Bailey, W.S. 1968. Air temperatures in the Australian wheat belt and their relationship to the aeration of stored grain. Technical paper of the Division of Entomology, CSIRO (Aust), No. 9, 1-24.

Bailey, S.W. 1979. The present position and the outlook for improved technology in the Australian grain storage system. In: Evans, D.E. (Ed), Australian Contributions to the Symposium on the Protection of Grain against Insect Damage during Storage, Moscow, 1978. In: Division of Entomology, CSIRO, Canberra, Australia, pp. 1-6.

Banks, H.J. 1998. Prospects for heat disinfestation. In: Banks, H.J., Wright, E.J. and Damcevski, K.A., (Eds), Stored grain in Australia. Pr Proceedings of the Australian Postharvest Technical Conference, Canberra, 26-29 May 1998, CSIRO, Canberra, Australia, pp. 227–232.

Champ, B.R. and Campbell-Brown, M.J. 1970. Insecticide resistance in Australian Tribolium castaneum. Journal of Stored Products Research 6, 53-70.

Desmarchelier, J.M. (1994) Carbonyl sulphide as a fumigant for control of insects and mites. In: Highley, E., Wright, E.J., Banks, H.J. and Champ, B.R., (Eds), Stored Product Protection. Proceedings of the Sixth International Working Conference on Stored-product Protection, 17-23 April 1994, CAB International, Oxford, UK, pp. 78–82.

Murray, W. 2003. Grains industry interaction with regulatory organisations. In: Wright, E.J., Webb, M.C. and Highley, E. (Eds), Stored Grain in Australia 2003. Proceedings of the Australian Postharvest Technical Conference, Canberra, 25-27 June 2003, CSIRO, Canberra, Australia, pp 86-94.

Qaisrani, R. and Beckett, S.J. (2003). On-farm heat disinfestation trials using a continuous-flow spouted bed. In: Wright, E.J., Webb, M.C. and Highley, E. (Eds), Stored Grain in Australia 2003. Proceedings of the Australian Postharvest Technical Conference, Canberra, 25–27 June 2003, CSIRO, Canberra, Australia, pp 36-42.

Ripp, B.E. (1983) Controlled Atmosphere and Fumigation in Grain Storages. Proceedings of an International Symposium "Practical aspects of controlled atmosphere and fumigation in grain storages", 11 – 22 April, 1983, Perth, WA, Australia. Elsevier, Amsterdam, The Netherlands.

Sutherland, J.W. 1968. Control of insects in a wheat store with an experimental aeration system. Journal of Agricultural Engineering Research 13, 210-219.

Van S. Graver, J. and Winks, R.G. 1996. A brief history of entomological problems of wheat storage in Australia. In: Highley E., Wright E.J., Banks H.J. and Champ B.R., (Eds), Stored Product Protection. Proceedings of the Sixth International Working Conference on Stored-product Protection, 17-23 April 1994, CAB International, Oxford, UK, pp. 1250-1257.

Winks R.G. and Russell G.F. 1997. Active fumigation systems: better ways to fumigate grain. In: Donahaye, E.J. and Navarro, S. (Eds), Proceedings of an International Conference on Controlled Atmosphere and Fumigation in Stored Products, 21-26 April 1996, Nicosia, Cyprus, pp. 293-303.

Winterbottom, D.C. 1922. Weevil in wheat and storage of grain in bags: a record of Australian experience during the war period (1915 to 1919). R.E.E. Rogers, Government Printer, North Terrace, Adelaide, Australia.