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REVIEW ARTICLE

Development of strategies for the incorporation of biological pesticides into the integrated management of locusts and grasshoppers

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Abstract

1. Effective biological pesticides based on oil formulation of deuteromycete fungal spores have been developed for use against locusts and grasshoppers. The isolate IMI 330189 of *Metarhizium anisopliae (flavoviride)* var. *acridum* has been registered, extensively field tested and its operating characteristics explored. It should form an powerful component technology in the integrated management of locust and grasshopper pests.
2. The particular advantages of *Metarhizium anisopliae* were found to be efficacy and persistence, low vertebrate toxicity, little environmental impact, conservation of natural enemies and potential for recycling. Additional socio-economic advantages include the possibility of local production, ease of disposal and versatility in use. The principal disadvantages relate to operating characteristics such as slower speed of kill and slightly greater lability in storage than chemical pesticides.
3. Strategies are being developed to integrate biological control agents into locust and grasshopper management schemes; for *Metarhizium* the accent is placed on: (i) treating the pest before it invades crops and (ii) situations with a high premium on environmental issues.
4. For some pest situations, fast-acting chemical pesticides will still be necessary for crop protection.
5. A cheaper biological agent, such as *Nosema locustae*, with the capacity to persist in the pest insect population would be useful. Research is recommended on the long-term impact of *Nosema* in Africa.
6. An evaluation of the utility of the manual destruction of egg pods leads to the conclusion that we should consider the possibility of importing egg parasitoids, such as *Scelio parvicornis* from Australia, into Africa.
7. Further development work is needed to clarify the economics and politics of locust and grasshopper control; to improve the regulatory framework for biopesticides; to inform key decision makers of the availability and potential of *Metarhizium;* and to implement the bio-intensive IPM strategies described.

Keywords *Anisopliae*, biological control, biopesticide, entomopathogen, fungus, grasshopper, insect pathology, IPM, locust, *Metarhizium*, microbial control.

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http://www.cgidr.org/iita/research/lubilosa/index.htm

Introduction

Locusts and grasshoppers are major economic pests of crops and grasslands throughout the world's dry zones. Their attacks attract much public attention; few other pests make headline news, and locusts are the only insect pests mentioned in the Bible and in oral histories of the Sahel (Cross & Baker, date unknown). Following a 30-year period of inactivity in much of Africa, locust plagues in the 1980s caught control organizations unprepared. In this article, we review the issues associated with this situation, and the research and development efforts of the past decade. We go on to suggest how the various elements should be brought together into realistic IPM strategies. Our focus is on Africa, but we draw on experiences elsewhere to illustrate certain points.

Locust plagues in Africa

Chemical pesticides have been the mainstay of control operations against locusts and grasshoppers for decades (Steedman, 1990). The period 1965–85 was characterized by very low activity levels of the principal locust species in Africa (all Orthoptera: Acrididae) (desert locust *Schistocerca gregaria* (Forskål), red locust *Nomadacris septemfasciata* (Audinet-Serville) and migratory locust *Locusta migratoria migratorioides* (Reiche and Fairmaire)). Brown locust *Locustana pardalina* (Walker) infestations did occur in the Republic of South Africa and were controlled during this period; effective administrative and practical infrastructures have been maintained in South Africa. For desert and other locust species, however, weather conditions were unsuitable for breeding and few infestations occurred; lack of activities led to a downward spiral in the efficacy of the agencies responsible for control operations (Pedgley, 1987; Haskell, 1992). In 1985 locust populations built up and found the authorities concerned unprepared. Budgets had been cut back, trained staff lost and the most effective chemical pesticide, dieldrin, banned in many countries. These factors led to the development of a full-scale plague lasting from 1986 to 1989. Despite spending more than $150 000 000 in campaign costs (Brader, 1988), the plague was brought to an end principally by weather conditions unfavourable to locusts (Showler & Potter, 1991). Subsequently, questions were asked about the costs, efficacy and environmental impact of the control operations (OTA, 1990; Joffe, 1995). Rowley & Bennet (1993) provide an overview, indicating the need for economics research and the development of alternative control agents.

Environmental issues

Environmental issues associated with the use of chemical pesticides against locusts are reviewed by Ritchie & Dobson (1995) and by Berger & Associates (1991), and are addressed by the FAO LOCUSTOX project, in Dakar, Senegal (Everts & Ba, 1997). The LOCUSTOX project investigates the environmental impact of chemical pesticide operations against locusts and grasshoppers. The project has followed a tiered approach, based on initial laboratory toxicity tests, field assays, full field tests and, eventually, monitoring of control operations (van der Valk & Nissay, 1997). Other organizations which have carried out research on environmental impacts have focused on the newer alternative chemicals, including CIRAD-PRIFAS (Centre de Cooperation Internationale en Recherche Agronomique pour le Developement, France) on fipronil (Balança & De Visscher, 1997), GTZ (Deutsche Gesellschaft für Technische Zusammenarbeit) on insect growth regulators (Peveling *et al.*, 1997a) and NRI (Natural Resources International, U.K.) also on insect growth regulators (Tingle *et al.*, 1997). Murphy *et al.* (1994) reviewed the toxicity of chlorpyrifos, fenitrothion, malathion and deltamethrin to non-target invertebrates and found that in 45–55% of the available records, these chemicals fell within toxicity rating 5 (mortality > 90%), with another 25–35% falling within rating 4 (mortality 30–90%). Moreover, Peveling *et al.* (1997b) showed that single field applications of even short-persistent fenitrothion against migratory locusts in Madagascar caused long-lasting (up to one year) population declines of >90% among epigeal collembolans. Recently, concerns have been raised about the hormone-mimicking effects of some persistent pesticides (Gillesby & Zacharewsky, 1998).

From the above it can be seen that the traditional and new chemicals currently in widespread use for locust and grasshopper control can all be classified as harmful to either key non-target insects, aquatic crustaceans and other invertebrates, vertebrate fauna, or combinations thereof. The costs of such environmental damage are difficult to estimate. Preliminary estimates of hidden costs associated with pesticide use for locust and grasshopper control in the Sahel were conducted by Houndekon & DeGroote (1998). We found that hidden costs were significant, based on medical and livestock costs and the costs of disposing of obsolete chemicals.

Economic and political issues

Although the costs of locust and grasshopper control operations are generally known, the benefits may be difficult to evaluate. Where high value crops such as citrus or gum arabic trees are attacked, there is no difficulty. Loss of fodder in grassland and loss of subsistence crops such as millet may give very low figures for economic benefit, but these figures are deceptive for several reasons. Firstly, failing to control locust infestations may lead to a pest population build-up in the subsequent generation and further losses. Secondly, the value of a subsistence crop such as millet is not constant through the year; the market value at harvesting may be low, but the value to the farmer later in the year may increase. Finally, there may be political will to control locusts irrespective of costs. These issues are discussed in reports by the US Office of Technology Assessment (OTA, 1990), World Bank (Joffe, 1995) and GTZ (Wewetzer *et al.*, 1993). A consensus is not clear, other than that there is a need for more data before conclusions can be drawn, and this is taking place within the framework of the Emergency Prevention System for Transboundary Animal and Plant Pests and Diseases (EMPRES) programme of the Food and Agriculture Organization of the United Nations (FAO) for desert locust.

Costs and benefits have been estimated more accurately outside Africa. For Australian plague locust *Chortoicetes terminifera* (Walker), Wright (1986) estimated a benefit : cost ratio between 23 : 1 and 29 : 1. Such data have been incorporated into decision support models (Wright, 1987; McCulloch *et al.*, 1993). Similar models have been developed for control of grasshoppers in US grasslands (e.g. Berry, 1995; USDA, 1996); these grasshoppers (mostly *Melanoplus* species) often do not pose risks to crop land; the economic benefits of treatments are lower but still substantial in range land (Hewitt & Onsager, 1982).

Some estimates have been made of losses associated with grasshoppers in the African Sahel. Perhaps justifiably, no attempts have been made to evaluate the loss of fodder. Estimates of losses in millet have been made by USAID (US Agency for International Development; Coop & Croft, 1993, 1994), GTZ (Krall *et al.*, 1995) and NRI (Jago, 1993). A draft decision support tool is available (Coop *et al.*, 1991) and generally gives positive returns on treatments with chemicals against grasshoppers during heavy infestations. However, the model needs further validation and wider application. Other factors which need to be taken into account in the model are the peak cost of millet at times of scarcity, the externalities of treatment costs (Houndekon & Dehroote, 1998), and the total risk of not treating (i.e. the risk of grasshopper populations becoming established and continuing to inflict losses, possibly on higher value crops).

Political factors are very important in locust and grasshopper control. Irrespective of the actual economic damage, there can be public demand for treatment, fuelled by popular press reporting. Political factors also intervene in agencies' selection of control agents; in Africa, donors purchase much pesticide. Regulations designed to protect developing countries from dumping of obsolete chemicals oblige donors to purchase chemicals registered in the donor country. The unpredictability of locust plagues inevitably leads to a need to stockpile chemical pesticides and dispose of surplus stocks; FAO spent $650,000 to dispose of surplus dieldrin stock from Niger in 1992 (Houndekon & DeGroote, 1998).

Need for IPM

These considerations point clearly to a need to develop integrated strategies of control that do not rely solely on the use of chemical pesticides. Although the economic benefits of locust control can be difficult to evaluate, the principle of 'at least, do no harm' would support the notion of environmentally friendly control options. FAO (1998), The World Bank and others similarly wish to place locust (and particularly desert locust) control within the context of integrated pest management (IPM) (Jago, 1991; Joffe, 1995). Moreover, the goal of the FAO EMPRES programme is to minimize the risk of desert locust plagues emanating from the Central Region (Red Sea basin) of the desert locust distribution area with strategies based around timely, environmentally sound interventions.

IPM component technologies

Biological and microbial control definitions and rationale

Classical biological control refers to an inoculative introduction of an agent not previously present, inoculative augmentation refers to the application of an indigenous agent with the objective of enhancing subsequent build-up in the pest population, and inundative augmentation refers to the mass application of an agent with the primary objective of high initial kill (e.g. van Driesche & Bellows, 1996). Where the active biological control agent is a microorganism or microbe, we can refer to microbial control, and when a microbial control agent is produced and formulated for application, it is referred to as a biopesticide, biological pesticide or microbial pesticide. In the case of a biopesticide whose active agent is a fungus, we refer to mycopesticide or mycoinsecticide. (The terms biopesticide and biological pesticide are sometimes used to include botanical derivatives and arthropods produced and delivered commercially.) Biopesticides are mostly used in an inundative augmentation mode, with some inoculative augmentation effects.

We can also refer to numerical and functional responses (Thomas & Waage, 1996); a control agent such as a chemical pesticide or a biopesticide used in inundative augmentation mode has an effect which is proportional to the amount of the agent applied – this is the numerical response. By contrast, biological agents with the capacity to reproduce may also have a functional response, where the impact of the control agent exceeds the initial numerical response.

Before considering possible biological control interventions for locusts and grasshoppers, we need to examine the existing natural enemy situation and population dynamics. It is important to appreciate the mobility of these insects, in space and time. Abiotic factors, principally rainfall and its effect on vegetation, are more important than biotic factors in determining population dynamics. Very few natural enemies are seen in the upsurge or build-up phase, while a rich parasitic and predatory fauna is associated with stable or declining populations (Greathead, 1992; Wilps, 1997). The conceptual basis for microbial control is that we can stock, or rapidly multiply, transport and apply microbes to reduce pest populations before natural enemies can 'catch up' with the pest population. The selectivity of microbial control agents is important because, unlike chemical pesticides, they do not interfere with the capacity of the natural enemy population to build up (Prior & Greathead, 1989; Prior & Streett, 1997).

Chemical pesticides

The current list of chemical pesticides approved by FAO (1998) for desert locust control is given in Table 1. As well as the standard organophosphate, carbamate and pyrethroid chemicals, some recently developed compounds have been tested. The insect growth regulators (IGRs) diflubenzuron and teflubenzuron have proven highly effective and persistent against *Locusta migratoria* nymphs in Madagascar (Dobson *et al.*, 1997); similarly the phenylpyrazole compound fipronil has excellent persistence (Rhône-Poulenc, 1995 [now Aventis Crop Science]). IGRs have favourable vertebrate toxicity profiles and pose little or no risk to operators or livestock. Fipronil has a mammalian toxicity comparable to the other broad spectrum insecticides (moderately hazardous according to WHO classification), but can be used at much lower dose rates. The main concern associated with the use of IGRs and fipronil seems to be their impact on nontarget arthropods (Balança & De Visscher, 1997; Tingle *et al.*, 1997).

Table 1 Chemical insecticides for use in locust control.

Insecticide	Aquatic environment	Terrestrial invertebrates	Terrestrial vertebrates	WHO toxicity class (human)$
Bendiocarb	M	H	M	II
Chlorpyrifos	H	H	M	II
Deltamethrin	H	M	L	U
diflubenzuron (blanket)	H	M	L	U
diflubenzuron (barrier)	H	M	L	U
Fenitrothion	M	H	M	II
fipronil (blanket)	L	H	L	U
fipronil (barrier)	L	H	L	U
lambda-cyhalothrin	H	M	L	II
Malathion	M	H	L	III
Metarhizium sp. (IMI 330189)	n.d.*	L	L	not classified$$
teflubenzuron (blanket)	H	M	L	U
teflubenzuron (barrier)	H	M	L	U
triflumuron (blanket)	H	M	L	U
triflumuron (barrier)	H	M	L	U

Risk is classified as low (L), medium (M) or high (H) based on FAO (1998) Table 2.
The WHO toxicity class was based on the LD_{50} of the active ingredient and the most concentrated formulation likely to be used in desert locust control (i.e. min. 0.5 L/ha).
* no data were available at the time of production of the FAO report; subsequent registration tests indicated no risk to fish or *Daphnia*.
$WHO class: II = moderately hazardous, III = slightly hazardous, U = unlikely to present acute hazard in normal use; $$ would be classified as 'III' or 'U' if based on the presently available acute toxicity data. Toxicity testing recommended for biopesticides differs from that used for chemical pesticides. Table simplified from FAO (1998).

Current chemical control options in north America (USA and Canada) are reviewed by Riegert *et al.* (1997); the principal difference between America and Africa is a greater reliance on granular and bait formulations, particularly of carbofuran, in America (Agriculture & Agri-Food Canada, 1993). Logistical problems preclude the use of baits and granules in most of Africa. A comprehensive grasshopper IPM strategy has been outlined by a USDA-APHIS project (USDA, 1996). A computer model, HOPPER, is available to aid farmers' decision-making. Despite the availability of two biopesticides (see below), control still centres on chemical pesticides. In Canada, the focus has been on reducing doses of carbamate baits and pyrethroid applications, with the objective of achieving mortality levels of around 70%. Such levels permit the survival of a range of predators, particularly birds (Martin *et al.*, 1997). Geographical information systems (GIS) have been used to determine and predict the distribution of grasshopper outbreaks in Canada (Johnson *et al.*, 1995). Work on spatial distribution of outbreaks in the US by Kemp *et al.* (1989) was continued by Schell & Lockwood (1997) to show that only small proportions of the area of Wyoming are regularly infested by grasshoppers. By focusing on these areas the total area treated can be reduced, reducing total environmental contamination without recourse to biological control. Thus, the North American approach to grasshopper IPM has been to use chemical pesticides as selectively as possible.

Microsporidia as microbial control agents

Various microbial options for control of locusts and grasshoppers have been explored. The first commercially available formulation was No-Lo®, a bait formulation of the protozoan *Nosema locustae* (Canning) (Microspora: Microsporidia: Nosematidae) produced by Evans Biocontrol. The production system is described by Henry (1985). No-Lo® is now produced by M. R. Durango (Colorado, U.S.A.), and a similar product, Semaspore®, is produced by Bozeman Biotech (Bozeman, Montana, U.S.A.). The product is popular amongst organic farmers, and is available, for example, in gardening catalogues. Field impact in replicated trials in Canada was variable (Johnson & Dolinski, 1997). In China, a locally produced *Nosema* is applied over some 100 000 ha annually, providing 40–60% population reductions (Johnson, 1997). Lange & De Wysiecki (1996) showed that in Argentina, *Nosema* had persisted and dispersed from applications conducted 12 years previously. Only three field trials have been conducted in the African region, in Mali in 1988 (Johnson, 1997), on the Cape Verde Islands in 1989 (Krall & Knausenberger, 1992) and in Niger in 1990 (Anon, 1990). Although within-season results were disappointing in all studies, longer-term follow-up observations would be worthwhile, particularly as grasshopper populations appear to have declined in the area treated near Mourdiah, Mali (authors' unpublished observations).

More virulent microsporidians are also known, such as *Nosema cuneata* Henry and *Nosema acridophaga* Henry, and the recently described *Johenrea locustae* Lange *et al.* (Microspora: Microsporida: Glugeidae) from Madagascar (Lange *et al.*, 1996). These may have application as classical biological control agents. Some laboratory observations on other protists such as *Malamoeba locustae* King and Taylor (Sarcomastigophora: Rhizopoda: Amoebida) have also been carried out (Raina, 1992).

Fungi as microbial control agents

Two fungi have been developed as commercially available biopesticides. The first is Mycotrol®, produced by Mycotech. The product consists of spores of a virulent isolate of *Beauveria bassiana* (Balsamo) Vuillemin strain GHA (Hyphomycetes: Moniliales); field tests have given control of grasshoppers in Canada (Johnson & Goettel, 1993), but subsequent trials revealed a temperature constraint when weather conditions permitted thermoregulation by the grasshoppers (Johnson *et al.*, 1992; Inglis *et al.*, 1996a). Nevertheless, the product has shown excellent activity against other insects, and is available commercially.

Another fungal product, *Metarhizium anisopliae (flavoviride)* var. *acridum* strain IMI 330189 (Metchnikoff) Sorokin (Driver *et al.*, 1999) (Hyphomycetes: Moniliales) developed by the LUBILOSA project (see Acknowledgements), is, or will be, available commercially from two companies, NPP (Natural Plant Protection) of Pau, France, and BCP (Biological Control Products) of Pinetown, South Africa as Green Muscle® (Bateman, 1997a; Neethling & Dent, 1998). It is effective against all the major acridid pest species; first observable mortality in the field generally occurs 7–10 days after application, and the full effects are seen 14–18 days after application (Lomer *et al.*, 1997a). Field studies measured half-life of the fungal spores as 6.8 days in north Benin, varying from 2 to 12 days in other environments (Thomas *et al.*, 1997a). In Niger, there was almost no loss in efficacy after 21 days; in fact, *Metarhizium* provided season-long control, while plots treated with the chemical standard, fenitrothion, were re-invaded after 15 days (Langewald *et al.*, 1999). Table 2 shows the extent of field testing of this product; results have been consistent across a wide range of ecozones, vegetation types, target species and application conditions.

Laboratory host-range studies indicate very few *Metarhizium* infections outside the Orthoptera; some mortality in Hymenoptera and Isoptera was observed (Prior, 1997). However, sporulation was not confirmed, and no impact on these insects was observed during field studies. In field tests with *Metarhizium*, predator activity was maintained or enhanced (Thomas *et al.*, 1998; Peveling *et al.*, 1999), and the impact on non-target organisms was considerably less than equivalent chemical pesticides (Peveling & Demba, 1997; Peveling *et al.*, 1999). Feeding tests showed no risks to birds from consuming infected hoppers (Smits *et al.*, 1999), and mammalian toxicity test results to standard protocols showed no hazard. These data are summarized in the LUBILOSA registration dossier, which has been accepted by the South African registration authorities and by the FAO Locust Pesticide Referee Group (FAO, 1998)

Studies are on-going on the storage of *Metarhizium* spores under tropical transport and storage conditions; predictive models developed by Hong *et al.* (1997, 1998) indicate that spores dried to <5% moisture content and stored in moisture-proof containers can resist temperatures up to 40°C for 9 months. Field experience confirms that, properly packaged, spores can be stored for 6 months under tropical conditions, and over several years with cool storage.

The cost of production of *Metarhizium* spores at the International Institute of Tropical Agriculture Cotonou pilot production plant is $21 per 100 g (enough to treat 1 or 2 ha

Table 2 Some field trials with *Metarhizium anisopliae* IMI 330189.

Target species	Description	Location	Result	Reference
Desert locust	Cage trials	Benin, Niger 1991	Cage mortality 90% in 7 days	Bateman *et al.*, 1998
Desert locust	Treatment of hopper bands	Mauritania 1993	80% mortality in 9 days in cages; treated hopper bands disappeared	Kooyman & Godonou, 1997
Desert locust	Hopper bands	Mauritania 1995	Hopper bands decreased by 70% in 8 days	Langewald *et al.*, 1997a
Tree locust	Nymphs in Gum Arabic trees, 25 ha plots	Sudan 1997	70% reduction in field population by day 18	Kooyman & Abdallah, 1998
Red locust	Medium plot trial	Buzi, Mozambique1997	98% mortality in 9 days. Band cohesion destroyed	Price *et al.*, 1997b
Brown locust	Enclosure trial	Karoo, South Africa 1994	Mortality in cages 80% in 18 days	Bateman *et al.*, 1994
Brown locust	Aerial trial	Karoo, South Africa 1995	Mortality in enclosures 80% in 16 days	Price *et al.*, 1997a
Brown locust	Registration trial	Karoo, South Africa 1998	Registration trial	Registration documents
Rice grasshopper	4 ha plots	Malanville, Benin 1993	70% field population reduction by day 14	Lomer *et al.*, 1997b
Senegalese grasshopper *	0.25 ha plots	Mourdiah, Mali 1993	70% field population reduction by day 10	Douro-Kpindou, 1997
Senegalese grasshopper	50 ha plots	Maine Soroa, Niger 1994	70% reduction in field population by day 16	Kooyman *et al.*, 1997
Senegalese grasshopper	50 ha plots, cf. toxic standard	Maine Soroa, Niger 1995	MF greater efficacy than fenitrothion	Langewald *et al.*, 1999
Senegalese grasshopper	800 ha plots, aerial app.	Maine Soroa, Niger 1996	MF efficacy confirmed; environmental impact data	Langewald *et al.*, 1999
Moroccan locust	0.125 ha	Ciudad Real, Spain 1998	99% mortality in 21 days, AST 10.5 days (cf 20.3 in controls)	M. Thomas unpublished

* Further unpublished field trials against Senegalese grasshopper, giving similar results, were carried out by national programmes of Chad, Senegal, Niger, Burkina Faso and Mali in 1996 and 1997 (LUBILOSA, 1997). AST = average survival time.

at currently recommended dose rates; Cherry *et al.*, 1999). As this cost is somewhat above the equivalent chemical pesticide cost, some subsidy might be necessary initially. This could be justified as a 'Green premium' calculated on the basis of the reduced externalities associated with a biopesticide compared with equivalent chemical pesticides (Houndekon & DeGroote, 1998). In the longer run, it is likely that economies of scale will allow for significant reductions in production cost. Fluctuations in the demand for a locust control product will pose problems in implementing *Metarhizium* mycopesticide as the production output of the companies is limited by the installed fermentation capacity. Several options for meeting demand can be envisaged, as well as for dampening the fluctuation in demand. Firstly, both biopesticide production companies produce other products, and in times of high demand for locust products, capacity could be diverted towards *Metarhizium* production. Secondly, the establishment of demand for *Metarhizium* for control of more stable and chronic pest problems such as Moroccan locust, brown locust, Sahelian grasshoppers and variegated grasshopper will enable more even production levels to be maintained. Thirdly, the market proportion envisaged for *Metarhizium* is variable; while we might expect 20–40% market share during recession periods, this might drop to 5–10% during plagues, when swarms are treated with chemical pesticides. Finally, with a wider acceptance of microbial products, for instance for thrips, temite, banana weevil and maize stem borer control (IITA, 1997), greater mycopesticide capacity is likely to be installed.

The variety of *Metarhizium anisopliae* (var. *acridum*) affecting acridids is pan-tropical and shows a high degree of genetic homogeneity (Lomer *et al.*, 1997a; Driver *et al.*, 1999). In principle, this variety could be freely transported between any countries where its presence has been reported; in practice, in the research phase, the FAO code of conduct for the import and release of exotic biological control agents is followed for any introductions between countries (FAO, 1996). Normally, national authorities consider the registration process to supersede this process once completed. Most development work within LUBILOSA has been on isolate IMI 330189 from Niger. In laboratory assays, this isolate was shown to have virulence similar to other var. *acridum* isolates (Bateman *et al.*, 1996). Although over 160 isolates were evaluated by the LUBILOSA Programme, none were considered to have properties that justified switching from this original 'standard' isolate for control of acridid locusts and grasshoppers (Jenkins *et al.*, 1997). Nevertheless, some research on other isolates of *Metarhizium anisopliae* var. *acridum* has continued, particularly in Australia, and is summarized in Table 3.

Microbial control agents in IPM

Some degree of recycling, horizontal transmission or functional response, has been observed with *M. anisopliae* under favourable environmental conditions (Langewald *et al.*, 1997b; Lomer

Table 3 Different isolates of *Metarhizium anisopliae* var. *acridum* under development.

Isolate	Origin	Steward institute	Field testing scale	Safety testing, registration	Special features	Reference
IMI 330189	Niger	CAB International	800 ha plots	Accepted by FAO and government of South Africa	Registered; commercial production in progress	Lomer *et al.*, 1997
FI 984 (ARSEF 324)	Australia	CSIRO	200 ha plots	Dossier with Australian authorities; granted organic status by Australian authorities	*Chortoicetes terminifera* Walk, *Phaulacridium vittatum* (Sjöstedt) and *Locusta migratoria*	Milner *et al.*, 1997; R. Milner, pers. comm.
I91–609	Benin	IITA	10 ha plots	Safety tests incomplete	Highly active against *Zonocerus variegatus*	Lomer *et al.*, 1993; Douro-Kpindou *et al.*, 1995
SP 9 (I-839)	Madagascar	MSU	10 ha plots	Safety tests OK Dossier with Madagascan authorities	Good activity against *Locusta migratoria*	Delgado *et al.*, 1997
ER 1	Eritrea	MSU	Field cages	Toxicity tests in progress		D. Swanson MSU, pers. comm.
DSM 11336 (MII5)	Madagascar	BBA	Cage trials	In progress	Blastospore production in liquid fermentation	Stephan & Zimmerman, 1997
CG 423	Brazil	EMBRAPA	Cage trials	In progress	*Rhammatocerus schistocercoides* Rhen	Magahalaes *et al.*, 1996 & 1997

ARSEF – US Agricultural Research Service Entomopathogenic Fungus collection.
DSM, BBA – Institute for Biological Control, Darmstadt, Germany.
FI – CSIRO, Commonwealth Scientific and Industrial Research Organization, Australia.
I – International Institute of Tropical Agriculture, Biocontrol and Biodiversity Project.
IMI – CABI Bioscience, Egham, UK.
SP, ER – Montana State University, USA.
EMBRAPA = Empresa Brasileira de Pesquisa Agropecuaria, Brazil.

* This characteristic is probably not confined to this isolate (Kleespies & Zimmermann, 1992); IMI 330189 produces both blastospores and conidia in submerged culture (Jenkins & Prior, 1993)

et al., 1997b). Such effects greatly enhance the theoretical efficacy of biopesticide application (Thomas *et al.*, 1995; Thomas & Wood, 1997). In particular, it is possible that the long persistence (>6 weeks) and long-term control observed during operational trials in Maine Soroa, Niger in 1997 may have been due in part to the production of new conidia from sporulating cadavers (Langewald *et al.*, 1999).

Some other key parameters associated with the use biopesticides have less importance in direct comparisons with chemical pesticides, but are extremely important in an IPM context. Infected insects are reported to consume less food (Thomas *et al.*, 1997c) and to be more prone to predation than healthy grasshoppers (Thomas *et al.*, 1998). Thermoregulation by infected insects is a constraint to the efficacy of microbial pesticides (Blanford *et al.*, 1998) and a geographical information system (GIS) approach is being developed by LUBILOSA to define the times and places when *Metarhizium* can be used to best effect; extreme hot and sunny conditions may limit the efficacy of the biopesticide.

Metarhizium is applied in the same way as a chemical pesticide, but functions as a biological agent; *Nosema locustae* shows direct vertical transmission to the second generation, but long-term studies on its persistence and potential are necessary in Africa (Johnson, 1997). Such microbial control agents occupy places along the continuum from augmentative inundation to inoculative augmentation. In both cases, an evaluation of functional responses will be important in developing the full economic justification for their utilization.

The introduction of agents capable of permanent establishment and reproduction (inoculative introduction, classical biological control) is economically advantageous (Norgaard, 1988). Entomophthoralean fungi have potential to be used in inoculative introduction (Hajek, 1997), and *Entomphaga grylli* (Pathotype III = *E. praxibuli*) (Fresenius) Batko was introduced to the U.S.A. from Australia in 1990 (Carruthers *et al.*, 1997; Lockwood & Ewen, 1997). This pathotype has a broader host range than the indigenous type; although control of *Melanoplus* spp. was initially good, subsequent unfavourable weather conditions caused a decline in incidence (Bidochka *et al.*, 1996). Table 4 provides a summary of the biological control options for locust and grasshopper control.

Egg pod destruction

The destruction of grasshopper and locust egg pods has been proposed at various times. Tamu (1995) and Modder (1986) found that farmers in Nigeria were aware of the oviposition sites of *Zonocerus variegatus* (L.) (Orthoptera: Pyrgomorphidae), but successful control was never implemented because farmers lack time and motivation. This constraint was removed in a large-scale test conducted in Mopti, Mali in 1996 by an NGO, Programme d'Accompagnement du Monde Paysan a l'Agriculture Durable de la Diocese de Mopti (PA/MP/AD), in which each sack of egg pods was exchanged for a sack of millet. Ten tonnes of egg pods were collected; the value of a 50-kg sack of millet is about $12.50, giving a total operation cost of $2500 not including overheads. The operation may have had an impact on grasshopper populations locally within fields, but farmers only concentrated on their own fields. Many grasshopper egg pods would be inaccessible amongst rocks and trees. No observations were made on natural enemies.

Clearly, farmers do not consider destruction of egg pods a worthwhile use of their time. Farmers are very busy during the short rainy season and are frequently absent from the farm during the dry season. Attaching a value to egg pods, either by exchanging for cash or food, or finding a use for them, such as chicken feed or building materials may offer a way forward. Even so, it is unlikely that farmers would wish to carry out extensive digging far from their fields. Any proposal to encourage egg pod destruction as a component of IPM would need to take careful account of the agricultural calendar, farmer's motivation, as well as the costs and returns on the intervention. Similarly, the natural mortality caused by egg predators and parasites, and the impact of the intervention on these mortality rates, would need to be taken into account. Some of the meloid egg predators are also pests on millet. Overall, manual egg pod destruction cannot be considered a very viable IPM option.

Biological control at the egg stage

Early observations on the impact of egg parasitoids on desert locust populations are reported by Greathead (1963, 1992). Shah *et al.* (1998) conducted extensive observations over four seasons on the natural enemies affecting egg pods in Malanville, north Benin. Meloid beetle predators accounted for up to 50% mortality (*Epicauta* sp., *Mylabris* (4 spp.) and *Psalydolytta* (3 spp.)), while parasitism by *Scelio africanus* Risbec and *S. mauritanicus* Risbec plus three further *Scelio* spp. accounted for a maximum of 3.3% mortality. Rainfall, in the form of periodic flooding which 'drowns' egg pods, was the most important factor determining population levels. The impact of soil types on grasshopper oviposition was studied by Yahaya (1998). Mortality by natural enemies reported include predation by meloid beetles at 4% (four species of *Hycleus*), parasitism by *Systoechus* sp. at 9% and by three species of *Scelio* at 8% (*S. africanus, S. corion* Nixon and *S. uvarovi* Oglobin). Dysart (1995) reports low rates of parasitism by the native American species, *S. opacus* (Prov.) and other species. Examining the possibilities for introducing the Australian *Scelio parvicornis* Dodd to the U.S.A., he consistently observed parasitism rates far in excess of those caused by the indigenous wasp (Baker *et al.*, 1996). However, to date, USDA-APHIS has not given authorization for the release of *S. parvicornis* in the U.S.A. (Lockwood & Ewen, 1997); the principal concerns raised by those opposing importation are the risks to non-target grasshoppers. However, the data available would strongly support the case for evaluating *S. parvicornis* and other species for introduction to Africa according to the test protocols provided for by the FAO (1996).

Semiochemicals

Research on desert locust pheromones has been carried out by the International Centre for Insect Physiology and Ecology, ICIPE, and reviewed by Schmidt (1997), Loher (1990) and Byers (1991). The pheromone system is rather complex and involves separate compounds or mixtures of compounds for maturation acceleration, egg pod formation stimulation, melanization, nymph aggregation, adult aggregation, mating and oviposition (Torto *et al.*, 1994). The chemical structures have been determined, and are mostly aromatic compounds such as phenol, veratrole, guaiacol, benzylnitrile and phenylacetonitrile (Rai *et al.*, 1997).

In practical terms, pheromones could either be used to disperse aggregations of locusts, leading subsequently to increased natural mortality, or to slow down movements of insects so that concurrent application of biopesticides becomes easier to monitor. A joint LUBILOSA/ICIPE trial in Sudan combining a pheromone component, phenylacetonitrile, with *Metarhizium* did lead to treated bands dispersing and moving more slowly before dying of fungal infection (A. Hassanali, ICIPE, Nairobi, personal communication).

Locust pheromones do not appear to act over long distances, and are thus of little benefit in monitoring. Procedures for the registration of pheromones in Africa are currently unclear, and this may delay implementation.

The attraction of acridoids to plant volatiles is an interesting area. Most work has focused on the attraction of *Zonocerus variegatus* to *Chromolaena odorata* and Fischer & Boppré (1997) propose a trap-and-bait system based on this attraction. This was explored by Adu-Mensah (1994), but a feasible implementation route was not clear at that time and this control option has not been pursued.

Botanicals

The two most promising botanical agents against locusts are extracts of seeds of trees in the family Meliaceae, such as neem *Azadirachta indica* Juss. and melia *Melia volkensii* Gürke (Schmutterer, 1995; Diop & Wilps, 1997; Mwangi *et al.*, 1997; Rembold, 1997). The effects of neem extracts have been most extensively studied. The effects vary with species; for example, in application of aqueous extract to foliage, there was high mortality in *L. migratoria migratorioides*, while a strong phagorepellent effect was observed with *S. gregaria, N. septemfasciata* and *Z. variegatus*. Topical application of neem oil formulations enriched with azadirachtin caused mortality, developmental defects (particularly at moulting) and behavioural abnormality (in particular failure of gregarious behaviour) (Langewald & Schmutterer, 1992; Nicol *et al.*, 1995). Thus we can envisage utilization of neem in IPM either to repel locusts from crops, or by topical application to increase mortality.

Neem trees grow abundantly throughout the arid tropics and are especially abundant in the Sahel; Melia is confined to East Africa. Relatively simple extraction procedures enable safe and effective botanical pesticides to be produced at the farm level. However, the optimum implementation route has yet to be determined; this could either be artisanal or farm-level preparation of aqueous leaf or seed extracts, or via a more professionally produced, registered product.

Integrating the IPM component technologies

Some of the IPM component technologies described above can be mixed directly. As described above, mixtures between *Metarhizium* and locust pheromones were promising in trials. Mixing *Metarhizium* conidia with neem oil was detrimental to the conidia (authors' unpublished observations). Some trials of mixtures between *Metarhizium* and chemical pesticides have been conducted; there was no synergism with fenitrothion (Gan-Bobo in LUBILOSA, 1997), but lambdacyhalothrin gave a strong synergistic effect in the laboratory (Sanyang & van Emden, 1996) and in the field (authors' unpublished observations), effectively combining the rapid knock-down effect of the pyrethroid with the longer persistence of *Metarhizium*. Diflubenzuron also gave promising synergistic effects with *Beauveria bassiana* in trials in Mali (Delgado *et al.*, 1999). For all such combinations, however, the environmental impact needs to be measured, and submission of a separate registration dossier would be necessary.

In the following sections, we explore the integrated management options opened up by the availability of *Metarhizium* as a control agent in more detail. Table 4 provides an overview of the biological components of IPM strategies, their mode of action and current state of development.

Outline IPM schemes for selected acridid pests

Many authorities have urged the development of environmentally sound integrated management schemes for grasshoppers and locusts (Joffe, 1995; Jago, 1997). However, until now, agencies with the responsibility of controlling locusts have had no options apart from chemical pesticides; 'IPM' is restricted to selective treatment of infestations according to 'economic thresholds' based on population dynamics rather than economic damage. Now, with the development of an effective and selective biopesticide, integrated control may become reality; in general, we can still expect to see fast-acting chemical pesticides being used to protect crops from invasion and to treat flying swarms, with *Metarhizium* the agent of choice to treat infestations in environmentally sensitive areas and infestations some distance from crops at risk. All stages of locust and grasshoppers are susceptible to *Metarhizium*, but the slow speed of kill makes it unlikely that treatment of adult swarms will be feasible.

Desert locust *Schistocerca gregaria*

Schistocerca gregaria breeds regularly in the Red Sea Basin (Central zone); when breeding is successful in this area, outbreaks and plagues develop which can invade a vast area from Mauritania in the west to India in the east. Once breeding populations are established in this larger outbreak area, further multiplication can take place under favourable environmental conditions (Steedman, 1990; Skaf *et al.*, 1990; Haskell, 1992). Development of an integrated strategic control scheme for *S. gregaria* is the principal focus for the FAO EMPRES programme; this programme has the objective of controlling locust outbreaks in the Central zone before swarms can spread to other breeding areas (Showler, 1995; FAO EMPRES project document, unpublished). The EMPRES programme will carry out field testing of IPM component technologies, with an important focus on monitoring and prediction of outbreaks.

Table 4 Biological control agents against grasshoppers and locusts.

Control agent	Mode of action	Organizations involved	Reports	Development stage
Arthropods				
Egg parasitoids	Inoculative introduction	USDA	Lockwood & Ewen, 1997	Stalled +
Predators of nymphs and adults	Conservation of natural enemies	LUBILOSA, GTZ	Greathead, 1963; Wilps, 1997	Include in IPM context, will be enhanced by use of mycopesticide
Microsporidia				
Nosema locustae	Inundative augmentation	M.R. Durango, Montana Biotech, Agriculture Canada; GTZ, USAID, Ciba-Geigy	Johnson, 1997; Krall & Knausenberger, 1992	In use in China & US, stalled in Africa +
Johenrea locustae	Inoculative introduction	Madagascar	Lange *et al.*, 1996	Stalled +
Viruses				
Entomopox virus	Inundative augmentation	MSU	Streett & Henry, 1990; Purrini, 1988	Stalled (efficacy and funding issues)
Fungi				
Entomophaga grylli III	Inoculative introduction	USDA	Bidochka *et al.*, 1996	Released, but low incidence
Metarhizium IMI 330189 *	Inundative augmentation	LUBILOSA	Lomer *et al.*, 1997a	Registered +
Metarhizium other strains	Inundative augmentation	LUBILOSA, CSIRO EMBRAPA	Lomer *et al.*, 1997a; Milner *et al.*, 1997; Vicentini & Magalhaes, 1996	Under development
Metarhizium blastospores	Inundative augmentation	BBA	Stephan & Zimmerman, 1997	Under development
Beauveria bassiana	Inundative augmentation	Mycotech, USDA, MSU	Johnson & Goettel, 1993; Inglis *et al.*, 1996a	Registered, but not effective under hot conditions

* fungal spores may be formulated in oil, as aqueous emulsions or in baits.
+ IPM options considered as priorities for further research and development work.
USDA = United States Department of Agriculture.
BBA = Biological Control Institute, Darmstadt, Germany.
CSIRO = Commonwealth Scientific and Industrial Research Organization, Australia.

Currently, civilian remote sensing equipment does not have adequate resolution to detect locusts, nor the sparse patches of greenness which will permit breeding. Early detection therefore depends on prediction of rainfall from maps of cold cloud cover, and follow-up ground surveys to determine actual locust infestations of subsequent vegetation; survey results are collated by FAO and published in the form of a monthly bulletin. A forecasting system (SWARMS) is currently being developed by FAO (Cressman, 1997).

Various debates surround the optimum application strategy. Symmons (1992) proposes swarm treatment at an early stage of outbreaks, arguing that detection efficiency is too low for hopper bands. However, these considerations are not borne out by practical experience, and keeping trained personnel active rather than on stand-by is an important issue. Joffe (1995) finds, in common with other economic studies, that the total crop loss may not justify the expenditure on control; however, as discussed above, crude economic benefit–loss calculations may mask valid biological, social and political considerations. The concept of strategic control is argued strongly by Showler & Potter (1991), and this is the conceptual basis for the EMPRES programme. Core teams are envisaged to evaluate biological control, population dynamics and environmental impact. A central feature of the programme will be early detection and control. The important break-through is that, with the development of *Metarhizium* as a microbial pesticide, for the first time, control teams will have an environmentally friendly option to replace chemicals to treat locust infestations.

Results to date with *Metarhizium anisopliae* var. *acridum* IMI 330189 indicate that its field performance against desert locust is as good as its performance against other locusts and grasshoppers (Kooyman & Godonou, 1997; Langewald *et al.*, 1997a). On the basis of published data, a mycopesticide based on *Metarhizium* spores should fulfil the requirements of the EMPRES programme for a control agent which is as effective and easy to apply as chemical pesticides but has reduced environmental impact. However, improved storage facilities and technical skills of spray teams are important prerequisites to achieving satisfactory levels of control. Considerable efforts will be necessary in this area to avoid unsatisfactory results which, as a consequence, might discredit the whole biological control approach.

The cost of locust control is normally shared between donors and affected countries, with the donor resources sometimes pooled by FAO. Most donors prioritize environmental issues and might be prepared to pay a Green premium for an environmen-

1. Surveillance
    hoppers present => 2
    no hoppers present – continue surveillance => 1
2. Quick population assessment
    immediate risk of flight and crop loss => 3
    population in nymphal stage => 4
    population in egg stage => 5
3. Environmentally sensitive area?
    yes => pyrethroid; in wetlands use *Metarhizium* and treat any emerging swarms with pyrethroid.
    no => treat with any approved chemical
4. Environmentally sensitive area?
    yes => treat with mycopesticide
    no => treat with mycopesticide or IGR
5. Sample egg pods to assess density and attack by natural enemies
    few present – no action
    many, with high natural enemy incidence – await emergence, prepare small amounts of mycopesticide for possible use
    many, with low natural enemy incidence – quantify need for mycopesticide.

Figure 1 Basic IPM decision tree for desert locust (modified from FAO, 1998).

tally friendly product, at least for an introductory period. In the longer run, we can expect the need for donor support to a Green premium to diminish as production costs fall with increasing demand and supply of biopesticides. Similarly, as we do not expect *Metarhizium* to be used against swarms, and as the EMPRES programme should lead to locust control in the recession areas, demand for *Metarhizium* should be more stable than the current demand for chemical pesticides.

An outline IPM decision tree is shown in Fig. 1. As has always been the case, good meteorological data, backed up by conscientious ground surveys, leading to early detection and warning of locust infestations is the absolutely critical element in the success of preventive control. Where there is no immediate risk of swarms flying and causing economic damage, the *Metarhizium* mycopesticide should be used. In situations where quick kill is essential, evaluation of the risk of environmental damage caused by different chemicals will guide the selection of the appropriate agent according to the habitat. In particularly vulnerable habitats such as wetlands, operators might opt to use *Metarhizium* even on fledgling adults.

Brown locust *Locustana pardalina*, South Africa

1. Reports from farmers, surveillance by government teams
2. Evaluation of control options by GIS including environmental vulnerability and likelihood of successful control by *Metarhizium*
3. Treatment of hopper bands.

Figure 2 IPM decision tree for brown locust.

Locustana pardalina has its outbreak area in the semiarid Karoo area of South Africa and southern Namibia. This locust has the highest outbreak frequency of any of the world's locusts and there have only been 5 years in the past 50 when no control campaign was mounted in the Karoo. Before the 1940s, when effective control measures became available, brown locust swarms used to regularly escape from the Karoo recession area and threaten food security in nine southern African countries up to the Zambezi river. The locust is a certified pest in South Africa – land owners are legally required to report outbreaks and the government is compelled to control these locusts. This law dates back to 1910. Farmers assist in the control operations and are reimbursed a mileage allowance for their involvement.

The current control strategy is to control outbreaks within the Karoo before swarms can migrate to the grain producing areas in the Orange Free State and North West Province and in the neighbouring countries. Although locusts do damage the grazing in the Karoo and compete with sheep for fodder to some extent, the main aim is to keep swarms out of the cropping areas and in this regard the South African locust control organization has been very successful. Beneficiaries of the treatment include both poor, small-scale farmers and large-scale farmers who have invested in their crops and have a lot to lose from locust invasions. Consequently, there is strong political pressure to prevent invasions. At the same time, there is strong pressure for a non-toxic product from conservationists and sheep farmers. Currently, locust targets are controlled by spot application of synthetic pyrethroid insecticide (deltamethrin) to roosting hopper bands and fledgling swarms. However, the repeated application of broad-spectrum insecticides in the unique Karoo biome is being increasingly questioned by conservationists and landholders.

Metarhizium is effective against brown locust (Bateman *et al.*, 1994; Price *et al.*, 1997a), and several features of this system favour the use of *Metarhizium* biopesticide. The pest is breeding and feeding far from the areas where it causes economic damage, so speed of kill is only of concern to the operators who wish to be certain that their work has been satisfactorily completed. A well-organized locust control organization is already in place and there is pressure for an environmentally sound product.

The company BCP (Biological Control Products, Pinetown) of South Africa, a small specialized company with existing expertise in production of microbial products, is producing the *Metarhizium anisopliae* var. *acridum* strain IMI 330189 and has successfully applied for its registration as 'Green Muscle®' from the South African authorities (Neethling & Dent, 1998). Locust control chemicals are purchased by the Ministry of Agriculture through the plant protection service; in the particular case of *Metarhizium*, the National Parks Commission has indicated a willingness to pay a Green premium for control operations in conservation areas.

The development of an integrated strategy for brown locust control will rely on an evaluation of the environmental value of conservation areas, and the damage by chemical pesticides. Considering the capacity of brown locust to thermoregulate and prolong its own survival time following treatment with *Metarhizium*, we may need to evaluate the appropriate times and places for *Metarhizium* use, compared with other areas where faster-acting chemicals may be appropriate. A *Metarhizium* module could be incorporated into existing brown locust geographical information systems (GIS) in South Africa

(Hartzer *et al.*, 1995). The IPM decision tree (Fig. 2) would still focus, as now, on treatment of hopper bands; there would be a choice between the chemical and biological control option, according to environmental conditions.

Senegalese grasshopper *Oedaleus senegalensis*, West Africa

Oedaleus senegalensis (Krauss) is the most damaging grasshopper pest in the Sahel (Geddes, 1990). The species has a generation time of about 45 days (Cheke, 1990; Launois *et al.*, 1996), enabling it to complete three generations in the short annual wet season. The first hatching occurs with the first rains in May or June and subsequent generations may breed *in situ* or migrate some distance in search of suitable oviposition sites. The second and third generations may follow the rains northwards; if all generations breed successfully, this can lead to a massive southwards migration of adults in September at the end of the rains, just as the millet crop matures. In reality, the situation is less clear-cut and attempts to predict the arrival of the southward-moving swarms have not been successful (Launois & Launois-Luong, 1988; Cheke, 1990). This final generation frequently oviposits in the millet fields themselves, which brings an added hazard the following year, when young nymphs may hatch and destroy the millet seedlings just as they are emerging. In general, the risk of loss is highest in the northernmost areas that are marginal for millet production.

Current control strategies focus on two main points: good surveillance and insecticide dusting of the early instars on emergence, and aerial application against heavy infestations and southward-moving swarms. For dusting, propoxur and fenitrothion are used, while the aerial application relies almost entirely on fenitrothion and fipronil. Village brigades and NGOs are involved in the early season applications, and may be active throughout the season, but the aerial application is undertaken by the plant protection services (Département de Protection des Végétaux in the case of Niger).

Various traditional methods are still known to the farmers, including driving hopper bands into trenches, killing them by beating with leafy branches, smoke and digging up of egg pods. However, in general, these methods are judged by farmers to be more time-consuming and less efficient than the use of chemical pesticides (Stonehouse *et al.*, 1997).

Metarhizium has been tested extensively against *Oedaleus senegalensis* in Niger and Mali (Kooyman *et al.*, 1997; Langewald *et al.*, 1999), and was found to be more effective than fenitrothion. Although fenitrothion had a quicker knockdown effect, within 10 days grasshopper populations had recovered, at about the same time as the populations in the *Metarhizium*-treated plots were falling. Effective, season-long control was obtained from a single application of *Metarhizium*, while this was not the case with fenitrothion.

Thus, in the prevailing control setting, *Metarhizium* already offers operational and environmental advantages over the current chemical-based model, and could be used to replace ground (using hand-held ULV spinning disk sprayers or vehicle-mounted ULV sprayers) and aerial (using rotary cage) application of pesticides (Bateman, 1997b). In order to improve efficacy of control, reduce costs and fully capitalize on existing natural enemies, it is likely that a 'bio-intensive IPM strategy' would need to be developed. The components of this strategy are shown in Fig. 3 in chronological order.

1. Reports from farmers; surveillance by PV
2. Treatment of young nymphs with *Metarhizium*.
3. Treatment of second or third generation populations or both with aerial application of *Metarhizium* in fallow and mixed crop/fallow areas.
4. Treatment of any escaping southward migrating swarms with fast-acting chemical pesticides where crops are threatened.

Figure 3 IPM decision tree for Senegalese grasshopper.

Several aspects of this proposed scheme need further action research: surveillance, optimum use of farmer observations, predictive modelling; cost-effectiveness of aerial treatment of fallow areas; efficacy of band/barrier treatments in preventing the invasion of crop land.

The cost of grasshopper control needs consideration. Costs of control operations in the Sahelian countries are shared between donors and the plant protection service of affected countries. Donors are more likely to be able and willing to afford a Green premium, while most of the affected countries are working to extremely tight budgets. In the longer term, we would expect to see efficiencies of scale leading to a reduction in the cost of the *Metarhizium* product. Although moves are sometimes made to involve farmers financially, this is unlikely to be successful in the case of highly migratory species. The particular advantage of *Metarhizium* is that donors may feel less reticent to help fund the purchase of a 'green' product compared with a standard chemical pesticide.

Further research on the microsporidian *Nosema locustae* for the large-scale treatment of fallow land would also be desirable. As discussed above, *Nosema* has been applied in Africa but follow-up observations have not been made.

Non-migratory Sahelian grasshoppers, West Africa

A complex of eight or nine species of non-migratory Sahelian grasshoppers, including *Kraussaria angulifera* (Krauss), *Kraussella amabile* (Krauss), *Hieroglyphus daganensis* Krauss, *Diabolocatantops axillaris* (Thunberg), *Cataloipus fuscocoeruleipes* Sjöstedt, *Pyrgomorpha cognata* Krauss, attacks crops in the Sahel. The species composition of the complex vaies with time and place (Popov, 1988). In general, these species oviposit under trees or bushes near farmers' fields, and move into the crops quite early in their life-cycle. On maturity, they leave the fields to find suitable oviposition sites.

The possibilities for intervention are more straightforward than with *Oedaleus senegalensis* as it is clearer when crops will be at risk. In general, village brigades and NGOs are able to intervene to treat crops invaded by these species. However, the cost of chemical pesticides is often beyond the means of farmers, and donors are increasingly reluctant to help with the cost of environmentally damaging products. Exceptions are made in the case of emergency interventions, leading to a tendency in some

Sahelian countries to exaggerate infestations, and a failure to develop a sustainable strategy (Kremer, 1988).

Metarhizium has been shown to be effective against these species (Douro-Kpindou *et al.*, 1997; Lomer *et al.*, 1997a). Participatory trials and socio-economic assessments (Stonehouse *et al.*, 1997) have indicated a favourable response from farmers and NGOs, which opens the way to a possible integrated implementation strategy. In the situation described above for Senegalese grasshopper there is a risk of sudden, currently unpredictable, invasions of southward migrating swarms at the time of the millet harvest, making village-level interventions difficult. By contrast, with the more sedentary species, control operations undertaken collectively by the village would have a recognizable, positive economic benefit. The IPM scheme would be similar to that described above for Senegalese grasshopper, but without the need for a back-up chemical pesticide intervention. Adequate surveillance should lead to timely treatments with mycopesticide. Preliminary surveys indicated that farmers are willing to pay about $7 per ha for crop protection (De Groote *et al.*, 1998). A simplified IPM decision tree for non-migratory Sahelian grasshoppers is shown in Fig. 4.

Variegated and Elegant grasshopper, *Zonocerus variegatus* and *Z. elegans*, Africa

Zonocerus variegatus (L.) and *Z. elegans* (Thunberg) are two closely related and biologically similar pyrgomorphid grasshoppers. Their ranges overlap to some extent in Central Africa, but essentially, *Z. variegatus* is a pest in West Africa, while *Z. elegans* is troublesome in Eastern and Southern Africa (Steedman, 1990). Compared to the major acridid pest species, these insects are slower moving and they have a broader range of plants in their diet. They attack a wide range of smallholder, horticultural and plantation crops including cassava, onions, tomatoes, chillies, pineapples and coffee. *Zonocerus variegatus*, in particular, is highly susceptible to its homologous *Metarhizium anisopliae* var *acridum* isolate, I91–609, and successful field control has been carried out at 1/10 the standard dose for IMI 330189 (10 g cf. 100 g/ha) (Lomer *et al.*, 1993; Douro-Kpindou *et al.*, 1995). An IPM strategy based on the destruction of egg pods has been proposed (Modder, 1986; Tamu, 1995), but has not been taken up, probably because farmers lack motivation prior to actual grasshopper eclosion (Müller *et al.*, 1999). By contrast, several observations lead us to suppose that *Metarhizium* will offer a highly effective and socially acceptable control option for *Z. variegatus*. Firstly, very few predators attack *Z. variegatus* (Chapman & Page, 1979) and insects killed by *Metarhizium* are left untouched by most scavengers (Lomer *et al.*, 1993). Thus, the theoretical possibility for spore recycling is present and has been confirmed experimentally (Langewald *et al.*, 1997b). Secondly, the entomophthoralean fungus *Entomophaga grylli* regularly causes heavy mortality in *Z. variegatus* populations (Paraiso *et al.*, 1992) and Blanford *et al.* (1998) demonstrated that *Z. variegatus* is a weak thermoregulator. Thus fungal infections do cause heavy mortality naturally, and mycopesticide applications can be expected to be similarly effective. Finally, and most importantly, farmer participatory trials in Benin showed farmers' willingness to purchase a biological product. In the trials, farmers were invited to select their own application strategy; most opted to control young instars while these were still aggregated near oviposition sites (Müller *et al.*, 1999). *Metarhizium* was effective when applied in aqueous suspension with a knapsack sprayer, by ULV or with a Chinese-made flit gun (simple air-shear nozzle or 'Pompi') sprayer. Farmers preferred the cheaper

1. Village-brigade-based surveillance
2. Treatment of young nymphs post-emergence with *Metarhizium*
3. Continued treatment of heavy infestations of nymphs with *Metarhizium*

Figure 4 IPM decision tree for nonmigratory Sahelian grasshoppers.

Table 5 Acridid pests for which *Metarhizium* could be substituted in the place of existing chemical pesticides without altering IPM strategy

Target insect	Region and crop	Special features	Reference
Red locust, *Nomadacris septemfasciata*	Southern Africa and Madagascar	Lives primarily in wet-lands; may be particularly suitable for control by fungus	Musuna, 1988; Materu, 1984; Bahana & Byaruhanga, 1992 Price *et al.*, 1997b
Migratory locust, *Locusta migratoria*	Madagascar, Southern Africa	Breeds on river banks, etc., removed from crop	FAO reports Delgado *et al.*, 1997
Tree locust, *Anacridium melanorhodon* (Walker)	Sudan; gum arabic plantations	Crop is sold as natural product	Steedman, 1990; Kooyman & Abdallah, 1998
Sudan plague locust *Aiolopus simulatrix* (Walker)	Sudan; sorghum and millet	Adults hidden in cracks in soil – possibility of bait formulation	Inglis *et al.*, 1996b
Moroccan locust, *Dociostaurus maroccanus* Thumberg	Spain, Greece, Turkey, Morocco Kazakhstan, China Wheat, etc	Known susceptibility to pathogens, vast areas of Kazakhstan and western China affected	Hernandez-Crespo & Santiago-Alvarez, 1997
Australian plague locust, *Chortoicetes terminifera* Walk	Australia	Control operations justified economically	Milner *et al.*, 1997 Wright, 1986
Wingless grasshopper, *Phaulacridium vittatum* (Sjöstedt)	Australia	Relatively immobile insect, field tests highly successful	Milner *et al.*, 1997
Rhammatocerus schistocercoides (Rehn)	Brazil	Short-distance migrations	Magalahaes *et al.*, 1996, LeCoq *et al.*, 1997

'Pompi' unless a large area, such as a cotton field, was to be treated. If pursued thoroughly, the strategy of controlling first instar aggregations should lead to control costs of about $1 per ha.

The possibility of combining *Metarhizium* with trapping systems based on simple plant extracts, such as crushed *Chromolaena* root could be further investigated (Fischer & Boppré, 1997). However, without more solid economic data for the pest status of *Zonocerus*, it is unlikely that such studies will be pursued with much vigour.

Direct substitution of biological pesticide for chemicals

We can identify several acridid targets against which chemical pesticides are currently used but where we believe an effective mycopesticide could directly replace the chemical, without an alteration in IPM strategy. These are listed in Table 5; control generally takes place outside the crop; where these pests have special biological features, which argue in favour of the use of a biological product, this is indicated in the table.

Conclusion

The professed objective of agencies involved in grasshopper and locust control is away from reliance on a single chemical control option, and towards an integrated approach. In reality, the approach is slow to develop, although it can be argued that selective spot treatment of infestations with chemicals is as close to IPM as has been feasible in these systems. IPM approaches need to be based on sound economic loss data and must bring together all available control options (Dent, 1991). For many grasshoppers and locusts, economic data are patchy and increased efforts in this area are essential if control options are to be adequately justified. The decision-making process in grasshopper and locust control is heavily influenced by political factors; control agencies may need to be seen to be spraying, even if economic and ecological arguments might favour other approaches. There may be little value in undertaking intensive data-collection if the end result is to be ignored. However, doubtless more could be done to collect and analyse data within the framework of on-going activities.

Donor agencies may be tied to using pesticides registered in their own country. Such regulations, designed to protect developing countries from dumping of dangerous pesticides, now risk blocking access to specific biological pesticides. Because of their specificity, there may be little incentive for a biopesticide producer to register the product in the donor country. A further regulatory issue associated with biopesticides is the difficulty of registering them under existing chemical pesticide regulations; their special features require special considerations; the US (EPA) have installed appropriate regulations, and an OECD report provides a synthesis of existing regulations in OECD countries (OECD, 1996). FAO (1988) has produced draft guidelines, but clearly more effort is needed in this area if the implementation of biopesticides is not to be severely constrained.

Metarhizium anisopliae var *acridum* IMI 330189 has been widely field tested and oil formulations could already substitute for chemical pesticides in some situations while comprehensive IPM strategies are developed. Field trial results and socio-economic and ecotoxicological studies have demonstrated a clear case for the use of *Metarhizium* as the key control agent to replace standard chemicals in many locust and grasshopper control situations. The remaining constraints to the wide-spread implementation of *Metarhizium* are regulatory, advocacy and information issues. It is necessary to ensure that donors, governments and NGOs funding locust and grasshopper control activities are informed, willing and able to purchase spores. With the establishment of demand, remaining obstacles to large-scale production are likely to fall away rapidly, and the cost should fall. Furthermore, because of the selectivity of *Metarhizium* and the conservation of the natural enemies of acridids, it should be easier to build up IPM schemes around *Metarhizium* than around chemical pesticides. Because of the biological nature of the *Metarhizium* product, improvements in operator training in product storage, transport and application will be needed.

Other strains of *Metarhizium* are unlikely to offer appreciable improvements in field performance over IMI 330189. By contrast, the long persistence and vertical transmission of microbial agents such as the microsporidian *Nosema locustae* are worth exploring in more detail in an African context. Several other microsporidians and fungi may have potential to be used as inoculative introductions or augmentations.

Destruction of egg pods is unlikely to be an attractive proposition to farmers; egg parasitoids such as the Australian *Scelio parvicornis* should be considered for introduction as classical biological control agents to Africa.

Overall, we can envisage IPM schemes which focus on monitoring and surveillance, with *Metarhizium* as the first choice control agent. Fast-acting short-persistence pesticides (fenitrothion, deltamethrin or lambdacyhalothrin) would be used to protect crops from swarms, and long-persistence agents (*Nosema* and *Scelio*) used to lower population pressures over large areas remote from crops.

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