Biological control methods for insect pests of stored grain in the tropics-constraints and prospects for developing countries

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Abstract

The conventional use of insecticides and fumigants to control insect pests in stored grain has given rise to environmental and health concerns and is hampered by reduced efficacy due to the development of insect resistance to these chemicals Such problems may be overcome by adopting integrated pest management (IPM), important components of which are biological methods of control. Constraints to the implementation of these methods are considered in detail. These include an inadequate knowledge of the nature of the grain storage systems and the pest complexes that occur in them and an insufficient body of trained staff to implement more sophisticated pest management Suggestions are given as to how biological methods might be adopted in farmer, trader and central storage, and examples are presented of some current initiatives in their use.

For biological methods to reach their full potential, an increased research effort is required. This could be stimulated by a greater awareness of the need to develop improved methods, closer partnerships with researchers in countries where such technologies are being developed and improved market incentives for better quality grain. A possible way forward to achieve successful implementation of improvements in storage pest management is discussed

Introduction

The potential of biological methods for the protection of durable commodities has been exercising the imaginations of storage entomologists for some years. In 1984, a special edition of Tropical Stored Products Information (Volume 48) considered the biological methods that might be used in the integrated control of storage arthropods in the tropics. These included pheromones, resistant grain varieties, micro-organisms and sterile insects In a similar vein, although not with tropical countries specifically in mind, a special edition of the Journal of Stored Products Research in 1997 was devoted to ecologically safe alternatives to the use of conventional pesticides and fumigants which included the use of pheromones (Phillips, 1997) and predators and parasites (Schöler et al , 1997) Two recent book chapters have also drawn attention to the subject. One presents what is known about the potential of predators and parasites in grain stores (Brower et al 1996). The other emphasises the need for an ecosystems approach to tropical grain storage (Haines, 1995), an important consideration in the development of effective pest management In addition, of the 233 research papers presented at the 6th International Working Conference on Stored Products Protection in 1994, thirteen were on aspects of predators and parasites of storage pests including a very detailed key-note address on the prospects in Africa for classical biological control of the exotic storage pest *Prostephanus truncatus* (Horn) by the histerid beetle *Teretrius nigrescens* (Lewis) (= *Teretriosoma nigrescens*) (Markham et al., 1994).

The aim of this address is not to present details of any particular biological methods Instead, consideration will be given to the constraints imposed by the grain storage systems used in developing countries in the tropics so that future prospects for biological control methods can be brought into focus This approach will unavoidably lead to generalisation, since the grain storage systems and markets in developing countries are diverse. Nevertheless this should not invalidate the analysis. Once the prospects for biological methods have been identified, attention will be drawn to possible ways to achieve their implementation. However, before dealing with the constraints to the use of biological control methods it is important to consider why developing countries actually need such techniques.

The Need for Biological Methods

Grain storage in tropical countries is no less difficult than in temperate regions. Indeed, in those areas where the climate is both hot and humid, it can present a substantial challenge as grain deterioration which can be exceptionally rapid if commodity management systems break down. A crucial element of commodity management is the control of storage pests, especially insects The techniques currently in use to limit losses caused by insects are either preventative, such as the application of insecticides to store surfaces or

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admixture with the grain itself, or curative such as the fumigation of grain stocks under gas-tight sheets with the gases phosphine or methyl bromide. In most developing countries, the use of these methods does not have a long history: only in the period after World War II and, in most cases, the post-colonial period, has their application become widespread.

The pest management techniques that are in use are not without their difficulties and draw-backs. The efficacy of treating store surfaces with insecticides is doubtful (Hodges et al., 1992; Gudrups, 1996); the admixture of insecticides is being called into question in developed countries on health grounds, at least in the case of the most widespread class of grain protectants, the organophosphorous insecticides (Ecobichon and Joy, 1993); the use of methyl bromide is in jeopardy owing to its action as a depletor of stratospheric ozone (Taylor, 1994); and insects are increasingly showing more tolerance to the gas phosphine, gradually making this gas less effective than it once was (Taylor, 1989). We are now aware that there are even cases where apparently natural tolerance to phosphine, such as shown by the storage Psocoptera, is sufficiently great that some recommended practice does not guarantee complete control (Pike, 1994; Ho and Winks, 1995).

Against this background, it is clear that practitioners of commodity management will have to continue to develop strategies to limit losses caused by storage pests. However, future technical developments not only have to take into account the need to limit grain losses, but also to respond to the needs of the societies they intend to serve. In many developing countries, but especially in Southeast Asia, there is a increasing awareness of quality issues so that the prevention of losses requires that not only the weight of the grain is conserved but also that there is little or no contamination with insect bodies and with either no pesticide residues or at least residues within prescribed limits. To meet these demands requires an appraisal of all the options open to commodity management; biological methods are one of these options.

The Constraints

Grain storage and marketing methods

Unlike their more industrialised counterparts, most developing countries operate a wide range of storage systems serving formal and informal markets. The influence and relative importance of these has been changing in the wake of grain liberalisation programmes across much of sub-saharan Africa (Coulter and Compton, 1991) and other places, although apparently not in the Republic of China. The large national monopolies, that used to purchase grain from farmers soon after harvest and supply it cheaply to urban consumers for the rest of the year, have lost much of their control so that now more grain remains on farm for longer and is subject to price negotiation between farmer and private trader. The main grain storage systems are as follows.

Subsistence farmers' stores

A large component of national storage rests with farmers who maintain grain on the farm not only for subsequent sale but also for their own food needs. Grain is stored in an array of different containers such as simple open cribs, lofts, woven baskets, jute bags, mud silos and even underground pits. The style of management for such stores is equally varied. In some cases, reliance is placed on the durability of the stored commodity to prevent it from attack, such as paddy rice with its tough seed coat or maize cobs with good husk cover. In other cases, farmers watch their stocks carefully, such as in South India, where, at the first sign of insect attack after the monsoon season, they will redry sorghum. Other farmers may protect grain for extended periods by admixing dilute dust insecticides or by spraying emulsifiable concentrates onto it, whereas others admix traditional grain protectants derived from local plant materials (Dales, 1996). Indeed, farmers may use one or a combination of these strategies and include fundamental hygiene measures such as removal of old storage residues at the start of a new storage season and careful selection of stock to ensure early consumption of poorer quality grain which might otherwise deteriorate rapidly. There is a wide range of traditional storage methodologies, which for the most part can keep storage losses within a range of 2 – 5% provided grain is not stored for very long periods. The challenge is to make the best use of the possibilities for income generation offered by grain market liberalisation by developing increased capacity for longer-term storage, while at the same time decreasing the need for insecticides and fumigants.

National Central Storage

As the market-support role of state marketing-boards has been largely or completely lost, these organisations are now more often responsible for national food security reserves. However, even this function is declining, owing to the high cost of holding stocks balanced against better forecasting of potential food shortages and easier access to grain from world markets. There is minimal silo storage, most grain being kept in jute or polypropylene bags. For pest management, major reliance is placed on fumigation and insecticide spraying. This is undertaken by trained personnel and sometimes by private contractors. Occasionally, more sophisticated techniques have been adopted, such as sealed stack storage in Indonesia (Nataradja and Hodges, 1989). The standards to which these pest management activities are undertaken are highly variable. In scaling-down national central storage there has been a tendency for the skill-base to be depleted as trained staff disperse, for a loss of central control of pest management operations, and for a reluctance to maintain the investment needed to support an efficient system

Trader stores

Trader storage is possibly the least well-known component of the developing country storage system It has received little attention since its commercial orientation has largely excluded it from national programmes and development projects funded by inter-governmental aid It would appear that although there are some quite large-scale operators, most traders have stores of less than two hundred tonnes capacity and that they hold grain in jute or polypropylene bags, and bulk storage is almost unknown It is likely that most traders have little or no formal training in grain conservation, employ staff who do not have access to suitable training, and if they do resort to pest control action then they are frequently reliant on the support of private pest control companies of uncertain competence. However, grain market liberalisation holds out considerable financial opportunities for traders, especially if they have the ability to maintain stocks long enough to benefit from seasonal price rises. Their ability to do this will depend on effective pest management. However, private traders generally have neither the will nor resources to involve themselves with new developments that are unlikely to give the quick returns needed from investments financed on capital borrowed at high interest rates.

Greater biological activity and a poorly understood ecosystem

The more extreme climatic conditions experienced in the tropics can result in particularly rapid development of insect pest populations Thus a high degree of vigilance is required to ensure safe storage. Most of the major pest species to be controlled in tropical countries are the same as those found in locations with warm climates, having been spread with international trade. However, there are pests which are still fulfilling their potential to spread, such as *Prostephanus truncatus* in Africa (Hodges, 1994) and the psocid *Lachesilla quercus* in *Australia* (Rees, 1994a) In many cases, although the pest species are known, there is little knowledge of their interactions with each other and the commodities they infest. There are moderate amounts of information on the autecology and population biology of major pests in the literature on tropical grain storage systems, but little on community ecology (Haines, 1995). It may not be clear whether one or a range of species need to be brought under control and what might be the consequences of applying specific biological interventions against one species and leaving others unchecked. An example of such complexities has been revealed in a study of psocid populations in tropical Queensland where fumigation with phosphine kills the major storage pests including *Tribolium castaneum* but not the eggs of the psocids *Liposcelis entomophila* and *Liposcelis paeta*. After fumigation there is rapid reinfestation by the psocids and populations reach excessive levels in the absence of predation by *T castaneum* (Roesli, 1996). The same phenomenon, including the possible elimination of predatory mites such as *Cheyletus* spp (Haines, 1995), may account for similar psocid problems elsewhere, particularly in Indonesia (Santoso et al , 1996) It is clear that there is a wide range of possible pest and commodity interactions and that each needs to be well understood before appropriate interventions, including biological methods, can be formulated

Training and education

The implementation of more sophisticated pest management practices, which may involve biological methods, requires a body of well trained staff capable of making decisions in response to changing circumstances. As noted above, in many countries this cadre is currently dwindling as large-scale storage under central control is dismantled

Research effort and dissemination of information

In order to implement biological methods as components of integrated pest management a 'critical mass' of research is needed Judging by the number of peer reviewed scientific papers, reported in the CABI bibliographic database, developing countries have not neglected biological methods In the last six years, the database has recorded 64 papers on this subject coming from 14 countries (Tables 1 and 2) Most effort has been expended on predators and parasites, although in some cases the research may have been focused on storage pests simply because they are convenient laboratory animals, particularly in the case of bruchid beetles (*Callosobruchus* spp). However, compared with the research effort expended on well established, conventional methods of pest management such as fumigation and insecticide application, 127 papers from 12 countries (Table 3 and 4), the priority given to biological methods is still relatively low In order for the biological methods to achieve their full potential, the research effort in this direction must be increased.

Besides the need for research, it is important that research findings are communicated to those who need them, both to inform of the potential of new techniques and to facilitate exchange of ideas and information between those engaged in research. Effective communication remains a constraint as many researchers in developing countries still work in relative isolation. There is also a need to close the information gap between the researchers who develop the ideas and those, concerned with the problems and practicalities of storage, who are seeking technical solutions.

Table 1. Number of scientific publications, by storage pest, relating to biological methods of pest control in developing countries, retrieved from the CABI Database January 1992 – January 1998.

Pest	Predators/ Parasites	Pheromone	Pathogen	Genetic	Number of Countries	% of papers globally*
Prostephanus truncatus	7	0	1	0	1	100
Rhyzopertha dominica	3	0	2	0	5	23
Lasioderma serricorne	2	0	3	0	5	35
Sitophilus spp.	6	0	4	0	6	19
Callosobruchus spp.	18	0	2	0	8	41
Tribolium spp.	3	0	2	0	5	16
Trogoderma granarium	2	0	0	0	2	40
Ephestia spp	1	0	2	1	2	3
Sitotroga cerealella	1	1	2	0	4	7
Psocoptera	1	0	0	0	1	50
Totals	44	1	18	1		

* Number of developing-country papers on this species as a % of the total number worldwide recorded on the CABI database

Table 2. Number of scientific publications, by country, relating to biological methods of pest control in developing countries retrieved from the CABI Database January 1992 – January 1998.

Country	No. public.	Country	No. public.	Country	No. public.
Argentina	2	Egypt	7	S. Africa	1
Bangladesh	17	India	15	Togo	8
Brazil	5	Iraq	1		
Burkina Faso	1	Mexico	1		
China	1	Niger	1		
Cuba	1	Pakistan	3		

Table 3. Number of scientific publications, by storage pest, relating to conventional methods of pest control in developing countries retrieved from the CABI Database January 1992 – January 1998.

Pest	Fumigation	Insecticides	Number of Countries	% of papers globally*
Prostephanus truncatus	2	5	3	100
Rhyzopertha dominica	4	10	4	35
Lasioderma serricorne	4	0	3	28
Sitophilus spp	7	23	4	38
Callosobruchus spp.	2	5	4	100
Tribolium spp.	6	33	11	41
Trogoderma granarium	7	2	2	66
Ephestia spp.	0	3	3	27
Sitotroga cerealella	3	7	7	78
Psocoptera	3	1	1	36
Totals	38	89		

* Number of developing-country papers on this species as a % of the total number worldwide recorded on the CABI database

Table 4. Number of scientific publications, by country, relating to conventional methods of pest control in developing countries retrieved from the CABI Database January 1992 – January 1998.

Country	No. public.	Country	No. public
Argentina	4	Indonesia	6
Bangladesh	2	Malaysia	1
Brazil	21	Pakistan	28
China	2	Tanzania	3
Egypt	8	Togo	3
India	41	Zimbabwe	8

The Prospects

Farm storage

For most small-scale farmers, storage has to be a very cheap, low-input activity. Nevertheless, improved protection need not necessarily involve a very large increase in costs Dobie (1984) has given an illustrative example of how traditional farm storage of maize (Figure 1) might be improved through the integration of biological and other means of storage protection (Figure 2). Two suggestions for initial improvements to the traditional system are the choice of a maize variety more resistant to insect pests and the use of a drying crib . The drying crib enables earlier harvesting thus reducing deterioration on the plant. After drying, the grain is shelled and treated with pesticide if storage is to be long-term. Alternatively, the grain could be stored without pesticide treatment in sealed containers, such as metal bins or good-quality mud silos

Farmers in Ghana have moved some way towards these improvements under the guidance of Sasakawa Global 2000, including adoption of a drying crib, originally developed by the International Institute of Tropical Agriculture (IITA), and treatment of the dried grain with pesticide. However, farmers still do not have access to maize with increased resistance to post-harvest damage. Although maize cultivars have been screened for such resistance for some years (Dobie, 1974; Kossou et al., 1993), varieties are not yet available to farmers that would reduce their problems with post-harvest pests. Currently, the International Centre for Maize and Wheat Improvement (CIMMYT) and IITA are both screening maize cultivars for resistance to post-harvest pests and sources of resistance of varying degrees have been identified. Similarly, cowpea cultivars are known with resistance either in the pods or in the pulse but have yet to result in varieties available to farmers with both good agronomic characteristics and resistance to bruchids (Lienard and Seck, 1994). In the future, it may prove possible to develop resistant varieties more rapidly. Gene transfer techniques can offer new opportunities and reduce the efforts involved in plant breeding, while more rapid screening of cultivars for potential insect resistance should be possible through the use of a biomonitor first developed in the USA (Shade et al., 1990) and now undergoing further development at NRI (Devereau, et al. in press). This equipment detects the ultrasonic emissions generated by insect feeding in individual grains. Resistant grains can be identified rapidly as they are associated with reduced feeding rates.

Other biotechnical solutions may also have a role to play Pheromone traps for *P truncatus* have so far been used to detect the presence of the pest and monitor its populations in research studies. However, it is possible that the traps could be used to help extension services determine the risk of *P. truncatus* infestation occurring in particular situations. This is of increasing importance as the pest appears to be becoming more sporadic in its occurrence in Africa. It is believed that initial host selection occurs by chance (Hodges, 1994; Scholz et al., 1997): thus, the probability of maize or dried cassava becoming infested depends upon the flight activity levels of dispersing *P. truncatus*. A study is currently underway in Ghana to test whether flight activity is the major factor determining the probability that undehusked maize cobs and cassava chips stored in open barns become infested. If it proves possible to use traps to predict when stores may be at risk, then extension services will know when and where to target their efforts to control the pest.

Pathogens are also being tested as possible protectants of farm-stored grain The use of the entomopathogenic fungus *Beauveria bassiana* against *Prostephanus truncatus* and *Sitophilus zeamais* is being investigated in Kenya. Several strains of the fungus, capable of killing both species, have been identified, and a dissemination method for the spore is being developed using vegetable fat pellets impregnated with the aggregation pheromone of *P truncatus* High-dose transfer has been achieved and work continues in order to refine the technique.

African farm stores are frequently open structures allowing insects to migrate in and out of store; they are thus potentially more favourable than, say, the bag stores used in large-scale storage, for the application of classical biological control (Markham et al , 1994). An example of a potential control system appropriate to the farmer is given by the tiny wasp *Uscana lariophaga* which is a voracious egg parasite of the bruchid beetle *Callosobruchus maculatus*. It has been suggested that a simple net bag, containing bruchid-infested cowpeas and the parasite, with a mesh size large enough to allow the release of the parasite but small enough to retain the bruchid, could be an ideal means of dispensing the parasite in farmers' cowpea stores (Rees, 1994b). This remains to be tested

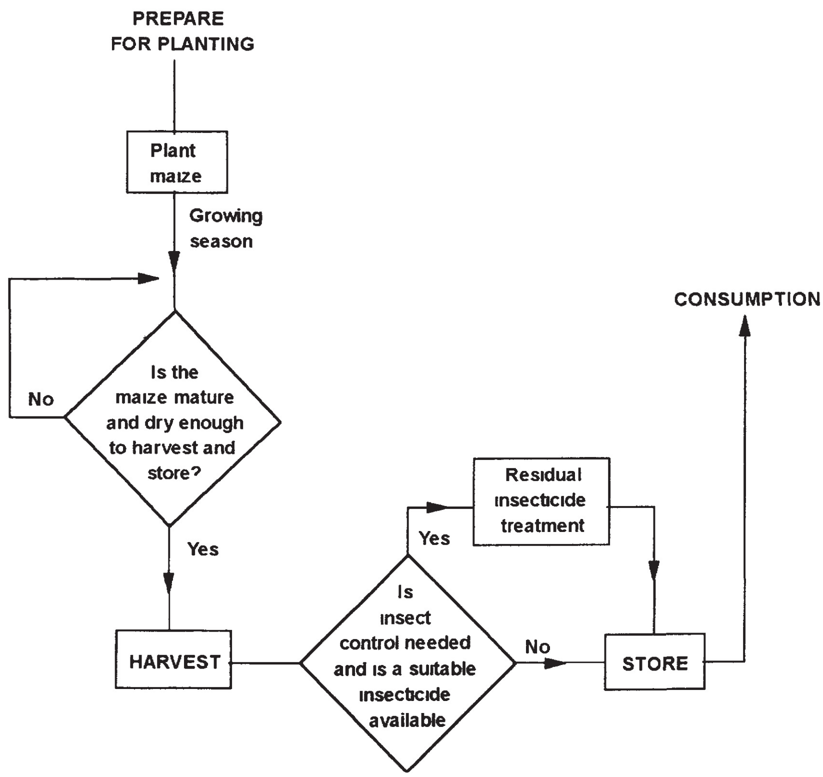

Fig. 1. A common management pattern for the production and on farm-storage of maize in the tropics (from Dobie 1984).

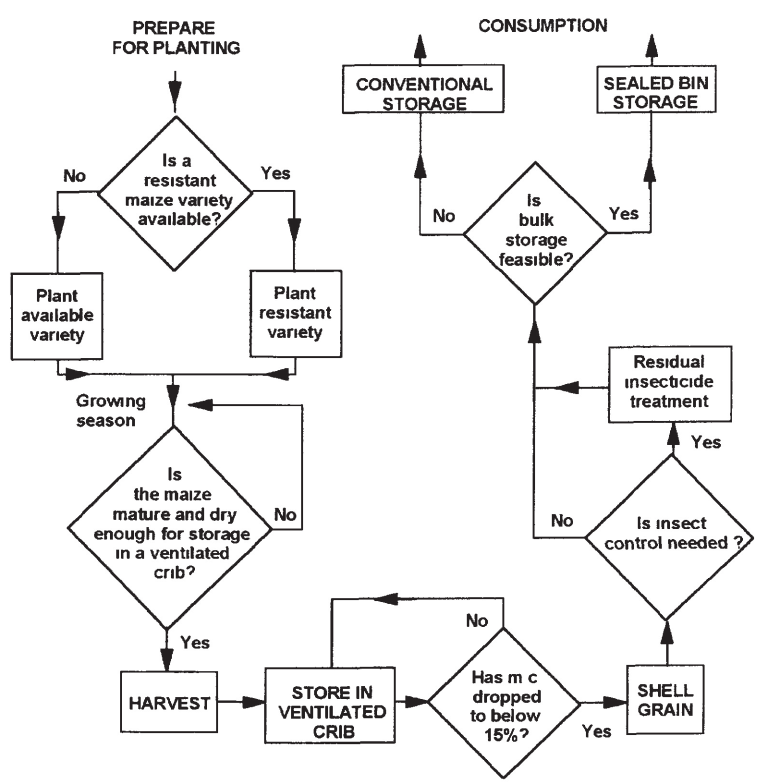

Fig. 2. A modification of the management pattern for the production and on-farm storage of maize in the tropics shown in Figure 1, including alternative options for pest control (from Dobie 1984).

There is one example of the actual application of classical biological control in farm storage: the release of the histerid beetle *T. nigrescens* to control *P truncatus*. The release of this predator in West Africa and speculation on its likely effectiveness were considered in detail during the Canberra Working Conference. Markham et al (1994) pointed out that it is by no means certain that *T nigrescens* will reduce losses caused by *P. truncatus* as, although it is long lived and capable of locating its host by a kairomonal response to the host aggregation pheromone, it develops only slowly and has a low reproductive rate. Releases of the predator have now been undertaken in Togo, Benin, Ghana, Kenya, Malawi and Zambia. Impact studies have been completed in Togo (Richter et al., 1997) and Benin (Borgemeister et al., 1998) where pest and predator populations have been compared by abundance in store and associated grain losses and by the numbers of both species engaged in dispersal as measured by the catch in pheromone traps. In both cases, there is some evidence that the predator is having a positive effect. In Ghana, impact assessment is in progress in 40 villages, in five clusters of release and non-release villages (J. Compton, personal communication). The predator has now spread even to non-release villages and a decline in *P. truncatus* and rise in *T. nigrescens* is shown in about half of the villages with no clear distinction between the release and non-release villages. To date, evidence from on efficacy of *T. nigrescens* is based largely on correlations between decline in *P. truncatus* numbers and rise in numbers of *T nigrescens*. Thus, there is still some uncertainty as to whether *T. nigrescens* is actually the cause of the observed fall in *P. truncatus* numbers or whether this results from other natural means of population regulation that may come into play once the pest has become well established in a new habitat. Whatever evidence there is of its efficacy, *T. nigrescens* has already passed into folklore as there is an African children story extolling its predatory virtues (Farrell, 1998). And it is clear that further release programmes, in new areas invaded by *P truncatus*, will be easy to justify as no negative impact has been observed, the costs of rearing and releasing the predator are low and once released it is capable of sustaining and distributing itself without further human intervention.

Trader and central storage

Trader and large-scale central storage are likely to be broadly similar with respect to the types of biological methods appropriate to their pest management requirements. Both typically use bag storage and Dobie (1984) quotes an example of the integration of biological methods into just such a system (Figure 3). Conventionally, the commodity is protected using an initial fumigation on arrival in store followed by residual insecticide treatment Thereafter, inspection by probe sampling warns of the need for further pest management action. Possible improvements might be to use a pheromone or food-baited trapping system to provide a more timely warning of pest attack (Figure 4). Where pest attack is by beetles, then fumigation is likely to be the most appropriate action if the commodity is to remain in store for a considerable period. If attack is by moths, then control might prove possible by use of pheromones for mating disruption (Hodges et al., 1984; Hagstrum and Davis, 1982; Mafra-Neto and Baker, 1996), application of formulations of *Bacillus thuringiensis* or the release of parasitic wasps

The mass release of predators in stores in developing countries would appear to be more acceptable to consumers than elsewhere in view of the generally higher tolerance of insects in the commodity. Successful mass release of the parasite *Bracon hebetor* against the moths *Ephestia cautella* and *Plodia interpunctella* has been achieved in a sultana store in S. Africa (Urban and Schmidt, 1993). Traditionally, the control of these moth and beetle pests was achieved by using two fumigations per season along with routine surface spraying of stores with contact insecticide and frequent space fogging On a test basis, it has proved possible to limit fumigation to once a season to control beetles, and to rely on mass release of *B. hebetor* to replace the use of surface sprays and space fogging for moth control To manage this system, appropriate traps were used to monitor the populations of beetles, moths and parasites.

Natural biological control, which places reliance on the predators and parasites that would normally be found in association with storage pests, may also offer some prospects The mite *Cheyletus malaccensis* is known as a predator of psocids (Haines, 1995) but is apparently more susceptible to fumigants and residual insecticides than the psocids themselves Adjustment of pest management regimes in favour of this mite may give more cost-effective control of the massive psocid infestations that are common in the humid tropics. One way forward has been demonstrated by investigation of the pesticide susceptibility of various strains of a related predatory mite, *Cheyletus eruditus* In temperate countries, it has been shown that it should be possible to select a more pesticide-tolerant strain and introduce this into stores where the pesticide regime is adjusted to ensure that the predator can be an effective part of an integrated pest management strategy against mite pests (Zdarkova, 1994 and 1997). There may well be potential for a similar approach in tropical climates.

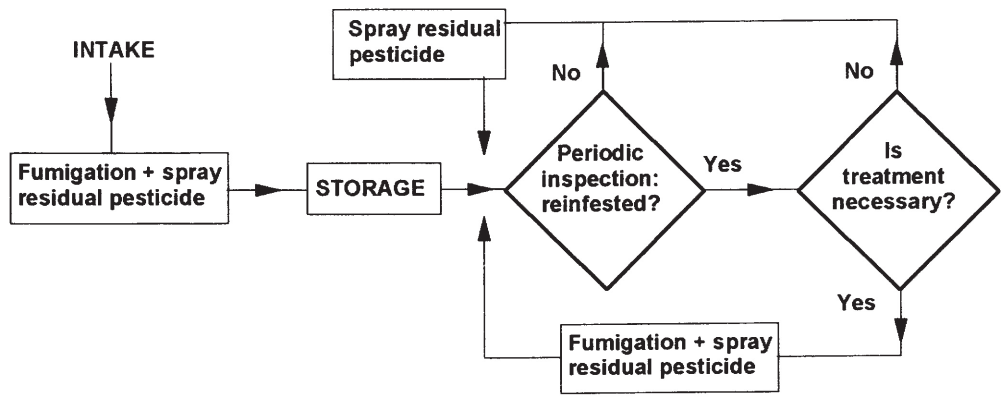

Fig.3. A common management pattern, for the storage of a bagged commodity in a medium or large warehouse, with dependence upon chemical pest control and conventional inspection methods (from Dobie, 1984, with modifications).

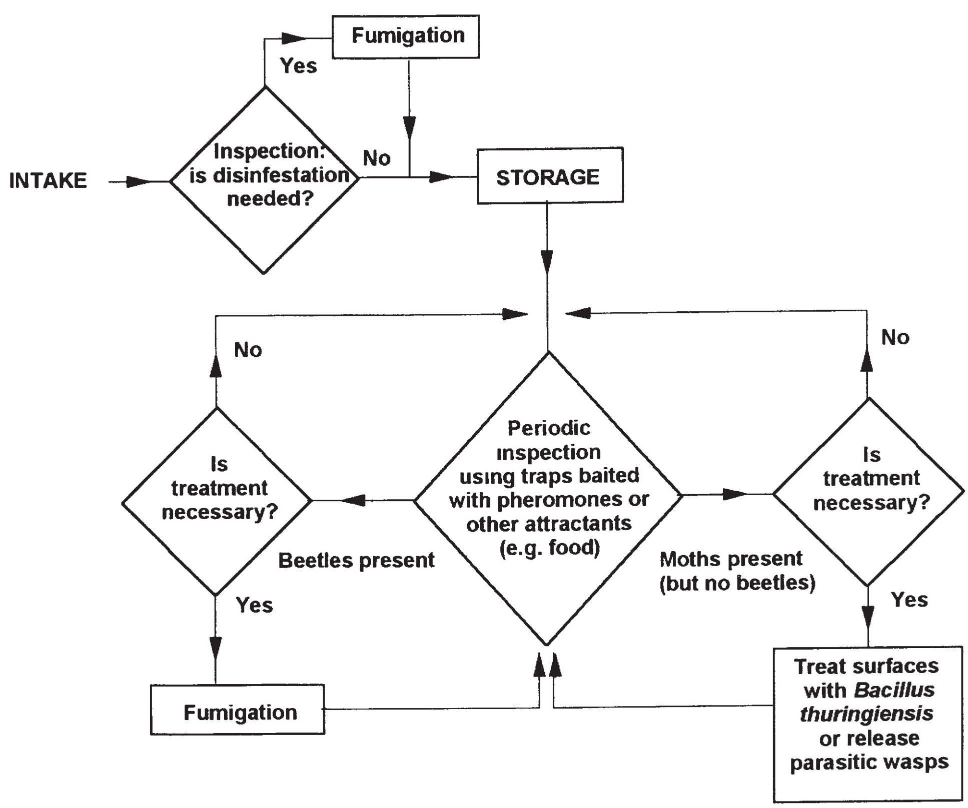

Fig.4. Possible modifications to the management pattern for the storage of bagged grain in a medium or large warehouse shown in Figure 3 (from Dobie 1984 – with modifications).

Whatever pest management techniques are to be employed, a key to their successful use is effective and timely action by pest control staff. In many circumstances the introduction of biological methods will increase the complexity of pest management to the extent that staff will require decision support aids to achieve good pest management Moves have already been made to develop expert systems that can offer control of storage operations, such as the Chinese version of the Australian Pest Man system which is operational in Szechuan, or offer advice on specific pest management problems as they occur in stores, such as the fumigation Decision Support System' developed by the Natural Resources Institute and BULOG for improving the cost efficiency of fumigating milled rice in bag stores (Hodges et al., 1996) Expert systems can also offer simulations to be used for staff-training, such as the training, Work Bench' developed by the Australian Centre for International Agricultural Research and the Indonesian National Logistics Agency (BULOG) (Longstaff, 1997; in press). As a range of control techniques is integrated, decision support systems can be developed further to ensure that cost effective stock protection is achieved.

Training, education and research

In view of the declining role of the old state-run grain enterprises, which generated a body of staff trained in pest management, new approaches are required to give those working in the grain sector the chance to acquire the skills needed to service their market as well as enable them to adopt new approaches and ideas. An important initiative in this respect has been launched by SADC (Southern African Development Community) with support from the European Union. A simple distance learning programme has been prepared by regional bodies, with technical support from the Natural Resources Institute (NRI), for storage management staff working for private grain traders This programme will be available at low cost, about 20 US dollars/student, through local training establishments which will be responsible for tutoring and assessing students. It seems likely that this basic course will be followed by more advanced ones, akin to the annual diploma course in Grain Storage Management currently run at NRI Whilst this might not advance the cause of biological methods in pest management directly, it will maintain the capability that is required for their application Prospects are also improving for the dissemination of information encouraging new approaches and lifting the isolation that surrounds many researchers in developing countries The UN Food and Agriculture Organisation has launched the Information Network on Post Harvest Operations (INP*h*O) (http://www.fao.org/inpho), which will grow in the years to come to enable on-line access to the latest development in post-harvest research while the new on-line magazine the new Agriculturist' (http://www.new-agri.co.uk), which specialises in agriculture in developing countries, provides a suitable forum for addressing the issues on that matter These developments should encourage more interest in research and stimulate the transfer of funds from the investigation of the well-known conventional methodologies to more novel approaches that tackle the environmental, health and efficacy issues that face the storage business.

A Possible Way Forward

The development and introduction of new methodologies requires a critical mass of research which can only be achieved if there is both a desire for change and sufficient investment. Such change could be driven by greater competition and increasing middle class demand for better quality products. In Indonesia, the marketing of premium grade rice through supermarkets has been a response to such demand. Providing goods to a quality-conscious export market can also be an effective stimulus and is particularly evident in the market for horticultural products. However, the institutions in the best position to fund and encourage the development of better pest management systems were the state marketing boards which are now in decline Thus, sources of support for pest management improvements are unfortunately scarce. But they do exist, one good example is the UN Environmental Protection Programme which has been encouraging proposals for the development of pest management methods that can replace methyl bromide. Indeed the prospects for support may be improving as the Technical Advisory Committee of the Consultative Group on International Agricultural Research has resolved that greater weight should be given to the post-harvest parts of the production-consumption continuum (TAC, 1997). Where local organisations want to explore the potential for the development of new post-harvest technologies, in collaboration with an International Agricultural Research Centre, then the costs of this could be met through the small grants fund offered by IDRC (International Development and Research Centre, Canada)

Establishing the technical feasibility of biological methods is the province of researchers and the options on offer will depend largely on research activities in those countries where there is sufficient investment by private and public institutions. The same has been true with the development of conventional insecticides and fumigants. Many of the options for biological control methods have already been identified; what is now required are attempts to adapt them to the needs of developing countries For institutions wishing to achieve improvements in pest management a general framework, prepared with developing countries in mind, is shown in Figure 5 (adapted from Hindmarsh and McFarlane, 1983) The way forward is a step-by-step approach. The primary objective of any improvement has to be established in relation to the commodity and its market. It is quite clear that this needs both technical and socio-economic appraisal (first two steps, Figure 5), these are well within the capability of the staff of academic and technical institutions in developing countries To date, there is no rigorous set of instructions on the best means to approach this appraisal, although members of the Group for Assistance on Systems relating to Grain After-harvest (GASGA) are currently engaged in preparing guidelines for post-harvest systems analysis which should prove helpful in this respect (GASGA, 1996) Another approach could be to use HACCP (Hazard Analysis Critical Control Point), this is a structured system for identifying where interventions are required to ensure that quality objectives are met (Knight and McHale, 1996)

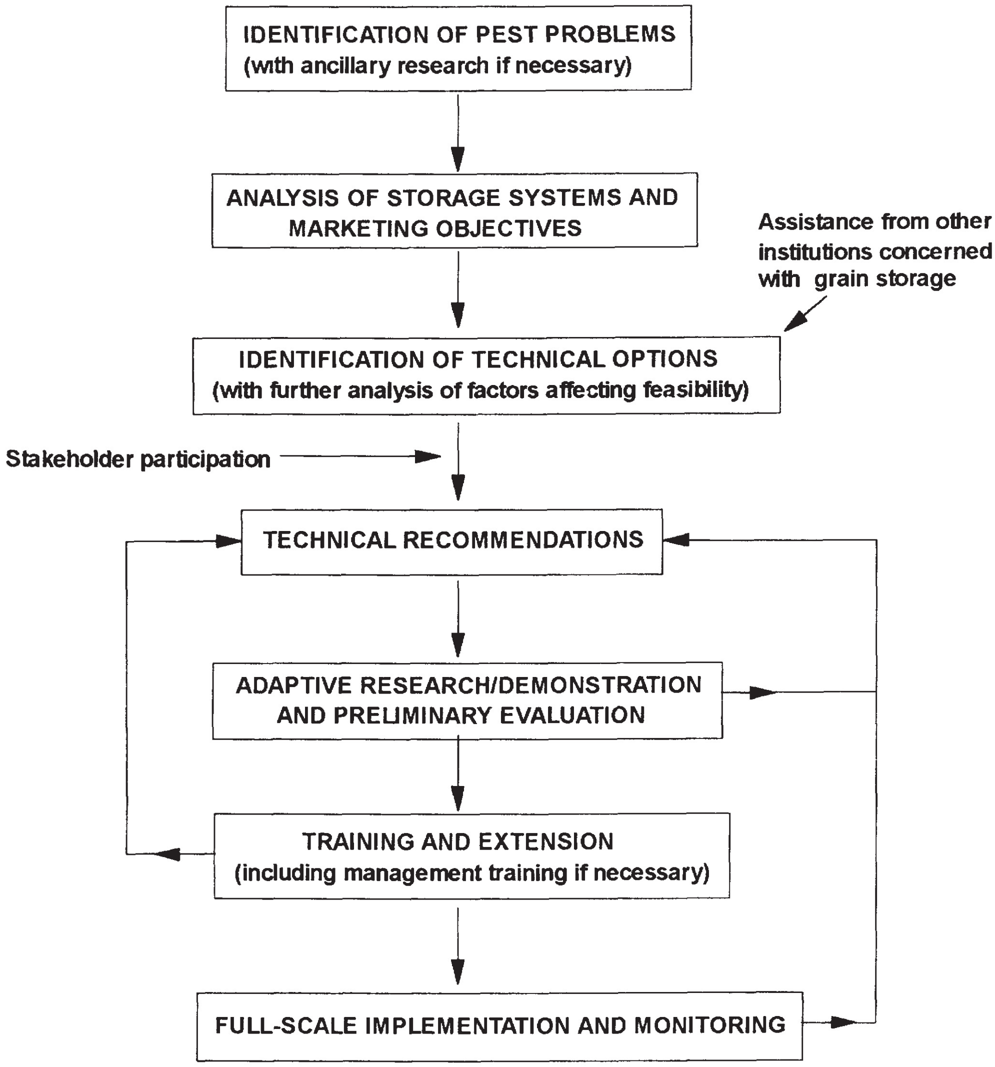

Fig.5. A stepwise approach to the development of pest management improvements. Modified from Hindmarsh and McFarlane (1983).

The third step, identifying pest management (technical) options, is more difficult and in many cases would require forging a link with one of several technical institutions around the world which offer grain-storage advice. However, before these options are proposed as changes to the current system there should be stakeholder consultation. Participatory methods have an important part to play here and Boxall et al (1997) have given some consideration of how this might be achieved in relation to improvements in farm grain storage. Similar approaches would be equally relevant in larger-scale storage systems. The ideal outcome would be well thought-out recommendations to test options that meet the objectives of the storage system through the integration of biological methods into pest management. Indications of some possible technical options were reviewed in the section describing prospects for biological methods. However, whatever possible solutions are identified, considerable adaptive research may be required to enable them to meet the needs of the pest complex, storage practice and marketing objectives for a particular commodity. Actually implementing these recommendations, in the form of adaptive research or a demonstration (Step 5) coupled with an evaluation, is likely to be a significant hurdle since, in many cases, the only opportunities to attract the necessary investment will be from external sources. If this step can be achieved, then a positive outcome to the evaluation will lead to appropriatetraining for staff and a successful implementation of the new technique (Step 7).

It may sound as if progress toward pest management innovations is complex and difficult This may not always be the case. External technical support and external funding are certainly not prerequisites for the adoption of new grain storage technology in developing countries A private enterprise in Zimbabwe, the Four Seasons Company, has developed a sealed storage system flushed with carbon dioxide for the preservation of its grain products Such initiatives may become increasingly common as old pest control measures are regarded as ineffective and/or environmentally unacceptable, and improved market conditions provide incentives for change

Acknowledgement

A number of colleagues have given help and advice in the preparation of this manuscript, I would particularly like to thank Prof Chris Haines and Drs Pete Golob, Steve Belmain and Lucy Birkinshaw.

References

Borgemeister, C , Djossou F., Adda, C., Schneider, H., Djomamou, B , Degbey, P., Azoma, B , and Markham, R. H 1997 Establishment, spread, and impact of *Teretriosoma nigrescens* (Coleoptera: Histeridae), an exotic predator of the Larger Grain Borer (Coleoptera: Bostrichidae) in southwestern Benin. Entomological Society of America, 26 (60), 1405 – 1415.

Boxall R., Golob P , and Taylor R. 1997 Pest management in farm granaries. Chatham, UK: Natural Resources Institute. 57

Brower, J.H., Smith, L , Vail, P.V., and Flinn, P.W 1996. Biological control In: Subramanyam, B , and Hagstrum, D.W., ed., Integrated Management of Insects in Stored Products pp 223 – 286. Marcel Dekker. New York

Coulter J , and Compton, J.A.F. 1991. Liberalisation of cereal marketing in sub-Saharan Africa: implementation issues. NRI Marketing Series, No. 1. Natural Resources Institute, Chatham, UK. iv +26 pp

Dales, M.J. 1996 A review of plant materials used for controlling insect pests of stored products. NRI Bulletin 65, Chatham, UK: Natural Resources Institute, pp 84.

Devereau, A., Credland, P., Appleby, J. and Jackai, L. (in press). Rapid screening of grain for insect resistance. Proceedings of the 7th International Working Conference on Stored Products Protection, Beijing, 14 – 19 October 1998.

Dobie, P 1974. The laboratory assessment of the inherent susceptibility of maize varieties to post harvest infestation by *Sitophilus zeamais* Motsch. (Coleoptera, Curculionidae) Journal of Stored Products Research, 10, 183 – 197.

Dobie, P 1984. Biological methods for the integrated control of insects and mites in tropical stored products. Tropical Stored Products Information, 48, 21 – 25

Ecobichon, D. J , and Joy, R. 1993. Pesticides and neurological diseases. 2nd edition. CRC Press.

Farrell, T. 1998. Dudus Cricket, 25 (6), 36 – 40.

GASGA 1996. Systems approach in post-harvest activities Proceedings of GASGA Executive seminar No. 8. Montpellier, France, 12 – 13 June 1996. GTZ, PO Box 5180, 65726 Eschborn, Germany, 40

Gudrups, I. 1996. Surface spraying in tropical warehouses: is it worthwhile? International Pest Control, 38, 58 – 60

Hagstrum, D. W , and Davis, L. R. 1982. Mate seeking behaviour and reduced mating by *Ephestia cautella* (Walker) in sex pheromone permeated atmosphere. Journal of Chemical Ecology, 8, 507 – 515

Haines, C.P. 1995. Grain storage in the tropics. In: Jayas, D.S , White, N.D.G., and Muir, W E., ed., Stored grain ecosystems. pp 55 – 99 Marcel Dekker, New York.

Hindmarsh, P S., and McFarlane, J A. 1983. A programmed approach to food storage improvements. Tropical Stored Products Information, 46, 3 – 9.

Ho, S. H , and Winks R G 1995. The response of *Liposcelis bostrychophila* Badonnel and *L entomophila* (Enderlein) (Psocoptera) to phosphine. Journal of Stored Products Research, 31 (3), 191 – 198.

Hodges, R. J 1994. Recent advances in the biology and control of *Prostephanus truncatus*. In: Highley, E., Wright, E. J , Banks, H. J and Champ, B. R., eds., Proceedings of the Sixth International Working Conference on Stored Products Protection. Canberra, Australia, 17 – 23 April, 1994. Volume 2, 929 – 934.

Hodges, R.J., Benton, F., Hall, D.R., and dos Santos Serodio 1984. Control of *Ephestia cautella* (Walker) by synthetic sex pheromones in the laboratory and store Journal of Stored Products Research, 20 (4), 191 – 197

Hodges, R J , Sidik, M., Halid, H., and Conway, J.A. 1992. Cost efficiency of respraying store surfaces with insecticide to protect bagged milled rice from insect attack. Tropical Pest Management, 38(4), 391 – 397.

Hodges, R.J., Smith, M , Madden, A., Russell, D., Gudrups I., and Halid, H. 1996. Development of a decision support system for the fumigation of milled rice bag-stacks in the tropics. In: Donahaye, E.J., Navarro, S., and Varnava, A., eds., Proceedings of the Controlled Atmosphere and Fumigation Conference, Nicosia, Cyprus, 22 – 26 April 1996 425 – 434.

Knight C , and McHale C. 1996. Assured crop production – A practical guide to developing a quality management system for primary food production. Campden and Chorleywood Food Research Association, Guideline No. 10., Chipping Campden, Gloucestershire, GL55 6LD, UK. 65.

Kosso, D.K., Mareck, J H , and Bosque-Perez, N A. 1993. Comparison of improved and local maize varieties in the Republic of Benin with emphasis on susceptibility to *Sitophilus zeamais* Motschulsky Journal of Stored

Products Research, 29 (4), 333 – 343

Lienard, V , and Seck, D. 1994. Revue des methodes de lutte contre *Callosobruchus maculatus* (F) (Coleoptera: Bruchidae) ravageur des graines niebe *Vigna unguiculata* (L.) en Afrique tropicale. Insect Science and its Application, 15(3), 301 – 311.

Longstaff, B.C. 1997. Decision tools for grain storage pest management. Journal of Stored Products Research, 33 (2), 99 – 114.

Longstaff, B. C. in press Decision support tools for managing pests in grain stores. In: Grain Quality from the Inside Out. GASGA Executive Seminar No. 9, Canberra Australia 16 – 17 September 1997.

Markham, R. H., Borgemeister, C , and Meikle, W. G. 1994. Can biological control resolve the larger grain borer crisis? In: Highley, E., Wright, E.J., Banks, H.J. and Champ, B.R., eds , Proceedings of the 6th International Working Conference on Stored Products Protection, Canberra, Australia, 17 – 23 April 1994. Volume 2, 1087 – 1097.

Mafra-Neto, A., and Baker, T C 1996. Timed, metered sprays of pheromone disrupt mating of *Cadra cautella* (Lepidoptera: Pyralidae). Journal of Agricultural Entomology 13 (2), 149 – 168.

Nataredja, Y , and Hodges, R J. 1989. Commercial experience of sealed storage of stacks in Indonesia. In: Champ, B R., Highley, E , and Bank, H. J., eds , Fumigation and Controlled Atmosphere Storage of Grain. ACIAR Proceedings No 25, Canberra, 197 – 202.

Phillips T W. 1997. Semiochemicals of stored-products: research and application. Journal of Stored Products Research 33 (1), 17 – 30

Pike, V. 1994 Laboratory assessment of the efficacy of phosphine and methyl bromide fumigation against all life stages of *Liposcelis entomophila* (Enderlein). Crop Protection, 13 (2), 141 – 146

Rees, D P 1994a Distribution and status of Psocoptera infesting stored products in Australia. In: Highley, E., Wright, E J., Banks, H. J. and Champ, B R , eds., Proceedings of the 6th International Working Conference on Stored Products Protection, Canberra, Australia, 17 – 23 April 1994 Volume 1, 583 – 587.

Rees, D.P 1994b Biological Control – Session Summary. In: Highley, E , Wright, E.J., Banks, H J. and Champ, B.R., eds., Proceedings of the 6th International Working Conference on Stored Products Protection, Canberra, Australia, 17 – 23 April 1994. Volume 1, 1165.

Richter, J., Biliwa, A., Helbig, J., and Henning-Helbig 1997. Impact of *Teretriosoma nigrescens* Lewis (Coleoptera: Histeridae) on *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) and losses in traditional maize stores in southern Togo. Journal of Stored Products Research, 33 (2), 137 – 142.

Roesli, R 1996 Population dynamics and management of *Liposcelis* spp. PhD Thesis, James Cook University of Northern Queensland. 281 pp

Santoso, T., Sunjaya, Dharmaputra, O S., Halid, H., and Hodges, R.J. 1996. Pest management of psocids in milled rice stores in the humid tropics. International Journal of Pest Management, 42 (3), 189 – 197.

Schöler, M., Prozell, S., Al-Kirshi and Reichmuth, Ch 1997 Towards biological control as a major component of integrated pest management in stored products protection. Journal of Stored Products Research, 33 (1) 81 – 97.

Shade, R E., Furgason, E S., and Murdock, L.L. 1990. Detection of hidden insect infestations by feeding-generated ultrasonic signals. American Entomologist 36 (3), 231 – 234

Scholz, D., Tchabi, A , Borgemeister, C., Markham, R. H., Poehling, H.-M , and Lawson, A 1997b Host-finding behaviour of *Prostephanus truncatus* (Horn) (Col.,Bostrichidae): primary attraction or random attack? Journal of Applied Entomology, 121, 261 – 269.

Taylor, R.W.D. 1989 Phosphine – A major fumigant at risk. International Pest Control, 31 (1), 10 – 14.

TAC 1997. Harvest and postharvest problems in agriculture, forestry and fisheries – The CGIAR contribution to research TAC Secretariat, Food and Agriculture Organization of the United Nations. pp 23.

Taylor, R.W.D. 1994 Methyl bromide, is there any future for this noteworthy fumigant? Journal of Stored Products Research, 30 (4), 253 – 260.

Urban, A., and Schmidt, H. 1993. Moth pests controlled biologically Plant Protection News, 31, 8 – 9 (In Afrikaans)

Zdarkova, E. 1994 The effectiveness of organophosphate acaricides on stored product mites interacting in biological control. Experimental and Applied Acarology, 18, 747 – 751.

Zdarkova, E. 1997. The susceptibility of different strains of *Cheyletus eruditus* (Acarina: Cheylidae) to organophosphate acaricides. Experimental and Applied Acarology, 21, 259 – 264