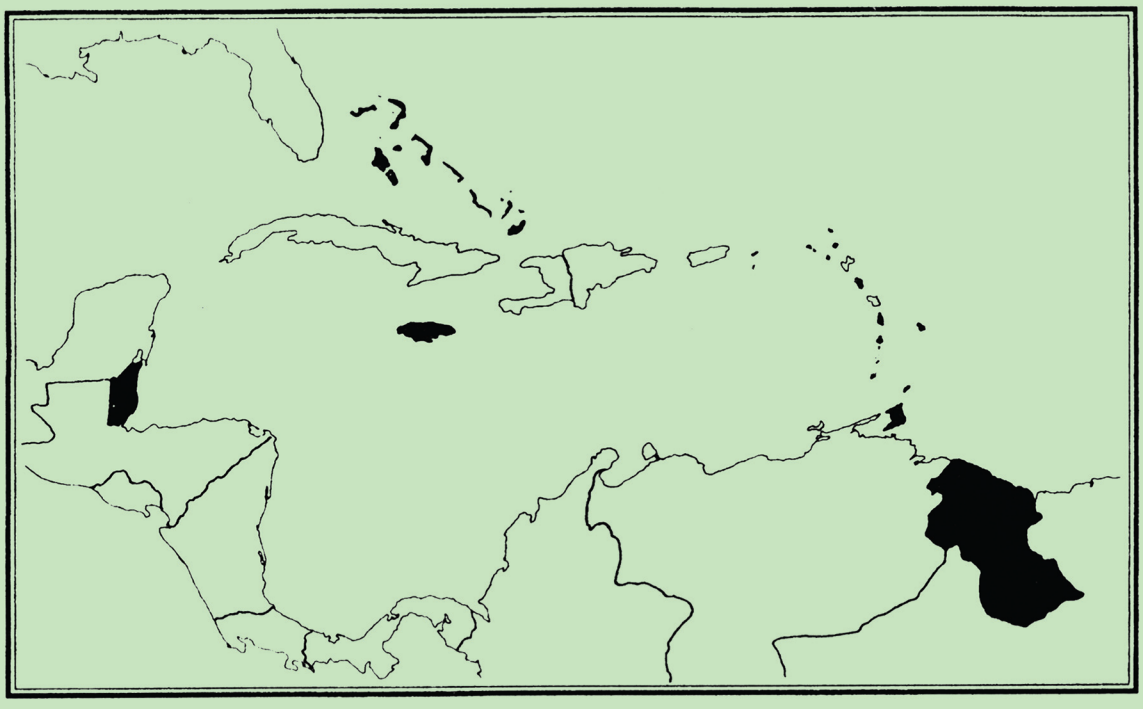
AGRICULTURE PROGRAMME SERIES

The Biological Control of Crop Pests in the Caribbean

Report of a workshop held in Roseau, Dominica, October 1992



COMMONWEALTH SCIENCE COUNCIL

TECHNICAL PAPER 312
NUMBER CSC(97)AGR24

AGRICULTURE PROGRAMME SERIES

The Biological Control of Crop Pests in the Caribbean

Report of a workshop held in Roseau, Dominica, October 1992

Edited by R Hall

Commonwealth Science Council

COMMONWEALTH SECRETARIAT

Designed, printed and published by the Commonwealth Secretariat
Marlborough House, Pall Mall, London SW1Y 5HX, Britain

Wherever possible, the Commonwealth Secretariat uses paper made from sustainable forests or from sources that minimise a destructive impact on the environment.

May be purchased from the Commonwealth Secretariat's distributors:
Vale Packaging Ltd, 420 Vale Road, Tonbridge, Kent TN9 1TD, Britain
Telephone: +44 (0) 1732 359387 Fax: +44 (0) 1732 770620

Agriculture Programme Series Number CSC(97)AGR24
Technical Paper 312

ISBN: 0 85092 512 6

Table of Contents

Introduction: Seventh Meeting of the Technical Advisory Committee of Plant Protection Directors 1

Microbial Control of Whitefly *(Bemisia Tabaci)* and Thrips Palmi in Trinidad and Tobago,
by Richard A Hall 3

Bemisia Tabaci (the Sweet Potato Whitefly),
by Professor Dan Gerling 9

Advances in Mycopesticide Formulation and Application,
by Chris Prior 17

Summary of Conclusions from Planning Session at Dominica Workshop,
by J Mumford 23

Appendix 1: List of Participants 25

Introduction

Seventh Meeting of the Technical Advisory Committee
Of Plant Protection Directors, Caribbean Area
October 26-30, 1992, Roseau, Dominica

The Seventh Meeting of the Technical Advisory Committee of Plant Protection Directors was held between 26 and 30 October, 1992, in Roseau, Dominica. The meeting was organised by the Commonwealth Science Council, London, the Inter-American Institute for Co-operation on Agriculture (IICA) and the International Institute of Biological Control. The meeting was essentially divided into two parts - one dealing with plant diseases, the other with crop pests. The proceedings of the first part, including the country reports, has been published in a report by IICA.

As far as crop pests are concerned, the meeting focused on the problems posed by whitefly (*Bemisia tabaci*) and *Thrips palmi*, which are the major pests of the region.

A small number of specialist presentations were made and these were followed by a round table discussion on possible strategies for combating the problems.

The presentations were made by Dr D Gerling of the University of Tel-Aviv, who detailed the biology of *Bemisia tabaci* and its predators and parasites; Dr R A Hall, in charge of the National Institute for Higher Education, Science and Technology (NIHERST) Biological and Integrated Control Projects in Trinidad and Tobago, who spoke on the use of pathogens to control whitefly and *T. palmi*; and Dr C Prior of the International Institute of Biological Control, who spoke on the control of locusts by pathogens. A short presentation on a new bioassay system for thrips and whitefly was given by Ms Dorothy Peterkin, a member of the NIHERST biological control group.

Microbial Control of Whitefly *(Bemisia Tabaci)* and Thrips Palmi in Trinidad and Tobago

Richard A Hall, NIHERST (National Institute of Higher Education, Research, Science and Technology), Victoria Avenue, Port of Spain, Trinidad and Tobago

Introduction

Problems with chemical control, whether due to resistance of insect pests to pesticides, the enormous cost of bringing new chemicals onto the market, or to environmental considerations, are beginning to dictate the pace at which the development of biocontrol agents is moving. The Government of Trinidad and Tobago has recently invested in several research programmes to develop alternative strategies to chemical control on vegetables and other edible crops. These research projects take the form of training programmes, the aim being to establish a permanent biocontrol capability in the region.

The training is accomplished through post-graduate research programmes targeted at the major pests of food crops in Trinidad and Tobago, as follows:

(i) control of whitefly by pathogens;
(ii) control of thrips by pathogens;
(iii) control of thrips by predators;
(iv) control of sugarcane froghopper by pathogens;
(v) control of caterpillar pests on vegetables; and
(vi) control of locusts by pathogens.

These projects are being financed and assisted by various organisations in Trinidad and Tobago, notably the National Institute of Higher Education, Research, Science and Technology (NIHERST), Caroni (1975) Limited, the Ministry of Agriculture, the International Institute of Biological Control and the Commonwealth Secretariat.

Since this workshop focuses on the problems posed by *Thrips palmi* and *Bemisia tabaci* (whitefly), I shall be talking exclusively about the potential of fungal pathogens of these pests.

Why only fungal pathogens?

Thrips and whitefly feed on plant juices which, being virtually sterile, contain no micro-organisms capable of causing disease in insects. Therefore, in order to provoke disease in such an insect and kill it, a disease causing micro-organism must invade via the cuticle, natural orifices or wounds. Invasion via the latter route would be expected to be comparatively rare and so will not be considered here. Of the various groups of micro-organisms (bacteria, viruses, protozoa and fungi) only fungi possess the ability to literally bore a hole through the insect cuticle thereby achieving infection. Thus, microbial control of pests such as thrips and whitefly means, exclusively, control by fungi.

Fungi Attacking Insects

Fungi from many taxonomic classes infect insects. However, we are concerned chiefly with the class Deuteromycetes. This is mainly because this class contains species which are highly infective for insects, and easy to culture and produce in both. The species with which we are concerned are, in addition, considered to be safe for plants, animals and humans and, due to strain specificity, also for non-target insect pests. Deuteromycete species reproduce asexually by spores called conidia or conidiospores.

Mention in this paper is also made of some species of the class Zygomycetes - the (Order) Entomophthorales. Species in this class tend not to be easily manipulable but I refer to them briefly as they are amongst the most effective of insect pathogens in nature.

Do Fungal Pathogens Work?

With very few exceptions, all fungi have an absolute requirement for high humidity (>93 per cent) for spore germination and growth. It does not matter whether this humidity requirement is satisfied at a micro-climatic or macro-climatic level. Although it appears that the microclimate humidity may be high on certain parts of the cuticle on some insects (particularly the supple connective tissue between sclerites), thereby possibly permitting germination of insect pathogens at low ambient humidities (Ramoska, 1984), there can be no doubt that infection will occur most efficiently on an insect cuticle during a period of high ambient humidity. The best successes have been recorded where humidity was expected to be high, e.g., in greenhouses, and we may cite the example of *Verticillium lecanii*, a pathogen of aphids and whiteflies. Several years' research by the author on many strains of this fungus culminated in the commercialisation of two such strains - an 'aphid strain'

('VERTALEC') and a 'whitefly strain' ('MYCOTAL') (Hall and Papierok, 1982). These two products are currently produced by the world's largest commercial producer of biological control agents, Koppert B V in Holland. There are not many other examples of commercialised fungal pesticides ('mycopesticides'). Bayer in Germany has recently brought a preparation of *Metarhizium anisopliae* ('BIO 1020') onto the market for the control of a subterranean pest, vine weevil (*Otiorhynchus sulcatus*). The same species is produced commercially for the control of froghopper (*Aeneolamia varia saccharina*) on sugarcane in Venezuela, and has enjoyed considerable success. M. *anisopliae* is used on a large scale in Brazil for the control of other sugarcane and pasture pests and elsewhere in South and Central America. There are numerous reports emanating from the former Soviet Union and China of fungi being used on a commercial scale.

The paucity of economic applications of entomogenous fungi is a little deceptive, as many research efforts failed to focus on those insect pests occupying a habitat where the essential physical requirements, notably temperature and humidity, would be adequately met. In addition, the relationship between the fungal pathogen and the population dynamics of the pest must be in favour of the fungus if the pest is a rapidly-reproducing one - such as whitefly or thrips. In those regions where fungi might be expected to have most potential, such as in the humid tropics, it is true to say that comparatively few in-depth studies have been carried out.

A few years ago, the answer to the question 'do fungi work?' might have been yes, as long as we did not stray too far from the ecological niche and host range within which these pathogens are naturally very (and sometimes dramatically) effective. However, very recently some developments have indicated that it might be possible to stretch the capabilities of fungi beyond their traditionally perceived limits. Instead of aqueous sprays, spores may be applied in oil-based formulations. Fungal spores have been shown to kill locusts at ambient humidities of 35 per cent (Goettel, 1992). Also, oil-based formulations appear to lower LC50s in bioassays (Prior et al., 1988). However, such formulations would not help a fungal pathogen spread from an infected insect to a healthy one if the humidity were not sufficiently high for a reasonable length of time to permit reproduction of the infectious propagule, i.e., sporulation on the insect body. Such spread of disease may be crucial in obtaining economic control of rapidly reproducing insect pest populations. To overcome this constraint, repeated applications at judiciously chosen intervals would be necessary to bring about the control of such insects.

Another strategy whereby fungi may be rendered more effective focuses on accelerating the infection process so that spores may germinate during a shorter 'window' of high humidity, or before they become dislodged, preened off or inactivated for whatever reason. At least two phenomena have been discovered by our group in Trinidad and Tobago which may lead to methods of accelerating the infection process. One discovery relates to the fact that spores produced in very young cultures germinate significantly faster than those from older (but still young) cultures. (These spores are probably the first-formed spores on a phialide). The elucidation of the reasons for faster germination may eventually result in more efficient spore preparations and possibly genetically modified strains with greatly improved epizootic potential.

Such improvements in application technology and a greater understanding of the fundamental key processes in the infection cycle will probably usher in a new and exciting era of research into pest control by fungi.

Pathogens of whiteflies

The following species have been and are being investigated as whitefly control agents:

Aschersonia aleyrodis
Verticillium lecanii
Paecilomyces fumoso-roseus
Bauveria bassiana

Their potential for controlling *Bemisia tabaci* will be discussed.

Aschersonia aleyrodis

This species is frequently found on whiteflies in lowland tropical zones, though we have yet to find it on *B. tabaci* in Trinidad. However, the species is common on citrus scale in Trinidad, as is *Aschersonia turbinata*. Apparently, *A. aleyrodis* has been shown to attack *B. tabaci* in Florida.

A. aleyrodis is an intriguing fungus. Being slow to germinate, it would be expected to infect insects rather more slowly than other pathogens such as the faster-germinating *V. lecanii*. In reality, against the glasshouse whitefly (*Trialeurodes vaporariorum*), the speed at which sprayed *A. aleyrodis* pores infect the pest is quite surprising - faster than *V. lecanii* - even when humidity appears to be sub-optimal. *A. aleyrodis* infects only the larval stages of whitefly, adults and eggs rarely becoming infected. Consequently, in European glasshouses, it does not spread from infected to healthy insects and so must be sprayed many times to achieve control of this

rapidly-reproducing pest. However, on citrus whitefly the fungus spreads extremely efficiently, as evidenced by virtually 100 per cent natural control of this pest each season. Osborne and Landa (unpublished) have recently made observations which may explain this apparent contradiction.

A. aleyrodis is highly specific for whiteflies and does not harm natural enemies. Therefore, in glasshouses, it may be used against whitefly in conjunction with the parasitoid *Encarsia formosa*, and is especially useful as a 'knock down' agent when whitefly populations have become too large for *E. formosa* to control. There are some outstanding problems with this fungus relating to mass-production and stabilisation of spores of this fungal species.

In Trinidad, we have tested in the laboratory a strain of *A. aleyrodis* which gave good results against *T. vaporariorum* in the UK (Hall, unpublished observations). However, we have not been able to achieve any infection of *B. tabaci* in Trinidad with this strain. We have recently acquired, from Dr Lance Osborne (University of Florida), a strain known to infect *B. tabaci*. If the results which I obtained in the UK on the glasshouse whitefly can be repeated on *B. tabaci*, then we shall be focusing a good deal of attention on this fungus.

Verticillium lecanii

There are many strains of *V. lecanii* attacking a wide variety of insect hosts and plant pathogens. The classification of this fungus is open to question, some workers preferring to split the complex into further species. Certainly *V. lecanii* can be divided into large-spored and small-spored strains. Large-spored strains are found exclusively infecting aphids, though in the laboratory they will also infect other pests including whitefly (Hall, 1982). The commercial aphid-killing product VERTALEC is based on such a large-spored strain (Hall, 1982). Strains from thrips, whitefly, mites and phytopathogenic fungi are always small-spored strains and the commercial product for whitefly and thrips (MYCOTAL) is based upon a small-spored strain (Hall, 1982). However, small-spored strains are sometimes found in nature on aphids also. To simplify the situation, small strains perform best against whitefly and thrips while large-spored strains do best against aphids. From the point of view of whitefly control, therefore, we are interested in small-spored strains. These have a temperature optimum of about 24°C which may limit their potential in the humid tropics where average temperatures are often higher than this. In general, constant temperatures a few degrees beyond the optimum have a dramatically negative effect on the performance of insect pathogenic fungi. While *V. lecanii* is the only fungus found infecting the glasshouse whitefly (*Trialeurodes vaporariorum*) in glasshouse environments in temperate regions and at high altitude in Colombian plastic houses, it is very rarely found infecting whitefly in lowland tropical areas. For this reason, I feel that *V. lecanii* has little potential against *B. tabaci* in such areas.

V. lecanii infects both larval and adult stages of whitefly but not eggs. This fungus may be mass-produced on solid-substrate or in liquid medium.

Paecilomyces fumoso-roseus

This species has a rather wide insect host range including whiteflies. Amongst the latter, both larval and adult stages are attacked and to a certain extent, if humidity is very high, the eggs. It has been investigated to some extent in Florida as a control agent of *B. tabaci* and by our group in Trinidad. This fungus has a temperature optimum of 28°C - considerably higher than the small-spored strains of *V. lecanii*. For this reason, I believe that from an ecological standpoint, *P. fumoso-roseus* is better adapted than *V. lecanii* to exploit the lowland tropical niche. It is not surprising therefore that *P. fumoso-roseus* is the only fungus found in Trinidad on *Bemisia*. By the same token, this species has, to my knowledge, never been found in European glasshouses or high altitude plastic houses in Colombia.

Since *P. fumoso-roseus* is amenable to mass-production and displays high virulence to *B. tabaci*, we are concentrating much of our research effort on this fungus.

Beauveria bassiana

The fungus *B. bassiana* is not considered to be a natural pathogen of whiteflies. However, it is included in this list because scientists in the USA claim that a strain of this fungus (isolated from the cotton boll weevil), provides very good control of *B. tabaci* in greenhouse and field vegetables. In arid areas in Arizona and California, they reported that oil-based formulations of *Beauveria bassiana conidia* gave adequate control. Eggs, larvae and adult stages are reported to be infected by this strain.

Pathogens of Thrips Species

Many of the species which attack whitefly also infect thrips. The fungi known to attack thrips species are as follows:

Verticillium lecanii

Paecilomyces fumoso-roseus

Beauveria bassiana

Neozygites parvispora (Entomophthorales)

Entomophthora thripidum (Entomophthorales)

Metarhizium anisopliae

Hirsutella spp

Verticillium lecanii

This species has been described above. In temperate zones, *V. lecanii* may easily be found infecting thrips species in glasshouses and, in both temperate and tropical zones, laboratory cultures. Small-spored isolates of the fungus are exclusively associated with these insects. The commercial product MYCOTAL also possesses the best thrips activity of any strain of *V. lecanii* so far examined. We have established that *Thrips palmi* is susceptible to the MYCOTAL strain but, for the reasons given above, it is not likely that the known strains of this fungus will be of much value in controlling *T. palmi* in lowland tropical areas.

Paecilomyces spp

Paecilomyces spp have rarely been associated with field infections of thrips. However, there is at least one report from Puerto Rico of a *Paecilomyces sp* infecting *Gynaikothrips ficorum*. Furthermore, we have encountered *Paecilomyces fumoso-roseus* killing *Thrips palmi* in laboratory cultures, and on one occasion in the field.

Beauveria bassiana

There are several reports in the literature of this species attacking thrips species, most notably *Selenothrips rubrocinctus* on cocoa. In the laboratory, *B. bassiana* is pathogenic to *Thrips palmi*.

Metarhizium anisopliae

There is only one report of this fungus attacking thrips *T. palmi*, in a greenhouse in Puerto Rico.

Neozygites parvispora and *Entomophthora thripidum*

There are numerous reports of these fungi attacking a range of thrips species. *N. parvispora* has been reported from Japan on *T. palmi*. These fungi provoke spectacular epizootics in thrips populations. However, neither of these fungi has been successfully cultured and so the prospects of producing sufficient infective material for wide-scale application are, at present, poor.

Hirsutella spp

Recently, several isolations of new *Hirsutella* species have been made. At least two have been made in Trinidad - one by Prior from *Limothrips* sp and a new species from *Thrips palmi* (Hall, 1992). The latter has been cultured and its potential is being investigated in the laboratory by our group in Trinidad.

To summarise, there are only two reports of fungi attacking *T. palmi* in natural field conditions - *Neozygites parvispora*, and *Hirsutella* spp *Metarhizium anisopliae* was found only once in a greenhouse in Puerto Rico. Of the fungi found consistently on thrips in general, we may cite *Beauveria bassiana*, *Verticillium lecanii*, *Hirsutella* spp and members of the Entomophthorales.

Research Strategy

Once we have a collection of pathogenic isolates of fungi, how do we decide which performs best against the target pest? The definitive way is to spray infective material in the field. However, when there are more than a very few such pathogens to be tested, this is impractical because field trials are expensive and time-consuming. Therefore, prior to investing scarce resources in field trials, one must develop laboratory systems which provide information which is reasonably predictive. Such a laboratory system for quantifying the ability of a pathogen to infect its host is called a bioassay. A well-designed bioassay system will provide information which will enable the researcher to predict which strains of pathogens will perform best under field conditions. An ill-conceived system will yield practically no information at all. For example, the literature abounds with examples of bioassay systems which do no more than demonstrate how insects react to a stressor (in this case a pathogen) in already stressful conditions e.g. continuous high humidity - which, of course favours the fungal pathogen. Some insects may react negatively to continuous high relative humidity and this is revealed by a high control mortality. Furthermore, small, highly mobile insects such as thrips may drown in small condensation droplets or they may escape or become trapped or hidden in crevices all of which contribute to a high control mortality. Whatever the reason, a high control mortality prevents an accurate assessment of the infective ability of a pathogen. Very little work has been published on the bioassay of fungi against thrips. However, high control mortalities have been a feature in many of these and, consequently, the significance of the results is questionable.

Therefore, it is important to develop a bioassay system which permits almost all control insects to survive apparently healthily to the end of the assay period. Us-

ing previously developed systems for thrips species, we first encountered unacceptably high control mortalities sometimes as high as 90 per cent. Consequently, we had to develop a totally new bioassay system which fulfilled the following important criteria:

- the insects must be individually contained to eliminate the risk of cross-contamination;
- the insect should be able to move freely within the bioassay chamber;
- the system should permit clear observation of the insects at all times;
- there should be sufficient air exchange to supply the needs of the insect and leaf tissue and to prevent condensation (in which small insects such as thrips may drown) on the walls of the chamber or on the leaf discs;
- the substrate, normally leaf tissue, must be maintained in a palatable form for the duration of the bioassay;
- there should be minimal handling of the insect;
- the control mortality must be within acceptable limits (below 10 per cent);
- the cages must be escape-proof; and
- the system must be reasonably simple to set up so that large numbers of assays may be performed without undue difficulty.

Our new system relies on using a Plaster of Paris matrix for supporting leaf discs, the whole contained in a compartmented square Petri dish. Control mortalities, including escapes, have been reduced from a maximum of 90 per cent using other systems to a maximum of 8 per cent using the Plaster of Paris system (Hall et al., 1993). Furthermore, a much simplified version of this system is suitable for sessile insects such as *Bemisia* immatures.

The function of a laboratory bioassay in terms of the epizootiological field characteristics of a pathogen requires further definition. If a pathogen is to infect only those insects which are hit by a spore spray - such as dry-season multiple application of oil-based spore sprays - then the sort of infectivity assay which has been described will probably be adequate. However, it is necessary to look at a new factor, the epizootic potential when we consider post-application spread of the pathogen from diseased insects hit by a spray to healthy insects. Epizootic potential becomes very important when, within rapidly reproducing pest populations, in conditions which are favourable for the fungal pathogen, we expect the disease to achieve control after only one or a very few applications. How do we measure epizootic potential? It is difficult conceptually to standardise and quantify the ability of a pathogen to spread. A good epizootic potential probably cannot be predicted from high infectivity as measured by bioassay. In the case of the fungus *Verticillium lecanii* on aphids, while strains with good epizootic potential always exhibited high infectivity, the reverse was most certainly not true (Table 1). We cannot measure epizootic potential but we can certainly compare epizootic potentials of pathogens, as the data in Table 1 adequately demonstrate.

TABLE 1: **Mortalities of adult aphids treated with pores of different strains of *V. lecanii* and their progeny acquiring disease from the adults through contagion**

Strain	Adult mortality per cent	Progeny mortality per cent	Epizootic potential
1-72	100	84	good
93-82	100	77	good
57-81	91	9	poor
79-82	100	0	poor
18-78	91	8	poor

Recently, there have been reports that bioassays at sub-optimal relative humidities may serve to select the most aggressive strains of fungi, and possibly those with good epizootic potential also. This may stem from the fact that, as I mentioned before, some insects are stressed under conditions of continuous high humidity, probably because they cannot get rid of excess moisture sufficiently rapidly. At sub-optimal humidities, insects may be in much better shape and only the most pathogenic organisms may be able to provoke significant mortality. In our laboratory we are modifying the Plaster of Paris assay system along these lines to test this possibility. To summarise, there are no hard and fast rules as to what sort of assay system one should employ to screen fungal pathogens prior to testing them in the field. What is important is that the researcher should have a very clear idea of what the objectives are, and therefore what pathogenic characteristics should be focused upon.

Progress of Research in Trinidad

Our microbial research projects in Trinidad have only been in progress for just over one year. However, what can we conclude so far about the potentials of the fungi at our disposal?

Bemisia tabaci

This pest is most serious in the dry season. Fungi are not going to be in an 'epizootic phase'. Therefore, in this scenario, only oil- or emulsion-based spore sprays would have any impact on populations at this time. At other times during the wet season, a strategy of wide-scale applications of fungal strains with good epizootic potential may eliminate populations from an area enabling farmers to have a 'clean start' at the beginning of the dry season. In the context of sound integrated pest management practices, this 'clean start' could be expected to last well into the dry season.

The candidate fungi likely to be developed successfully for whitefly control in the short term are *Paecilomyces fumoso-roseus* and, in the light of the favourable reports from the USA, one cannot ignore *Beauveria bassiana*. *Verticillium lecanii*, which can so spectacularly control whitefly in glasshouses in temperate regions (Hall, 1982), is not likely to have a significant role in lowland tropical areas. The fungus *Aschersonia aleyrodis* should be tested against *Bemisia* as it has given good results against other whitefly species.

Thrips palmi

We still have little information on the abilities of the pathogens mentioned earlier to control *T. palmi*, either in the field or in the laboratory. Now that we have developed a good bioassay system, the laboratory evaluation phase is well under way. Again, *T. palmi* is mainly a dry season pest and the principles propounded above for whitefly are also appropriate for the control of this pest.

Conclusions

We probably already have in our collections the best species and strains of pathogens of *Bemisia tabaci* and *Thrips palmi*. In the past, we would have been restricted to wet-season application of infectious spores of these fungi in high-volume aqueous suspensions. Oil-based spraying technologies now also open up the possibility of dry-season application. Further advances hold the promise of increasing the natural efficiency of these pathogens. For example, our work in Trinidad and Tobago has revealed two methods of accelerating spore germination, and by implication the infection process. Given that in the field, fungal spores can only germinate during a 'window' of favourable humidity and temperature which occurs usually at night and is usually of limited duration, such discoveries could lead to a disproportionately high increase in infectivity or epizootic potential. These developments give cause for pathogenic fungi. It is highly likely that fungi will have an important role in future integrated pest management programmes for whitefly and thrips control.

References

HALL, R A, and PAPIEROK, B (1982). Fungi as biological control agents of arthropods of agricultural and medical importance. *Parasitology*, 84, 205-240.

HALL, R A (1982). Control of whitefly, *Trialeurodes vaporariorum* and cotton aphid, *Aphis gossypii*, in glasshouses by two isolates of the fungus *Verticillium lecanii*. *Annals of Applied Biology*, 101, 1-11.

HALL, R A (1992). A new pathogen on *Thrips palmi* in Trinidad. *Florida Entomologist*, 75, 380-383.

HALL, R A, PETERKIN, D, and POLLARD, G V (1993). A system of caging *Thrips palmi* for laboratory bioassay of pathogens. *Florida Entomologist*, 76, 171-175.

GOETTEL, M S (1992). Fungal agents for biocontrol. In: Biological Control of Locusts and Grasshoppers. (eds. C J Lomer and C Prior), CAB International, pp.122-132.

PRIOR, C, JOLLANDS, P, and le PATOUREL, G (1988). Infectivity of oil and water formulations of *Beauveria bassiana* (Deuteromycotina: Hyphomycetes) to the cocoa weevil pest, *Pantorhytes plutus* (Coleoptera: Curculionidae). *Journal of Invertebrate Pathology*, 52, 66-72.

RAMOSKA, W A (1984). The influence of relative humidity on *Beauveria bassiana* infectivity and replication in the chinch bug, *Blissus leucopterus*. *Journal of Invertebrate Pathology*, 43, 389-394.

Bemisia Tabaci (the Sweet Potato Whitefly)

Professor Dan Gerling, Department of Zoology, Tel Aviv University, Ramat Aviv 69978, Israel

A. The history of the pest

It is useful to consider the history of this homopteran pest in three phases.

Phase 1: Local outbreaks

There are descriptions of *Bemisia tabaci* from Greece in 1889, but it probably originated in Pakistan or Western India. Records of outbreaks from India exist from the early years of this century. Since 1927, *B. tabaci* has caused severe problems on vegetables in Palestine, and then in Israel, but until about 1968-9 it was only a pest of local significance. *B. tabaci* caused mainly two types of damage: (1) direct damage by feeding on the plants, and (2) transmission of plant viruses.

Phase 2: A worldwide cotton pest

In the late 1960s things started to change. *B. tabaci* became a very serious problem in the Sudan where the cotton industry suffered badly from sticky lint caused by the honeydew secreted by the insect. Early in 1970 the Sudanese had problems selling their cotton on account of its stickiness. Heavy outbreaks occurred in Turkey in 1973 and in 1976 in Israel. Very large numbers of *B. tabaci* caused heavy damage, and the means formerly known to control it no longer seemed to work any more. In 1981 the same thing happened in California on cotton, but this time lettuce plants were also attacked. *B. tabaci* grew on cotton, then landed on lettuce when cotton was defoliated around September, and although the whitefly does not reproduce well on lettuce, it transmitted Lettuce Infectious Yellowing Virus, which caused heavy losses.

Phase 3: Proliferation of new biotypes (type B or silverleaf whitefly)

The third phase of the history started in 1986 when heavy infestations occurred in Florida. In this case, Poinsettias and Hibiscus were severely attacked. In a short time the same problem turned up in California and it was traced to certain plants shipped there from Florida. No internal quarantine existed because at that time the *B. tabaci* occurring in Florida was not recognised as being any different from that in California (see below). Within a short period it moved (on greenhouse cultures) to many parts of the USA and later to the Caribbean and Mexico as well as South America. *B. tabaci* (strain affiliation unknown) has also invaded urkmenistan, (which used to be one of the Soviet Union Asian Republics) in 1985-87, as well as Japan. Thus, within 10 to 15 years what was a local problem has extended to become a global pest in most tropical and subtropical climates.

B. Biotypes of *Bemisia tabaci*

It is generally accepted that *B. tabaci* biotype B, which was found and typified in Florida and since then has shown up in many other places, differs considerably from the biotype that was previously known from California, and now designated as biotype A. Moreover, recent work suggested that 'B' may be a different species altogether. Molecular work done in the UK and the USA indicates that biotype B has invaded most of the world and is the dominant species in many countries. In addition to biotypes A and B, one can distinguish numerous additional types in various countries. In general, the methodology involved in *B. tabaci* biotype determination can be classified as follows:

(a) A single *B. tabaci* individual can be run through an electrophoretic plate to test for enzymatic differences. The only enzymes where meaningful differences have been found are the esterases. The different bands that show up on the electrophoretic gel were compared for *B. tabaci* collected in Israel ten years ago to those found in California, Florida (post-1986) and Kenya. All were distinctively different from each other. In Colombia we found four different strains, one for each valley between the mountain ranges of that country. A modification of the electrophoretic method, called iso-electric focusing, allows for comparing between individuals using more enzymatic patterns. This method was used to suggest that biotype B may constitute a distinct species.

(b) The insect can be tested for various biological parameters, such as longevity, flight behaviour and fecundity, and con-specificity can be tested through mating experiments. In order to do this it is very important to standardise techniques and methods, with both test groups being kept in the same place. This has been done for biotypes A and B in cultures in Britain, California and Arizona. The understandable reluctance of scientists to introduce questionable strains of this pest into their country greatly limits the use of this method. Some of the results of the biological tests include the findings that biotypes A and B differ in the amount of eggs they lay and their speed of development, and the two biotypes have great difficulty mating together.

(c) Host range: in the CABI literature review *B. tabaci* has a host range that is practically unlimited; between 500 and 700 plant species. When the host range reaches this level, the number of species affected becomes immaterial - there are probably plenty more hosts that have yet to be discovered. To be classified as a host means only that at least one insect has been found growing from egg to maturity on it. There is a world of difference between classifying plants as hosts and stating that *B. tabaci* is an agricultural pest. Thus, there are records of *B. tabaci* being in the Caribbean for many years. But this only means that it was able to reproduce successfully on plants in this region, but not necessarily that it was a pest.

We can observe different host ranges that may be typical to different biotypes. However the distinction is rarely absolute, as for example in the case of cassava, a root crop introduced into Africa and Asia from South America that has now become a staple crop for millions of people. In Africa, cassava is heavily attacked by *B. tabaci*, which directly affects yield and also transmits a mosaic virus which causes severe problems. This is not a problem in South America, however, where *B. tabaci* is not a serious pest of cassava. This is an example of host range inconsistencies, caused perhaps by strain differences.

Similarly *B. tabaci* was not known historically as a pest of crucifers. Nowadays, however, *B. tabaci* infestations on broccoli are a serious problem in California. The Imperial Valley is a major agricultural area where farmers grow cotton in the summer, broccoli in the autumn and lettuce later on. Before *B. tabaci* attacked crucifers the farmers left a gap between planting cotton and lettuce. This was sufficient to allow the whitefly populations to die down, since the pest cannot survive in the hot temperatures (40°C to 45°C) encountered in the Imperial Valley during that season, without suitable host plants. Now that broccoli is also attacked, they have a severe problem with whitefly, especially with virus transmission to the lettuce.

We mentioned previously the differences in esterases between the original Israeli whitefly and samples from Florida and California. Recently, however, the Israeli *B. tabaci* has begun to attack broccoli and other crucifers, and it has been shown by scientists in Britain that the Israeli strain now has the same characteristics as strain B. In addition, some experiments conducted in the United States Department of Agriculture laboratory in Salinas show that the esterase pattern of the Israeli *B. tabaci* is now similar to strain B.

Therefore, host range can now be used as a criterion for separation of strains, albeit a flexible one. One must always remember that when there are millions of pest individuals looking for food, there are very strong selection pressures to vary or change host range. With enough pressure, *B. tabaci* may manage to overcome some of the allelochemicals that might be discouraging attack. This probably occurs with relative ease in a species whose records show that it may have a very extensive host plant range. The overall picture is of different *B. tabaci* strains at different times and places, but this is no more than a convenient way to describe the *status quo* and is not an absolute means of classification. There will probably always be questions that can not be reconciled by strain testing. For example, the B strain in Florida is a pest of Hibiscus but in Israel it does not touch Hibiscus (at least not at the moment) - just to remind us that the host range is flexible.

C. Climatic factors

Bemisia tabaci is a typical warm climate insect pest - it does best between 25°C and 32°C. In laboratory experiments we have shown that it cannot survive over 34°C. This does not mean that when ambient temperatures exceed 35°C it will die out; indeed, *B. tabaci* is a serious pest in the Sudan and Egypt where summer temperatures reach 40°C and above. This is possibly due to the microclimate that surrounds the plant that is lower than the ambient temperature. In subtropical climates found in, for example, Israel and California, there are dramatic declines in whitefly populations caused by cooler temperatures, though infestations may continue to be severe on protected crops in greenhouses. Therefore, care is needed when comparing control strategies between countries or regions because climates can be so very dif-

ferent. A strategy unit might work well at a certain time of the year in Israel, but may not work in the Caribbean because of climatic differences.

B. tabaci does not do well in high humidities (above 65-70 per cent Relative Humidity) or extremely low humidities (below 20 to 25 per cent RH). In Israel, for example, when humidity is low (between May and July for one or two days each month, there can be dry winds with 15 per cent RH or less) the population drops to almost zero. At the other extreme, under rain forest conditions, *B. tabaci* does not do well and it is usually not a pest in such climates.

D. Biology

Eggs are laid on the underside of the leaf - preferentially along the veins. The female customarily sticks her mouth-parts into the leaf and starts ovipositing. With her stylet remaining in the leaf she rotates a little so that the eggs are laid in the pattern of a semi-circle or even a complete circle. Eggs hatch into crawlers which start to move around, but unlike scale insects they do not leave the leaf on which they have hatched. After a while they settle, stick their mouth-parts into the leaf and start developing into the 2nd, 3rd and 4th instars, and then into the a pupa, which is actually a continuation of the 4th instar. The adult emerges from the pupa through a T-shaped opening in the dorsal integument (parasitoids make a round hole when emerging).

Males are somewhat smaller than females. Usually the largest number of adult *B. tabaci* are found on the youngest growing parts of the plant, and these are normally the areas of the plant bearing most eggs and young immatures. Eggs are laid on the young growth and it takes approximately 20 days (the shortest development is about 14 days at about 30°C) for development to the adult stage. During this time, the plant keeps on growing, often very fast, so that the pupae are usually found lower on the plant than the eggs. Once they emerge, the adults may stay on the leaf for between 1 to 3 days and at the same time they may also deposit a few eggs on that original leaf. However, adult females often look for a more suitable place to oviposit, and so they start moving upwards to younger leaves or move to a different plant.

Moving to a different plant is a process still not completely understood, but some things are clear. In certain conditions, it may be that the plants are disturbed or over-populated and the whiteflies take flight to neighbouring plants or straight up into the air. They are very light insects and may be thought of more or less as aerial plankton rather than active flyers. They have very limited powers to move against prevailing air currents. They can be found 6-8 metres or higher in the air, sometimes in vast numbers. When they want to land, we presume that they spot a suitable place, fold their wings and plummet downwards towards the chosen place. If we monitor the fallout of whiteflies in a heavily infested area by placing a small yellow board on the ground (whiteflies are extremely attracted to the colour yellow) we find that the majority show up around 09.00 am. During heavy infestations as many as 100 *B. tabaci* may land each minute on a 16 x 20 cm board. Roughly 80 per cent of landings occur between 06.00 and 10.00 am.

B. tabaci prefer to land as close to the ground as possible. As many as 10 times more may be caught in a yellow trap at ground level as compared with 1m above the ground.

It would be instructive to know to what extent *B. tabaci* are able to choose their desired landing spot, and whether they can differentiate among the different crops such as melon, cassava or cotton. Experiments have shown that whereas they may be able to distinguish vegetation from bare earth, they cannot distinguish between a very attractive host, for example, melon, and a less attractive one such as cotton. Discrimination will occur only after they have landed on the plant when they decide, often after probing it, whether to stay or to move on. This behavioural pattern is the same for both the greenhouse whitefly and *B. tabaci* and indicates that whiteflies do not know what they are landing on. This trait is used to control for whiteflies - by mulching (see below). This inability to discriminate before landing is also exploited in the design of the whitefly trap (see below).

In *B. tabaci*, sex determination is similar to bees: males are haploid and females diploid. Thus a population can start even if only one female survives quarantine in a shipment to another country. If there is one female on a leaf in that shipment, perhaps in the pupal stage, and she survives to the adult stage, she will lay male eggs (because she is unfertilised) but she may live long enough to subsequently mate with her male offspring and thereby produce females. The sex ratio fluctuates around 50 per cent. In sub-tropical climates there is a preponderance of females in the early summer (about 60-70 per cent) and the summer will end with about 40 per cent females. The sex ratio variation is probably not of great significance for control in the field because there are always sufficient males and females around for the population to continue.

One of the important and unpleasant features of whiteflies is the secretion of honeydew. This is an important feature because honeydew makes the product (e.g., cotton lint or aubergine fruits) sticky and causes sooty moulds to grow. The honeydew of whiteflies differs from that of aphids, and its attraction to ants is much lower. For example, in laboratory whitefly cultures there

are very few problems with ants. All instars secrete honeydew except the pupa, the late instars producing the most.

A final point on the biology of *B. tabaci* in relation to control strategy. At harvest time the whitefly population will quite often be extensive. It is usually not harmed by the harvesting process, and being deprived of the harvested crop, it will migrate to other crops in quest of food. This has advantages and disadvantages: if the whitefly population in the original crop shows heavy parasitism on one crop crucifers, we should consider what we do with the harvest residues so that the parasitoids go on working for us on the new crop. On the other hand if there are relatively few parasitoids we should think carefully about reducing a potential source of infestation for following crops.

E. Damage

Bemisia tabaci causes several types of damage.

1. Direct damage by sucking the sap

For crops like cotton or vegetables which are often damaged by various viruses, and may have sooty mould and honeydew stickiness problems, we often tend to ignore the direct damage caused through the loss of nutrients. Recently it has been shown that whitefly feeding causes direct damage to various characteristics of the cotton crop, including fineness of the lint, strength of the cotton fibre and its length.

On squashes, the whitefly feed on the leaves and cause separation of the epidermis of the leaf from the parenchymal layer. Air enters and causes a characteristic silvering, firstly on the veins. On an infested leaf the green leaf tissue can be seen with whitish veins in between. This is a characteristic feature, and is different from silvering that may be caused by thrips, for instance. It seems that no virus is associated with this phenomenon. Silvering will only occur on leaves which were on the plant while *B. tabaci* was feeding on it. The symptoms will not spread from leaf to leaf, and once the whiteflies are removed, new leaves will not show silvering. Although it is damaging, the losses caused are by no means as devastating as the tomato mosaic virus, for example.

2. Honeydew and sooty mould problem

The main damage is to cotton lint, with costs running into millions of dollars. Some damage occurs to vegetables such as aubergines or melons and cantaloupes.

3. Viruses

Mosaic viruses may cause symptoms such as yellowing, curling or blackened leaves, loss of fruiting capacity or deformed fruit. Plant tops may be bunchy and small. Tomato mosaic virus is a particularly severe virus problem which may cause fruit loss through failure to produce fruit altogether, fruit rotting, or alternate green (unripe) and red patches on the developing fruit which make it unmarketable, all depending upon the age at which the plant is attacked.

The key to virus control on tomatoes is to delay attack until the fruits start to set. After this, even though the plant may suffer, some ripe marketable crop will still be obtained. One way to do this is by using screens (see below). A second way is to exploit the fact that the tomato virus develops mainly in tomato plants and only rarely has alternate hosts. Therefore, strict sanitation can greatly limit the spread of the disease.

There are many other viruses transmitted by *B. tabaci*. In fact, it transmits over 20 different viruses, which probably is the largest number of viruses transmitted by any one insect in the world. Therefore, it is important to remember that this insect is very capable of picking up viruses from the environment and introducing them into the crop plants, and that it does so very efficiently. This is probably what happened with the cassava mosaic which originated in Africa, because the disease does not occur in South America, where the cassava plants originated.

4. Irregular ripening (in tomatoes)

This is a disorder caused by a physiological response of the plant to heavy attack of whitefly adults during fruit set, producing alternate stripes of white and red on the ripening fruit. Irregular ripening is rather easier to control than a virus problem, because it occurs only when whitefly populations are very high during fruit set.

B. tabaci strain B is somewhat less proficient in virus transmission but is a much more devastating insect as far as direct damage, irregular ripening and squash leaf silvering are concerned. In the laboratory, it lays more eggs, develops faster and produces much more honeydew on the plant than strain A. The Imperial Valley recently lost all its vegetable production (at a cost of around $200 million) because the vegetables were directly killed by strain B. The plants were killed when they were between one week and one month old. In July 1992, farmers in the region had to plough under their cotton because *B. tabaci* was killing the cotton plants through direct feeding.

F. Biological control

There are many parasitoids and predators associated with *B. tabaci* (see Tables 4.1 and 4.2 of CABI's literature survey of *B. tabaci*) but the mere existence of many known natural enemies does not necessarily mean easy or efficient biological control. Nevertheless, this large complex of potential control agents is there to be drawn upon and studied to determine what effect they are having and how they might best be employed for whitefly control.

Parasitoids: A number of genera of parasitoids attack whiteflies. The most important are *Encarsia* and *Eretmocerus*, both of which include species capable of controlling whiteflies under certain circumstances. The third genus is *Amitus*, which was not known to include parasitoids of *B. tabaci* until recently, when it was reared on whitefly in the Caribbean and South America. Since *B. tabaci* did not originate in the Caribbean or South America, this *Amitus* sp must have moved onto *B. tabaci* from a local indigenous whitefly. For various reasons *Amitus* does not appear to be a very promising control agent for *B. Tabaci Encarsia* and *Eretmocerus* have distinctly different host relations. *Eretmocerus* females, either virgin or mated, will always attack unparasitised whitefly nymphs. Virgins will lay male producing eggs and mated females will lay either female or male eggs. *Encarsia* species, on the other hand, exhibit heteronomous progeny development where the female producing eggs will develop like those of *Eretmocerus* on whitefly nymphs. However, the males are not parasitic on whitefly, but instead are usually parasitoids of parasitic hymenoptera. Thus, the *Encarsia* female (whether mated or not), wanting to lay a male egg, will lay it in a whitefly already parasitised by a hymenopteran. Her male offspring will therefore develop at the expense of the female larva of a hymenopteran which is inside a whitefly nymph. This is a complex life history, and there are debates about its suitability in biological control. However, there have been good results using *Encarsia* as a control agent for whitefly species, including *B. tabaci*. *Encarsia* spp parasitise both whitefly and diaspid scales. In contrast, all members of the genus *Eretmocerus* are exclusively parasitoids of whiteflies. All of the known females of *Eretmocerus* are yellow; they have a very large club on their antenna and most have green eyes when alive. These features make it relatively simple to pick out individuals from this genus following their emergence from whiteflies.

Encarsia lay their eggs inside the whitefly nymph (endoparasitoid). The *Eretmocerus* female on the other hand, finds the whitefly, climbs onto it, examines it and then gets off and sticks the eggs between the whitefly and the leaf, where the egg remains for about three days. The larva then hatches, and through a complex sequence of events, kills the host.

A useful way to tell if a whitefly has been attacked by *Encarsia* or *Eretmocerus* is as follows: *Encarsia* deposits a meconium, or faecal packet before pupating. This remains within the empty host integument. Immature *Eretmocerus*, on the other hand, do not deposit any faeces at all. Thus, if faecal deposits accompany the parasitised host, then the parasite is *Encarsia*. The absence of faecal deposits means that the parasite is *Eretmocerus*. Furthermore, *Eretmocerus* will always leave an empty yellowish-white host, whereas some *Encarsia*, such as *Encarsia transvena*, may leave a black pupal sac. Such simple diagnostic features are useful at the field level to determine events throughout the season.

All the experiments conducted so far have failed to show direct attraction of an infested leaf to parasitoids. The situation known to occur in various parasitoid species, as in braconids that attack lepidopterous larvae, is that they find the host by following kairomone trails liberated by the feeding host. In the whitefly, however, experiments have so far failed to show that there is such an attraction. Once the parasitoids have found a whitefly, however, the presence of honeydew will act as an arrestant to reduce the tendency of the parasitoid to take off again and look for a parasitoid. A heavily infested leaf may therefore keep more parasitoids for a longer time, but it will not attract more parasitoids to the leaf than a lightly infested leaf.

Predators: It is difficult to assess exactly how much damage is caused to whitefly populations by predators, since their activity is much harder to follow than parasitoids. They are often not present on the plant for much of the day and what and how much they ate cannot be determined. Traditionally, success with whitefly parasitoids has been sometimes spectacular, but not with predators. Some coccinellids are important predators of whitefly, some almost specifically so. Whitefly predators may belong to a number of insect orders, including coccinellids lacewings (Neuroptera), predatory heteroptera, flies, and predaceous mites. The coccinellids that feed on whitefly do not belong to the same group as the large predators that feed on aphids, but are much smaller, with some belonging to the genera *Scymnus* and *Delphastus*. Neuroptera may be common and, at times, can be important predators of whitefly. Of the bugs, there are mainly mirids and anthocorids that are known to attack whiteflies. There are also whitefly predators that belong to the Diptera and to the Acarina. Predators behave differently under laboratory as compared to field conditions. Specificity can be a problem. Even predators reared on whitefly in the laboratory may not, when released, look for and destroy the whitefly, but may show preference for another host.

We have evidence that lacewings (*Chrysoperla* spp) have become adapted to feed on whitefly. In laboratory tests conducted in 1978-79, we had great difficulty in getting lacewings to feed on *B. tabaci*. Now, however, the lacewings feed and develop readily on whitefly. In Israel, some authorities claim that the lack of problems with whitefly on cotton is largely due to the action of predatory mites.

Parasitoids vs predators: Parasitoids may not be efficient when they get to a leaf that is too heavily infested with whiteflies, as the leaf becomes gummed up with honeydew (and full of exuvia and other matter) which make it hard to climb on. Therefore, it takes the parasitoid a long time to get from one whitefly to the other, and it also may abandon the leaf prematurely.

The combination of the lack of response to kairomones and the hindrances caused by heavy whitefly attack result in a moderately or lightly infested leaf having a better chance of being completely parasitised than a heavily infested leaf. Predators, on the other hand, thrive best on heavily infested leaves. Their juvenile stages cannot fly to another leaf in search for food, and so it is advantageous for the predator to oviposit on a leaf with an abundance of whitefly immatures. Thus parasitoids and predators complement each other for different host population levels.

Inundative releases: *Encarsia formosa* which is successfully used in greenhouses to control whitefly, especially the greenhouse whitefly *Trialeurodes vaporariorum*, is also being tried out against *Bemisia*. The parasitoids are released at the rate of four parasitoids per host, three to four times at 10-day intervals. A problem often arises in the control of a mixed population, since *E. formosa* prefers to attack the greenhouse whitefly and may ignore *B. tabaci* in the presence of the former. This method of control may work well in greenhouses but is not recommended in field conditions, where dispersal is so much greater. Furthermore, the number of necessary parasitoids to be released at even the same density as in the greenhouse, would be economically prohibitive for a field crop that is usually grown less intensively and on a larger scale than a greenhouse crop. Therefore, the idea is not to obtain control through eradication, but through classical methods (i.e., the release of natural enemies that will become established in the field and reduce the pest populations). If this does not work, we have to find other ways such as the use of selective insecticides.

[Note: The developing *Encarsia formosa* within greenhouse whitefly nymphs causes the whitefly puparium to become black. This distinctive feature does not develop when *E. formosa* develops on *B. tabaci*. Black puparia may form also in other species of parasitoids and whitefly, yet they usually can be distinguished from those formed by *E. formosa*.]

G. Monitoring

Yellow traps: this is a simple flat board that is bright yellow. Various sticky materials such as Tanglefoot or Stickum are used to trap the whitefly. If it is to be used only for a short time, say, a few hours, oil of almost any type can also be used. Monitoring *B. tabaci* is difficult. Many adults are caught but there is often no good correlation between what is caught and what exists on the leaves. The sex ratio of the catch may vary from 70 per cent male to 70 per cent female. It is important to bear in mind that whiteflies tend to land on the lowest spot relative to the ground, so that the trap should be placed close to the ground. The trap should be horizontal, because if it is placed vertically only a small percentage of the horizontal orientation may be caught. If the trap is placed the previous evening or in the early morning a good measure of events will be obtained by 11.00 am since most flight occurs before that time. The measure obtained is obviously influenced by the proximity of plants. If a trap is placed in a fallow field you may not catch as many. Always place the trap so that it is exposed to the sunlight, as up to 10 times more will be caught in the sunlight than in the shade. Decisions should be made at a local level on exactly what height and size of trap to use. It is possible that placing the trap off the ground is easier and will still catch adequate *B. tabaci* for your monitoring purposes.

Another monitoring device is to use a sticky pan placed next to a plant and shake the plant onto it during a certain interval (e.g., a few seconds). This is a practical method which may be found useful, and may even give a better idea of what is actually on the plant than the stationary trap. The horizontal trap will pick up adults moving into or off the crop, but ina stationary situation, in which *B. tabaci* are already on the plant, a horizontal trap placed between the crop rows may not be very effective in monitoring them. Farmers in particular try to estimate the levels of the pest for the purpose of deciding when to treat by simply passing through the crop and assessing how many adults fly up as a result of the disturbance. However, this is not recommended. Some people have also found yellow traps good monitoring devices for parasitoid adults. In Israel, however, we have not found this useful for monitoring parasitoids.

Counting of immatures on the leaf is a reliable but tedious method. Whiteflies should be 3rd instars and up; 1st and 2nd instars are really too small and too numerous to count correctly. Counts can be done on whole leaves or part of the leaf. Numbers can be assessed at different levels or parts of the plant, depending on the plant species and crop. There is a large body of litera-

ture on sampling that should be consulted for details.

In addition, whilst counting immatures, parasitism can also be monitored. This can provide very useful data because if high levels of parasitisation are found, one may want to avoid spraying. However, a word of caution - we have found that once the whitefly has emerged, the empty puparium of the whitefly whether parasitised or not, may not remain on the leaf for a predictable amount of time. Therefore, it is only possible to estimate parasitism by counting full, living late larvae or pupae, before arriving at counting the leaf.

H. Control

Since *B. tabaci* transmits viral diseases, preventing damage by this pest will often mean changing cultural practices; e.g. in Florida and the Dominican Republic large scale sanitation procedures are now undertaken for tomatoes. These include coordinating uniform planting times, treatments and harvesting over the largest possible area, so that a minimal transfer of viruses from mature to young plants will occur. This approach includes a period during which the field is left fallow without either crops or weeds in order to reduce the possibility of the virus being carried over to the next tomato crop.

Due to the resistance that *B. tabaci* has built up, many insecticides have proven to be ineffective against whitefly. Thus, it is very important to consider ways to conserve those materials that can still be used so that they will continue to be useful in the future. Moreover, it is important to coordinate the correct use of insecticide over wide areas because if resistance starts in one small region it will rapidly spread with the movement of the whiteflies.

Mulching

Whiteflies are strongly attracted to the colour yellow. In a 1927 publication of work done in Palestine it was mentioned that when the ground between plants was covered with straw, the whiteflies did not affect the tomatoes that would otherwise have been heavily infested. The reason was that the whiteflies preferred to land on the straw due to its yellow colour. The straw heated up from direct sun rays and its temperature reached some 50° to 60°C. Once the whitefly had landed they were overcome by the heat and could not manage to fly off again and were killed. This worked as long as the straw was exposed and yellow, and was not shaded by the growing plants. Nowadays, we may use yellow or aluminium coloured plastic mulch or fabric which is very effective as long as it receives direct sunlight. In Florida, yellow, white and aluminium mulches were tested and found to be equally effective, delaying subsequent insecticide treatments by 10-20 days. Although it is not a complete solution, the delay in treatment is important in itself since it will also delay the build-up of resistance.

Screening

Plants can be protected by a nylon screen or mesh which stops the whitefly from reaching them. The mesh must be about 0.5 mm. It is not possible to screen off a whole field but the idea is to protect seedlings grown in a small area which are subsequently moved to the field. For example, tomatoes can be kept under screening for the first six weeks after sowing. In this way, the plant has a whitefly- and virus-free period to establish itself and in many cases, even though whitefly then attack, the plant will have already set some fruits before it has been attacked by viruses, and only a moderate degree of additional protection (e.g., through insecticides) is necessary in order to obtain a satisfactory crop. Such a crop would not have been attainable without the early protection of the plants.

Natural enemies

Although natural biological control is important, it is often too slow in the case of *B. tabaci* to be of use to farmers, who want immediate action. It is very difficult to expect them to wait and see their crops being attacked in the hope that natural control will eventu ally bring the pest under control.

In the case of the Caribbean, if we look hard enough, many natural enemies will undoubtedly be found. They may be able to assist in controlling *B. tabaci* but it is not realistic to expect them to control the problem over the short term. A solution must be found for the immediate short term whilst at the same time allowing the long-term effect to take place. To help this process we can use:

1. **Refuge plants,** such as ornamentals or shrubs. If we do not mind certain plants being attacked by *B. tabaci*, they can be a useful refuge for natural enemies to build up on.
2. **Resistant/tolerant crops:** there is no edible vegetable crop or variety which is totally resistant to *B. tabaci*. There will always be some attack, but by using tolerant or resistant varieties it is possible to reduce populations to levels where other control measures (e.g. biological control) can more readily bring about adequate control. For example, in Israel a resistant tomato variety has been developed against Gemini virus. Additional varieties exist, which

exhibit some tolerance to virus infection, so if these are used in conjunction with other methods (e.g. mulching, screening) a good crop can be obtained.

3. **Banker plants:** Lance Osborne (Florida) reports that papaya can be used as a banker plant because it the only host of the papaya whitefly. He placed a large number of predators on papaya trees within a greenhouse with ornamentals that he wanted to protect; after a short time the predators reduced the whitefly populations and then moved over to the adjacent ornamentals where they started to feed on *B. tabaci.*

   It is quite possible that parasitoids of the genus *Encarsia* could also be used in the same way because they, like predators, have a wide host range. Such a technique might be especially suitable for the tropics where a large number of whitefly species and natural enemies exist, and many of these are not species-specific.

4. **Selective insecticides:** detergents - it has been known for many years that soap will kill insects on plants. However, the soap can also kill the plant. A detergent has been developed which is completely biodegradable and will not harm the plant. It serves as an immediate form of control and has no residual action; i.e., it exerts no protective effect, but it is a useful way to reduce the whitefly population drastically. The soap will kill adult parasitoids but those developing parasitoids inside their hosts will tend to survive.

Insect growth regulators (IGRs) - e.g., buprofezin (Applaud) or pyriproxyfen (Tiger): the main effect of these substances is on egg hatch and instars 1 & 2 of the whitefly nymphs. They hardly affect instars 3 and 4 of the whitefly. Interestingly, parasitoids (except for *Amitus* species) only rarely affect instars 1 and 2, and mainly attack and develop in instar 3 and 4. In theory, therefore, IGRs will kill instars 1 and 2, but not the parasitoids nor the adult whitefly. One should thus obtain a drastic reduction of the next generation of whitefly but with little effect on the parasitoid population. IGRs are relatively persistent so eggs laid by whitefly after treatment should suffer a high mortality. Those eggs that are laid on unsprayed vegetation will develop, but may later be attacked by parasitoids when they reach the 3rd instar.

So far we have little knowledge of the effect of IGRs on predators, but there is some indication that they may affect them adversely.

Timing and dose rates are, of course, important, but when used judiciously with other control techniques IGRs can work to kill whitefly and yet be favourably integrated with the activity of natural enemies. However, caution must be exercised not to overuse any material, since the chances of resistance build-up are directly proportional to the frequency of exposure to the material. Therefore, materials like IGRs should be used once each season, while the encouraged natural enemies and other methods should do the rest.

Integrated control

As already stated, no one method can bring about satisfactory *B. tabaci* control for all crops and crop conditions. Consequently, it is important to learn to recognise the particular conditions under which a crop is grown and then to formulate the best combination of control measures available. In all cases, it is most advisable to encourage natural enemies, since they are the only permanent solution against which no resistance builds up, which do not pollute the environment and are not hazardous to use.

In this connection, it should be emphasised that virus infections are a function of the number of vectors in the environment. Thus, it is very important to reduce overall populations in order to reduce the amount of potential virus inoculum in the environment. Natural enemies on non-crop plants are very important in this regard, because they are the only agents that are permanently present controlling these populations.

Advances in Mycopesticide Formulation and Application

Chris Prior, Programme Leader, IIBC/IITA/DFPV Locust Biocontrol Research Programme, IIBC, Silwood Park, Ascot, UK

Introduction

The use of chemical pesticides has increased continuously since their invention in the 1920s and 1930s. They have enabled farmers to achieve high standards of pest control and thereby to produce high yields of blemish-free crops. Unfortunately, there are several well-known disadvantages to intensive use of chemical pesticides including environmental pollution, destruction of non-target organisms, induction of secondary pest problems and pesticide resistance. In order to achieve pest control without these problems, chemical pesticide use must be reduced and this has led to the concept of integrated pest management, where non-chemical control methods - biological control, cultural control and host plant resistance are given greater prominence in management systems.

Biological control is increasingly an important component of pest management systems and, in its most spectacular form may be the only management tool required. This is particularly true in the "classical" programmes of biological control where the pest is an imported species which multiplies in the new environment without its co-evolved natural enemies to control it. In such cases, the introduction of one or more of these natural enemies to the outbreak area may achieve spectacular control; the suppression of the exotic cassava mealy bug *Phenacoccus manihoti* in Africa by introduction of the parasitoid *Epidinocarsis lopezi* from the mealy bug's native home in South America is a recent example.

In other cases, however, control may not be achieved so easily. This is particularly true in the case of pests which are a problem within their native range, where introduction of co-evolved natural enemies is not possible. Even in the case of some exotic pests, the introduction of natural enemies may not lead to adequate control, possibly because these natural enemies do not flourish in the new environment or possibly because their impact on the pest is simply insufficient. In these cases, if biological control is to be used, then some form of augmentative use of natural enemies will be required. This may be done by the mass release of parasitoids, as in the case of *Trichogramma* spp, or it may be done by the use of "biopesticides". These latter are naturally-occurring pathogens of the pest, applied for control in the same way that a chemical pesticide would be used. There are many pathogenic micro-organisms that may be exploited for this purpose but only fungal pathogens will be considered here.

Fungal pathogens of arthropods

Arthropods, including most major agricultural, medical and veterinary pests, are attacked by a wide range of microbial pathogens including viruses, bacteria, protozoa and fungi. There are numerous fungal genera that have no counterparts among the pathogens of vertebrates and these entomopathogenic fungi are of particular interest for five reasons:

1. They are very diverse, attacking all major pest groups.
2. They penetrate the host directly through the cuticle and therefore do not need to be ingested to be infective.
3. They show a wide range of specificity and so may be exploited for control of both narrow and wide ranges of target pests.
4. Some can be grown easily on simple industrial substrates, making them suitable for mass production.
5. They have been extensively safety tested, in most cases without any adverse effects on vertebrates.

Because of their widespread occurrence, great diversity and sometimes spectacular ability to cause epidemics in pest populations, the entomopatho-genic fungi have long been claimed as potentially valuable pest control agents. However, attempts to exploit them for this purpose, which began in the last century, have seldom been successful. Two of the earliest of these attempts were in the Caribbean region: the "friendly fungi" in Florida and the control of sugarcane froghopper in Trinidad. The work is well summarised in Allard (1987) and Samson et al. (1988).

The "friendly fungi" are members of the genera *Aschersonia*, *Fusarium* and *Aegerita* which attack diaspidid and aleyrodid pests of citrus in Florida. In the early years of this century there was considerable interest in these fungi for pest control, based on the observa-

tion that natural epidemics could destroy insect populations in the field, and naturally infected material was sold to commercial growers to induce epidemics in their fields. The attempts ended in controversy because it could not be shown that these efforts led to improved control (Samson et al., 1988).

The sugarcane froghopper *Aeneolamia varia saccharina* is a major pest in Trinidad, originating from native grasses. In cane it multiplies rapidly, but suffers regular epidemics of *Metarhizium anisopliae* which may cause local collapse of the pest population, though unfortunately this usually happens after serious economic damage has been done. The pioneer entomologist and entomopathologist Rorer set up large-scale production of this fungus in Trinidad in 1910 and applied it to the cane in an attempt to control the pest, but again, a successful population reduction was never demonstrated (Allard, 1987).

After these and other attempts at using these fungi for control, interest lapsed for fifty years with the introduction of chemical insecticides. More recently, as problems with pesticide use have increased, there have been several large scale programmes to develop fungal pathogens for pest control. These include spraying *Metarhizium anisopliae* for sugarcane pests in Brazil (Mendonca,1992) and rice pests in the Philippines, spraying and soil granule application of *Beauveria brongniartii* for cockchafers in Switzerland (Keller, 1992) and spraying *Beauveria bassiana* for Colorado beetle in eastern Europe and USA, and corn borer in China. Among these programmes, the Brazilian programme continues and is often counted a success, although population reductions are not great compared to what would be expected from chemical spraying; the Swiss programme continues and a product is commercially available for soil treatment, but the aerial spraying programme has lapsed; the east European and Chinese programmes have lapsed; the Philippines work has not led to any implementation programmes. In fact, the record is not particularly encouraging and one may ask, why not?

Limitations on the effectiveness of fungal pathogens for pest control

Fungal pathogens in the genera most commonly investigated for pest control have no active means of dispersal and rely either on chance contact with the host, or on wind or rain to carry their spores to the host. This means that simply liberating the fungus in the pest's environment, as was done with the "friendly fungi", cannot achieve useful infection. This limitation has been largely recognised, and circumvented, by the use of spraying machinery to apply the fungi as sprays. However, a closer examination of spraying systems points to some possible limitations when they are used for applying fungal spores.

In order for a fungal pathogen to be an effective pest control agent, it must infect the host successfully. A farmer with a pest control product, the active ingredient of which is live fungal spores, must therefore suspend the spores in a suitable liquid (or dust them directly, but this is never done because of the difficulties in handling dusts effectively and safely) and atomise the suspension into small drops using a sprayer. These droplets must then either hit the insect directly, adhere to it and thus place the spore in a position where it can infect, or adhere to the foliage and be collected on the insect's cuticle later by secondary contamination.

Hazards for the spores occur at all stages. The spores of *Metarhizium* and *Beauveria*, the two most widely used genera, are dry, dusty and hydrophobic. They do not suspend easily in water and so are not easy to spray. In addition, there are a number of inherent problems associated with the spraying machinery used to atomise the suspension. The droplets produced by hydraulic knapsack sprayers or motorised mist blowers - the machines most frequently used for pest control in the tropics - are much larger than the optimum size for impaction on insects (Matthews, 1992). Thus the insect is bombarded with a relatively small number of droplets which contain many times the dose of spores needed to infect it. This is wasteful, since spraying is always inefficient and most drops miss the target; efficiency would be greatly increased if the suspension were broken up into much more numerous, optimally sized droplets. Those few droplets from conventional sprayers that do hit the target are likely to bounce off because insect cuticles are hydrophobic. Wetting and sticking agents can be used for chemical insecticides but many of these stickers cannot be used with spores because they are toxic. Where infection is achieved by spraying fungal spores, it is much more likely to be by secondary contamination of the insect from spores deposited on the plant surface than by direct contact, but here there are many hazards such as ultra-violet light and desiccation that reduce spore viability. These limitations reflect the fact that pesticide spraying is an imperfect process and much of the success of chemical pesticides is due to their very high activity rather than the efficiency with which they are applied to the target. It is notable that by far the most efficient transfer of pesticide to an insect target was achieved during aerial spraying of a locust swarm in flight, where only 5.5 per cent of the pesticide was transferred to the pest (MacCuaig and Watts, 1963); in other cases, the amount is invariably much less than 1 per cent.

In order to overcome these problems, application technologists have developed the concept of controlled droplet application (CDA). Recognising that there is an optimum droplet size for impaction on insects and that larger droplets are wasteful, CDA technology seeks to atomise all the pesticide into droplets of the optimum size, usually defined as about 70 μm diameter.

Under normal climatic conditions, water cannot be used to produce such small droplets, because evaporation is almost instantaneous and the droplets therefore become too small to impact and drift away. To overcome this problem, chemical pesticides are suspended in non-volatile liquid diluents. Oils are very suitable for this purpose.

A major advantage of CDA is that the volumes of spray that are needed can be greatly reduced when such small droplets are used, because all the pesticide goes into droplets of the optimum size and none is wasted. Further economies in volume are obtained by increasing the concentration of active ingredient and in some cases, pure active ingredient may be sprayed. Thus pest control can be achieved at application rates of <5.1 /ha. Such low rates are referred to as Ultra Low Volume (ULV) application. The question is, therefore, can the advantages of CDA at ULV rates be extended to the use of fungal pathogens? It was with the objective of demonstrating the application of fungal spores by this technology that the IIBC/IITA/DFPV locust biocontrol programme was set up.

The IIBC/IITA/DFPV Locust Biocontrol Programme

Locusts and grasshoppers

Grasshoppers which can congregate to form very large swarms are called locusts and they cause enormous damage to world crops (Haskell, 1992). The most notorious is the Desert Locust, *Schistocerca gregaria*, which caused the biblical plagues and broke out across Africa and Asia as recently as 1986-1988. Some adults from this plague crossed the Atlantic and caused consternation by landing on some of the east Caribbean islands, although they did not cause any serious subsequent problems.

The adults of some locust species can fly hundreds of miles, which means that huge numbers of insects can suddenly invade agricultural areas. A large swarm of *S. gregaria*, for example, can weigh as much as 20,000 tonnes and contain ten thousand million insects, all of which can eat their own weight of green vegetation every day. Non-congregating grasshoppers are also very serious agricultural pests in many countries, and in the Sahel region of West Africa more than 20 species can damage crops. Control measures are often needed.

Chemical control of locusts and grasshoppers

Chemical pesticides have provided the only effective control method for locusts. The most effective of these have been the persistent organochlorine pesticides, especially dieldrin. However, the use of dieldrin was banned in the 1970s because of concern about its effects on the environment and in the last plague in 1986-1988, only less persistent pesticides such as fenitrothion were permitted. Very large amounts of pesticide were applied, often by air, but much of it failed to hit its target (Symmons, 1992).

This heavy and often ineffective use of pesticides has caused great controversy and concern, both in the afflicted countries and among the international donors who provide major financial support for control campaigns. As a result, there has been great interest in alternative, safer methods of control and one of these is biological control.

Prospects for biological control

Among the wide range of natural enemies of locusts and grasshoppers (Prior and Greathead, 1989), only the entomopathogenic fungi are suitable for development as biological control agents, for three reasons:

- "Classical" biocontrol using introduced parasitoids is not an option because the pest is native throughout its range. Augmentation of parasitoids is impractical because of the scale of the operation that would be necessary.
- Only those agents which can be mass-reared cheaply and quickly can be considered and this means that only a few microbial pathogens may be considered.
- Direct contact action is preferable because biological agents do not persist well in the desert conditions where control is carried out. The fungi are the only microbial pathogens which infect on contact.

Fungal pathogens as mycopesticides for locust control

Fungi exist which are unique, specific and highly virulent pathogens of insects and those in the genera *Metarhizium* and *Beauveria* fulfil the criteria we have described for a locust biological control agent. They have been tested in aqueous formulations against a wide range of pests, and in some cases have been used on a commercial scale. However, if they are to be used against locusts they must be adapted for use using Ultra Low Volume (ULV) technology (Lomer and Prior, 1992).

ULV technology was invented for locust control and is the only feasible way to spray locusts from the air, which is essential because of the large areas and remote location of much locust control.

When we began our research, we already knew that the dry, hydrophobic conidia of *Beauveria* could be suspended in vegetable oil and we also knew that this gave another, very great benefit, which is a large increase in the infectivity of the conidia (Prior et al., 1988). We believe this occurs because the oil causes the conidia to adhere more effectively to the insect, which has a waxy surface. During the course of the programme we have confirmed experimentally that formulation of *Metarhizium flavoviride* conidia in oil greatly reduces the LD_{50} (dose that kills 50 per cent of the insects in 5 days) for Desert Locust, even at the low relative humidity of 35 per cent (Bateman et al., 1993).

The central objective of our research programme is therefore to formulate these water-repelling conidia in oils suitable for ULV application and show that they will be infective under desert conditions. We thus aim to use existing and proven technology, but to replace the chemical pesticides with a biological alternative which has no adverse effect on the environment. Although we already knew that fungal conidia could be suspended in oils and would infect insects, we still had to show that oil suspensions could be sprayed effectively at appropriate rates using the existing machines, and we had to show that these suspensions would be infective under the hot, dry conditions where control operations are carried out. The results of our research on these topics have been very encouraging.

Research progress to October 1992

1. Selection of fungi

So far, we have examined over 100 isolates of *Metarhizium* and *Beauveria*, concentrating on those from Orthoptera. Only a minority have shown high virulence to Desert Locust. However, we now have virulent isolates from both within and outside Africa. In particular, we have more than 20 isolates of *Metarhizium flavoviride* from west and east Africa, all from acridoids and with high virulence to a range of acridoids including Desert Locust. We have chosen one of these, code IMI 330189 from Niger, as a standard for further development.

2. Infection at low humidity

In our assay experiments, the insects are inoculated with an oil suspension of conidia and held under standard conditions of a low relative humidity of 35 per cent and high temperature of 30°C. The five-day LD_{50} for conidia in oil is 8900 conidia/insect.

In contrast, water formulations will not kill 50 per cent of the insects at any dose in five days. Conidia formulated in water do in fact kill under the bioassay conditions of low relative humidity, but take about one day longer. This is an encouraging result: oil suspensions kill independently of relative humidity and more quickly than water suspensions (Bateman et al., 1993).

Oils do not affect viability of the fungus. Conidia of *Metarhizium flavoviride* in oil germinate on the locust cuticle after application in an oil suspension and form appressoria (the structure that the germinating conidium uses to penetrate through the cuticle of the insect).

3. Effects of ultra-violet radiation and high temperature

As well as low humidity, another hazard for conidia in the field is ultra-violet (UV) light, which can kill them very rapidly. We know from chemical insecticide work that locusts continue to collect insecticide by secondary uptake from deposits on the vegetation for several hours after spraying. It is therefore quite likely that there would be advantages in prolonging the residual life of the conidia for a few hours after spraying and this has led us to study UV protectants, or sun screens, and temperature tolerance.

The formulating oils themselves protect conidia from UV, but we can greatly increase survival by adding protectants. In the case of one of these compounds, 1 per cent oxybenzone which is widely used in suntan lotions, germination after three hours' exposure to artificial sunlight was increased from about 30 per cent to >80 per cent.

Another important question is, how long can the formulation survive at the high temperatures which it may encounter in the field? We have carried out experiments on storage of conidia of our standard isolate of *Metarhizium flavoviride* in various oils at different temperatures. When the conidia are dried correctly, they show no loss of viability after one year at 17°C in several oils suitable for formulation. Short exposures for a few hours to temperatures as high as 55°C do not reduce viability. It appears that the conidia are more tolerant of high temperatures than we had thought and we are working now to find the limits of this tolerance.

4. Field trials

We have carried out a preliminary field trial against *Schistocerca gregaria* at Niamey and Agadez, Niger with the kind assistance of GTZ. Adult locusts were collected in the field from their breeding area in Wadi Anu Makaren, north of Agadez, and sprayed there in the early

morning using our formulation. They were returned to cages at Agadez for incubation. These results clearly show that the formulation can be taken to the field and sprayed effectively (Bateman, 1992).

We have also sprayed adult locusts in large wire mesh cages in the field at DFPV, Niamey. Temperature and humidity in these cages do not differ significantly from values in the field outside and mortality in these cages is therefore a demonstration of effective kill under field conditions. Adult *S. gregaria* sprayed in these cages with realistic field doses die in 6 - 12 days, with peak mortality on days 7 - 9.

Grasshoppers are also susceptible in the field. We sprayed field populations of the variegated grasshopper *Zonocerus variegatus* in the Lama teak forest in southern Benin. At the time of the trial the humidity was only 35 per cent. In samples taken directly after spraying, more than 90 per cent of the insects died of fungal infection. Similar results have been obtained with grasshoppers in field trials of up to 1 ha in Mali, northern Benin and Niger.

Conclusions

We conclude that:

- There are isolates of *Metarhizium* with high virulence to locusts and grasshoppers.
- We can formulate their conidia in oils for spraying at ULV rates using existing machinery. The formulations are more infective than water formulations and kill locusts at low relative humidities under both laboratory and field conditions.
- First field trials in west Africa have shown that the formulations can be sprayed successfully against locusts and grasshoppers.

The major aim for the next phase of our programme from 1993 - 1995 will be to consolidate the field trial results in different environments against different grasshoppers and locusts. We will include some comparisons with formulations of a USA isolate of *Beauveria bassiana* which has proven very effective against grasshoppers in the USA and Cape Verde. The field trials will be carried out in close co-operation with Montana State University, GTZ and the national research programmes of Benin, Niger and Mali.

How can these ideas be extended to the control of other pests?

In principle, the advantages of CDA technology at ULV rates which have been demonstrated in our work on locusts and grasshoppers should be applicable to a wide range of pests. There is no doubt that suitably virulent isolates of *Metarhizium* or *Beauveria* can be found for most pests; the list of hosts already known for these two genera encompasses almost every insect order. However, we cannot assume that all pests will succumb to such sprays until some important questions are answered. To conclude, I will discuss briefly some of the questions that must be addressed if we are to consider using ULV formulations of mycopesticides against other pests.

Will this technology work on small pests?

Locusts and grasshoppers are large, often gregarious insects. They are excellent spraying targets, being non-cryptic and easy to hit. Other pests are usually much smaller and may be well hidden in vegetation. They may be much harder to hit with CDA droplets. For example, whiteflies are usually on the underside of leaves where droplets seldom impact, and thrips are often hidden inside flowers.

Will secondary uptake be effective?

This leads directly from the above question: if the insects cannot be hit directly, they may still become infected from formulation which has impacted on the foliage. In this case, the effectiveness of the application will depend on how well the foliage is covered, how long the fungus survives and how readily it can be transferred from foliage to insect. There are many unknown factors at work here: we know little of the adhesiveness of formulations to leaves or of the effect of plant surfaces on spore survival.

Is spray drift a problem?

ULV technology often relies on drift to carry the spray to the target. This is not always desirable, because the wind may not be reliable and accurate placement of the spray may be impossible for farmers spraying small plots. The directionality and penetration of the droplet cloud can be enhanced by air-assisted spraying, where the rotary atomiser is mounted in the air blast from a mist blower so that the farmer can direct the droplets. This technology adds to the cost of application, however.

Drift of chemical pesticides may be undesirable because of the problem of contamination of non-target areas (exodrift). However, since biopesticides are inherently safer than chemicals, this should not be a problem. In any event, the greatest problems of drift arise with the very small droplets of <20 µm produced by conventional sprayers. Good CDA minimises the production of these very small droplets by ensuring accurate atomisation into droplets of the desired size.

Can conventional sprayers be used?

As discussed above, conventional mist blowers can be used with CDA attachments. However, the most widely used sprayer in the Caribbean, the hydraulic knapsack, cannot be used for CDA or for oil-based formulations. The battery operated spinning disc sprayers designed for CDA are very cheap and easy to operate, but training in their use will be required.

Who will produce the fungi?

In Brazil, Colombia and Costa Rica there are already small-scale commercial enterprises producing *Metarhizium* and *Beauveria* for use in the coffee and sugarcane industries. Where the demand exists, it is well within the capacity of local enterprise to meet it. This is a great advantage of mycopesticides compared to their chemical counterparts; the technology for production is not complex and is very suitable for small-scale business.

Acknowledgements

The IIBC/IITA/DFPV is a collaborative research programme carried out by the International Institute of Biological Control (IIBC), the International Institute of Tropical Agriculture (IITA) and the Département de Protection en Formation des Végétaux (DFPV) and financed by the overseas aid agencies of Canada (CIDA), The Netherlands (DGIS), UK (ODA) and USA (USAID).

References

ALLARD, GB (1987). Prospects for the biocontrol of the sugarcane froghopper with particular reference to Trinidad. *Biocontrol News and Information* 8, 105 - 115.

BATEMAN, RP (1992). Controlled droplet application of mycopesticides: an environmentally friendly way to control locusts. *Antenna* 16, 6 - 13.

BATEMAN, RP, CAREY, M, MOORE, D and PRIOR, C (1993). The enhanced infectivity of *Metarhizium flavoviride* in oil formulations to desert locusts at low humidities. *Annals of Applied Biology* 122, 145 - 152.

HASKELL, P (1992). Infamous species: the locust. *Biologist* 39, 111 - 117.

KELLER, S (1992). The *Beauveria-Melolontha* project: experiences with regard to locust and grasshopper control. In: Lomer, C.J. and Prior, C. (eds.) Biological control of locusts and grasshoppers, 279 - 286. CAB International, UK.

LOMER, CJ and PRIOR, C (eds.) (1992). Biological control of locusts and grasshoppers. CAB International, UK, 394.

MacCUAIG, RD and WATTS, WS (1963). Laboratory studies to determine the effectiveness of DDVP sprays for control of locusts. *Journal of Economic Entomology* 56, 850 - 858.

MATTHEWS, GA (1992). Pesticide application methods, 2nd ed. Longman Scientific and Technical, 405.

MENDONCA, A (1992). Mass production, application and formulation of *Metarhizium anisopliae* for control of sugarcane froghopper, *Mahanarva posticata*, in Brazil. In: Lomer, C.J. and Prior, C. ibid., 239 - 244.

PRIOR, C, JOLLANDS, P, and le PATOUREL, G (1988). Infectivity of oil and water formulations of *Beauveria bassiana* (Deuteromycotina: Hyphomycetes) to the cocoa weevil pest, *Pantorhytes plutus* (Coleoptera: Curculionidae). *Journal of Invertebrate Pathology* 52, 66 - 72.

PRIOR, C. and GREATHEAD, D.J. (1989). Biological control of locusts: the potential for the exploitation of pathogens. *FAO Plant Protection Bulletin* 37, 37 - 48.

SAMSON, RA, EVANS, HC, and LATGE, J-P (1988). Atlas of entomopathogenic fungi, Springer Verlag, Berlin.

SYMMONS, P (1992). Strategies to combat the desert locust. *Crop Protection* 11, 206 - 212.

Summary of Conclusions From Planning Session At Dominica Workshop

(Chairperson: J Mumford)

Two working groups, one dealing with *Thrips palmi* and the other with *Bemisia tabaci*, presented conclusions of their deliberations with respect to the need for future action.

1. *Bemisia tabaci*

1.1. Short term (now)

There is a need to study and implement the following:

Foliar fertilisers

Economic thresholds and timing of applications

The use of existing tolerant varieties (virus resistant)

The role of traps and mulches

Crop sanitation

Virus surveys to determine true situation in the region

1.2. Medium term (up to 3 years)

Use of shade houses to protect from early damage

Classical biological control introductions

Screening for better pesticides including mycopesticides

Implement better application technologies

Change cultural practices to improve pesticide efficiency

1.3. Virus epidemiology

2. *Thrips palmi*

2.1. Short term

Trials with insect growth regulators

Improve application techniques and efficacy

2.2. Medium term

Study the effects of mulches (not in wet season)

Study the effects of commodity treatments (postharvest treatments)

2.3. Long term

Research the use of mycopesticides

Do more biocontrol research (introductions)

Develop action thresholds

APPENDIX 1

Carol Abraham
Agricultural Officer
Plant Protection & Quarantine Unit
Division of Agriculture
Botanical Gardens
Roseau, Dominica
Tel: (1 809) 448 2401 Ext. 420

Richard Allport
Agricultural Officer
Division of Agriculture
Dominica

Everton Ambrose
Plant Protection Specialist
IICA
PO Box 1223
Castries, St Lucia
Tel 451 6760/1/3

Dunley Auguste
Deputy Director
Agricultural Services
Ministry of Agriculture Lands
Fisheries & Forestry
Union Agricultural Station
Castries, St Lucia
Tel: (1 809) 450 2375

P S Baker
Head of Colombia Cenicafe
IIBC, Silwood Park
Buckhurst Road
Ascot
Berks SL5 7TA
Tel: 01344 872 999
Fax: 01344 875 007

George Bala
Plant Pathologist
Central Experiment Station
Crop Research
Ceteno (via Arima P.O.)
Trinidad & Tobago
Tel: (1 809) 646 1645; 646 4334-7

Jean Dominique Bayart
G.R.S.I.P., Domaine Duclos
BP 1232, 97185 Pointe à Pitre Cedex
Martinique, Guadeloupe
Tel: 25 5984
Fax: 25 5985

Philippe Cao Van
IRFA Researcher / Citrus Agronomist
CIRAD IRFA, PB 153
97200 Fort de France
Tel: 596719201

Carl Castleton
Area Director, APHIS
Unit 5527, APO AA 34043
Santo Domingo
Dominican Republic
Tel: (1 809) 685 9780
Fax: (1 809) 686 0979

Raymond Dugas
Co-ordinator
Agricultural Health Programme in Brazil
SHIS Q15, CONJ 9, B1 "D"
Cx. Postal 02995
CEP 71615090, Brasilia, DF, Brazil
Tel: (061) 2485805

Dale Francis Ellis
Pest Management Officer
Ministry of Agriculture
St George's
Grenada
Tel: (1 809) 440 0019

John Greer
Plant Protection Officer
PO Box 272
Plymouth
Montseratt
Tel: (1 809) 491 2075

Professor Dan Gerling
Department of Zoology
Tel Aviv University
Ramat Aviv 69978
Israel
Fax no: (972) 3 640 9403

Peter de Groot
Agricultural Project Officer
Commonwealth Science Council
Marlborough House
Pall Mall
London
Tel: (0171) 747 6213

Richard A Hall
Biological Control Specialist
Ministry of Agriculture
St George's
Grenada
Tel: (1 809) 440 0019

E. Roberto Hector
Department of Agriculture
Charlestown
Nevis
Tel: (1 809) 469 5521 Ext 208689

Kenneth A Heidweiller
Crop Protection
Department of Agriculture
Klein Kwartier #33
Curaçao
Neth. Antilles
Tel: 370 288
Fax: 370 723

Bruno Hostachy
Service de la Protection des Vegetaux
BP 241
97 257
Fort de France
Martinique
Tel: 633972
Fax: 739040

Wen Li Hung
Chief
Agricultural Technical Mission of R.O.C.
Stock Farm
Dominica
Tel: (1 809) 448 4250

Jeffrey E Jones
Entomologist
Entomology Section
Ministry of Agriculture
Christ Church
Barbados
Tel: (1 809) 428 9980/2

Mona T Jones
Entomologist
Central Experiment Station
Centeno, via Arima (P.O.)
Trinidad
Tel: (1 809) 646 4334-7

Mark John
Agricultural Instructor
Division of Agriculture
Dominica

Jean Luc De Lapeyre
CIRAD-IRFA
Station de Neufchateau
97 A30
Capesterre Delle Eau
Guadeloupe
Tel: (590) 86302A

Wayne Lees
CARAPHIN Co-ordinator
IICA
P O Box 1318
Port of Spain
Trinidad
Tel: (1 809) 622 2373

John E Link
Head, Plant Protection Section
Ministry of Agriculture
Central Farm
Cayo District, Belize
Tel: (501) 922 640

John McIntyre
Agricultural Officer
Ministry of Agriculture
Roseau
Dominica
Tel: (1 809) 448 2401 Ext. 423

Debbie Martin
Coordinator
NGO Agric. Diversification Project
Madrelle, Dominica
Tel: (1 809) 448 4377

Urban Martin
IICA
Roseau
Dominica
Fax: (1 809) 448 5898

John D Mumford
Entomologist
Imperial College
Silwood Park
Ascot, Berks SL6 7TA
Britain
Tel: (44) 344 294 206
Fax: (44) 344 294 339

Roy C Murray Chief
Plant Protection Officer
Bodles Research Station
Old Harbour
St Catherine
Jamaica
Tel: (1 809) 983 2242,
2243, 2267 & 2281

Dorothy D Peterkin
Research Student
NIHERST
20 Victoria Avenue
Port of Spain
Trinidad
Tel: 625 2110

Gene V Pollard
Senior Lecturer in Entomology
Faculty of Agriculture
University of the West Indies
St Augustine, Trinidad
Tel: (1 809) 663 1364
Fax: (1 809) 662 1182

Chris Prior
Pathologist
IIBC
Ascot, Berks SL5 7TA
Britain
Tel: (44) 344 872 999
Fax: (44) 344 875 007

Llewellyn Rhodes
Entomologist
CARDI
PO Box 346
Roseau
Dominica
Tel: (1 809) 448 2715

B O Robinson
Dominica

Alexander Stephenson
Ministry of Agriculture
Botanical Gardens
Dominica
Tel: (1 809) 448 82401 Ext. 424

Earl Thomas
Plant Protection Officer
Ministry of Agriculture
Church Street
Basseterre
St Kitts
Tel: (1 809) 465 2335

Urban Zamore
Agricultural Officer
Division of Agriculture
Dominica

Biological control offers farmers a safe, effective and environmentally friendly way of safeguarding their crops against damage caused by insects and other pests. Using the natural enemies of pests as control agents, biological control is an increasingly attractive alternative to chemical pesticides, the overuse of which, especially in concentrated cocktails, can have serious detrimental effects on human health and on the environment. Chemical pesticides can also be costly, as they must be applied with increasing frequency as the pests develop resistance to the chemicals.

This volume contains authoritative papers from leading experts on the biological control of thrips and whitefly, two major pests in the Caribbean region.

ISBN: 0 85092 512 6

ISBN 978-1-84859-608-5

9 781848 596085