



Review

Grain Protectants: Current Status and Prospects for the Future

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Abstract—Since the 1960s grain protectants have been used as a primary means of insect pest management in bulk storages, especially in countries which store large amounts of grain for domestic food production and export trade. With the increasing costs of development and registration of insecticides, the number of available protectants has begun to decrease, a trend that will no doubt continue. Furthermore, there are several biological, economic and sociological influences that are causing a gradual shift from chemical-based pest management to integrated pest management utilizing computer-based decision support systems. This paper will discuss several factors in terms of their potential impact on the use of conventional grain protectants, including insecticide residues and consumer perceptions, resistance to protectants in major pest species, the direct and indirect costs of insecticides, development and registration of biopesticides, inert dusts, new technologies for fumigation and controlled atmosphere treatments, the expanded use of aeration in management programs, biological controls, and the development of expert systems. In this paper the term 'grain protectants' will be used to refer to only organophosphorus, pyrethroid, or carbamate insecticides that are applied directly to grain for residual control.

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INTRODUCTION

Since the 1960s residual grain protectants, chiefly organophosphorus, pyrethroid and carbamate insecticides have been employed on a world-wide basis in management programs for insect pest control in stored raw agricultural commodities. Protectants are usually applied when commodities are loaded into storage, and residues from this single application are expected to protect grain throughout the storage interval. Protectants are used primarily in areas where environmental or economic considerations limit the use of alternative control strategies. Snelson (1987) published a detailed monograph which reviewed individual protectant insecticides and gave literature citations regarding performance and efficacy.

Alternatives to conventional chemical pesticides are being advocated in many agricultural ecosystems, including the post-harvest arena. Biological controls, mechanical cooling through low-volume aeration and other forms of temperature manipulation, microbial pathogens, insect growth regulators, plant extracts, and inert dusts are receiving increased attention and research for use in storage environments. There are questions regarding the compatibility of preventative protectants with modern pest management programs which emphasize monitoring and detection to determine if insect populations are present, and if these infestation levels require controls to prevent economic damage.

The importance of conventional protectant chemicals in management programs for stored raw grains will probably decrease as we approach the next century. There are a number of biological, economic, and sociological factors that will contribute to this decline. The purpose of this paper is not to present an in-depth discussion of each available alternative to conventional grain

protectants, but to identify some key issues and discuss how these issues could contribute to a reduction in the scope and application of grain protectants on stored commodities. In this paper I will use 'grain protectants' to refer only to traditional organophosphorus, pyrethroid, and carbamate insecticides that leave a residue on the grain.

INSECTICIDE RESIDUES IN FOODS AND CONSUMER PERCEPTIONS

Although national authorities within specific countries and international organizations, such as the World Health Organization and the Codex Committee on Pesticide Residues, establish safe residue limits and tolerances for insecticides, one of the most explosive and argumentative issues affecting agricultural production in industrialized countries is the perception that pesticide residues in the food supply constitute a serious health risk (Macht, 1994; Laliberte, 1995). These assertions are countered by arguments that pesticides enhance and maintain the safety of the food supply, and furthermore the actual amounts of any residues are inconsequential and there is little scientific evidence of risk (Acuff, 1993; South, 1993). Results of market surveys consistently indicate that consumers believe pesticide residues in food are a problem (Jolly *et al.*, 1989; Beall *et al.*, 1991; Bryne *et al.*, 1994), and they are willing to pay higher prices for foods that can be certified as residue-free as long as there is no detectable loss in quality (Ott, 1990; Brewer *et al.*, 1994).

If these trends regarding the negative attitude of consumers toward residues in foods continue they could impact the use of protectants on grains by influencing standards set by importing countries. Most of the insecticidal residue from protectant applications is removed when raw commodities are milled, and do not present a problem in finished goods. However, this fact may be of little consequence if domestic and international food processors respond to current consumer demands by specifically stating that they will not accept grain treated with a chemical pesticide that leaves a residue on the grain.

RESISTANCE TO PROTECTANTS IN MAJOR PEST SPECIES

The development of insecticide resistance is a constant concern in post-harvest ecosystems. Malathion resistance has been extensively documented for many important stored-product insect pests throughout the world (Subramanyam and Hagstrum, 1995). In the United States there is widespread geographic resistance to malathion among populations of *Tribolium castaneum* (Herbst) (Zettler, 1974, 1975, 1982, 1991; Bansode and Campbell, 1979; Haliscak and Beeman, 1983; Horton, 1984; Halliday *et al.*, 1988; Subramanyam and Harein, 1990; Arthur and Zettler, 1991). Isolated incidences of resistance have been reported for *Rhyzopertha dominica* (F.) (Haliscak and Beeman, 1983; Zettler and Cuperus, 1990), *Sitophilus* spp. (Haliscak and Beeman, 1983), and *Typhaea stercorea* (L.) (Wienzierl and Porter, 1990). In Australia and Great Britain, populations of *Oryzaephilus surinamensis* (L.), *R. dominica*, *T. castaneum*, and *T. confusum* (du Val) are resistant to malathion (Muggleton, 1987; Herron, 1990; Muggleton *et al.*, 1991). Resistance is present in populations of *Plodia interpunctella* (Hübner) in the United States (Beeman *et al.*, 1982; Zettler, 1982; Sumner *et al.*, 1988; Arthur *et al.*, 1988) and Australia (Attia *et al.*, 1979).

Beetle species are developing resistance to other organophosphorus grain protectants. In the United States, populations of *R. dominica* in the state of Oklahoma have developed resistance to chlorpyrifos-methyl (Zettler and Cuperus, 1990; Arthur, 1992). However, only isolated incidences of resistance have been reported from other areas of the country (Subramanyam *et al.*, 1989; Beeman and Wright, 1990). In Australia, *O. surinamensis* has developed resistance to chlorpyrifos-methyl, fenitrothion, and pirimiphos-methyl (Herron, 1990; Collins *et al.*, 1993), while in Great Britain *O. surinamensis* has developed resistance to methacrifos and etrimfos in addition to chlorpyrifos-methyl, fenitrothion, and pirimiphos-methyl (Muggleton *et al.*, 1991). *R. dominica* populations from central storages in Australia are developing resistance to bioresmethrin (Collins *et al.*, 1993). Insecticide resistance could lead to the elimination of some protectants from management programs, and if alternative protectants are not registered and available, other control options would be implemented.

DIRECT AND INDIRECT COSTS OF INSECTICIDES

The increasing costs of research, development and legal registration of conventional pesticides in developed countries will limit the availability of new compounds for all agricultural uses, including stored products. The process of registration in the United States may require 8–12 years and a capital cost of 40 to 80 million U.S. dollars (Lethbridge, 1989; Woodhead *et al.*, 1990). Also, any chemical registered before 1986 (such as malathion) must be reregistered under the same process. These registration costs are prohibitive for many agricultural systems, because any product that is registered or re-registered must generate a tremendous volume of annual sales to recover these costs. It seems unlikely that many new registrations for protectants will be pursued because of the limited economic market in post-harvest systems as compared to agricultural field crops or the urban pest control market. Desmarchelier (1994) presents a discussion of the regulatory process and the associated costs, and outlines several possibilities for reducing these costs.

Although there are obvious benefits provided by agricultural insecticides, including those used as protectants, there are indirect costs that must also be considered (Pimentel *et al.*, 1991, 1992). Pesticide poisonings resulting in sickness or death are relatively rare in post-harvest systems, but when they occur the costs associated with the event can be significant. Long-term chronic exposure to organophosphate residues may cause neurological problems (Ecobichon *et al.*, 1990). The development of resistance in insect pests associated with raw commodities often results in additional applications being required to control the target pest or replacement with alternative protectants, which will increase costs. Many countries are developing programs and action plans to reduce all pesticide usage by 50% (Pimentel *et al.*, 1993; Matteson, 1995). Although many of the negative effects of pesticides may be more of a problem in field crops than in stored grains, these general trends toward pesticide reductions will affect the availability of residual grain protectants.

DEVELOPMENT AND REGISTRATION OF BIOPESTICIDES

Biopesticides can include viral and fungal pathogens, insect growth regulators, and natural plant products. Consistent with the transition from pesticidal chemicals to integrated control, many agricultural chemical companies have increased funding for microbial research to complement their existing agrochemical divisions (Woodhead *et al.*, 1990). There has been an effort on the part of the U.S. Environmental Protection Agency to accelerate registration of biopesticides by simplifying requirements and reducing the amount of toxicological data required for registration as compared to data requirements for conventional pesticides (Plimmer, 1993). The costs of bringing a biological pesticide to market in the United States are estimated at 2 to 3 million U.S. dollars compared to 40 to 80 million U.S. dollars for a conventional pesticide (Lethbridge, 1989; Woodhead *et al.*, 1990), while in many other countries the regulatory process is similar for conventional pesticides and biopesticides (Rodgers, 1993). In general there is considerable potential for the development of microbial products and the expansion of biopesticides for stored grain in most developed countries.

Currently the majority of biopesticide sales are those products which contain *Bacillus thuringiensis* (*B.t.*) as the active agent (Rodgers, 1993). One formulation is registered in the United States to control lepidopteran pests of stored grains but there are no products to control coleopteran pests in the same environment, which limits the use of *B.t.* products because of the significance of beetle pests in stored grains. In addition, some moth species, including *Plodia interpunctella*, can develop resistance to *B.t.* (McGaughey, 1985; McGaughey and Beeman, 1988; McGaughey and Johnson, 1992).

There are many published reports concerning the efficacy of insect growth regulators as grain protectants. Methoprene is marketed in the United States but is primarily used in tobacco storages. Formulations were available for grains and oilseeds but were considerably more expensive than conventional protectants. However, in Australia methoprene is used at a reduced rate in combination with organophosphorus compounds to control strains of *R. dominica* that are resistant to pyrethroids (Daglish *et al.*, 1995). Additional growth regulators may be available in the future, but if they are not cost-effective they will not be used on a widespread basis and will be limited to speciality situations.

Natural plant extracts are used in many developing countries to control insect pests in small-farm

storages because economic conditions do not justify conventional protectants (Niber, 1994). There appears to be an increasing emphasis on research with natural products as different extracts are being evaluated for insecticidal efficacy. For example, from January 1990 to April 1995 15 papers were published in the *Journal of Stored Products Research* on the subject of conventional protectants and 21 papers were published on research with natural products. Most of these trials with natural products were conducted in African and Asian countries. Trials conducted in Europe or the Americas are usually based on plant derivatives of African or Asian origin, and the research is conducted to benefit storage systems in the countries from which the plants were imported. One published report gives the results of a study conducted in France with the intention of benefiting farmers in that country (Regnault-Roger and Hamraoui, 1993). While products derived from plant extracts are not likely to replace existing protectants in developed countries, there may be increased opportunities for using natural products for specific small markets.

INERT DUSTS

There is a considerable amount of historical data concerning desiccant dusts and their insecticidal effects on stored-product insects (Subramanyam *et al.*, 1994). Most of these early formulations were not widely accepted by the grain industries in developed countries for a variety of reasons including the high rates required for mortality, variation in toxicity among target species, damage to grain handling equipment, and health problems with worker exposure to dusts. With the current concerns of protectant resistance and the desire of consumers for residue-free grain, these dusts are receiving increased attention.

New formulations of inert dusts have been developed that are more efficacious than the older products. Research studies in several countries have shown that silica aerogels control a variety of insect species (Le Patourel, 1986; Desmarchelier and Dines, 1987; White and Loschiavo, 1989; Aldryhim, 1991, 1993). A new formulation of diatomaceous earth is also effective as a grain treatment (Subramanyam *et al.*, 1994). Although these new formulations can potentially cause a dust problem in grain, there are markets for increased use, particularly in speciality situations where residue-free grain is required.

NEW TECHNOLOGIES FOR FUMIGATION AND CONTROLLED ATMOSPHERE TREATMENTS

Phosphine is the primary fumigant used to control insects in on-farm and commercial storages throughout the world, and much of the current research involves new methods and technologies for improved efficacy. Scattered publications of these studies appear in the standard international entomological journals. However, the Proceedings of several recent international conferences, including the 5th and 6th International Working Conferences on Stored-Product Protection, Bordeaux, France, 1990 and Canberra, Australia, 1994, the International Conference on Controlled Atmosphere and Fumigation in Grain Storages held in Winnipeg, Canada, 1992 and the recent International Conference on Controlled Atmosphere and Fumigation in Stored Products held in Nicosia, Cyprus, 1996, contain numerous research reports on new technologies. These new techniques and modifications include, but are not limited to, improved methods for sealing (Andrews *et al.*, 1994), recirculation and recycling systems for improved distribution and emission control (Winks, 1993; Noyes and Kenkel, 1994), and new formulations for the controlled release of phosphine (Waterford *et al.*, 1994).

The insecticidal effects of modified atmospheres, principally the use of high concentrations of CO₂ or N₂ to create an oxygen-deficient environment, have been well-documented in the scientific literature. The proceedings of the international conferences cited also contain many papers on research with modified atmospheres. The structural modifications described for phosphine application can also be adapted for use with modified atmospheres. The addition of carbon dioxide can enhance the toxicity of phosphine and improve penetration within the grain mass (Ren *et al.*, 1994). Hermetic sealing has been utilized in traditional agriculture for centuries; strategies for modern pest management are reviewed and presented by Navarro *et al.* (1994). Biogenesis of

CO₂ could expand the use of modified atmospheres in small-scale storages, especially in developing countries (Paster *et al.*, 1990, 1991).

New application techniques and methodologies for improved efficacy of phosphine fumigation, and the use of modified atmospheres could effectively lower the economic costs of these treatments, which could in turn decrease applications of grain protectants. Recirculation systems could enable fumigations in structures that could not be effectively sealed by conventional means. Fumigation and controlled atmospheres may be more compatible than grain protectants for use in modern grain management, because treatment decisions could be based on estimates of insect density provided by a monitoring program. The sociological problems associated with pesticide residues may be reduced by substituting fumigants or controlled atmosphere treatments for a grain protectant.

EXPANDED USE OF AERATION IN MANAGEMENT PROGRAMS

Cooling stored wheat by low-volume aeration is used in northern Europe (Armitage and Llewelin, 1987; Lasseran and Fleurat-Lessard, 1991; Armitage *et al.*, 1994), Canada (Metzger and Muir, 1983), the midwestern United States (Cuperus *et al.*, 1986, 1990; Gardner *et al.*, 1988), Australia (Ghaly, 1984), and Israel (Navarro *et al.*, 1969; Navarro and Calderon, 1982). Most aeration studies have been conducted on wheat, which is usually binned and stored during the summer. Because the crop is susceptible to insect infestations before the onset of cooler weather, chemical controls are often required. Aeration may potentially reduce protectant applications on fall-harvested crops such as corn and sorghum because the cooling process can be initiated when the commodity is binned. Recent studies show benefits of aeration in management programs for corn stored in Georgia, which is a leading producer of corn in the southeastern United States (Arthur, 1994; Arthur and Throne, 1994; Arthur and Johnson, 1995).

In most aeration programs the grain is initially cooled to seed dry-bulb temperatures of 15–18°C, which are the approximate lower developmental temperatures for most stored-product insects (Howe, 1965; Evans, 1987). If stored grains are cooled to wet-bulb temperature, instead of dry-bulb temperature, minimum developmental temperatures are effectively increased because of the interactions between temperature and moisture content (Desmarchelier, 1988). Dry grain does not have to be cooled as much as wet grain to achieve the same degree of insect control (Desmarchelier, 1991; Wilson and Desmarchelier, 1994). As the moisture content of the grain decreases, the threshold temperatures required to limit population growth can be increased. This would allow increased utilization of aeration in warm dry climates (Wilson and Desmarchelier, 1994).

Refrigerated aeration systems that chill ambient air and force this air through the storage system have been experimentally tested in a number of studies during the past 30–40 years (Burrell, 1982; Evans, 1983). These systems are currently receiving increased attention for use on stored grains (Maier *et al.*, 1992; Mason *et al.*, 1994). Maier (1994) reviewed the historical development of chilled aeration in the United States, described tests conducted on a variety of stored commodities in different geographic regions, referenced studies conducted in other countries, and predicted increased utilization of this technique. One barrier to the inclusion of chilled aeration in management programs is the capital expense required for the equipment and the apparent cost of treatment (Longstaff, 1994a). However, if economic and social conditions justify the cost, chilled aeration could replace protectants in some situations.

INCREASED EMPHASIS ON BIOLOGICAL CONTROLS

In all agricultural systems there are renewed efforts to develop and refine biological control agents for inclusion in pest management programs and thereby reduce chemical inputs. Bibliographic citations of research and reviews on the potential of biological controls in post-harvest systems can be found in several publications (Arbogast, 1984; Brower, 1990; Brower *et al.*, 1995). However, most of the research reports are life history studies on particular beneficial species, population modelling and computer simulations, or small-scale laboratory tests. Brower *et al.*

(1995) also summarize the various beneficial species that have been investigated for use on stored grain insects.

There are relatively few published reports of field studies that document suppression of pest populations by biological controls. In a single unreplicated trial, Keever *et al.* (1985) reported that an inundative release of *Habrabracon hebitor* (Say) reduced *Plodia interpunctella* and *Cadra cautella* (Walker) populations in stored peanuts, as compared to peanuts treated with malathion. In two other field trials, one on stored sorghum (Parker and Nilakhe, 1990) and one on stored rice (Brower *et al.*, 1995), biological controls did not prevent economic damage, partly due to the migration of pest species into the experimental bins. Recently the predatory beetle *Teretriosoma nigrescens* (Lewis) has been introduced into west Africa to control *Prostephanus truncatus* (Horn), with moderate success (Markham *et al.*, 1994). Validation studies will be necessary to fully determine the potential for biological controls as replacements for insecticidal protectants, and currently such data are lacking for most grain storage systems throughout the world.

The negative effects of agricultural pesticides on natural control agents is often cited to support the development of alternatives to chemical controls. The impact of pesticides on natural enemies and the resulting outbreaks of secondary arthropod pests has been documented in many field agricultural systems (Croft, 1990). There are many review articles summarizing the interactions between chemical pesticides and beneficial organisms; a partial listing can be found in Baker and Weaver (1993). The presence of residues on grains in storage will alter faunal composition in those systems (White *et al.*, 1986). White and Sinha (1990) report that when chlorpyrifos-methyl was applied to oats, several predatory mite species were virtually eliminated while prey mites were unaffected. Two years later the ecosystem equilibrated with reduced predator diversity. In a similar test with pirimiphos-methyl on stored wheat, arthropod populations were lower in treated wheat than in untreated wheat except for a single mite species, and the arthropod community had not re-established 24 months after the insecticide treatment (White *et al.*, 1994).

Biological controls are not normally considered to be compatible with protectants. However, there is potential to select for insecticide resistance in certain parasitic and predatory species (Baker, 1994, 1995; Baker and Arbogast, 1995). Economic considerations will probably limit the application of biological controls in many storage systems. However, as additional research is conducted and new data are available, new possibilities will arise for specific situations.

DEVELOPMENT AND MARKETING OF EXPERT SYSTEMS

Good integrated control programs are based on reliable methods for estimating insect population levels to determine if control measures are warranted. Probe traps and pitfall traps are more efficient than trier samples for detecting insects in stored grain (White *et al.*, 1991). Computer-based decision support systems that use biological and environmental data to predict population trends and evaluate the need for insecticidal inputs have been developed for stored-product storage systems in several countries (Flinn and Hagstrum, 1990; Wilkin *et al.*, 1991; Jones *et al.*, 1993; Longstaff, 1994b). In certain situations protectants may be eliminated and insect control may be achieved through temperature manipulation or supplemental fumigation should infestations occur during storage. As more of these expert systems are developed management decisions may shift to computer-based pest management.

BENEFITS OF GRAIN PROTECTANTS

There are obvious advantages of conventional protectants that should be presented in any discussion of pest controls in stored grains. Conventional protectants are generally less expensive than most insect growth regulators, microbial pathogens, natural products, and biological controls. Raw grain is of comparatively low economic value, and sometimes conventional protectants are the most cost-effective means of control. Protectants are generally easy to apply in field situations. Mammalian toxicities for most protectants are relatively low and applicator exposure is minimized, compared to the more toxic chemicals used in agricultural production systems. In many regions, temperatures during the initial months of crop storage are in the optimum developmental range for most insect pest species, and protectant applications may be necessary to prevent crop damage

until temperature controls can be implemented. Economic and practical considerations may dictate the use of storage structures that cannot be sealed and fumigated if infestations occur, therefore protectants may be necessary for those situations as well. Finally, protectant applications may be required as a condition of commodity sale for export markets. The impending global restrictions on the production and use of methyl bromide as a fumigant could actually increase protectant applications in speciality situations.

CONCLUSIONS

Grain protectants will remain a necessary part of management programs, and they should continue to be a viable control option for stored grains. Eliminating them entirely could have serious economic consequences, especially in industries with narrow profit margins. However, alternative biological and microbial controls, mechanical controls, environmental manipulations, and expert systems will increase in importance as management systems change in response to consumer demands, biological factors, economic conditions, and advances in integrated research. All of these factors will interact to cause a gradual decline in protectant applications. In the coming years new challenges and issues will undoubtedly arise as insect pest management moves into the 21st century.

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