SOILBORNE PLANT PATHOGENS: NEW OPPORTUNITIES FOR BIOLOGICAL CONTROL

G. C. PAPAVIZAS

Soilborne Diseases Laboratory, Plant Protection Institute, Agricultural Research Service, U.S. Department of Agriculture, Beltsville, Maryland 20705

ABSTRACT

Although fungicides and fumigants are available to reduce losses from important and widespread soilborne plant diseases, these pesticides are not used extensively due to lack of effectiveness, or because of various economic or environmental reasons. Biological control with the use of antagonistic microorganisms is advancing as a potential control method for soilborne diseases. Although biocontrol is not progressing as rapidly as originally anticipated, prospects for its success are now brighter than ever before because of increased efforts to understand the intricacies of the soil and root microhabitat and of the use of new ecological concepts to implement biocontrol; the discovery of new, effective mycoparasites enhancing the potential of biocontrol of sclerotial plant pathogens; the induction of new biotypes of biocontrol microorganisms (by genome modification) possessing enhanced biocontrol abilities and tolerance to pesticides; the development of new systems of growth and delivery; and the implementation of new concepts to combine biocontrol agents with other control technologies to suppress single or multiple soilborne diseases.

INTRODUCTION

Of the plant pathogens that afflict the more than 1200 cultivated plants in the U.S., none is more insidious and unpredictably destructive than those that enter the plant through the root system or survive in the soil. Soilborne plant pathogens play a major role in the root disease complex causing damping-off, root rots, seedling blights, crown rots, foot rots, seed decay, collar and fruit rots, root browning, and wilts on many important field and horticultural crops. Soilborne diseases, caused by about 50 genera of fungi, and a few bacteria and viruses, found the world over, cause about 50% of the total estimated annual losses of economic crops due to plant diseases (James 1981). It is conservatively estimated that in the U.S. alone soilborne diseases cause at least $4 billion losses on crops annually. Since most of the damage to plants by soilborne diseases is below ground, or results from below ground infection, crop losses from such diseases are greatly underestimated.

Because of lack of plant resistance to most soilborne plant pathogens, and of the current political, environmental, and economic constraints imposed on the use of pesticides for disease control in the U.S., biological control is increasingly capturing the interest and imagination of the public and is gaining stature as a feasible control technology of the future (Cook & Baker 1983, Papavizas & Lewis 1981). In this presentation we are concerned only with the direct introduction of biological agents to soil to suppress soilborne plant pathogens. The direct approach involves mass introduction of antagonistic microorganisms into soil, with or without a food base, to inactivate pathogen propagules, to reduce their numbers, or to interfere with their disease-producing activities.

NEW MICROBES FOR AN OLD BIOCONTROL CONCEPT

The terms mycoparasitism and hyperparasitism are used to describe the phenomenon of one fungus parasitizing another (Ayers & Adams 1981a). Although it is known for more than 50 years that mycoparasitism is widespread among all groups of fungi, the ecological importance of the old concept and the role it plays in the biocontrol of soilborne plant pathogens have been questioned (Boosalis 1964). The criticism that survival of pathogens in soil is not greatly affected by mycoparasitism (coming from knowledgeable students of the old concept) virtually eliminated mycoparasitism as a viable concept or workable mechanism of biocontrol. These critical evaluations remained incontestable in the 1960's and 1970's and the only solace remaining in the hearts of its proponents was the somewhat successful attempts to control Sclerotinia wilt (Sclerotinia sclerotiorum) of sunflower (Huang 1980) and white rot (Sclerotium cepivorum) of onion (Ahmed & Tribe 1977) with the mycoparasite Coniothyrium minitans.

Questioning the ecological significance of the old concept was not entirely unjustified since mycoparasitism had received limited attention as a mechanism of biocontrol and had not been shown to occur in natural systems (Boosalis 1964). The discovery in 1977 of a new, unusual, dematiaceous hyphomycete on sclerotia of Sclerotinia minor in soil at Beltsville, Maryland and subsequent research summarized in 1981 (Ayers & Adams 1981a) dispelled the previous conclusion that mycoparasitism may not be important under natural conditions. The new mycoparasite, Sporidesmium sclerotivorum, detected in soils from many areas in the U.S. and from other countries, displays several extremely unusual properties: (a) Macroconidia of S. sclerotivorum germinate within 3 days in soil adjacent to sclerotia of Sclerotinia spp. (germination may occur at distances up to 9 mm from a sclerotium) and grow through soil from one sclerotium to another, producing many new dark macroconidia along a network of threadlike, branching hyphae throughout the soil mass; (b) one or more diffusible compounds essential for germination are released by living, but not dead, sclerotia in soil, and the active materials appear to persist in soil for at least several days; (c) the mycoparasite colonizes live sclerotia much more readily than autoclaved sclerotia; (d) it has exacting nutritional requirements for growth and infection of sclerotia, but is active over a broad range of environmental conditions in agricultural soils; (e) the mycoparasite, originally thought to be an obligate parasite, cultured axenically only on media prepared from sclerotia of host fungi, is deficient for thiamine and biotin and grows best in media containing glutamine or casamino acids; and (f) it attacks and destroys sclerotia of Sclerotinia spp., S. cepivorum, and Botrytis, but not those of Sclerotium rolfsii. The new mycoparasite was able to infect and destroy more than 95% of sclerotia of S. minor within 10 weeks or less in soil.

Adams and Ayers (1982) reported that application of the mycoparasite to field plots infested with S. minor in May, 1978 reduced the population of sclerotia by 94% in 6 months and provided 63 to 83% control of lettuce drop in two consecutive crops in 1979, and 65 and 82% control in 1980, without further treatment of the soil. The magnitude of biocontrol depended on the rate of mycoparasite application and maintenance of favorable moisture level during the growing season. Sporidesmium sclerotivorum is now produced experimentally by private enterprise in the U.S. for biocontrol of Sclerotinia spp. (P.B. Adams unpublished).

This is one of the best documented cases of biocontrol of a plant disease by a mycoparasite for which the mechanism of control (destructive mycoparasitism in soil) has been established. The discovery of Sporidesmium and also of a new mycoparasite, Teratosperma oligocladum (Ayers & Adams 1981b), demonstrated the existence of a previously unrecognized group of beneficial mycoparasites in soil responsible for the destruction of sclerotia produced by a large group of soilborne plant pathogens. Because of those discoveries, mycoparasitism is now being recognized as an important mechanism with considerable potential for exploitation in applied biocontrol.

NEW CONCEPTS FOR OLD BIOCONTROL AGENTS

Biocontrol in the ecological complexity continuum - chances of success

Success in biocontrol depends on many factors, none of which is more important and intricate, and less understood, than the microecology of the soil. The expected impact of ecological complexity on the practice of biocontrol can be seen if one visualizes the soil ecosystem as being an ecological continuum ranging from an extremely simple system (e.g. two interacting microorganisms in a petri plate) to a complex system such as a managed forest (Marois 1984). The simpler the ecosystem, the more likely to obtain success in biocontrol with introduced microorganisms. For instance, biocontrol is more likely to succeed in hydroponic culture, annual greenhouse crops, intensely managed row crops, and transplanted crops than in field and no tillage crops, perennial field crops, or woody fruit crops.

The relationship between the simplicity in the ecological complexity continuum and probability of success in biocontrol can be elucidated by recent research at Beltsville on the biocontrol of Verticillium wilt (Verticillium dahliae) of eggplant. Eggplant seedlings treated with Talaromyces flavus (teliomorph of Penicillium vermiculatum, an ascomycete isolated from sclerotia of Sclerotinia minor decaying in natural soil) by applying ascospores to the glasshouse transplanting mix before moving the seedlings to the field had 67 to 72% less Verticillium wilt than controls (Marois et al. 1982). Field applications of the antagonist together with sublethal amounts of a soil fumigant (Telone C17) gave as good control of wilt as the full rate of the fumigant. In two preliminary field tests T. flavus increased potato yield by about 12 and 21%, respectively, in V. dahliae - infested fields. Although T. flavus produced very good biocontrol of Verticillium wilt of eggplant in production systems, very little research has been done on its biocontrol potential on other crops susceptible to V. dahliae and V. albo-atrum. The antagonist also may have good biocontrol potential against soilborne pathogens other than Verticillium spp.

Another example of the positive correlation between the simplicity of the soil ecosystem and enhanced probabilities of success in biocontrol is the suppression of Fusarium wilt (Fusarium oxysporum f. sp. chrysanthemi) of chrysanthemum by controlled recolonization of soil or soil mixes with Trichoderma viride. In an attempt to reduce dependency on chemicals for control of this disease in glasshouse culture, several organisms were tested at Beltsville for their potential to reduce Fusarium wilt. It was found that T-1-R9, a biotype of T. viride in which tolerance to benomyl was induced with u.v. light treatments

(Papavizas & Lewis 1983), controlled Fusarium wilt as effectively as the present practice of integrating $Ca(NO_3)_2$ fertilizer, benomyl soil drenches, and lime (Locke et al. 1984). Bare conidia in a water suspension of the genetically marked biotype are added to soil following a "selector" treatment such as soil pasteurization which creates a partial microbial vacuum and allows the antagonist to colonize the soil, proliferate utilizing nutrients that would be otherwise available to the pathogen, and prevent reinvasion by the pathogen.

Induction of new biotypes

Although wild strains of various fungal antagonists are used experimentally to suppress certain soilborne plant pathogens, no attempts have been made to improve their biocontrol efficiency by capitalizing on the natural genetic variation, on mutation followed by selection, on hybridization and recombination, or on protoplast fusion, gene splicing and transformation. There may be practical difficulties, but there are no theoretical reasons why we cannot use the same genetic principles that served as the foundation for many dramatic increases in productivity of higher plants and animals, or the modern gene splicing and transformation technology that has been successful with prokaryotes and some eukaryotes. Induced mutagenesis, for instance, has been successful with *Trichoderma* spp.(Mandels et al. 1971).

Attempts to induce tolerance or resistance to fungicides in *Trichoderma* at Beltsville embodied three simple approaches. The first approach involved purposeful induction of tolerance or resistance to fungicides in *Gliocladium* and *Trichoderma* and selection of stable biotypes for use with fungicides. New biotypes tolerant to the fungicides chlorothalonil, procymidone, iprodione, and vinclozolin were developed by exposing conidia to increasing concentrations of the fungicides in culture media and selecting surviving colonies for additional exposure to concentrations higher than those on which the colonies developed (Abd-El Moity et al. 1982). Certain biotypes tolerant to fungicides showed enhanced ability for suppressing some soilborne pathogens. For instance, *T. harzianum* Th-1(ipro-2M), a selection of Th-1 that tolerated 2000 μg iprodione/ml of medium, suppressed white rot of onion more effectively than the wild parent Th-1. Several fungicide-tolerant strains, however, lost their ability to tolerate the fungicides after repeated transfers to fungicide-free media.

The second approach involved genome modification by induced mutagenesis using u.v. light or N-methyl-N^1-nitro-N-nitrosoguanidine. A major difficulty in using the induced mutagenesis-selection approach with *Trichoderma* is the lack of visible markers associated with desired qualities (enhanced biocontrol ability, survival in soil, low toxin production, good growth and profuse sporulation, long shelf life). If such markers do not exist, or are not known, one has to test hundreds or thousands of variants for disease control, sometimes an impossible task. To alleviate this difficulty, we used the ability of *Trichoderma*, *Gliocladium*, or *Talaromyces* to tolerate fungicides of the MBC group (e.g. benomyl, thiabendazole) as a marker in a selection system following induced mutagenesis. Using this approach, we developed several genetic variants from wild strains of the three antagonists (Katan et al. 1984; Papavizas & Lewis 1983, Papavizas et al. 1982). The induced biotypes can tolerate benomyl up to 50-500 mg active ingredient per L of medium. Several new biotypes differed from their respective parents in growth characteristics, sporulation, survival in soil and suppression of the competitive saprophytic activity of Rhizoctonia solani. Several u.v. - induced biotypes were more effective than the wild strains in suppressing damping-off (R. solani) of cotton, potato, and radish; white rot (Sclerotium cepivorum) of onion; and damping-off and blight (S. rolfsii) of bean. The realization of techniques for protoplast isolation, culture, and fusion and cloning of Trichoderma DNA into yeast may result in a further development of technologies for genetic manipulation and strain improvement.

The third approach involved application of hybridization and recombination techniques to strains of T. flavus. Application of such techniques to strains of filamentous fungi has proved considerably more difficult than anticipated, although some progress has been made (e.g. construction of vigorous diploids of Penicillium chrysogenum). Recent research at Beltsville with T. flavus, a homothallic antagonist against V. dahliae that produces asci and ascospores readily in the dark, has shown that it is feasible to produce mutants resistant to benomyl and thiabendazole. Crosses between mutants resistant to benomyl and sensitive wild types, as well as between different resistant isolates showed that the two levels of benomyl resistance encountered are conferred by different alleles at a single locus (Katan et al. 1984). In addition to resistance to MBC fungicides, some of the new double crosses and back crosses possessed superior ability to suppress damping-off (R. solani) of cotton compared to the wild types or to the mutants. This study showed for the first time that genetic recombination in fungi obtained by conventional genetic techniques can be used successfully to improve performance of biocontrol fungi.

New systems of growth and delivery

During the last few years, fungal and bacterial biotechnology has moved to new areas such as production of biological insecticides and mycoherbicides (Churchill 1982). In contrast, technology for fungal biocontrol agents of plant diseases has been slow to develop for a variety of reasons. Consequently, only one biocontrol agent is in commercial use against soilborne plant pathogens - Agrobacterium radiobacter to control crown gall of rosaceous plants (Kerr 1980). If widespread biocontrol of soilborne plant pathogens is to be realized by soil augmentation or seed treatment, mass-production and formulation of promising antagonists is an essential step towards that end. Experimental preparations for field delivery of Trichoderma formulated from fungal biomass on inexpensive products in solid fermentations were used in the U.S. and elsewhere. These were tabulated in a recent review (Papavizas & Lewis 1981). Solid fermentation, however, may not be a practical approach for mass-production of biocontrol fungi.

Papavizas et al. (1984) have shown that it is possible to use inexpensive and readily available liquid media (molasses, brewers yeast, corn steep liquor) to produce large amounts of viable biomass of several potential biocontrol fungi (Gliocladium, Trichoderma, Talaromyces, Coniothyrium) with a deep-tank fermentation system simulating large-scale industrial production. Various formulations were prepared using unfiltered liquid biomass or filtered wet and dry biomass. Granular dusts were produced from dry mats by separating the solids from the broth with a cotton fabric filter, air-drying the solids, and milling them through a 425-μm screen. The resulting powder was used as is or was mixed with Pyrax ABB® (anhydrous aluminum silicate) as a carrier. Biomass propagules (conidia, chlamydospores, dried mycelium) of Gliocladium and Trichoderma, added to soil at $5x10^3$ colony-forming units (cfu)/g, fragmented or proliferated greatly in soil to attain numbers from $2x10^6$ to $6x10^6$. Conidia of Trichoderma or Gliocladium, added to soil without a food base, did not proliferate.

A recent approach that may revolutionize delivery technology of biocontrol agents for soilborne disease control involves encapsulation of propagules. This process is based on the ability of aqueous solutions of sodium alginate to react with certain metal cations (e.g. Ca^{++}) to form gels, a process used to formulate chemical herbicides (Walker & Connick 1982). The ease with which various biocontrol fungi can be incorporated in sodium alginate gels in an aqueous system was exploited by Walker and Connick (1983) to prepare pelletized formulations of mycoherbicidal fungi and by others (Fravel et al. 1984, Lewis & Papavizas 1984) with fungi antagonistic to soilborne plant pathogens. The encapsulation technique was improved further (Lewis & Papavizas 1984) by incorporating a nutrient carrier (e.g. bran) together with the alginate to provide a food base in intimate contact with, and close availability to, the biocontrol fungus. When alginate-bran pellets of Trichoderma or Gliocladium were added to natural soil great proliferation, representing an increase as high as 10^6-fold, occurred as indicated by the dilution-plate method. Alginate-kaolin pellets, which contain no additional food base, did not allow an increase in cfu regardless of whether the biomass used to make the pellets was wet or dry. The efficacy of the formulations for biocontrol was also shown by their ability to reduce populations of R. solani, disease severity caused by this pathogen on cotton, tomato, or both.

BLENDING CONTROL TECHNOLOGIES

Perhaps success in reducing losses from the most difficult-to-control soilborne diseases would likely depend on clever blending of biocontrol technology with other control components. Integration of several control technologies may be used to reduce pathogenic activities to a tolerable or permissible threshold, with chemicals applied only when absolutely necessary. Experimental biocontrol fungi have been studied largely by themselves rather than as synergistic or additive components blended with other control technologies. If blending involves pesticides, such an approach can be successful only if the biocontrol agents are compatible with the pesticides. For instance, possession of tolerance to MBC fungicides by biotypes of Trichoderma or Talaromyces developed by u.v. radiation or chemical mutagens would be an important characteristic and a first step in making them good candidates for blending technologies. Formulations of such biotypes could be used in tank mixtures of pesticides or fertilizers, spray programs, together or immediately following soil fumigants, coated onto seeds together with infused seed treatment fungicides (Papavizas 1981), or in soil together with fungicides (e.g. use of the benomyl-resistant biotype T-1-R9 of T. viride together with benomyl to control soilborne Fusarium wilt of chrysanthemum). The use of such tolerant strains together with selective pesticides may offer a distinct possibility of control of soilborne diseases where no single components are currently effective.

Blending biocontrol agents with pesticides is not the only integrated approach to reduce losses from soilborne plant pathogens. Beneficial interactions can also be obtained with combinations of cultural practices and biocontrol agents. In warm humid areas, fruit rot (R. solani) causes serious losses on cucumber and tomato. Excellent control of cucumber fruit rot in the field was achieved by combining normal plowing (20-25 cm deep), instead of disking the soil surface, and T. harzianum or Laetisaria arvalis preparations (Lewis & Papavizas 1980). The use of the antagonists in association with plowing reduced disease more than when either component was used individually. Plowing itself reduced disease by c. 50% by burying R. solani inoculum and colonizable organic debris to depths where the pathogen could not survive. Control of this soilborne disease represents one of very few documented examples of the integration of biocontrol agents with cultural methods against plant pathogens.

CONCLUSIONS

Despite the many years of intensive research and the thousands of papers published on soilborne plant pathogens, practical methods of biocontrol have not yet materialized for most soilborne diseases. Some of the reasons for our limited successes can be summarized as follows: (1) We have expended great efforts to perform precise studies to unravel mechanisms of biocontrol, but not enough efforts to study biocontrol per se, or to build theories or reveal principles under production systems; (2) most scientists working on biocontrol have disregarded the importance of the ecological complexity continuum principle, beginning their studies in more complex ecosystems rather than the opposite; (3) plant pathologists and soil microbiologists working on biocontrol most often disregard the economic feasibility of biological control; (4) we have produced many elegant papers on principles, mechanisms, mathematics, etc, but have not seriously attempted to close the astonishing gap in cooperation between research institutions and private enterprise; (5) we are expending too much time on old biocontrol approaches while still disregarding the modern tools for biotechnology and bioengineering.

Recognition of these and other shortcomings should stimulate us to learn to manage the biocontrol agents in the field for maximum effectiveness and for environmentally and economically successful biological control.

REFERENCES

Abd-El Moity, T.H.; Papavizas, G.C.; Shatla, M.N. (1982) Induction of new isolates of Trichoderma harzianum tolerant to fungicides and their experimental use for control of white rot of onion. Phytopathology 72, 396-400.

Adams, P.B.; Ayers, W.A. (1982) Biological control of Sclerotinia lettuce drop in the field by Sporidesmium sclerotivorum. Phytopathology 72, 485-488.

Ahmed, A.H.M.; Tribe, H.T. (1977) Biological control of white rot of onion (Sclerotium cepivorum) by Coniothyrium minitans. Plant Pathology 26, 75-78.

Ayers, W.A.; Adams, P.B. (1981a) Mycoparasitism and its application to biological control of plant diseases. In: Biological Control in Crop Production G.C. Papavizas (Ed), Totowa, New Jersey: Allanheld, Osmun, pp. 91-103.

Ayers, W.A.; Adams, P.B. (1981b) Mycoparasitism of sclerotial fungi by Teratosperma oligocladum. Canadian Journal of Microbiology 27, 886-892.

Boosalis, M.G.; (1964) Hyperparasitism. Annual Review of Phytopathology 2, 363-376.
Churchill, B.W. (1982) Mass production of microorganisms for biological control. In: Biological Control of Weeds with Plant Pathogens R. Charudattan and H.L. Walker (Eds), New York: John Wiley & Sons, pp. 139-156.
Cook, R.J.; Baker, K.F. (1983) The Nature and Practice of Biological Control of Plant Pathogens, St. Paul, Minnesota: American Phytopathological Society, 539 pp.
Fravel, D.R.; Marois, J.J.; Connick,W.J., Jr. (1984) Encapsulation of potential biocontrol agents in sodium alginate aggregates. Phytopathology 74, 756.
Huang, H.C. (1980) Control of Sclerotinia wilt of sunflower by hyperparasites. Canadian Journal of Plant Pathology 2, 26-32.
James, W.C. (1981) Estimated losses of crops from plant pathogens. In: CRC Handbook of Pest Management in Agriculture, Volume I D. Pimentel (Ed), Boca Raton, Florida: CRC Press, pp. 79-94.
Katan, T.; Dunn, M.T.; Papavizas, G.C. (1984) Genetics of fungicide resistance in Talaromyces flavus. Canadian Journal of Microbiology 30, In Press.
Kerr, A. (1980) Biological control of crown gall through production of agrocin 84. Plant Disease 64, 25-30.
Lewis, J.A.; Papavizas, G.C. (1980) Integrated control of Rhizoctonia fruit rot of cucumber. Phytopathology 70, 85-89.
Lewis, J.A.; Papavizas, G.C. (1984) Proliferation of Trichoderma and Gliocladium from alginate pellets in natural soil and reduction of Rhizoctonia solani inoculum. Phytopathology 74, 836.
Locke, J.C; Marois, J.J.; Papavizas, G.C. (1984) Biological control of Fusarium wilt of greenhouse-grown chrysanthemum. Plant Disease 68, In Press.
Mandels, M.; Weber, J.; Parizek, R. (1971) Enhanced cellulase production by a mutant of Trichoderma viride. Applied Microbiology 21, 152-154.
Marois, J.J. (1984) Biological control in plant pathology. In: Biological Control in Agricultural Integrated Pest Management Systems. M.A. Hoy and D.C. Herzog (Eds), New York, New York: Academic Press, In Press.
Marois, J.J.; Johnston, S.A.; Dunn, M.T.; Papavizas, G.C. (1982) Biological Control of Verticillium wilt of eggplant in the field. Plant Disease 66, 1166-1168.
Papavizas, G.C. (1981) Survival of Trichoderma harzianum in soil and in pea and bean rhizosphere. Phytopathology 71, 121-125.
Papavizas, G.C.; Dunn, M.T.; Lewis, J.A.; Beagle-Ristaino, J. (1984) Liquid fermentation technology for experimental production of biocontrol fungi: Phytopathology 74, In Press.
Papavizas, G.C.; Lewis, J.A. (1981) Introduction and augmentation of microbial antagonists for the control of soilborne plant pathogens. In: Biological Control in Crop Production G.C. Papavizas (Ed), Totowa, New Jersey: Allanheld, Osmun, pp. 305-322.
Papavizas, G.C.; Lewis, J.A. (1983) Physiological and biocontrol characteristic of stable mutants of Trichoderma viride resistant to MBC fungicides Phytopathology 73, 407-411.
Papavizas, G.C.; Lewis, J.A.; Abd-El Moity, T.H. (1982) Evaluation of new biotypes of Trichoderma harzianum for tolerance to benomyl and enhanced biocontrol capabilities. Phytopathology 72, 126-132.
Walker, H.L.; Connick, W.J., Jr. (1983) Sodium alginate for production and formulation of mycoherbicides. Weed Science 31, 333-338.

BIOLOGICAL CONTROL - A COMMERCIAL EVALUATION

N.W. HUSSEY

CIBC, Silwood Park, Ascot, Berks SL5 7PY

ABSTRACT

Current constraints on the purely pesticide approach to pest control have provided a favourable environment for the wider use of biological control. However, while the benefits of using natural organisms are immediately apparent, the economic problems associated with a biological control "industry" are considerable. This paper emphasises these problems and suggests broad approaches to their solution.

THE CURRENT PEST CONTROL SCENE

We are all aware of the complex of natural forces which prevent any single living organism from reproducing and surviving until it dominates our planet. It has, for instance, been computed that if all the progeny of a single aphid survive and themselves survive to reproduce for successive generations then, within a year, the earth would be completely covered by a layer of aphids.

Of course, the principal mortality factor preventing this catacylsmic situation is the starvation which would follow exploitation of their major food source but even this situation is usually prevented by predators, parasites and diseases. This complex of natural enemies affects all living things and it is their action which ensures that the wild plants and trees survive their many pests to maintain the natural environment with which we are familiar.

When man selects a wild plant for culture, he attempts to maximise the yield of its fruits, leaves or roots for his economic purposes. This economic demand necessitates a yield greater than that which the plant would naturally produce. Man has protected this increased production by devising control techniques to reduce pest numbers. During the last century, he has relied more and more on pesticides which have become increasingly sophisticated and effective. The grower naturally relies on those insecticides which give him the most effective results and hence uses them repeatedly. This action creates a continuous and severe selection pressure which, by the simple laws of Mendelian inheritance, results in the survival of individuals possessing enzyme systems which detoxify the active ingredients. As first, this process of selection is slow but then increases rapidly. The grower ofter loses control of the pest on his plants before tolerance can be detected in the laboratory but, within a few months, very high levels of resistance may be evident.

Traditionally, growers have been advised to 'ring the changes' with pesticides to which no resistance has yet been selected. For some time this strategy succeeded in delaying the onset of resistance but, in recent years, the economics of the pesticide industry have been under increasing pressure. Further, the public have developed a phobia for safety as the reaction to smoking, asbestos and processed foods bear ample witness. At the same time, there has been an increasing awareness of the threat to the environment posed by industrial processes, urban sprawl and side effects of the application of pesticides to large agricultrual areas. For instance, in June 1984, the Soil Association published a report entitled "Pall of Poison" which argued that 1,000m gallons of pesticide were applied to farmland in Britain during 1983, part of which constituted an environmental hazard. To date, most of these pressures have been directed towards the agrochemical industry but I have little doubt that some vociferous group will soon turn its attention to the hazards of biological control. "Cruelty to pests" - aphids suffer a slow death at the hands of parasites - will become the rallying call of some well-meaning individuals!

All these trends have increased the pressure on the pesticide registration authorities to demand more sophisticated and costly tests. The result has been that the development, clearance and manufacture of a new pesticide now costs around $50m. This cost is naturally slowing down the flow of new pesticides to the market and hence the practicality of rotating effective materials. This economic pressure is illustratd by the common reaction of the major pesticide companies to the synthetic pyrethroids. Most companies have marketed different pyrethroids which, since they are related, have incurred substantially reduced R & D costs. Regrettably, although they have many different trade names, they exert similar selective pressures on target pests so that we cannot view their active commercial life without concern.

Many of these pyrethroids, while safe to man and even to bees, often display a very long persistence of harmful effects to parasites on treated foliage. Not surprisingly, there have already been some 'rebound' pest problems following their use. The virtual elimination of natural enemies has contributed to the upsurge of several, hitherto, minor pests which have become major problems. The outbreaks of whitefly on cotton in the Sudan where the widespread use of monocrotophos was followed by pyrethroids and of leaf-miner on flower crops in Colombia following the use of permethrin for caterpillar control are outstanding examples.

Another important, influence on the pesticide industry is the rapid shift to ultra-low volume application. With these systems, only 1 litre or so of pesticide per hectare is used compared with more than 100x that volume utilised by conventional systems. The sophistication of ULV technology brings us closer to the possibility of "target specific spraying" with its fascinating possibilities of selectivity by the spatial separation of pesticide and beneficial organism.

It is against this background that biological control enters its most important decade.

Traditionally, biological control has been considered largely in its 'classical' form as practised by the Commonwealth Institute of Biological Control. This technique is attempted when it has been established that a pest in a particular country has probably been introduced from another part of the world where it is naturally indigenous. In these circumstances, it is often only partially controlled by those local natural enemies which attempt, with various degrees of success, to adapt to it. However, in the pest's natural home, a whole complex of natural enemies will have evolved with it over the passage of time and often ensure that it is a little known component of the local fauna.

Following a study of the literature, searches are conducted in those countries believed to be the natural home of the pest in order to locate and identify effective natural enemies. Long experience has shown that it is rarely possible to establish which of these enemies is likely to prove successful in the territory in which the pest is causing a problem. Detailed field observations and laboratory studies provide some indication but ultimately the species must be introduced on a "suck it and see" basis to determine whether it will establish, spread and provide control.

The situation is, therefore, strikingly similar to that involved in the empirical screening of potential pesticides. Despite the well understood differences in molecular structure of chemicals and man's ability to create new combinations almost at will, it has not proved possible to predict whether a given structure will provide the active moiety of a commercial pesticide. Thousands of empirical tests have to be made before one active compound is found which has the desired characteristics. In both cases, the empirical approach has been remarkably successful so that both strategies of pest control can claim successes.

The agrochemical industry is heavily capitalized and so operates with excellent facilitates. Its well qualified chemists and biologists are technically effective and engender grower confidence through their highly professional standards. The products are serviced by well-organised sales teams. These companies are in the fore-front of national economies so that the logic of their strategies have rarely, until recently, been challenged. In the face of this industrial competence, it is fashionable to dismiss biological control merely on the premise that the number of completely successful programmes is small. Although several authors have sought to demonstrate the proportion of unsuccessful introductions over the past century, no one publicizes the thousands of chemical structures which are expensively created and rejected by the chemical industry.

Classical Biological Control

When viewed purely on grounds of cost-benefit ratio, adequately funded biological control would often be more attractive than the pesticide approach.

Such a statement must be viewed from different vantage points before it is summarily dismissed. The cost-benefit ratio of any pest control operation differs according to the standpoint of the grower, the consumer, the producer of microbial pesticides or the national economy. Classical biological control is funded only by international aid agencies, national governments, by large plantation companies or grower associations. These investors in biological control are usually meeting the costs from restricted budgets and therefore approach the costings negatively, rarely taking the potential economies into account - only the plantation companies have a clear view of the potential advantages to their profits and hence are the group most likely to fund in a positive fashion.

Classical biological control has, therefore, almost always been conducted "on the cheap" so that costly mistakes have occurred through lack of sufficient investment to complete the following essential steps:-

1. Searching teams to visit 'problem' area.
2. Searching teams to seek biological agents in the natural home of the pests, often in several countries in a single continent, with provision of adequate taxonomic support.
3. Production and evaluation of natural enemies at a suitable laboratory in (2).
4. Dispatch of promising species to a quarantine station.
5. Dispatch of 'clean' beneficial to problem area.
6. Releases following local production
7. Follow-up surveys to prove establishment and spread.

As small teams are involved, a high proportion of the costs are for travel and the maintenance of officers in overseas stations involving appropriate additional allowances. Depending on national economies, they may appear to some agencies to be "expensive" scientists involved in operations the value of which is not immediately apparent to administrators. Items (1) and (7) are usually contested and hence not funded, with serious results - as illustrated by the current campaign to control cassava mealybug, Phenacoccus manihoti, in almost 40 African countries. This pest was introduced to Africa in the early 1970s when it was found in Zaire and, within 10 years, had spread across much of Central Africa. Cassava was known to have originated in S. America, and so aid agencies financed searches in that continent by scientists who had never visited Africa. The mealybug was apparently readily found in northern S. America but natural enemies sent to Africa over the next 5 years all failed to establish. It was not until a scientist, familiar with the African situation, was able to visit South America, that it was recognised that the mealybugs on the two continents were different. Searches in S. America were then extended and the "African spp". ultimately located in Paraguay and S. Brazil. A parasite, Apoanagyrus lopezi, was subsequently found and successfully established in Nigeria. The inability of the teams to be familiar with both the "problem" and "search" areas resulted in 5 years of fruitless effort in the wrong areas with consequent waste of resources. This salutory story also illustrates the importance of adequate taxonomic support, a field which is notoriously under-funded by national agencies, since its fundamental importance is rarely appreciated. A further difficulty is that taxonomists are frequently associated with museums or institutes not directly involved in pest control projects.

It is probable that, to be effective, classical biological campaigns should each be financed with support of up to $1m annually but that this sizeable cost should be viewed against the permanent control that could ensue. The losses caused by the current cassava problem in Africa have been costed at about $2 billion annually so that the value of complete, or even partial, control (reducing the overall severity of the problem), becomes incalculable since biological control by a key parasite is permanent. Herein lies the problem for those organisations working in this field. There are neither royalties or other financial rewards for success - they must make their operating profit on the "costs" of the operation and it is the "customers" who reap the profits. Further, even the recognition of a task efficiently executed is rapidly forgotten. Man has to battle with a permanent problem by regularly applied controls for recognition of an effective product or control strategy.

Manipulated Biological Control

There is a very different type of biological control in which the method is employed in successive crops as an alternative to routine pesticide treatment. Such an approach is best illustrated in intensive horticulture where successive crops are grown throughout the year, and where these are protected, or at least semi-protected, by glass or polythene then pest problems are usually quite severe and very intensive spray programmes are routinely adopted. Such unique ecological situations, in which more or less 'closed' populations are regularly treated with pesticides, create a high selection pressure and the almost inevitable selection for resistance. This problem has now developed in mites, aphids, whiteflies and leaf-miners, with serious consequences.

When the problem was first encountered in tetranychid mites on cucumbers in 1958, much research focussed on the genetic and biochemical aspects of resistance but without finding a rational solution. Attention was then diverted towards establishing the economic damage thresholds (ie, populations below which no detectable yield loss occurs) of the most serious pests. In vegetables, where the threshold was high, the way was open to adopt biological control as we felt we had room to manoeuvre. Techniques for red spider mite and whitefly were developed quite rapidly but then followed the long, slow process of convincing growers and technical advisors that such an approach could succeed on crops worth at least £50,000/acre. Gradually, our trials attracted sufficient attention to justify commercial supplies of the necessary parasites and predators. As a result, several companies were set up in Europe: UK(5), Sweden(1), Switzerland(1), Holland(1), France(1). After some ten years of competition, about four of these now share the bulk of the business.

The Grower's Viewpoint

The grower's view of biological control tends to change with his experience of the technique. At first, although incredulous, severe difficulties with resistance may force him to 'take the plunge'. As his confidence increases, he finds that reducing his pesticide programme actually improves control. He then begins to realise that where pesticides have been used almost every week, crops are severely 'hardened' with consequent loss of yield and quality. In glasshouse crops, these losses are of the order of 15%. This economic advantage is gained with considerable savings in pest and disease control costs. When the Glasshouse Crops Research Institute developed the biological control techniques, they were designed to cut pesticide cost by 50%. While such striking advantages may not accrue in other crops, the pattern of advantage remains. In Columbia, chrysanthemum growers were applying between 20-30 sprays to control leaf-miner but when parasites were used, the number of sprays was reduced to only 2 or 3. The degree of control achieved is still sufficient to export 95% of the production to the USA.

In Europe, the present public obsession with health has raised the market value of 'residue-free' produce so that some growers are obtaining a useful premium on fruits harvested from crops protected by biological control. Apparently, the grower has little to lose and much to gain from the use of natural methods.

However, Fenemore and Norton (1984) have drawn attention to the need for the economic, managerial and political feasibility of making any changes in pest control practice. In intensive cultural systems the grower makes a large financial investment and he therefore demands an early and sustained high revenue. These authors have considered the situation facing apple production in the UK.

Supervised control, involving monitoring systems to ensure that pesticides are used only when required, reduces insecticide/acaricide usage by £30/ha but necessitate monitoring costs of £9/ha. Hence the net savings are £21/ha which should be viewed against total production costs of £1,500/ha for a 25 tonne crop. The method is less effective than a purely pesticide approach so that some increase in damage (4%) lowers the fruit grade at a cost of £60/ha. Hence, on this cosmetic product, even a slight shift in "grade out" could turn the potential cost saving with supervised control into a loss. The risk would be still higher with a full biological programme.

Inevitably, the market for high value crops strongly influences the type of crop protection system attractive to growers.

Natural Enemy Producer's Viewpoint

The total area of glasshouse production in Europe (5000 ha) scarcely provides these companies with a sufficient market share on which to develop a business. Further, there is a strong seasonal periodicity in demand so that facilities and staff tend to be under-employed from July to December. This has tempted some firms to exploit the potential market afforded by the very large area of temporary, plastic structures employed for vegetable production along the Mediteranean coast from Morocco to Macedonia. However, the expertise of these private biological control firms lies largely in production techniques rather than field use so that the unique problems associated with these unfamiliar cultural techniques were not appreciated. Initially, failures occurred and discouraged a rapid exploitation of this market though there are now several commerical projects under development which could change the situation.

It has been all too easy to regard artificially-produced natural enemies as biotic pesticides. This philosophy can go seriously adrift if those concerned, both growers and salesman, are not fully appraised of the effects of variations in crop culture on the interaction between pest and natural enemy. In N. Europe, we have a reasonably predictable environment controlled by thermostats and computers whereas, further south, the grower takes advantage of a congenial climate to produce crops cheaply. Vegetable crops are usually sown in the autumn when infestation by pests first occurs, to be followed by very low temperatures when pests seem to disappear but, of course, eggs and other stages adapted to cool conditions are ready to exploit the rapid rise in temperature in early spring. Natural enemies are less able to exploit these conditions to their advantage so that it is essential to devise a comprehensive integrated programme in which a complex of control methods is harmonized into a total package.

Even in N. Europe, successful programmes must also deal with the whole crop protection field simultaneously so that control of pests, diseases, plant growth and weeds are harmonized into a practical programme. Such harmonization is, at present, dependent upon the resources of certain state research institutes at Littlehampton, Darmstadt and Versailles to evaluate the side-effects of agrochemicals on biological control agents. Gradually, therefore, firms producing natural enemies are being drawn into providing integrated control advice to their customers.

A second diversification has been to seek to exploit new biological agents, such as phytoseiid mites for thrips and parasites for leaf-miners, for use in protected environments or even to undertake the production of biotic agents merely because the companies have mass-production expertise, ie, Trichogramma for European Corn Borer and sterile males for control of Onion Fly.

These weaknesses in their commercial viability have, and will continue to restrict the growth of biological control especially since other weapons in the armoury of natural control viruses, fungi, bacteria and nematodes demand a degree of microbiological expertise which is expensive to acquire and operate. They are, therefore, most unlikely to be developed by any of the existing companies. Further, even if such biotic products are developed, they tend to have a limited market and a rather longer R & D component than their chemical competitors. They therefore need to be developed by companies manufacturing a large range of products ensuring a cash flow until a biotic product is ready for the market. From many points of view, the most obvious firms are those in the agrochemical industry. As you will know, several pesticide companies have attempted in the past to develop viruses and fungi but these ventures have largely proved abortive.

The reason for these failures is, of course, the selectivity of biotic products which is self-defeating in marketing terms. However, the pesticide companies are themselves facing the problems to which I have alluded earlier. Perhaps the solution will demand that the commericial product becomes "control" and that pesticide firms provide a total integrated package for particular cropping systems. This would enable R & D costs to be spread across the package, the sale price of which would still constitute a small proportion of the crop production costs, so remaining attractive to the grower.

An example of this "cost-spread" is provided by year-round chrysanthemums where aphid and caterpillar control can be achieved either chemically or biologically. Purely on grounds of the cost of individual products, the grower would choose chemicals but using aphid fungi and Bacillus thuringiensis, the total pest and disease control programme can, in practice, be operated effectively with a 15% saving.

How can we ensure that these benefits are realised while those who produce biotic agents can be assured of adequate returns? If we do not find a solution, growers, or at least grower associations, will embark on cheap 'do-it-yourself' operations. While this is attractive for parasites and predators, it would not be suitable for pathogens. Indeed, some would regard it as hazardous. I would not subscribe to that extreme view and, failing a genuine interest by pesticide firms in marketing integrated chemical biotic programmes for major crops, I would advocate that research institutions should investigate the potential of simple, controlled formulation methods to extract viruses from infected larvae, and develop crude field production of bacilli and fungi as has been done so elegantly by the Chinese.

National Viewpoint

Governments, world-wide, are committed to improving environmental quality and so give lip service to supporting research on non-chemical approaches to pest and disease control, but some caution is called for. Long experience in Hawaii, where biological control is practised as a first option has lessons for all.

Whereas the field performance of pesticides is always accurately appraised by producers to ensure that products have a proven efficacy in order to justify sales campaigns, biological control operations in those islands were frequently pursued on a "let's try again" basis. Failures were often followed by more introductions of other species. Elsewhere, this approach is largely the result of limited financial resource but it is imperative that releases should be properly evaluated to prove whether a new natural enemy has contributed effectively to the total life-table of the pest. Establishment is not necessarily beneficial. There are cases where introductions have been made to control nuisance problems which could have been as simply solved by cultural manipulation. Further, some introduced pests may, after an initial surge in numbers, settle at lower population levels not justifying control. So the 'insurance' philosophy is just as likely to be followed with biological agents as chemicals.

When considering economics of biological control, by whose definition would an introduction be classified as "useful"? The Australian experience with Patterson's Curse, Echium plantagineum, a weed which smothers useful pasture, and yet is called Salvation Jane in drier areas since stock can be feed upon it in drought conditions, is a case in point. Biological agents were introduced into Australia in 1980 to solve the pasture problems on good land but subsequently bee-keepers brought a legal action against the authorities as it was claimed that this weed was a real benefit to them!!

Adequate socio-economic evaluation is equally important with either approach to pest and disease control. Natural enemy producers must, therefore, invest as heavily as chemical companies in market appraisal.

Experience shows that the total pesticide path has not always been in the customer's interest and some agrochemical companies now appreciate that if the effective commercial life of valuable products is to be extended then they must encourage adequate investment in the development of integrated control programmes and so stimulate development of effective biotic agents. Biological control has demonstrated that it can provide lasting solutions to introduced pest problems and even provide effective control on high-value crops where it could be said to be displacing products developed with millions of dollars. The present haphazard investment of a fraction of a million dollars in biological control must be changed if manufacturers, growers and consumers are to benefit from the proven manipulation of natural forces. Further, some accounting device should afford economic benefits to organisations providing permanent control from "one-off" operations.

REFERENCE

Fenemore, P.G.; Norton, G.A. (1984) Problems of implementing improvements in pest control: a case study of apples in the U.K. Crop Protection (In Press).

PRESENT TRENDS IN PESTICIDE DEVELOPMENT REGARDING SAFETY TO BENEFICIAL ORGANISMS

G. J. JACKSON

Imperial Chemical Industries PLC, Fernhurst, Haslemere, Surrey, England

ABSTRACT

The present decade is seeing a surge of new pesticides and techniques with improved safety to beneficial organisms. The ideas behind these new developments are often quite old, but till now their practical implementation has been hindered by the lack of supporting technology. However recent advances in chemical and biological technologies are removing these constraints. Several of these new developments are discussed: insect growth regulators, sex pheromones, and insect viruses, together with current trends towards rendering broad spectrum compounds safe in practice to beneficials. The difficulties faced by the agrochemical industry in developing selective pesticides are described, and a solution - collaborative development between governments, the scientific research community and the industry - is proposed. It is concluded that we can expect to see much more progress made in the next ten to fifteen years regarding safety to beneficials.

INTRODUCTION

The importance of beneficial organisms in agriculture is well documented (Coppel & Mertins, 1977) and today there is wide acceptance of the need to develop pesticides, and programmes of use, which are in harmony with the beneficial organisms present in crop ecosystems. This is a pre-requisite for the introduction of integrated pest management systems into modern agriculture.

One must acknowledge that many of the ideas in this area have been around for 20-30 years or more, but hardly any of them have been put successfully into practice on a wide scale. I will illustrate this briefly with two examples, the use of sex pheromones for population suppression by mating disruption, and the use of insect viruses.

Pheromones, of course, are not pesticides at all in the normal sense of the term, but insofar as they are chemicals which can be used to suppress populations of pests, I will include them here. The idea of using pheromones as mating disruptants dates back to a paper by Beroza (1960), but despite years of work they have not yet been commercially successful in the control of important pests on major crops. There are a number of reasons for this of course: their specificity is a hindrance where a pest complex is present, they lack stability and they are difficult to apply to large areas.

As far as insect viruses are concerned, in the sixties and seventies there was a surge of hope that they would provide a means of controlling some of the major pests of the world, e.g. Spodoptera and Heliothis. This hope died away when the practical problems, such as specificity, chemical instability and cost proved insurmountable.

This story could be repeated a number of times, but there is a common theme: the idea, or the chemical compound, may have been available, but the technology needed to put it into practice was lacking. In other words, we knew what should be done, but we didn't have the tools to carry out the job. The thesis of this paper is that the tools for the job are now becoming available, and that over the next 10-20 years we shall see many of the old ideas being put into practical use, with much wider use of beneficials in genuinely integrated pest management systems.

In the term "beneficials" I include two types of organism: on the one hand there are the predators, parasites, etc. which can be used to suppress populations of pests, and on the other hand there are the pollinators. I will now describe some trends in the agrochemical industry's development of new pesticides which, either incidentally or by design, are leading towards greater safety to these beneficials in practical field usage. I will look at three examples where the margin of safety is achieved by using target-specific materials, which are intrinsically non-hazardous to beneficials: insect growth regulators, sex pheromones, and insect viruses. I will also examine what is being done to render broad spectrum compounds safer to beneficials than they might be.

TARGET-SPECIFICITY

Firstly, in the category of target-specific materials, I will deal with the insect growth regulators or IGR's. There is a wave of these reaching the market. One might ask why there should be a sudden interest in IGR's, when very little was done in the 1970's. The answer seems to be that the climate of thought was not favourable: everybody was looking for new, safe broad-spectrum molecules, like the pyrethroids, with which to replace the old, hazardous organophosphates and carbamates, etc. for the major pest complexes of the world. Of course that search continues, but now many agrochemical companies are placing more emphasis on IGR's. Japanese companies have been particularly active in this revitalisation and one can instance two valuable new products from this source: buprofezin for the control of sucking pests especially on rice, and chlorfluazuron for Lepidoptera and Coleoptera.

Let us look at the properties of these compounds which make them so interesting. The net result of their action is that the cuticle is not properly formed and the insect dies at or shortly after the next moult. This mode of action gives them a very low toxicity to non-arthropods. Consequently they are very safe to the end-user which is especially important in third world countries. Another favourable point is that they are effective at very low rates: as little as 25 g a.i./ha in some cases; thus the overall amount of pesticide applied to the environment is low.

Because their mode of action is entirely different from that of organophosphates, carbamates, pyrethroids, etc., they are effective on strains resistant to these compounds: chlorfluazuron provides excellent control of multi-resistant Plutella and Spodoptera in Thailand. Furthermore, they show useful selectivity: chlorfluazuron acts mainly by ingestion, with contact activity being only slight especially at the low rates needed to kill the target species. The hazard to predators, parasites and pollinators is thereby greatly reduced. An example of this is in the control of bagworm Metisa plana on oil palm in Malaysia, where it is important to retain a sufficient population of the imported pollinating weevil Elaeidobius kamerunicus. Buprofezin, although acting by oral, contact and vapour routes, nevertheless shows selectivity which appears to be physiologically based: it has given excellent control of whitefly on citrus in Spain, but is completely harmless to the predatory phytoseiid mites and to the important parasite Cales. Both compounds are safe to bees.

One can therefore see why these compounds are so interesting: they are safe to use, applied at low rates, effective on resistant strains, and can be used selectively as a management tool, preserving essential beneficial organisms. We may expect more IGR's with these properties to become available over the next ten years.

My second example in the target-specific category is the use of sex pheromones for population suppression, which appears to be on the point of birth into the commercial world some 30 years after conception. Their limitations were mentioned earlier. Their advantages are that they are totally non-hazardous, they can be used to pick off one particular target species without affecting directly any other organism within the crop, and they are therefore ideal tools for use in more sophisticated pest management programmes involving parasites and predators. Nevertheless, up till present times there has been no successful large-scale commercial development of the use of pheromones for population suppression.

Recent events may change this, however. In Egypt in 1984 two companies ICI and Sandoz, sold commercial formulations of the sex pheromones of the pink bollworm, Pectinophora gossypiella. The ICI formulation is a water-based suspension of polyurea microcapsules containing the pheromone; the microcapsules permit slow release of the pheromone to give activity over a three week period or longer. The product is applied by normal aerial spray equipment in 50 l of water/ha. The Sandoz formulation utilises the Conrel hollow fibre system, and is applied aerially from special pods fitted to the aircraft. Other formulations currently under test for the same purpose are plastic laminated flakes, and hollow "straws" which are bent and hung over the twigs of the cotton plant (these are now being marketed in Japan for control of tea tortrices). Thus we see that recent advances in formulation technology have provided the means of delivering a pheromone to the target site economically, keeping it stable, and providing slow release over a period of weeks. It is this new technology which has provided the needed stimulus for pheromone usage, and I believe we shall see a considerable expansion of this over the next decade.

My final example in the target-specific category is insect viruses. It is probably true to say that the main factor inhibiting their development on a wide scale was cost of production. For example work by ICI in Egypt in the late seventies on Spodoptera littoralis showed that from a technical standpoint, control by a virus was feasible. The material could be applied early so as to catch the early-instar larvae, which are many times more susceptible than the later instars, before damage occurred. The instability of the virus, a nuclear polyhedrosis, under U/V light could be overcome by adding various stabilising agents to the formulation. An exciting combination could be made by putting the virus through the ICI "Electrodyn" spray system, which would deliver an even deposit of droplets to the underside of the cotton leaves, where the 1st. instar larvae feed. Finally, there was an excellent prospect for the positioning of such a spray at the beginning of the cotton pest control programme in Egypt, where hand-picking of Spodoptera eggs masses is done on a vast scale, but where any substitute system must preserve the highly-valued predators and parasites in the crop.

The problem, however, proved to be cost of production: using in-vivo culture, and extraction from larvae, the cost of an adequate dosage of the virus was simply too high. However, at present the technology of in-vitro virus culture is making great strides, and it may well be that ten years from now we are fulfilling the ambition of so many entomologists in the sixties and seventies, of using the highly-specific, environmentally safe and non-hazardous insect viruses on a wide scale.

In IGR's, pheromones and viruses we have three important examples of techniques using specificity to preserve the beneficials. Products of this type are necessarily limited in their outlets and therefore can provide only a limited return to the companies developing them. This was always quoted as the major reason why companies could not afford to develop compounds of this type: the cost is hardly less than that for a major broad-spectrum product (currently around $20 million), and "small" products simply could not bear this level of investment.

One may ask, then, what has changed? I have already referred to one factor: we now have technological tools which allow us to put into practice methods which were impractical before. One must also recognise a growing interest on all sides (Government and Industry) in finding pesticides with less environmental impact. There is also the perception that these products can fill small but valuable niches, e.g. control of multi-resistant pests. Most important of all, however, has been collaboration between Government and Industry.

An example of such collaboration is the development of the pheromone systems in Egypt. This was done with the British and Egyptian Governments, and took the form of a three year programme of research with the agrochemical companies providing formulation technology and other expertise, the Tropical Development and Research Institute in London co-ordinating the programme and providing expert personnel, and the Egyptian Ministry of Agriculture and

University of Aim Shams in Cairo executing the programme and providing essential support. As a result the burden of work and cost was shared. Furthermore, because the system uses an already-known chemical for which a toxicology package was available, basic development costs were lower than usual. The relatively low requirement for 'up-front' investment enabled the companies concerned to enter a technically new, difficult, and therefore high risk area, where the returns could not possibly justify the multi-million pound investment normally needed for a new agrochemical.

Nevertheless, the problem of limited market size for such a specific compound can still inhibit further development. This is because to register it in other countries requires a trials programme lasting years and costing a considerable amount, not only in money but also in terms of expert personnel tied up and prevented from working on other projects. Furthermore the pheromone system remains a high risk project: although it has been shown to be practical in a selected area of Egyptian cotton, we must remember that every country, every crop environment, every pest complex presents its own problems, and these may in any given case render the pheromone system inappropriate.

I believe this difficulty can be overcome by extending the programme of collaborative development. My experience is that senior people in agriculture ministries and scientific institutions are extremely keen to reduce the usage of broad spectrum insecticides in their crops, particularly where such compounds present a degree of hazard to humans. If such leading figures collaborate with international research bodies and with agrochemical companies to formulate development projects for their countries, it should be possible to obtain further assistance with finance from the international aid organisations.

The level of funding needed is quite small, and need not be measured in millions of dollars, but would permit the development of compounds like pheromones which the companies could not bring forward on their own because the potential returns could not justify the investment risk.

If this collaboration could be achieved, it would lead to much greater interest and development in the area of target-specific pesticides, safer to beneficials and to the environment in general. This in turn will greatly strengthen the hand of entomologists working in the field of integrated pest management.

BROAD-SPECTRUM MATERIALS

Leaving now the target-specific area, I will turn to another interesting trend, which we may call the 'safety-in-practice' concept. This refers to the fact that some broad-spectrum compounds are by no means as hazardous to beneficials as might be thought from a simple examination of their toxicology, laboratory activity etc. In this matter, one cannot generalise:

every crop, every pesticide, and each beneficial organism must be studied in depth. Furthermore this study must include behavioural and ecological aspects and may extend over several seasons. I can illustrate the concept by a brief look at two important areas: firstly safety to pollinating bees, where concerns are widespread, and secondly safety to soil-dwelling predators in cereal crops.

A number of pyrethroids, while intrinsically toxic to bees, can be safe to bees under practical conditions of field use. Recent detailed studies in oil seed rape have shown this to be the case for a range of pyrethroids, and in Switzerland in 1984 these compounds have been provisionally classified as "not dangerous to bees" and use outside the bees' flight period has been recommended (Gerig 1984). We confidently expect this recommendation to be adopted more widely.

My second example concerns winter cereals, where even a light aphid infestation in autumn can result in a serious yield loss from Barley Yellow Dwarf Virus (BYDV). Applications of cypermethrin have been recommended in autumn to eliminate the risk of aphid transmission of BYDV, but concern was also expressed that such usage might adversely affect beneficial soil-dwelling predators present in the crop. To examine this, a large study is currently being conducted by ICI in winter cereals (Cole & Wilkinson 1984). This work is showing that application of cypermethrin in autumn has no lasting effect on ground predator populations; transient depression of the population does occur but it is outside their "useful" period for that season. By the time these predators are needed to be active again the following year, immigration to the treated area brings the population back to a satisfactory level. Thus the cypermethrin spray can actually be integrated into an overall control programme which includes the soil-dwelling predators. This finding underlines the need for population dynamics studies in trials on safety to beneficials.

It is relevant here to mention recent field work on fish with the intrinsically fish-toxic pyrethroids. A number of recent studies have demonstrated, by direct application to water at recommended agricultural rates, that the effect on fish populations is negligible (Stephenson 1984, Bocquet & L'Hotellier 1984, Kingsbury & Kreutzweiser 1984). ICI have established that cypermethrin is completely harmless to fish when used to control lepidopterous pests of paddy rice in the Philippines, and this usage is now recommended by the Ministry of Agriculture there.

Much more work is required in these areas, but it is becoming clear that the pyrethroids, in addition to all their benefits of safety to mammals, reduced rates of a.i., and lack of "subliminal phytotoxicity", are much safer in the environment than one might predict from laboratory work.

The safety of broad-spectrum compounds to beneficials raises another interesting area of work: the selection of resistant strains of predators, parasites, etc. Work so far has concentrated on predators, and there are a number of successful examples among which one may note the organophosphateresistant strains of phytoseiids developed in the U.K., in Australia and elsewhere. Most pyrethroids have suffered from the drawback of mite resurgence, which has hindered their development in the top fruit sector. ICI is funding work in New Zealand aimed at producing phytoseiid strains resistant to cypermethrin, and we are confident of success.

The "safening" of broad-spectrum compounds to beneficials can also be achieved by microencapsulation. For example, a compound with both oral and contact activity can be microencapsulated with the effect of reducing its contact action but leaving it effective by the ingestion route. It would still be active against gross leaf feeders such as Leptinotarsa, Lepidoptera larvae etc., but much safer than the standard formulations to predators and parasites which would not ingest the compound. Of course the idea of producing these effects by microencapsulation is not new, but the state of the art has improved very considerably in recent years, and we expect to see this practice become more widely used. This technique of formulation is actually a very potent weapon in our armoury, in that it can combine the safening effect with other attributes such as slow release, which has been referred to earlier in connection with pheromones.

Thus we see that, even with broad-spectrum compounds which are intrinsically toxic to beneficial organisms, there is a strong trend towards finding ways to use them selectively.

SUMMARY AND CONCLUSIONS

The trends in pesticide development which I have briefly described here fall naturally into two categories : target-specific materials, and 'safety-in-practice' with some broad-spectrum compounds. Developments in both these categories have until recently been very slow, and the consequent paucity of selective pesticides has in turn seriously hindered the progress of integrated pest management.

The last few years have seen a considerable improvement in the position, and the change is gathering momentum. There are a number of reasons for this, the main one being the advent of new chemical and biological technologies which can be applied to bring many ideas, which have been virtually shelved for decades, into practical usage in the field.

Another important reason is that the agrochemical industry, at last provided with the tools for the job of developing these old ideas, has been able to indentify adequate niches for selective pesticides in the market place. Once released from technical constraints, the industry is now also finding ways to surmount the obstacle of inadequate financial returns on small, selective products, through collaborative development programmes with governments and research institutions. In this way the financial burden is shared, and the benefits accrue to all parties - to the farmer in terms of safer products and possibly increased yields from better pest control; to his government in terms of improved agricultural productivity;

to the agrochemical company from a small though profitable new product; to the home government from increased tax revenue and often from license fees on the fruits of the collaborative programme; and last but not least to the earth's ecosystem from the reduction in environmental impact of agricultural pesticides.

In conclusion I return to my original thesis. These are exciting times for agricultural zoologists, and I believe that the next two decades will see a flowering of our art. The wide scale development of integrated pest management, which has been our dream for too long, is approaching reality. More effective pesticides, which are either selective or safe in practice to beneficials, will play a major role; and this in turn will be greatly aided by the collaboration of all parties - governments, the scientific research community and the agrochemical industry.

REFERENCES

Beroza, M. (1960) Insect attractants are taking hold. Agricultural Chemicals 15 (7), 37-40.

Bocquet, J-C.; L'Hotellier, M. (1984) Effect of deltamethrin on aquatic environments. In : Society of Chemical Industry Pesticides Group Symposium. Pyrethroid Insecticides in the Environment. Southampton University, England 11th-13th April 1984.

Cole, J.F.H.; Wilkinson, W. (1984) The effects of autumn sprays of cypermethrin, dimethoate and pirimicarb on cereal arthropods. In : Society of Chemical Industry Pesticides Group Symposium. Pyrethroid Insecticides in the Environment. Southampton University, England 11th-13th April 1984.

Coppel, H.C; Mertins, J.W. (1977) Biological insect pest suppression. Advanced Series in Agricultural Sciences 4, 314 pp. 1st. Edition. Springer-Verlag Berlin, Heidelberg.

Gerig, L. (1984) Testing bee toxicity of synthetic pyrethroid insecticides. In : Society of Chemical Industry Pesticides Group Symposium. Pyrethroid Insecticides in the Environment. Southampton University, England 11th - 13th April 1984.

Kingsbury, P.D.; Kreutzweiser, D.P. (1984) The impact of permethrin on aquatic ecosystems in Canadian forests. In : Society of Chemical Industry Pesticides Group Symposium. Pyrethroid Insecticides in the Environment. Southampton University, England 11th - 13th April 1984.

Stephenson, R.R. (1984) Assessing the hazard of pyrethroid insecticides in the aquatic environment. In : Society of Chemical Industry Pesticides Group Symposium. Pyrethroid Insecticides in the Environment. Southampton University, England 11th - 13th April 1984.