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THE POTENTIAL USE OF BIOLOGICAL CONTROL OF PESTS IN STORED GRAIN

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THE POTENTIAL USE OF BIOLOGICAL CONTROL OF PESTS IN STORED GRAIN

by

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EXECUTIVE SUMMARY

International data suggests that there are a number of approaches to the biological control of pests in stored grain that could be applied in the UK. These would include the addition of predatory insects and mites, and the use of some microbial agents which cause disease in pest species. However, there are only limited data on the use of biocontrol under commercial conditions and no data that would give complete confidence that procedures used elsewhere would be effective in this country. The most promising agents would not appear to offer any toxic risks to the consumer and only very limited risk to the user.

The world-wide research programme on the biocontrol of pests in stored grain is very small and fragmented. Currently, there is very little research on this topic applicable to European conditions within the UK or any EC Member States.

The storers and end-users of grain in the UK do not seem to have major concerns about current pest control practices. Whilst the idea of biocontrol is not dismissed out of hand by storekeepers, they would only be seriously interested if there were major changes in the availability of current measures or biocontrol was equally effective and less expensive than current methods. End-users are against the addition of biocontrol agents to grain on the grounds that this would constitute contamination.

Protozoa, fungi, bacteria and viruses that might be used as biocontrol agents would require registration under the Control of Pesticides Regulations. This is an expensive process and is likely to limit the interest of producers. Conversely, predatory or parasitic insects, mites and nematodes would not require registration and so could be offered for sale at minimum cost on the part of the supplier. It therefore seems likely that, in the short term, any future development of biocontrol for grain pests in the UK will come from the use of predators or parasitoids.

1. BACKGROUND

The aims of this review were:

(i) To liaise with the UK cereals industry in order to determine the circumstances under which biocontrol might become acceptable and/or necessary.

(ii) To examine current research world-wide on the topic and to list the most promising options.

(iii) To consider the operational problems surrounding the introduction of biocontrol programmes.

The review has been prompted because traditional, chemical based methods of pest control in grain are under threat for several reasons. Firstly, the numbers of available pesticides are dwindling, because of fears about safety and the enormous costs of the registration process. Secondly, end-users are equally unhappy about receiving grain containing pests or pest-damaged grains. Therefore, research efforts are being directed towards an ever wider range of alternative pest control options which either reduce pesticide application or which do not use any conventional pesticide. One of the latter approaches is to use biological control agents. These take the form of an insect, mite, nematode, protozoan, fungus, bacteria or virus which attacks insect and mite pests that damage grain during storage.

The concept of using biological agents to control pests is well known and has been used in some areas of agriculture for many years. However, its application in stored grain usually takes the form of a natural occurrence. Stored grain is a man-made extension of the much older, natural environment that might have been found in the food stores collected by small mammals. Insects and mites that evolved to exploit food stocks held in these nests and burrows were accompanied by predators, parasites and diseases which also evolved to cope with the changing environment of their hosts. Therefore, in most grain stores natural biological control occurs with some pests being killed by any one of a wide range of agents. However, the proportion of the pest population that is killed is usually small and any decline in pest numbers is often slow. Predator or disease organisms only increase rapidly when the pest density is sufficient to provide an abundant food supply and when there is rapid transfer between hosts. Work with predatory insects and mites has shown that their numbers only begin a rapid increase after the pests are well into the exponential growth stage. The natural lag that occurs between the increase in pests and predator is shown in Fig. 1 which charts pest and predatory mite populations in grain (133). This gap between the pests and predators can be several months, allowing a damaging pest population to develop before the numbers are reduced by predation. In other words, although some degree of biocontrol probably occurs in most bulks of stored grain, the numbers of pests killed and the speed of kill, are not sufficient to reduce the population to a point where other forms of control are unnecessary.

The pest control process covered by the description "biological control" or "biocontrol", takes place when a naturally occurring biological agent is introduced to control a pest. It normally involves adding the biocontrol agents to an environment before pest numbers reach an exponential rate of growth, so changing the balance between pests and control agents. This approach has been used with great success in horticulture, and both world-wide and in the UK there are a number of commercial enterprises which breed and supply control agents.

Biocontrol of pests in grain is likely to be an emotive topic as end-users may not be happy about the principle of ADDING a biological control agent to grain. Widespread use would also require recipients of grain to distinguish between beneficial insects and pests during quality testing at intake. The same principle could apply to fungi or bacteria added to grain as biocontrol agents but these are likely to cause fewer problems during intake procedures. Despite potential drawbacks, the method does offer some advantages such as reduced usage of chemicals and providing a fresh alternative to compensate for the loss of other control options. It could also be of particular interest to certain sectors of the cereal industry, such as "organic" producers and end-users.

In the UK, comparatively little interest has been shown in biocontrol of grain pests over the past 30 years. However, in other parts of the world, research programmes are underway and biocontrol is used to deal with infestation in commercial stocks of grain. This review assesses the potential for biological control of grain pests in the context of storage, both by the producer and in commercial stores, and by end-users of grain in the UK. The potential is judged in relation to conditions currently prevailing and also in the context of possible future developments affecting use of pesticides and/or changes in consumer preferences.

This review makes use of information from a range of sources including:

Published data in the scientific literature
Current, active research programmes
Users and suppliers of biocontrol agents in the UK and other parts of the world
UK and EU regulatory authorities
Potential producers of biocontrol agents
End-users of grain

2. ADVANTAGES AND DISADVANTAGES OF BIOLOGICAL CONTROL

2.1 Advantages

(i) Uses naturally occurring organisms that are already found in grain.
(ii) No chemicals involved so that it can be used on "organic" grain.
(iii) Minimal toxic risks to farmers and storekeepers.
(iv) Minimal risk to end-users and consumers.
(v) Some biocontrol agents may be able to seek out pests inaccessible to many other methods.
(vi) Reduced risks to the environment compared to chemical control measures.
(vii) Some approaches to biocontrol fall outside the "Control of Pesticides Regulations" so would place no statutory obligations on the user or producer.
(viii) Fits readily into an integrated approach to pest control.
(ix) Development of resistance to non-microbial biocontrol agents is likely to be slower than to chemical agents.

2.2 Disadvantages

(i) Biocontrol rarely eliminates pests.
(ii) Tends to be a management-intensive process, both in terms of application and subsequent monitoring. Most forms of biocontrol do not fall into the category of "Treat and forget".
(iii) Involves contaminating the grain with insects, mites, protozoa, fungi, bacteria or viruses.
(iv) May be more expensive than current chemical control measures.
(v) Currently, no expertise or infrastructure exists to supply control agents or support the use of biocontrol of grain pests within the UK.
(vi) Usually not suitable for dealing with heavy, established infestations.
(vii) Biocontrol agents usually have limited "shelf-life" and often must be obtained directly from the producer on an "as needed" basis.

3. REVIEW OF THE SCIENTIFIC LITERATURE

3.1 Introduction

The use of biological agents to control insects and mite pests of stored products has been the subject of numerous scientific studies. Most of the information for the present review has been obtained from the comprehensive collection of references held at the CSL Library, together with computer searches of other databases. Literature searches have been concentrated mainly on papers published during the last 25 years. Although the emphasis has been on work dealing with the biocontrol of stored grain pests in regions of the world with a temperate climate similar to that of the UK, some biocontrol studies in related areas, such as other stored products and horticulture, have also been included where they have relevance as examples of an approach or technique.

Following the initial literature scans, about 500 papers, books and other publications from around the world were selected for closer study and to form the basis of this review. These showed that a number of organisms had either been suggested as potential control agents or had been tested under laboratory or field conditions. In some cases, descriptions of methods of use and results from practical trials in grain stores or bulk grain were reported. The information has been summarised in the form of tables, one for each of the main groups of biocontrol agents: predatory or parasitic insects and mites, nematodes, protozoa, fungi, bacteria and baculoviruses. For each group, the Tables (1-7) list the target pest species (hosts), where laboratory and field studies have been conducted, details of any commercial use together with the current registration requirements and status in the UK. Table 8 provides a further summary of the strengths and weaknesses of each type of biocontrol agent, together with an indication of the most likely areas of application in UK storage situations. Because of the large number of potential control agents found during the literature review, the tables concentrate on those biocontrol agents that occur naturally in the UK and/or which have been the subject of the most research to date.

3.2 Predators

The two insect predators listed in Table 1, *Xylocoris flavipes* and *Lyctocoris campestris*, are heteropteran bugs, dark brown in colour with long piercing and sucking mouthparts. *L. campestris* can grow to a length of 4mm whereas *X. flavipes* is usually only half that size. Both species kill by sucking the juices from the bodies of their prey and will attack a wide range of grain pests.

The predatory mites, *Cheyletus eruditus* and *Blattisocius tarsalis*, are only about 0.5mm in length and attack their prey by feeding on their body fluids. *C. eruditus* is a translucent cream colour while *B. tarsalis* is pale yellow with darker legs. *C. eruditus* attacks stored products mites and has been used to control grain mites under commercial conditions in Eastern Europe. It will survive for long periods in the absence of prey, and under extreme conditions survives by resorting to cannibalism. *B. tarsalis* will attack stored grain mites and will also feed on eggs and small larvae of insects.

The mite *Pyemotes* sp. is difficult to categorise as either a predator or parasite. The adult female mite attacks a single host, first paralysing it and then attaching to it to feed. The next generation completes its development within the swollen body of the female and mature adults emerge ready to mate and to seek new prey. These mites will attack a wide range of insects, both adults and larvae. The venom that is used by *Pyemotes* to paralyse large insects is so powerful that there have been some investigations of its potential as a control agent. However, the venom is also associated with serious reactions in man.

3.3 Parasitoids

Parasitoids are obligate parasites in their juvenile stages with a free-living adult stage (Table 2). They are tiny wasps belonging to the order Hymenoptera, the adults typically reaching a length of around 1-2mm although those of *Venturia canescens* can grow to 6mm long. The female uses her ovipositor to lay eggs inside the body of the host insect which is eventually killed after the egg hatches and the larva feeds on the host's internal tissues.

3.4 Nematodes

Nematodes are minute worm-like organisms, the infective stage of *Steinernema feltiae* being about 0.5mm long and only 0.02mm wide (Table 3). This particular species carries within its intestines the entomopathogenic (ie. an organism causing disease in insects) bacteria *Xenorhabdus nematophilus*. The infective stage of the nematode enters the mouth, anus or spiracles of their host and releases the bacteria that multiply in the insect haemocoel (i.e. the blood-filled body cavity of insects) and kill the host. The bacteria serve as food for the nematodes.

3.5 Protozoa

Protozoa are single-celled, microscopic organisms and the sizes of those associated with insects are in the range 2.0-20.05µm. All the species appearing in Table 4 are entomopathogens, usually entering the host insect by ingestion. The Gregarinida and Coccidia are parasites of the fat body, Malpighian tubes or gut of insects, and are characterised by a resistant, spore-like or encysted stage. The microsporidian *Nosema* spp. are found in the insect fat body, and can be spread from insect to insect by mouth or through the egg stage.

3.6 Fungi and fungal metabolites

The two species of entomopathogenic fungi listed in Table 5, *Beauveria bassiana* and *Metarhizium anisopliae*, initiate infection by a germinating microscopic spore which penetrates the cuticle of an insect. Infection then spreads through the haemocoel and the insect's body fills with fungal mycelia. Hyphae grow out of the insect and produce spores which disperse to infect other insects. Mycotoxins are the natural but highly toxic by-products of the growth and development of several species of fungi, and some of these, produced by species of *Penicillium* and *Fusarium*, are toxic to storage pests.

3.7 Bacteria

Bacteria are the most abundant type of micro-organism associated with insects. The two species of *Bacillus* mentioned in Table 6 usually invade the insect's haemocoel via infective spores that enter the alimentary tract. Pathogens, including *Bacillus thuringiensis*, also may be introduced into the insect haemocoel by way of the ovipositor of parasitic hymenoptera such as *Venturia canescens*.

Each *B. thuringiensis* cell contains a toxic crystal protein which can paralyse the gut of an insect, thus allowing easier penetration by the vegetative cells of the pathogen. The vegetative cells multiply rapidly and soon fill much of the haemocoel. After death, the insect disintegrates and releases spores into the environment to infect other insects. *B. thuringiensis* is a complex species existing in numerous different varieties which are pathogenic to different ranges of insects. These varieties produce different amounts of several types of toxins, the two commonly used as insecticides being the crystal or delta-endotoxin and the beta-exotoxin.

Taxonomically, *B. cereus* is closely related to *B. thuringiensis* except that the former does not produce the delta-endotoxin. As well as causing disease in insects, *B. cereus* is a common saprophytic organism (i.e. one obtaining its nourishment directly from dead or decaying organic matter) found in the soil.

3.8 Baculoviruses

Viruses are disease-producing particles too small to be seen by an optical microscope but visible with an electron microscope. They are only capable of multiplication within a living cell, each type of virus requiring a specific host cell. Many insect pathogens show similarities to viruses found in plants or vertebrates. However, the granulosis viruses and nuclear polyhedrosis viruses, usually grouped together as baculoviruses, seem to have their virulence restricted to invertebrates. So far, baculoviruses have only been found to kill arthropods belonging to the Lepidoptera, Diptera, Hymenoptera, Neuroptera, Trichoptera and Crustacea. For example, those listed in Table 7 will kill moth pests of stored products but not beetle pests.

Natural infection of the moth larvae occurs by ingestion of the virus and subsequent disintegration in the gut and release of infectious virus particles. Infection of cells lining the gut occurs, followed by transfer to the fat body tissues by way of the haemolymph (i.e. insect blood). Within a few days of ingesting the virus, the larva stops feeding. Eventually the fat body fills with virus particles which are released into the environment when the larva disintegrates, thus spreading the infection to other larvae.

4. CURRENT RESEARCH PROGRAMMES

4.1 Collection of data

A scan of published literature and conference proceedings was used to ascertain those countries and research units in which research was likely to be concentrated. Sixteen scientists in twelve countries were contacted by letter, informed of the terms of reference of this project and asked to contribute information about the biological control of grain pests. Most of these scientists had published papers on biocontrol of grain pests within the last five years. Exceptionally, one or two scientists were contacted because they were known to be key sources of information on pest control in stored grain within a particular country or sector of the industry.

4.2 Data obtained

More than half those approached replied and provided an interesting insight into current views of the role of biological control and the direction of research.

The majority of research programmes, both in terms of the numbers of workers and the level of funding, are aimed at specific problems in developing countries. For example, major efforts are being directed at developing a biological control strategy for use against the Greater Grain Borer, *Prostephanus truncatus*. This pest is a recent introduction into East Africa and is causing extensive damage to a range of stored food products. It has proved difficult to halt its spread using conventional chemical control measures, so alternatives are being sought. The key aims of these programmes are to investigate the pest in its natural habitat, Mexico, and try to determine why it appears to be a less serious pest in that country. Part of the work is directed towards identifying any natural enemies of *P. truncatus* in Mexico and assessing their suitability as biocontrol options in Africa. Unfortunately, this work seems to have little to offer pest control in developed countries in the near future.

Some other R&D is being directed at reducing losses of stored food in developing countries by changing storage systems so that they favour naturally occurring populations of predators or parasites. Once again, this approach is unlikely to yield much benefit for cereal storage in the UK as its likely effect will be to reduce the scale of loss rather than eliminate a pest completely.

There are two research programmes which are immediately relevant to the UK: one in Australia and one in the USA. Of these, the American effort is more substantial and has been established longer. Both these programmes are government funded and have been established as part of national commitments towards the reduction in pesticide usage. A further programme, in what was Czechoslovakia, and another in Vietnam may also have relevance to UK problems.

4.3 Research in the UK

At present, there is no programme of work specifically concerned with the biocontrol of stored product pests in the UK. However, CSL has an interest in this field and is working with biocontrol agents including parasitoids, fungi, nematodes and baculoviruses, for other types of pests. It also holds stocks of some key predators and parasitoids of grain pests. There are some limited programmes in a few universities in the UK but these are concerned mainly with the population dynamics and modelling of predator/parasitoid/prey relationships at the laboratory level.

4.4 Research in Australia

This programme is at an early stage but seems to be based on a proper assessment of the needs of the industry and is targeted at areas where it is most likely to be accepted and to yield benefits: the organic food trade, feed grain and initial, on-farm storage. The Australian grain industry has a commitment to export "pest-free" grain and there is general agreement that it would be impossible at the moment to persuade customers that beneficial insects, for example, should be accepted. The other limitation of biological control is that it rarely eliminates pests, hence this also reduces the likelihood that it could be used as a primary method of pest control for bulk grain intended for export. There is, however, some enthusiasm for the idea at the farmer level, where its use might help to reduce infestation pressure further down the supply chain, and at port silos, without increasing problems of pesticide resistance or residues.

Current work centres around using species of the smaller parasitic wasps (*Trichogramma* sp.) in food processing plants. Data suggest that these will attack and control the immature stages of several of the most important moth pests and yet the adult wasps are so small as to be unnoticed by end users. The scientists are co-operating with producers of biocontrol agents, and have the initial aim of developing control measures suitable for empty farm grain stores and for use in grain intended for animal feed. Given success here, they will move on to stores used for organic food grain. However, they feel that biocontrol is still a long way from being commercially viable for more general applications.

4.5 Research in the USA

This programme began in an *ad hoc* manner in the mid 1970s but was given more impetus during the 1980s by the Environment Protection Agency's commitment to use government resources to reduce the dependence on chemical control measures in agriculture. Current work is split between several universities and government agencies but the main research programme with core funding is at the Grain Marketing Research Laboratory, Manhattan, Kansas. The work has investigated a range of parasites and predators, as well as insect diseases. Other groups are working on the topic but much of the funding for this project is via "soft" money and short-term contracts and some groups seem to have lost funding recently.

A number of laboratory investigations have been completed and reported, including some large-scale, simulated field trials. The work has identified several agents that are relatively specific to individual storage pests. Some of the US field trials, particularly in stored peanuts and sorghum, suggest that the degree of control obtained can compete with chemical methods, but other trials produced inconclusive or disappointing results. Assessments of the cost of bio-control using parasitoids or predators give figures ranging between about 5 times that of contact pesticides down to about one tenth of the cost of admixture of a contact pesticide. These lower figures come from claims made by a company selling beneficial insects.

Much pioneer work was done on the use of the insect pathogen *Bacillus thuringiensis* to control moths infesting stored grain. An extract containing the toxin and viable spores of this organism has been registered by the EPA for direct admixture with grain for at least 15 years. However, its commercial uptake has not been great because of cost, patchy efficacy and some fear that the moths have developed resistance. Published data suggests that, whilst *B. thuringiensis* can give 100% control of moths in laboratory tests, field results never give more than about 80% control. There is more work underway to try to develop a strain of *B. thuringiensis* that is more effective against beetles.

The long-standing research programme in the US has stimulated some commercial follow-up and there are at least two companies supplying beneficial insects for pest control in stored grain. Initially, the commercialisation of this approach to biocontrol caused some bizarre occurrences. The Federal Court ruled that it was illegal to adulterate grain by adding beneficial insects and, at one stage, Federal Marshals arrested some bins of grain in Texas. More recently, the situation was normalised when the Environmental Protection Agency gave a dispensation for the use of beneficial insects on stored grain. However, the Food and Drugs Administration have not, as yet, relaxed their tolerance for insect fragments in flour and other grain products. This must influence the end-users of grain.

4.6 Research in Vietnam

A government-funded programme of research has been under way for several years to develop biological methods of reducing losses in stored rice. Much effort has been devoted to the use of *B. thuringiensis*. The interest and relevance of this work is that they have substantial field data from large-scale government storage. This shows that *B. thuringiensis* will provide adequate control of the most important moth pests. However, the strain used has almost no effect on beetle pests. The work gives an insight into the practical applications and associated problems, and the scientists have been very helpful to the writers of this review.

4.7 Research in Czechoslovakia (Czech Republic)

A long-term research programme was carried out under the previous socialist régime to develop a biological method of controlling stored product mites in grain and grain stores. The predatory mite, *Cheyletus eruditus,* was used and the research included the development of methods of producing and maintaining stocks of predators. It culminated in the establishment of a widespread programme of biocontrol in Czechoslovakia under practical conditions. Several papers have been published but these data do not give conclusive evidence of efficacy or provide a clear technique for use of the method in bulk grain. Contact with the scientists involved in the programme has provided more data and this is discussed in section 9.2.3.

Despite the limitations of the published data, the work could have immediate implications for the UK as it would be feasible to import predatory mites from the producer in the Czech Republic for use in UK grain stores. These predators could have a role in limiting mite infestations in stored grain or oilseeds.

4.8 Research in other European countries

Holland appears to have the largest programme of any EU country but the work, based at Wageningen, is aimed at developing countries and has no current application for the UK. There is a programme in Germany based in Berlin, but this also is mainly orientated towards developing countries.

Currently, there is no formal research on biocontrol of grain pests in France but workers at the INRA research station at Bordeaux have an interest in the area. Their view is that any further erosion of availability of pesticides could leave the grain industry seriously exposed and they are therefore considering initiating some work on biocontrol for specific stored product pests.

5. POSSIBLE BIOCONTROL AGENTS FOR STORED GRAIN

Information from Sections 3 and 4 has allowed lists of biocontrol agents with the most potential for the control of UK grain pests to be drawn up. This information is presented in Tables 1-7, one table for each of the main groups of biocontrol agents. Table 8 summarises the strengths and weaknesses of each type of agent.

Most of the predators and parasites noted in the Tables already occur regularly in grain and are therefore assumed to offer little or no toxic risk. The mites, *Cheyletus eruditus* and *Pyemotes* sp., are exceptions as the latter is known to cause lesions in man and there is some circumstantial evidence to suggest that the former may also bite man. Some of the microbial agents are known to carry a toxic risk but those likely to be used in stored grain are regarded as safe. In some cases, their toxicity to higher animals has been studied extensively.

6. LEGISLATION AND BIOCONTROL AGENTS

6.1 Registration

The use of pesticides in the UK is controlled by a number Statutory measures. The most important is the Control of Pesticides Regulations (COPR) which sets out requirements for efficacy and safety which must be met before any pesticide can be offered for commercial use. There is a formal registration process in which data must be submitted by the manufacturer or distributor of the product and this data package is then assessed by a series of experts. For a conventional pesticide, the costs of developing the necessary data can be several hundreds of thousands of pounds. The charges made by the Pesticide Safety Directorate of MAFF who are the body in charge of pesticide registration, would be about £18,000/product.

Biocontrol agents pose some interesting issues with regard to the registration process. Organisms other than bacteria, protozoa, fungi, viruses and mycoplasmas used for destroying or controlling pests are not included in the COPR and do not require registration. Therefore, insects, mites and nematodes used as biocontrol agents would not have to go through the registration process. Furthermore, if the insect, mite or nematode was regarded as an endemic species in the UK, supplies intended for use as control agents could be imported without the need for an import licence.

Protozoa, bacteria and viruses must be registered by a producer or distributor before they could be sold as a biocontrol agent in the UK. The registration package would have to include data on efficacy which showed that the product gave an acceptable level of control against each pest species that was mentioned on the label. This efficacy would have to be compared to other, standard products and would have to simulate the conditions found in UK grain stores. Data would also have to be presented to show that any residues in the grain arising from the use of these products were harmless and did not affect processed products such as bread or beer. Finally, the manufacturer would have to show that the use of the product would not affect adversely the environment or non-target organisms.

Similar regulations exist in other EU Member States. However, there is some interchange of information between the various regulatory authorities so that much of a data package generated in the UK could be used in other countries, so spreading the costs of registration.

Currently, discussions are underway in the EU to introduce the "FAO Code of conduct for the import and release of exotic biological control agents" to ensure greater harmonisation of approach in this important area (126).

6.2 Food safety regulations

The food safety regulations have been drawn up primarily to protect the consumer and to ensure that food for human consumption is not injurious to health. Nevertheless, as mentioned earlier, in 1988 a grain storage company was prosecuted in the USA, under Federal Regulations, for releasing beneficial insects into grain, even though they were added for the purpose of reducing pests and pesticide usage (127). However, as a result of the publicity that this case produced, the regulations were revised and now all genera of insect predators and parasitoids known commonly to attack stored food insect pests can be added to bulk or bagged grain and are exempt from these regulations (128).

The situation in the UK at the present time is not entirely clear as the 1990 Food Safety Act (129) does not distinguish between beneficial and pest species in food products. Similarly, it is uncertain how EU food regulations might be interpreted. These uncertainties will probably only be resolved if and when a test case is taken through the Courts. However, as far as the presence of insects and mites in finished cereal products for human consumption are concerned, no country appears to distinguish between pests and beneficial species. Thus, any beneficials in grain carried over from the store or warehouse would need to be removed during the usual sieving and other cleaning procedures before final processing for human consumption.

7. VIEWS OF THE UK CEREALS INDUSTRY AND END USERS OF GRAIN

Information was sought from several sections of the UK grain industry, including some end users of grain, by approaching a range of individual companies and organisations. Mostly the approach was by letter but on occasions a meeting was held.

In order to assess the reaction of the various parts of the industry, a series of simple options covering the most likely ways in which biocontrol might be adopted in the UK were drawn up. These were coupled to some specific questions about any objections that would have to be overcome before biocontrol could become acceptable.

Storekeepers approached were interested to hear of the possibility of controlling grain pests using biological control agents. However, there was a universal opinion that current methods are giving satisfactory results. The key issues would seem to be that the cost and efficacy of biocontrol would have to at least match current methods. There was also a strong feeling that the attitude of end users would influence any decision on the part of storekeepers.

Flour millers were opposed to the concept of adding any biological agents to grain intended for milling into flour. Beneficial insects would give much the same problems to millers as the pest species. Identification of pests at the intake points of mills remains a problem and the possible inclusion of beneficial insects would only add to this problem. Microbial agents which carry a "bio" tag, would also be unacceptable because of negative marketing image. Millers supported the view of storekeepers that current methods work well and, given proper use, pesticide residues present no problems for the industry. The firm negative views of the milling industry would appear to make biocontrol unlikely to be applicable to milling wheat in the foreseeable future.

The Guild of Conservation Grade Producers gave a positive endorsement to the idea of biocontrol and indicated that their members would be interested in adopting biological means of controlling pests in grain. However, the end users of Conservation Grade cereals were more cautious, particularly because some of their products use cereal grains in a relatively unprocessed form. Any insect contamination, regardless of status, is unacceptable in such products. This issue would have to be addressed before biocontrol became a practical proposition.

Surprisingly, it proved impossible to obtain a definitive response from "Organic Producers", as none responded to requests for comment.

One end user of grain for human consumption pointed out that the addition of insects to grain could constitute an offence under the Food Hygiene Regulations. This topic is discussed in more detail in section 6.2 of this review.

In spite of the general satisfaction within the UK cereals industry with current pest control methods, the industry is aware of continued public concern over control strategies that rely heavily on chemical pesticides especially where food is concerned. In 1987 a House of Commons select Committee on Agriculture drew attention to public concern about the possible chronic health effects of pesticide use, and the need for more information and research on the safety of pesticides including the potential long-term effects of their use. However, there appears to be no scientific data linking the use of pesticides on stored grain to any public health issues in the UK or anywhere else in the world.

It is very likely that, given the choice, the general consumer would prefer food to be free from all pesticide residues. However, at the same time it seems unlikely that consumers would accept lower standards of food hygiene, the presence of beneficial insects in food or much higher costs.

8. VIEWS OF COMMERCIAL SUPPLIERS OF BIOCONTROL AGENTS IN THE UK

Information was also sought from companies operating in the UK that supply biocontrol products for the horticultural market. Both large and small companies saw stored products as a potentially new market for supplying predators and parasitoids to control insect and mite grain pests. Although not producing any biocontrol products for stored grain pests at present, as soon as they perceived a demand for such products they would be eager to respond. They considered that demand was most likely to be stimulated by pressure from end users for pesticide-free grain and grain products, such as maltsters and large food retailers, rather than the cereals industry itself. Stricter UK or EU legislation, for example restricting pesticide usage and residues in food, and other environmental issues, could provide further encouragement to seek alternatives to chemical control and fumigation or at least reduce their use through integrated pest management strategies.

The biocontrol companies responding to our requests for information were confident they could adapt existing production units and release systems for grain pest biocontrol agents. However, before committing the necessary resources they would need to be convinced of the efficacy of any potential biocontrol agent. More importantly, they would need assurance that the market was sufficiently large and secure to justify the start-up costs involved. The general opinion was that the need for biocontrol would have to be sufficiently great to force the cereal industry to accept higher costs of pest control before this venture would become commercially viable.

As far as microbials were concerned, there are several promising candidates awaiting development but the size and potential return from the market in the UK does not appear to justify the costs of registration.

9. STRATEGIES FOR USE

This section summarises data from published information or from suppliers of biocontrol agents regarding the effectiveness of biocontrol agents against a range of grain pests. Wherever possible, some indication of potential efficacy under practical conditions is given. Three strategies are described using the agents/approaches that appear most suitable for UK grain stores. Finally, the use of biocontrol as part of an Integrated Pest Management strategy is considered.

9.1 Published experimental data

The following data are included to give some indications of the efficacy and methods of use for several key organisms with potential to control pests in stored grain in the UK.

9.1.1 Predators

Cheyletus eruditus

Following laboratory studies and field trials in grain stored near Prague (18) the following recommendations were made. Predators were introduced in ratios of between 1:100 and 1:1000 (predator:pest mites) by sprinkling over the surface of grain between April and June before harmful mites become too abundant (i.e. over 1000/kg of grain). Predators can also be added to non-infested grain as a preventive in the ratio of 1 predator/100kg of grain.

More recent trials in empty Czechoslovakian grain stores (12) where pest mites had reached a maximum density of 2200 flour mites, *Acarus siro*, per square metre, release of 2000-3000 predators per $100m^2$ markedly reduced pest populations.

Xylocoris flavipes

Warehouse trials were conducted in the USA by introducing between 10 and 80 pairs of predators into bins containing 6 bushels of peanuts artificially infested with 80 pairs of the red flour beetle, *Tribolium castaneum* (1). Populations of the pest were significantly reduced by all densities of predator.

In laboratory experiments, 32 litre lots of maize were infested with 20 pairs of the saw-toothed grain beetle, *Oryzaephilus surinamensis*, after which between 5 and 30 pairs of predators were added (124). After 15 weeks at 27°C, the predators had reduced population growth of the pest by at least 95%, even when only 5 pairs were added.

Laboratory experiments were conducted at 26°C in 1500 cu. ft rooms by sprinkling 500g lots of peanuts, maize and rolled oats on the floor which were infested with 1000 late instar larvae of the tropical warehouse moth, *Ephestia cautella*. Twenty five pairs of predators were then released at 2 weekly intervals for 5 releases. Populations of the pest were suppressed by 78% (38).

9.1.2 Parasitoids

Anisopteromalus calandrae

Five hundred grams of wheat infested with the rice weevil, *Sitophilus oryzae*, was scattered in a 44.7 cu m room kept at 27°C, after which pairs of the parasitoids were introduced (22). The experiment was repeated using between 10 and 50 pairs of parasitoids. Compared to untreated controls, the pest population was suppressed by over 90% when 30-50 pairs of parasitoids were introduced.

Experiments were conducted in the laboratory at 28°C, and in outdoor fluctuating conditions in the USA averaging 18.6°C, in 2 litre cartons each containing 250g maize infested with 40 maize weevils, *Sitophilus zeamais* (125). When 5 female parasitoids were added to each carton, pest population growth was reduced by over 50% in both environmental conditions compared to that in the absence of the parasitoids.

A computer simulation model for the control of *S. zeamais* by *A. calandrae* at 25°C recommended an optimal strategy of 2-3 releases of about ten times as many parasitoids as adult weevils at 9-day intervals as soon as the first hosts of suitable size (i.e. >15 days old) are available (26).

Bracon hebetor

Laboratory experiments were conducted at 26°C in 1500 cu ft rooms by sprinkling on the floor 500g amounts each of maize, rolled oats and peanuts infested with 1000 late instar larvae of *E. cautella* to which were added 50 pairs of the parasitoid at 2 weekly intervals for 5 releases. Populations of the pest were suppressed by 97% (38).

B. hebetor, released at a rate of 1000 pupae per week for 11 weeks, suppressed populations of *P. interpunctella* and *E. cautella*, in stores under USA natural storage conditions each containing 450 kg of peanuts, by 66% and 97% respectively (36). In each store the peanuts were infested by seeding with 4000 eggs of *E. cautella,* while an unknown number of *P. interpunctella* had emigrated from surrounding buildings.

At a dried fruit store in South Africa, a minimum of 18,000 parasitoids are released each week for 8 months to control reinfestation of 40,000 tonnes of sultanas by *P. interpunctella* and *E. cautella* (32).

Choetospila elegans

Experiments were conducted in the laboratory at 28°C, and in outdoor fluctuating conditions in the USA averaging 18.6°C, in 2 litre cartons each containing 250g maize infested with 40 *S. zeamais* (125). When 5 female parasitoids were added to each carton, pest population growth was reduced by 50% and 25% under outdoor and under laboratory conditions, respectively, compared to that in the absence of the parasitoids.

Trichogramma pretiosum

This parasitoid, released by sprinkling over peanuts at a rate of 1500 parasitised moth eggs per week for 11 weeks, suppressed populations of *E. cautella* and *P. interpunctella,* in stores each containing 450kg of peanuts under natural USA storage conditions, by 97% and 37%, respectively (36). In each store the peanuts were infested by seeding with 4000 eggs of *E.*

cautella, while an unknown number of *P. interpunctella* had emigrated from surrounding buildings.

Venturia canescens

Laboratory experiments were conducted at 26°C in 1500 cu ft rooms by sprinkling on the floor 500g amounts each of maize, rolled oats and peanuts infested with 1000 late instar larvae of *E. cautella* to which were added 50 females of this parthenogenic (i.e. development of egg without fertilisation) parasitoid at 2 weekly intervals for 5 releases. Populations of the pest were suppressed by 92% (38).

9.1.3 Nematodes

There are no data published for use of nematodes against storage pests. Indeed, their application to stored grain is extremely unlikely as they usually require a wet environment to infect their host.

9.1.4 Protozoa

Mattesia trogodermae

In experimental arenas (2x2m) populations at densities of 32 adult males per m^2 of the dermestid beetle, *Trogoderma glabrum*, lured to a source of the protozoan pathogen by a beetle pheromone, increased only fourfold in the first post treatment generation and to below pre-treatment levels in the second generation. This was compared to control population increases of 24-fold in the first generation and 100-fold in the second (73).

Nosema whitei

Laboratory dose-mortality experiments at 30°C showed that a dose of 5.4 x 10^7 spores/g was sufficient to kill 50% of newly hatched *T. castaneum* larvae (77).

Infections by this protozoan were found to be density dependent in larvae of *T. castaneum* (70).

9.1.5 Fungi

Beauvaria bassiana

Standard laboratory methods indicated that at 25°C a dose of this fungus in the range of 2 x 10^8 and 5 x 10^8 conidia/ml was required to kill 50% of adult *S. granarius* (85).

In Vietnam, when two hundred adults of *Sitophilus* and *Tribolium* spp. were added to experimental bags of milled rice, and the bag surfaces subsequently sprayed with fungal spores at the rate of 10 spores per ml., mortality after 20 days was between 53 and 61% of insects present (86).

9.1.6 Bacteria

Bacillus thuringiensis

Application procedures for commercial formulations of *B. thuringiensis* were evaluated in southern USA grain silos and bins (105). Infestations of *P. interpunctella* were reduced 50-60% in wheat and >80% in maize. Dust and wettable powder formulations were equally effective. Treatment of grain in the auger as it was elevated into the bins gave uniform distribution of both formulations. Application by raking into the surface layer of filled bins gave acceptable distribution of the dust, but poor distribution of the wettable powder leading to poor control. Spray volume had no effect on distribution or efficacy of wettable powder treatments. More recently, some laboratory strains of *P. interpunctella* have developed high levels of resistance to *B. thuringiensis* after only a few generations of selection (131). This suggests that resistance could develop in the field and so might threaten the future effectiveness of this microbial pesticide.

Bacillus thuringiensis var. tenebrionis

Preliminary laboratory tests in India indicated that 250ppm of primary product (82 x 10^6) spores/mg) should be sufficient to check the population of *R. dominica* and control the development of other beetle pests in stored wheat, including *T. castaneum, S. oryzae* and *T. granarium* (100).

9.1.7 Baculoviruses

Granulosis virus

A dose of 1.875 mg of formulated virus/kg of grain gave good control of *P. interpunctella* at 25°C (116). Treatment of the surface layer of wheat or maize to a depth of 100mm was more effective than treatments applied to depths of 33 or 67mm and was almost as effective as treating the entire grain mass.

Laboratory tests on a freeze-dried preparation of granulosis virus-infested *P. interpunctella* gave a dose of 7.9×10^4 viral capsules per gram of diet as being required to kill 50% of the moth pest (115). Loss of activity under typical USA warehouse conditions appeared to be insignificant commercially.

9.1.8 Combinations of biocontrol agents

Bracon hebetor with *Trichogramma pretiosum*

In stores each containing 450 kg of peanuts under natural USA storage conditions, *Bracon hebetor* with *Trichogramma pretiosum*, released at rates of 1000 pupae and 1500 parasitised moth eggs/week for 11 weeks, respectively, suppressed populations of *P. interpunctella* and *E. cautella* by 84% and 98%, respectively (36).

Bracon hebetor with *Xylocoris flavipes*

The two biocontrol agents were released six times over a 3 month period into a commercial warehouse in the USA containing 36 tonnes of peanuts with only traces of malathion (2). A total of 324,000 *B. hebetor* and 191,000 *X. flavipes* were released to suppress *E. cautella* and *P. interpunctella*. A control warehouse, containing 409 tonnes of peanuts for sampling, received no biocontrol agents but contained peanuts conventionally treated with malathion. Moth populations in the biocontrol treated warehouse were 54-83% smaller than populations in the control warehouse throughout the storage period and peanuts sustained less damage.

Choetospila elegans with *Cephalonomia waterstoni*

Field studies were conducted under natural USA storage conditions using 6 bins each filled with 27.2 tonnes of wheat (47). Two hundred and seventy adult lesser grain borers, *Rhyzopertha dominica*, and 270 adult rust-red grain beetles, *Cryptolestes ferrugineus*, were released into each bin at monthly intervals from July to October. Three weeks after the first beetle release, 540 adults each of the 2 parasitoids were added to the tops of 3 of the bins, and a month later another 900. *C. waterstoni* were also released into these bins. After 198 days of storage, control bins averaged 2.06 *R. dominica*/kg and treated bins 0.05 *R. dominica*/kg, well below economic levels. Suppression of *C. ferrugineus* by *C. waterstoni* could not be measured because large number of *C. waterstoni* entered the control bins.

9.2 Strategies for use in UK grain stores

Commercial approaches, dosage and release rates for potential biocontrol.

9.2.1 Biofac system

Biofac, a company in the US supplying beneficial insects and mites to control pests in stored grain, make a series of recommendations for pest control in stored grain. These include the staged release of a mixture of predators and parasitoids throughout the storage period on a weekly basis. The company considers that it is essential to have expert evaluation of the pest problems and employ advisors for this purpose. The species and numbers of beneficials released are then adjusted according to the level of pests. This process seems to be management intensive but good results are claimed.

The costs of the Biofac system are hard to establish because there is some conflict between data given by the company and information published in the scientific literature. The range would seem to be about 13 - 50p/tonne using Biofac data, to £1.20/tonne using published figures.

The beneficial insects and mites used in this system are known to occur in the UK or to be regularly found on imported commodities. Therefore, registration would not be required. Biofac have indicated their interest in entering the UK market.

9.2.2. Use of *Bacillus thuringiensis* to control moths

One product, Dipel produced by Abbott Chemicals, containing *Bacillus thuringiensis* is registered in the US for the application to grain to control moths. This material is applied to the surface of grain as a dust or wettable powder diluted in water. This latter is sprayed onto the surface of the grain at the rate of about 10g of active ingredient/sq m in about 1 litre of water. Current US prices suggest the costs of Dipel would be about 22p/sq m of grain surface. However, it is notoriously unreliable to use comparisons of pesticide price between countries.

This system could not be used immediately in the UK as Dipel, or equivalent products produced by Sandoz, Ecogen and Ciba, would first require registration by the Pesticides Safety Directorate.

9.2.3 Use of *Cheyletus eruditus* to control mites

Cheyletus eruditus are used in the Czech Republic to control mites in grain and empty stores. These predatory mites are supplied in packs containing about 2000 adults and are applied at the rate of one pack per 100 sq m of floor area in an empty store. When treating grain, the predators must be applied early in the storage season to the surface layers of a bulk or bin and sufficient predators must be applied to give a predator:prey ratio of at least 1:100. Under cold conditions (less than 20°C) or in the presence of heavy pest populations, a ratio of 1:10 must be used. It is likely that a repeat treatment would be needed during prolonged storage.

Costs to treat empty stores would appear to be about £2/100 sq m. Costs of treating bulk grain are much harder to determine as the numbers of predators required will be influenced by the depth of grain, the pest density and the grain temperature. However, given average conditions, a cost to the user of about £2 per 2000 *Cheyletus eruditus* to treat 100 sq m of grain surface area would seem a good starting point.

This system would appear to have immediate application in the UK, particularly in relation to the control of mites in stored oilseeds and would not require registration However, the suppliers have indicated that the predatory mites must be monitored if success is to be assured. They also warn that *Cheyletus eruditus* is much less effective when grain temperatures fall below 18°C.

9.2.4 Biocontrol within an Integrated Pest Management strategy

Further progress in the use of biocontrol for stored grain may come through its incorporation into an Integrated Pest Management (IPM) strategy. IPM combines different types of control methods to reduce to a minimum the use of chemical pesticides without reducing the market value of the product due to pests. A wide range of options is available, ranging from biotechnological and plant breeding techniques, improved hygiene and pest detection methods, use of inert dusts, modified atmospheres, cooling, improvements in physical barriers and packaging, through to better application of conventional pesticides. Some types of biocontrol agents may be suitable for incorporation into an IPM system for storage pests.

The use of IPM for stored product insects has been reviewed recently by Subramanyam and Hagstrum (130). They concluded that IPM may be more complex and requires more effort than other control strategies, but will provide more reliable pest management decisions. An IPM strategy for UK grain storage has been developed with the aid of HGCA research funding (132) and is widely used. This strategy couples close monitoring of the physical condition of the grain and of pest numbers with a cooling strategy and restricted application of pesticides. Pests are prevented from developing and storage costs are reduced. It might be possible to replace conventional pesticides with biocontrol agents in this strategy but, in general, predators, parasites and diseases are more effective at higher temperatures.

10. FUTURE DEVELOPMENTS IN BIOCONTROL

Most R&D on biocontrol agents is aimed at applications well removed from stored grain and world-wide there is only a minute and fragmented programme on post-harvest applications. However, there are some possibilities for the development of new options or approaches. These may result from any or all of the following lines of research, although careful assessment of all the health, safety and environmental implications will be needed.

(a) Conducting field searches and laboratory studies to identify new biocontrol agents.

(b) Isolating improved strains of existing biocontrol agents by selective breeding programmes.

(c) Combining different types of biocontrol agents to increase efficiency, for example using parasitoids to spread pathogens amongst storage insects.

(d) Using pheromone and food lures to attract pests to point sources of biocontrol agents.

(e) Reducing the cold tolerance of storage insects by treating grain with ice-nucleating-active bacteria.

(f) Inserting genes for insect toxins, such as *B. thuringiensis* endotoxin, into recombinant baculovirus to increase pathogenicity.

(g) Improving the performance of existing biocontrol agents using other forms of genetic manipulation, for example to increase the speed of action of fungal and viral pathogens.

Several of these areas of development have the potential to produce a dramatic increase in the commercial viability of the biocontrol of grain pests. Work to some degree is under way on all of the above ideas but their rapid transfer to use against grain pests is unlikely without properly targeted research funding.

11. CONCLUSIONS

There is a large body of data to show that all pests of stored grain are susceptible to a range of biological agents. Most of these data come from laboratory trials and the amount of field data is more limited. However, there are clear indications that, under some circumstances, the use of biocontrol agents will reduce pest populations and reduce the risk of damage and loss of grain during storage.

A critical look at potential biological control agents suggests that only a relatively small number have any possibility of commercial viability for use on stored grain in the UK. This is borne out by the reports of field trials carried out in other countries. There is a small group of beneficial insects and mites that would have some application and share the advantage of not requiring to go through the registration process. The sale of these organisms in the UK merely requires an agent or supplier. However, their adoption by farmers and storekeepers would depend upon the costs and efficacy of particular systems, neither of which can be judged accurately under our conditions. A further and very important constraint is the attitude of end users of grain and it seems unlikely that the food industry, for example, would be ready to accept the addition of beneficial insects at present.

Concerns about the efficacy of current control measures or levels of pesticide residues in grain do not seem likely to influence the UK cereals industry with regard to the use of biological control, at least in the short term. Cost appears to be the major driving force and, if a biological approach to pest control were as effective as current measures but less expensive, there would be substantial interest. The only future development within the industry that might bring a change to this attitude would be the withdrawal of all current chemical control measures, including fumigation with phosphine, or a massive increase in energy costs. Additionally, increased demand from the large food retailers and other specialist groups, such as 'organic' food suppliers and maltsters, might stimulate more interest in the industry. Surprisingly, there was little positive response from organic producers and end users of organic grain when approached for their views in connection with this review.

An improved strain of *Bacillus thuringiensis* which has the potential to control beetle pests as well as moths, appears to have potential for further development. However, such a product would require registration which is an expensive process and is only likely to be cost effective if the manufacturer was interested in a World Market or the product had application in other areas. Given the small UK market for grain protectants and the very high costs of registration, it seems unlikely that any new product will be registered in the near future.

There is hardly any current research in the UK that is likely to assist the development or adoption of biocontrol of grain pests despite the aims of central government to reduce the use of pesticides in the food chain. The small amount of effort world-wide would probably benefit from some co-ordinating force such as WHO/FAO.

Despite the lack of enthusiasm in the industry for the introduction of biological control at the present time, its further development does deserve consideration. It can be regarded as a possible option that could be used if current strategies become unviable for some reason.

12. RECOMMENDATIONS

If biocontrol of grain pests were to be considered in the UK a first essential would be to produce efficacy and cost data generated in this country. The realistic options seem very limited and any work should be directed towards only those methods that have been shown to work in other countries and for which a supplier of appropriate products would be available. This would seem to limit the choices to using a mixture of beneficial insects in grain or using predatory mites in grain or oilseeds.

The development of biocontrol agents that would require registration is only worthwhile given support from a manufacture who was prepared to assemble the data package necessary to secure registration and to meet the costs of this process.

In view of the uncertainties currently prevailing, there is a need to seek further clarification of the status of biocontrol agents for stored grain in relation to UK and EU food regulations.

The potential of biocontrol as a fall-back control option for stored grain should not be underestimated, and some thought should be given to limited strategic planning in this area. One useful approach would be to encourage liaison between the small numbers of workers in various parts of the world so that a comprehensive database of R&D information can be maintained.

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Table 1. PREDATORS

Examples of species studied (+ country)

SPECIES	HOSTS	LAB/FIELD STUDIES	FIELD RELEASE	COMMERCIAL USE	POTENTIAL FOR CONTROL +	POTENTIAL FOR CONTROL -	UK REGISTRATION	REFERENCES
INSECTS *Xylocoris flavipes*	Most stages of many beetles and moths especially smaller larvae and eggs.	USA/USA	USA	USA - several companies supply, limited data on success.	Mop up pests in old grain residues before new harvest. Wide pest host range. Rapid reproduction. Cannibalistic when prey scarce.	Cannot attack pests inside grain or in bulks. May be less acceptable due to large size and foraging.	Not required since established in UK.	1, 2, 3, 4, 5, 6, 31, 38.
Lyctocoris campestris	Many moths and beetles especially larger larvae.	UK + USA/USA	-	-	Mop up pests in old grain residues before new harvest. Wide pest host range. Rapid reproduction. Cannibalistic when prey scarce.	Cannot attack pests inside grain or in bulks. May be less acceptable due to large size and foraging and has been known to bite humans.	Not required since native to UK.	7, 8, 9, 10.
MITES *Cheyletus eruditus*	Acarid mites and very young stages of beetles, moths, psocids.	UK, USA, E Europe	E Europe	Former Czeckoslovakia (one company), limited data on success.	Tolerant of pesticides used to control pest species. Can be stored at low temperatures. Cannibalistic when short of food.	Less effective at low temperatures and low humidities.	Not required since native to UK.	11, 12, 13, 14. 16, 17, 18.
Blattisocius tarsalis	Prefers moth eggs but can survive on beetle eggs.	UK/E Africa	-	-	Spread by host. Reproduce more rapidly than host.	Usually only preys on moth eggs.	Not required since native to UK.	15, 19, 20.

Table 2. PARASITOIDS

Examples of species studied (+ country)

SPECIES	HOSTS	LAB/FIELD STUDIES	FIELD RELEASE	COMMERCIAL USE	POTENTIAL FOR CONTROL +	POTENTIAL FOR CONTROL -	UK REGISTRATION	REFERENCES
CHALCIDOIDEA Anisopteromalus calandrae (A)	Larvae & Pupae *Sitophilus* spp *R. dominica* *L. serricorne* *S. paniceum* *T. granarium* *P. truncatus* *Bruchidae*	USA/USA, Mexico	USA	USA - several companies.	Some strains highly resistant to pesticides. (A) Useful for mopping up pests in store fabric. (A) (E) Can attack pests inside grain kernels. (A) (C)	Less effective against pests below grain surface layers.	Not required since native to UK.	21, 22, 23, 24, 25, 26, 27, 28, 31, 37, 46, 57.
Trichogramma evanescens (B)	Eggs of many stored product lepidoptera.	Canada, USA, Germany/USA, Germany	USA	USA - one company. Holland - Moths in Glasshouses not Storage.	Can prevent infestation of packaged goods. (A) (E) (F) Minute size allows parasitoids to be removed from grain along with dust after storage. (A) (B) (C) (D) (E) (G) H)	May attack moths other than storage pests.	Not required since native to UK.	21, 31, 39, 41, 42, 43.
Choetospila elegans (C)	Larvae + Pupae *Sitophilus* spp *R. dominica* *S. paniceum* *S. cerealella* *Bruchidae*	Holland, USA, S. America/ USA	USA	-	Parasitised larvae are paralysed and stop feeding immediately. (E) (G) (H) Good penetractor - can attack pests in grain bulks as well as on surface. (C)	-	Not strictly native but regularly introduced registration?	21, 44, 45, 46, 47, 48, 49, 50, 57.

Table 2. PARASITOIDS (Contd.)

Examples of species studied (+ country)

SPECIES	HOSTS	LAB/FIELD STUDIES	FIELD RELEASE	COMMERCIAL USE	POTENTIAL FOR CONTROL +	POTENTIAL FOR CONTROL -	UK REGISTRATION	REFERENCES
Dibrachys cavus (D)	Larvae of *Sitophilus* spp *S. cerealella* *P. interpunctella* *Bruchidae* + Many non-storage insects	China	China - in cotton warehouses v. *Pectinophora.*	-	Attacks pests before larvae can feed. (B)	May attack non-pest species.	Not required since native to UK.	21, 44, 59, 60, 61.
ICHNEUMONOIDEA *Bracon hebetor* (E)	Larvae of *Ephestia* spp *interpunctella*	UK/ USA, S. Africa	USA, S Africa	USA - several companies.	Rapid development compared to pest. (C) (F)	-	Not required since native to UK.	29, 30, 31, 32, 33, 34, 35, 36, 38, 55, 57.
Venturia canescens (F)	As for *B. hebetor*	UK, France, USA/USA	-	-	Can increase spread of *B. thuringiensis.* (F)	Parasitised larvae may continue feeding for some time. Larger than other parasitoids.	Not required since native to UK.	38, 40, 51, 52, 53, 54, 55, 56, 99.
BETHYLOIDEA *Cephalonomia tarsalis* *(G)*	Larvae of *Sitophilus* spp *O. surinamensis*	-	-	-	One of very few parasitoids to attack *O. surinamensis.* (G)	-	Introduced under artificial conditions. Registration?	33, 62.
Cephalonomia waterstoni *(H)*	Larvae of *Cryptolestes* spp	UK/USA	USA	USA - one company.	One of very few parasitoids to attack *C. ferrugineus.*	-	Introduced under artificial conditions. Registration?	31, 47, 62.

Table 3. NEMATODES

Examples of species studied (+ country)

SPECIES	HOSTS	LAB/FIELD STUDIES	FIELD RELEASE	COMMERCIAL USE	POTENTIAL FOR CONTROL +	POTENTIAL FOR CONTROL -	UK REGISTRATION	REFERENCES
Steinernema feltiae = *Neoaplectana carpocapsae*	*S. oryzae* (A) *T. castaneum* (L) *T. granarium* (L) *T. molitor* (L) *R. dominica* (A) *E. kuehniella* (L) *A. obtectus* (A) *T. audax* (L) *T. madens* (L) *G. mellonella* (L)	Lab. studies on damp filter paper only. Canada, France, Poland.	USA/UK	Available in UK, Canada and USA for control of growing crop pests before harvest; also nuisance flies, fungus gnats.	-	Most stored grain likely to be too dry for successful pest control by nematodes, unless possibly pests can be attracted to a nematode infested point source.	Isolates from UK do not require Registration.*	31, 64, 65, 66 67, 96.
	A. transitella (L) (A = Adult) (L = Larvae)	Field trial in USA Almond Orchards; controls pests within nut.	USA					63, 69.
Howardula mutilatus	C. mutilatus	Lab and field trial in India on maize cob kernels.	-	-	-	*C. mutilatus* only found on imports to UK	Not known in UK:. Import Licence required from DOE.	68

* Registration under review since insects killed by bacteria (*Xenorhabdus nematophilus*), carried within nematode, rather than by the nematode itself.

Table 4. PROTOZOA

Examples of species studied (+ country)

SPECIES	HOSTS	LAB/FIELD STUDIES	FIELD RELEASE	COMMERCIAL USE	POTENTIAL FOR CONTROL +	POTENTIAL FOR CONTROL -	UK REGISTRATION	REFERENCES
GREGARINIDA *Mattesia dispora*	*Cryptolestes* spp. *E. kuehniella* *P. interpunctella*	UK, France	-	-	Invisible to naked eye.	Enter host by ingestion. Slow acting when used as control agents on their own. Generally have low virulence and poor persistence.	Require Registration	74, 79.
Mattesia trogodermae	*Trogoderma* spp.	USA	-	-	Effective when used with pheromone lure to aid dissemination.			73, 75.
Lymphotropha tribolii	*T. castaneum*	UK	-	-	-			76.
Farinocystis tribolii	*Tribolium* spp.	UK, Eastern Europe/UK	-	-	-			81, 82.
COCCIDIA *Adelina tribolii*	*Tribolium* spp.	UK, Eastern Europe/UK	-	-	-			80, 82.
MICROSPORIDIA *Nosema whitei*	*Tribolium* spp. *O. surinamensis*	UK/UK	-	-	Synergistic effects on mortality in *T. castaneum* when used with chemical insecticides.			30, 70, 71, 77, 82, 97.
Nosema oryzaephili	*O. surinamensis*	UK	-	-	-			71, 72.
Nosema plodiae	*P. interpunctella*	USA	-	-	-			78.

Table 5. FUNGI AND FUNGAL METABOLITES

Examples of species studied (+ country)

SPECIES	HOSTS	LAB/FIELD STUDIES	FIELD RELEASE	COMMERCIAL USE	POTENTIAL FOR CONTROL +	POTENTIAL FOR CONTROL -	UK REGISTRATION	REFERENCES
FUNGI *Beauveria bassiana*	Adults and larvae *A. obtectus* *O. surinamensis* *Sitophilus* spp. *G. mellonella* *Tribolium* spp. *P. truncatus*	France, UK, Eastern Europe, Vietnam, W. Africa	-	Available in Eastern Europe to control Colorado beetle. In Czechoslovakia, in combination with pirimiphos-methyl. It is registered for treatment of empty Stores and Silos.	Broad insect host range. Infects host by invasion through cuticle.	May affect beneficials. Requires high humidity for development of fungus and re-infection. Comparatively slow acting.	Requires Registration.	83, 84, 85, 86, 87, 95, 97, 98, 107.
Metarhizium anisopliae	Adults and larvae *A. obtectus* *G. mellonella*	France, USA, W. Africa.	-	Available in S. America v. rice pests in field. Available in USA v. leafminers and cockroaches. Registered in Germany and Austria v. black-vine weevil.	Broad insect host range. Infects host by invasion through cuticle.	Allergic reactions to spores reported in some workers both for *B. bassiana* and *M. anisopliae*		31, 83, 87, 88, 89, 107.
FUNGAL METABOLITES *Penicillium* spp.	*Tribolium* sp. *Lasioderma* sp. *Attagenus* sp. *E. kuehniella*	USA	-	-	-	Queries concerning toxicity to humans.		93, 94.
Fusarium spp.	*Tribolium* sp. *Alphitobius* sp. *T. bisselliella*	USA, UK.	-	-	-	Queries concerning toxicity to humans.		90, 91, 92.

Table 6. BACTERIA

Examples of species studied (+ country)

SPECIES	HOSTS	LAB/FIELD STUDIES	FIELD RELEASE	COMMERCIAL USE	POTENTIAL FOR CONTROL +	POTENTIAL FOR CONTROL -	UK REGISTRATION	REFERENCES
BACILLUS THURINGIENSIS *(1) Delta-endotoxin* *B.t. var. kurstaki*	Larvae of *Ephestia* spp. *Plodia* and some other lepidoptera	UK, USA, Europe, Canada, W. Africa.	USA, Vietnam	World-wide for a variety of insects including storage pests.	Invisible to naked eye. Can be cultured in artificial media. Toxic protein crystals rapidly halt larval feeding. Protein crystals not toxic to humans. Easy to use in dry conditions of stores.	Potential for resistance detected in some strains of *Plodia*.	Some products already registered, although not for storage pests.	97, 102, 103, 104, 105, 108, 109.
B.t. var. tenebrionis	Larvae and adults of *R. dominica* and some other storage beetles. Also Colorado beetle.	Germany, India, USA.	USA	USA for crop pest beetles.				97, 100, 101.
(2) Beta-Exotoxin thuringiensin	*E. kuehniella* *G. mellonella* and many other insects.	Germany, France, Finland, USA, S. America, UK.	Finland, S. America.	In Finland v. poultry manure flies. In S. America v. spider mites.	-	Toxic to vertebrates.	Requires Registration.	103, 110, 111, 112, 113.
BACILLUS CEREUS	Larvae of *L. serricorne*	USA.	-	-	-	Incriminated in some human infections and food poisoning.	Requires Registration.	103, 106, 107.

Table 7. BACULOVIRUS

Examples of species studied (+ country)

SPECIES	HOSTS	LAB/FIELD STUDIES	FIELD RELEASE	COMMERCIAL USE	POTENTIAL FOR CONTROL +	POTENTIAL FOR CONTROL -	UK REGISTRATION	REFERENCES
Granulosis Virus Nuclear Polyhedrosis Virus	Moths including *P. interpunctella* *E. cautella* *E. elutella* *T. bisselliella*	UK, USA/USA.	-	-	Invisible to naked eye. Comparatively easy to use. Highly host specific. No adverse effects on non-target organisers detected so far, including humans. Sub-lethal effects include reduced reproductive capacity.	Viruses have to be ingested by host to be effective. Have to be produced in a living host. Slow acting. Less stable than B.t. endotoxin.	Requires Registration.	97, 114, 115, 116, 117, 118, 119, 120, 121, 122, 123.

Table 8. **SUITABILITY OF BIOCONTROL AGENTS FOR STORAGE SITUATIONS**

AGENT	STRENGTHS	WEAKNESSES	AREAS OF APPLICATION
PREDATORS	1. Often have wide host ranges, so can attack several pest species. 2. Often self-regulating (cannibalistic) when prey is scarce. 3. Good searching ability. 4. Rapid reproduction. 5. Registration not required for species native to UK. 6. Not harmful to humans, although have occasionally been known to bite. 7. Rapid spread by own activity. 8. Development of resistance by pest unlikely.	1. Unable to attack pests inside whole grain or deep bulks. 2. Some species less acceptable due to large size. 3. Less effective at low temperatures. 4. May be affected by pesticides. 5. Long term storage may be difficult. 6. May attack non-pest species. 7. Mass production only possible on living hosts.	1. Can clean up pests in stores before new grain is introduced.
PARASITOIDS	1. Many species are very small, enabling them to attack pests in grain bulks. 2. Some species can attack pests inside grain kernels. 3. Good searching abilities. 4. Some strains highly resistant to pesticides. 5. Small size allows parasitoids to be removed from grain along with dust after storage. 6. Some species can attack pests before damage occurs; others paralyse prey which cease feeding immediately. 7. Not harmful to humans. 8. Registration not required for species native to UK. 9. Rapid spread by own activity. 10. Development of resistance by pest unlikely. 11. Some species can attack a range of pre species.	1. Some parasitoids may attack non-pest species. 2. Although usually smaller than the pests, most are visible to the unaided eye. 3. May be affected by pesticides. 4. Long term storage may be difficult. 5. Mass production only possible on living hosts.	1. Can clean up residual pests in store fabric. 2. Can be used to prevent infestation of packaged goods. 3. Some species can be used to attack pests within grain bulks as well as on surface.
NEMATODES	1. Invisible to unaided eye. 2. Not harmful to humans. 3. Has some limited searching abilities. 4. Isolates from the UK do not require registration.	1. Most stored grain environments likely to be too dry for successful pest control by nematodes. 2. Mass production only possible on living hosts.	1. None, unless pests can be attracted to nematode-infested point sources.

Table 8. SUITABILITY OF BIOCONTROL AGENTS FOR STORAGE SITUATIONS (Contd.)

AGENT	STRENGTHS	WEAKNESSES	AREAS OF APPLICATION
PROTOZOA	1. Invisible to unaided eye. 2. Can have synergistic effect on pest when used with pesticides. 3. Not harmful to humans. 4. Easy to use.	1. All require registration. 2. Comparatively slow acting. 3. Generally have low virulence and poor persistence. 4. Require ingestion by pest. 5. Mass production only possible on living hosts.	1. May be effective in stores if used with a pheromone lure to aid dissemination. 2. Could be used where other pathogens or chemicals are ineffective or prohibited.
FUNGI	1. Some species have a wide host range. 2. Infects prey by invasion through cuticle. 3. Spores are highly resistant to adverse conditions. 4. Easily spread through the air. 5. Invisible to the unaided eye. 6. Some can grow on artificial media.	1. All require registration. 2. Some species may affect beneficials. 3. Most species limited by need for high humidity. 4. Some species may pose health risks to humans. 5. Production costs fairly high, and production problems may lead to erratic performance.	1. Possible application where humidity is high or in conjunction with an insecticide acting as a stressor.
BACTERIA	1. Invisible to unaided eye. 2. Easy to mass produce on artificial media. 3. Spores are highly resistant to adverse conditions. 4. Easy to use in dry conditions of stores. 5. Some strains highly specific. 6. Many highly virulent.	1. All require registration, although some products already registered. 2. Some species may pose health risks to humans and other vertebrates. 3. Pests may develop resistance to attack. 4. Require ingestion by pest.	1. Toxic proteins can be used in similar ways to conventional insecticides.
BACULOVIRUSES	1. Invisible to the unaided eye. 2. Highly host specific. 3. No adverse effects detected on non-target organisms, including humans. 4. Highly virulent. 5. Easy to use.	1. All require registration. 2. Require ingestion by pest. 3. Mass production expensive and only possible in living hosts at present. 4. Comparatively slow acting. 5. Less stable than B.t. endotoxin.	1. Can be used to control storage moths in similar ways to conventional insecticides.

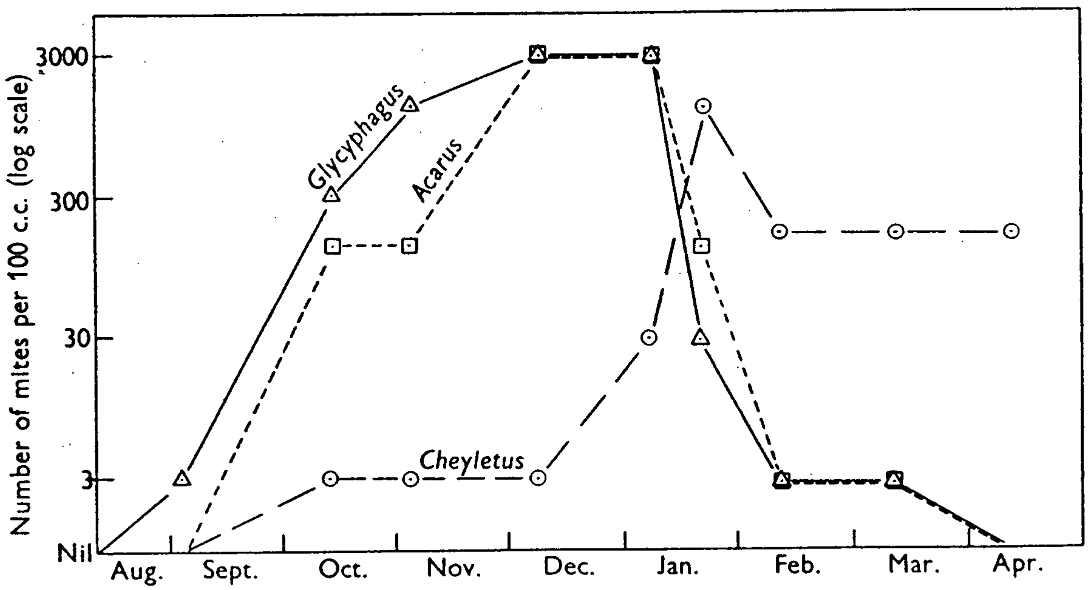

Fig. 1. Relative population densities in bulk wheat during the control of a heavy mite infestation by *Cheyletus eruditus*.

Fig. 2 The predatory bug, *Lyctocoris campestris*, attacking a moth larva.

Fig. 3 The parasitoid, *Anisopteromalus calandrae*, on a grain.