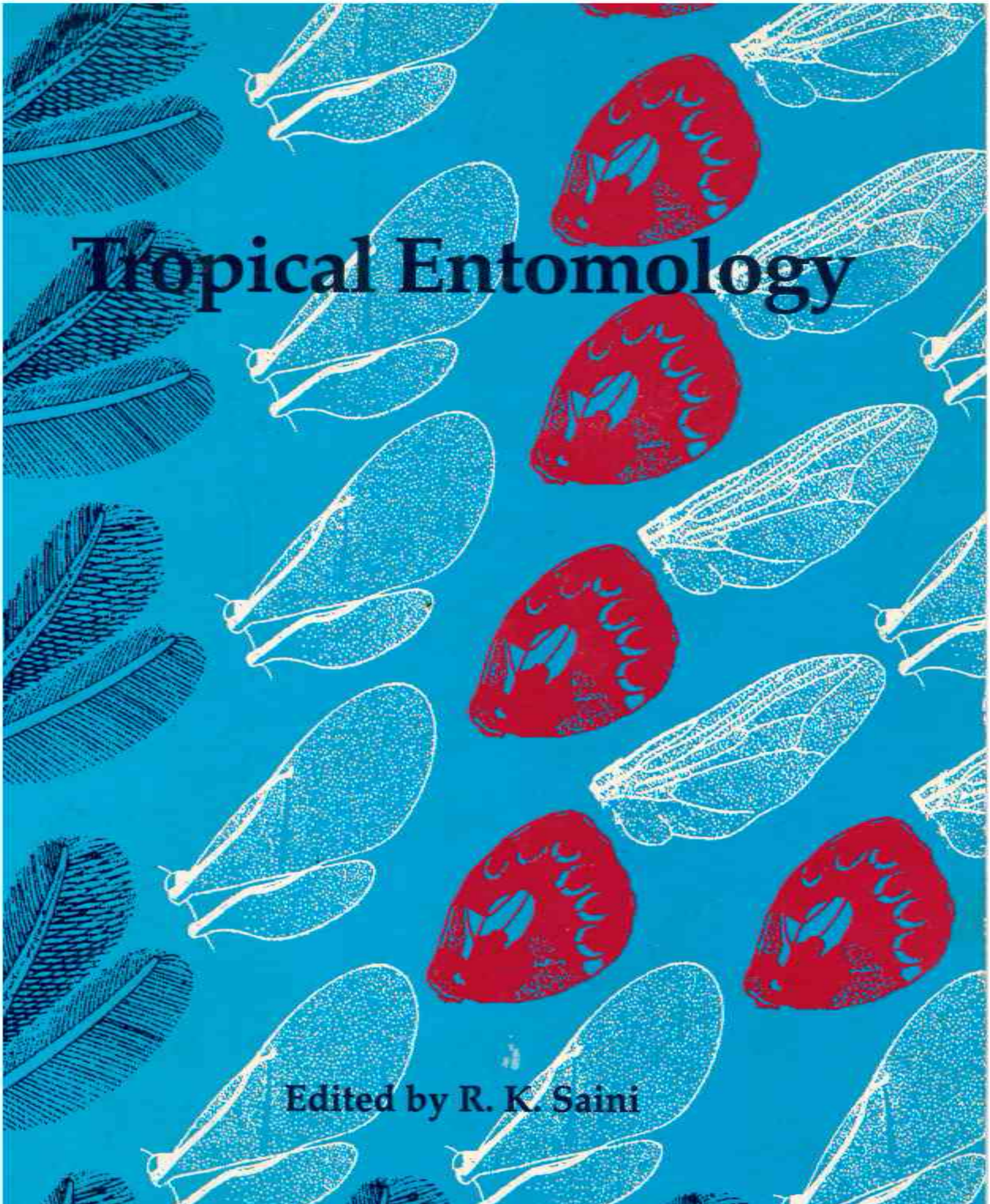

Tropical Entomology

Edited by R. K. Saini

ceedings of the 3rd International Conference on Tropical Entomology
Nairobi, Kenya

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Preface

The International Conferences on Tropical Entomology have become an important forum for insect scientists to advocate and exchange advanced knowledge and technology. The third conference in this series, held at the UNEP conference facilities at Gigiri Nairobi from 30th October to 4th November, 1994 was most successful and was attended by over 200 scientists from 35 countries. Their presentations focused on a wide range of disciplines, including basic biology, biological control, biodiversity, behaviour and chemical ecology, natural products, IPM of crop borers and community involvement in pest management. This book is comprised of the specialised symposia and plenary papers presented at the conference.

Appreciation for assistance in production of this Proceedings must be extended to a large number of people. Firstly, I would like to extend my gratitude to all the symposia convenors, namely Drs. W. A. Overholt, M. G. Hill, S. K. Moloo, K. V. Sheshu Reddy, G. E. Moya Borja, S. El-Bashir, J. A. Wightman, S. Sithanantham, A. Hassanali, R. K. Bagine and M. D. Meyer, who not only organised the highly successful and stimulating symposia, but also assisted in editing the papers in their respective sections. My gratitude also goes to all the scientists who contributed their papers for publication in the Proceedings. Special thanks also go to the various committee members who contributed immensely to the success of the conference (see page 409). Credit must also go to Dr. Annalee Mengech for her assistance in the publication of this book. I also owe a debt of gratitude to Mrs. Remedios Ortega, for all her assistance in making the conference in Nairobi and the satellite meeting on Tsetse Behaviour and Ecology in Mombasa a resounding success.

The following donor agencies and institutes also deserve our gratitude for their financial and material support, not only for the organisation of the Third International Conference on Tropical Entomology, but also for their contributions towards the publication of these Proceedings:

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Biological Control in Tropical Crops Habitats: Challenges and Opportunities

Convenors: *Dr W. A. Overholt*
ICIPE, Nairobi, Kenya
and
Dr M. G. Hill
IIBC, Nairobi, Kenya

Biological Control of Floating Aquatic Weeds

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Abstract—Floating aquatic weeds (FAWs) have become a scourge in many tropical and subtropical regions of the world outside their native range. The most damaging species are water hyacinth, *Eichhornia crassipes* Martius Solms-Laubach, salvinia, *Salvinia molesta* Mitchell and water lettuce, *Pistia stratiotes* L. Intensive research has resulted in host-specific natural enemies being available for biological control of all three species. Two weevils, *Neochetina bruchi* Hustache and *N. eichhorniae* Warner and a moth, *Sameodes albiguttalis* (Warren) are most frequently used against *E. crassipes*. A weevil, *Cyrtobagous salviniae* Calder and Sands is used against *S. molesta* and another weevil, *Neohydronomus affinis* Hustache against *P. stratiotes*. Control agents have been released against *E. crassipes* in at least 23 countries, against *S. molesta* in 11 and against *P. stratiotes* in 6. Many of these releases have given excellent to good biological control, others have been less satisfactory because of unfavourable conditions (e.g. abnormally high plant growth rates under eutrophic conditions) or projects being inadequately resourced. Unfortunately, in many countries with serious FAW problems, projects have not been implemented. Worldwide there are many opportunities for application of biological control of FAWs with expectations of excellent results. Challenges are to convince authorities that biological control is a safe viable option, to find resources to properly support well designed projects and to bring on line additional natural enemies of *E. crassipes*. The environmental impact resulting from invasion of ecosystems by FAWs is substantial, with changes in water quality and biodiversity being particularly evident. Introduced host-specific control agents reduce infestations of target FAWs thereby reversing these undesirable trends. Following reduction of FAWs, most ecosystems will gradually revert towards their pristine state. In certain situations the time frame to achieve biological control can be reduced by careful integration with physical and chemical control methods. However, in the long term, sustainable, economical and environmentally sound control of FAWs relies on effective biological control using host-specific exotic natural enemies.

Key Words: floating aquatic weeds, exotic natural enemies, water hyacinth, salvinia, water lettuce, ecosystems

Introduction

Floating aquatic weeds (FAWs) belong to two groups of plants, introduced plants and native plants. Both can cause very serious problems in waterways and wetlands. When the water surface is covered by FAWs boat transport and fishing are impeded, sedimentation and flood damage increase, infrastructure such as dams, bridges and hydroelectric plants may be damaged, water quality is affected (e.g. oxygen level may fall to zero), biodiversity is reduced, vectors of animal and human diseases increase, etc. Together these problems can lead to a decline in the social, economic and health standards of whole communities.

Sometimes native plants increase and become weedy following changes to the historical hydrological regime and nutrient levels of the waterbody in which they live. For example, reduction of flow rates may prevent periodic flushing of waterways and higher nutrient levels may increase plant growth rates. Generally problems due to native plants cannot be solved using biological control. There is, however, an exception, discussed below, where a native moth has been used to control water lettuce in Thailand.

In contrast to native plants, most of the world's FAW problems are caused by exotic weeds. Research has already shown that these weeds are amenable to classical biological control.

Many plants, when introduced into a new region, increase to population densities far in excess of those found in their native range. One important factor allowing this increase is that they are usually transferred to their new region without their natural enemies. Biological control seeks to redress this situation. Natural enemies that keep the plant under control are sought in the native range, carefully tested for host specificity and, if safe (i.e. they can survive only on the target weed), are introduced to re-establish the association where the plant has become a pest. In a successful project, the natural enemies (control agents) increase and reduce the weed to a tolerable level.

Although research to identify effective, host-specific control agents for major FAWs is still in progress, safe, effective agents are known for *Eichhornia crassipes* Martius Solms-Laubach, *Salvinia molesta* Mitchell and *Pistia stratiotes* L. These three plants, known colloquially as water hyacinth, salvinia or Kariba weed and water lettuce or Nile cabbage, are 3 of the 4 most serious, widespread FAWs in the world. The fourth, alligator weed, *Alternanthera philoxeroides* (Martius) Grisebach, does not occur in Africa. Growth rates are exceedingly high; for example, water hyacinth can double in 5 to 6 days and salvinia in less than 3 days. In this paper we briefly describe the biological control regime for each of these weeds, the likely effects of establishing control agents and discuss the challenges and opportunities which exist in this fascinating and important facet of biological control.

Biological Control of Water Hyacinth

Insect agents for control of water hyacinth were released first in 1971. Since that time one or more agents have been released in at least 23 countries (Harley, 1990, Harley unpubl. info.). To date three insects, the chevroned water hyacinth weevil, *Neochetina bruchi* Hustache, the water hyacinth weevil, *N. eichhorniae* Warner and the water hyacinth moth, *Sameodes albiguttalis* (Warren) have been the most widely used and effective control agents (Julien, 1992).

The two *Neochetina* spp. are 3.5 to 5.0 mm long and have similar modes of attack on the plant. Minor differences in biology ensure that they are not competitive. Adults are nocturnal; they feed preferentially on the upper surface of leaf lamina and the upper 1/3 of petioles making characteristic sub-circular pits. Heavy feeding causes desiccation of leaves. Oviposition is in petioles and ligules. Larvae tunnel towards the base of petioles and into the crown where they excavate small pockets which occasionally become contiguous. Pupation occurs under water in a cocoon made from root hairs. The generation time for *N. bruchi* is ca. 96 days and for *N. eichhorniae* ca. 120 days. Heavy attack causes plants to float lower in the water and can lead to waterlogging, rotting and plant death. For a more detailed summary of the biology and host-specificity of these species see Harley (1990). *Neochetina* spp. are very good control agents, especially under tropical conditions, but their relatively long life cycles means that high population densities are slow to develop.

Sameodes albiguttalis discriminates between different growth forms of water hyacinth (Center, 1984) causing patchy distribution. Young larvae are unable to enter leaves with a hard cuticle and attack is predominantly on young plants with bulbous petioles found in areas of low plant density, but may also occur on lush larger plants (Wright and Bourne, 1986). Generation time is ca. 34 days. *Sameodes albiguttalis* complements the damage to water hyacinth caused by *Neochetina* spp. For further details see Harley (1990).

These insects achieve a good level of sustainable control under a range of conditions. Typically, heavy infestations covering 60% or more of the water's surface can be reduced to 20 to 25% cover within 3 to 5 years of release of the agents. However, there are situations where the reduction in population density of water hyacinth is less than desired, e.g. under eutrophic conditions when the growth rate may be particularly high. In addition, it would be advantageous to reduce cover below 20 to 25% and achieve the reduction in a shorter time. Consequently, other natural enemies which may improve control are currently being evaluated.

When implementing a project on biological control of water hyacinth it is usual to establish first one then the other species of *Neochetina* and later *S. albiguttalis*. The reason being that the weevils attack well established, crowded, tall water hyacinth that causes most problems whereas the moth attacks the smaller, fast growing plants that grow at the weed-mat/open-water interface.

Staff with experience and skill, and resources for rearing, distribution and monitoring are required for all projects in biological control of FAWs. Even with adequate resources for rearing and releasing agents in large numbers, reduction in infestations of water hyacinth is unlikely to occur under three years and more likely five years. Unfortunately too many projects are inadequately resourced and of too short a duration. These projects are likely to fail and bring biological control intc disrepute.

- ***Where water hyacinth has invaded we recommend that both water hyacinth weevils and the water hyacinth moth should be introduced as soon as possible.***

Biological Control of Salvinia

Biological control of salvinia began in 1970 when three control agents, a weevil, a grasshopper and a moth, were released in African countries and later in India, Sri Lanka and Fiji. These insects had been collected from *Salvinia auriculata* Aublet in Trinidad but failed to control the target weed, *S. molesta* (Julien, 1992).

During the late 1970s, a second attempt to control salvinia was conducted by CSIRO Australia. The native range of the weed was located in southeastern Brazil and a new natural enemy, the salvinia weevil *Cyrtobagous salviniae* Calder and Sands, was discovered and imported into Australia. This weevil was released in 1980 and within several years brought salvinia under control in the Australian tropics (Room et al., 1981; Room, 1986).

Cyrtobagous is a small dark weevil, 2 mm long, that eats the buds of salvinia and lays its eggs in the stem and roots. Larvae also eat the buds and tunnel in the stems and roots. Since this weed only reproduces asexually, the combined damage of destroying buds and disrupting the root-shoot link kills the weed causing it to sink. The generation time for the weevil is 8 to 9 weeks.

The weevil rarely flies and disperses by walking or is dispersed on salvinia moved by wind or water flow. Hence, left unaided, spread between water bodies is slow. To achieve control in the shortest possible time, a biological control project must include mass rearing and distribution of the weevil to all infested waterbodies. On large lakes or rivers releases must be made at a number of sites.

Successful control by this weevil has been repeated many times, in Africa, India, Asia and the South Pacific. In tropical countries control was achieved within 2 or 3 years of releasing the weevil and the weed was reduced to less than 10% of its former level (Forno, 1985).

Another control agent was also studied, the moth *Samea multiplicalis* (Guenée). However, this insect is not recommended for release because it has not contributed to control of the weed in countries where it has been released, i.e. Zambia in 1970, Botswana 1972, Fiji 1976 and Australia 1981 (Julien, 1992).

- ***Wherever salvinia has invaded we recommend that the salvinia weevil should be introduced as soon as possible.***

Biological Control of Water Lettuce

Although water lettuce, *Pistia stratiotes*, is the least aggressive of the three FAWs discussed in this paper, it does cause similar problems to the other two species. Furthermore, it is likely to increase following their control.

In 1982 a weevil, *Neohydronomus affinis* Hustache, was released in Australia for control of *P. stratiotes*. Adults are 2 mm long. Adults and larvae feed on the foliage of water lettuce. The generation time in tropical conditions is 4 to 6 weeks (DeLoach et al., 1976). The weevil has been released in 6 other countries (Julien, 1992, P. Neuenschwander pers. commun., 1994). Excellent control has been achieved in Botswana (I. W. Forno, pers. commun.), South Africa (Cilliers, 1991) and Zimbabwe (G. Chikwenhere, pers. commun.) but control has been variable in USA where the weevil failed to establish at some sites, established at 45 others and controlled the weed at 5 of these (Dray and Center, 1993). Results have also been variable in Papua New Guinea (M. H. Julien pers. commun.). The release in Senegal is too recent to have results.

In Thailand a native moth, *Spodoptera (=Epipsamea) pectinicornis* (Hampson) has been used to control the weed (Suasa-ard and Napompeth 1982). The moth was bred continuously so that when an infestation of the weed was found, inundative releases could be made. This is an abnormal situation. Weed control by inundative release is usually restricted to fungal control agents applied as mycoherbicides.

Spodoptera pectinicornis was imported to USA where it was studied and found safe to use as a classical biological control agent. It was first released in 1987 but, despite considerable effort, it has failed to establish in the field (Dray and Center, 1993).

- ***Where water lettuce has become a problem we recommend that the water lettuce weevil should be introduced.***

The Likely Effects of Establishing Control Agents

To evaluate the effects of establishing agents for biological control of *E. crassipes*, *S. molesta* and *P. stratiotes* in the regions where they are not native we must take careful account of certain facts.

- These FAWs are exotic invaders which have increased to pest proportions and caused detrimental changes to the character and ecology of the ecosystem.
- Changes caused by FAWs affect the hydrological regime and biodiversity, jeopardise sustainable utilisation by man of natural resources (e.g.

fisheries) and increase the incidence of human and animal diseases.

- Mats of FAWs may disrupt or stop activities fundamental to village society such as transportation and communication.
- Biological control does not introduce pesticides into the environment.
- Biological control agents are host-specific natural enemies which depend on the target weed for their continued existence, i.e. agents cannot survive on any plant except their specific target.

What then are the likely effects of establishing these agents in regions where these weeds are not native and have become pests?

- The prime benefit is reduction in the surface area of water covered by the target weeds and reversal of the undesirable effects referred to above.

Reduction in infestations of these FAWs by biological control agents has been demonstrated in many regions of the world. In no case have significant undesirable effects occurred. The worst effect known was temporary inconvenience to residents in parts of Louisiana, USA, when exceptionally high populations of *Neochetina* spp. were attracted to bright lights.

One can argue that the invasion of new regions by these aggressive, exotic weeds has had disastrous results and therefore we should not introduce other exotic organisms. This argument may be true as a general concept, but is not valid for biological control agents. Of all organisms, plants or animals, which are moved between countries, biological control agents for weeds are the most studied in relation to the possibility of them ever becoming pests or having detrimental effects. Agents for weed control have been transferred between countries on over 600 occasions since 1836 and in no case has a biological control agent for weeds become a serious pest (Julien, 1989).

The basic concept of biological control is to introduce natural enemies (control agents) into the exotic range to reduce the density of a weed and establish a natural balance. It is anticipated that the new balance (cover or density of the weed) will be considerably less than in the absence of control agent(s). The result is to halt and reverse the detrimental effects caused by the weed.

A waterbody is often infested with more than one FAW. Control of one simply makes more space for another. For example, successful biological control of salvinia on Lake Naivasha has been followed by an increase in water hyacinth. To avoid this occurring biological control should be instigated against all species present.

Challenges and Opportunities

The challenge for the future is not only to ensure that biological control of weeds is viewed favourably but that it is considered the preferred technique because of its safety, excellent benefit to cost ratio and positive environmental impacts. Secondary is the challenge of obtaining adequate resources and training to undertake the work. The opportunities to meet the challenges are available but require the initiative of senior scientists and managers to be proactive in the following issues.

Convincing Governments and Regulatory Bodies That Biological Control Is Effective, Beneficial and Safe

The challenge. The idea of deliberately introducing insects or fungi is often quite alien because teaching has emphasised the problems caused by pest species in these groups and largely neglected the fact that the majority are beneficial. Most insects and many fungi interact to help maintain order and diversity. It is a significant challenge to explain the concept of biological control and that it is safe to introduce properly screened biological control agents to policy makers and administrators. The notion of biological control is often new and although many ornamental plants, crops and farm animals have been introduced into every corner of the world, the introduction of a beneficial insect to reduce a pest is an idea which is not readily accepted.

The opportunity to undertake biological control of FAWs comes at a time when these weeds are causing considerable concern in Africa. Biological control of FAWs has been well researched by a number of government organisations, organisations that have no agenda other than to protect and preserve the waterways and wetlands of the world.

- ***We recommend that governments should adopt a policy of biological control of FAWs for reduction of the problem and sustainable, economical control. Biological control may be integrated with other control measures if it is necessary to reduce aquatic weed infestations immediately.***

Planning the Project, Provision of Resources, Staff and Management

Having adopted biological control as the preferred long term control strategy the next steps are to plan the project, provide resources, staff and management, and to import proven control agents.

Unfortunately, a number of projects in Africa and elsewhere have not been well planned, are under-resourced and lack experienced leadership. These projects are likely to fail. Failure will not only be a disaster for the country concerned but may well lead some people to conclude that biological control does not work. Worldwide, experience has demonstrated that properly planned, well supported projects are more likely to succeed than those which are poorly planned and do not have adequate support.

The challenges are to ensure that a project is properly designed, adequately supported by funding bodies and national institutions, has trained staff, and is managed by a scientist experienced in biological control of aquatic weeds.

Major features of a properly designed, adequately funded project

- Design should be based on a survey of the existing situation, authoritative identification of the weed species and determination of any major constraints.
- Identify national institution(s) which will be involved and the resources and staff that they can contribute.
- Document and cost all other resources, staff and training required to effectively run the project for its duration (at least 3 to 5 years).
- Identify a scientist experienced in biological control of aquatic weeds who is available for the position of project manager.
- Develop a project document for submission to donor agencies for funding. In addition to the items mentioned above, this document should include objectives, organisation and management, scheduling, monitoring and quality control, expected achievements and risks, benefit/cost analysis and justification for the project.

The opportunities. There are abundant opportunities to implement projects on biological control of FAWs. This is especially true for Africa where these weeds have increased at a phenomenal rate during the last 5 to 10 years. Training programmes, such as the annual short course on biological control of tropical weeds run by The Centre for Tropical Pest Management in conjunction with the University of Queensland, Australia, are available and more specialised courses are possible. Scientists with extensive experience in biological control of FAWs are available to help develop project documentation, to manage projects and to assist with in-country training.

With so many countries experiencing massive problems due to FAWs and with due regard to available expertise, why are there so few well planned projects?

We believe that awareness of FAW problems in Africa and of the effectiveness of biological control has improved since a workshop sponsored by the Commonwealth Science Council (CSC) and the International Institute for Biological Control (IIBC) in Zimbabwe in 1991 and establishment of the CSC *Program to Promote the Control of Water Weeds*. The bottle-neck appears to be in preparation and submission of well documented project proposals to donor agencies and in consideration of proposals by donor agencies. The opportunities are there and the world community must exert itself to grasp those opportunities and relieve the suffering of many thousands of Africans and preserve the biodiversity of this unique continent.

The Need for Further Research

Many years of painstaking research has resulted in a suite of biological control agents which give very effective, sustainable control of FAWs in most situations. However, as mentioned earlier there are some situations where the level of control is not as good as we wish or the time to effect control is rather long. For these reasons, countries with a long history of biological control of FAWs are still improving strategies and studying additional control agents.

The challenges. Areas of fundamental research that are currently being addressed are as follows:

- Studies of the interaction between control agents, water hyacinth and nutrient levels in water are being researched by CSIRO scientists to better understand the role of biological control in eutrophic waterways.
- Studies of the biology and host-specificity of additional control agents for water hyacinth. The challenge is to improve both the level of control and reduce the time it takes to achieve control. New agents are being evaluated in complementary research by Plant Protection Research Institute, South Africa; USDA, Florida and CSIRO, Australia.
- Studies of the effects of FAWs on the ecosystem. The impact of water hyacinth on fish diversity and biomass is being studied in Uganda with funding by ODA; studies of effects on biodiversity are the cornerstone of a Global Environment Facility project proposed for Côte d'Ivoire.
- Studies on remote sensing as a method to survey FAWs are being made in Uganda by IIBC with funds from the Rockefeller Foundation. An extension of this is the use of remote sensing to assess the results of control activities.
- Studies of the effects of watershed management on FAWs are included in a proposed Global Environment Facility project in Côte d'Ivoire.
- Management strategies which will enhance biological control of salvinia under certain ecoclimatic conditions are being developed by CSIRO.

- Improvement of biological control of water lettuce in USA is being studied by University of Florida/USDA.

The opportunities. The results of this research will improve our ability to deal with aquatic weed problems and will be available to countries with projects on biological control of FAWs.

Conclusions

Opportunities to implement effective, properly supported biological control projects against FAWs remain largely neglected. Many countries with severe problems either have not attempted to instigate biological control projects or have been unable to obtain the funds necessary to start an effective project. This is deplorable and reflects on the world community charged with mitigating pest problems. We implore donor agencies to support the application in Africa of this vital technology before wetlands and waterways become even more heavily infested and biodiversity, riverine and fishing communities suffer further.

References

Center T. D. (1984) Dispersal and variation in infestation intensities of water hyacinth moth, *Sameodes albiguttalis* (Lepidoptera: Pyralidae), populations in peninsula Florida. *Environmental Entomology* 13, 482–491.

Cilliers C. J. (1991) Biological control of water lettuce, *Pistia stratiotes* L. (Araceae), in South Africa. *Agric., Ecosyst. Environ.* 37, 225–229.

DeLoach C. J., DeLoach A. D. and Cordo H. A. (1976) *Neohydronomus pulchellus*, a weevil attacking *Pistia stratiotes* in South America: Biology and host specificity. *Ann. Entomol. Soc. Am.* 69, 830–834.

Dray F. A. Jr and Center T. D. (1993) Biocontrol of waterlettuce (*Pistia stratiotes*). *An annual report. Proceedings of the 27th Annual Meeting, APCRP, 1993,* pp. 118–123.

Forno I. W. (1985) How quickly can insects control salvinia in the tropics? pp. 271–276. In *Proceedings of the 10th Asian-Pacific Weed Science Society Conference,* Chiang-Mai, 1985.

Harley K. L. S. (1990) The role of biological control in the management of water hyacinth, *Eichhornia crassipes. Biocontr. News Info.* 11, 11–22.

Julien M. H. (1989) Biological control of weeds worldwide: Trends, rates of success and the future. *Biocontr. News Info.* 10, 299–306.

Julien M. H. (1992) *Biological Control of Weeds. A World Catalogue of Agents and Their Target Weeds* (3rd Edition). CAB International, Wallingford. 186 pp.

Room P. M. (1986) Biological control is solving the world's *Salvinia molesta* problems, pp. 271–276. *Proceedings of the EWRS/AAB 7th Symposium on Aquatic Weeds,* Loughborough, 1986.

Room P. M., Harley K. L. S., Forno I. W. and Sands D. P. A. (1981) Successful biological control of the floating weed salvinia. *Nature* 294, 78–80.

Suasa-ard W. and Napompeth B. (1982) Investigations on *Episammia pectinicornis* (Hampson)(Lepidoptera: Noctuidae) for biological control of the waterlettuce in Thailand. *Technical Bulletin, National Biological Control Research Centre,* Kasetsart University/National Research Council 3, 10 pp.

Wright A. D. and Bourne A. S. (1986) Effect of leaf hardness on penetration of water hyacinth by *Sameodes albiguttalis. J. Aquatic Plant Manage.* 24, 91–92.

Biological Control in Tropical Plantation Forest Insect Pest Management: Challenges and Opportunities

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Abstract—Afforestation and agroforestry projects involving native and fast growing exotic tree species have escalated during the latter part of this century in most tropical regions. Many of these plantations have, however, been invaded by native and exotic insect pests. In general, the economic impact of pests is poorly understood and, as a consequence, forest pest management policy is lacking within most forestry programmes worldwide. In cases where control has been implemented, biological control using natural enemies has been a low-cost and significantly successful strategy; in particular, classical biological control has provided a very useful form of pest management for invading exotic insect pests. On the basis of this, it is suggested that biological control is appropriate for the management of many more tropical forest insect pests, both native and exotic. However, new initiatives in biological control are unlikely to attract support unless more emphasis is placed on quantifying the importance and impact of forest pests. Several challenges face biological control practitioners. In particular, there is a need to integrate biological control with other forms of pest management. Furthermore, given the number and increasing importance of native pests, there is an urgent need for research on the conservation of natural enemies.

Key Words: plantations, biological control, tropical forest insect pests

Introduction

Within the tropical region, defined here as the area lying between 27°N and S of the equator (Evans, 1982), an increasing amount of land has been devoted to large- and smallscale tree plantations during the course of this century. In fact, during the last 30 years or so, afforestation and agroforestry programmes involving softwoods, hardwoods and multipurpose trees have escalated in all parts of the tropics. This is largely because of the demands of forest industries, soil stabilisation programmes and local fuelwood and fodder needs (Anon, 1985; Evans, 1986). Recent estimates put the worldwide total area of tropical plantations of all types close to 38 million hectares with an annual increment of approximately 1.2 million hectares (Sargent and Bass, 1992).

Despite the fact that many tropical countries have, and continue to invest in, forest monocultures, there is much evidence to show that plantations of this type seem to be at high risk from insect and other pests (Gibson and Jones, 1977). For example, since their development after World War II, conifer and other tree plantations in eastern and southern Africa have, from time to time, experienced outbreaks of various native insect pests, particularly lepidopteran defoliators and coleopteran woodborers (Gibson and Jones, 1977). In addition, there has been an increasing number of dramatic outbreaks of exotic pests, examples of which include the cypress aphid, *Cinara cupressi* Buckton (Homoptera: Aphididae), which attacks a wide range of cypress and cedar trees (Ciesla, 1991); the woodwasp, *Sirex* sp. (Hymenoptera: Siricidae), which has recently been discovered attacking pines in South

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[+] Address for correspondence

Africa (F. Kirsten, pers. commun.); and the psyllid, *Heteropsylla cubana* Crawford (Homoptera), which attacks *Leucaena* spp., important multipurpose agroforestry trees (van den Belt and Napompeth, 1992).

Although some insect pests are known to cause catastrophic losses in yield while others pose severe constraints on the planting of some tree species, in most cases, the impact that pests have on trees is unknown. As a consequence, forest pest management in many tropical regions is either absent or poorly developed. Nonetheless, and despite limited resources, many national forestry programmes have turned to biological control methods involving the use of natural enemies to solve pest problems. This has been for a number of reasons. First, forested regions are usually large and thus the application of insecticides for the control of insect pests has been too expensive to contemplate by some countries; in contrast some biological control strategies, for example, the introduction ('classical') technique, are cheap in comparison, and seem appropriate for large areas because natural enemies can usually disperse effectively by themselves. Second, and more generally, the long rotation time for most tree crops (30–100 years) and the infrequent application of silvicultural practices are, in principle, conducive to the use of natural enemies.

In view of the increasing economic importance of plantations to tropical countries and the problems posed by insect pests, it is necessary that pest management strategies are critically reviewed such that their value in crop protection can be properly assessed. Several authors (for example: Hall and Ehler, 1979; Hall et al., 1980; Greathead, 1986; Waage and Greathead, 1988; Greathead and Greathead, 1992) have used the historical records of the introduction technique in biological control to assess the success of this method in agriculture and forestry on a global basis, and to determine what factors, if any, influence the chance of success. Although these broad analyses have generated some useful statistics about the introduction technique in general, they provide little information about the success of this technique under particular environmental conditions. In this paper, we review the biological control projects of all types that have been implemented against tropical forest and agroforestry insect pests and discuss the opportunities and challenges for the further use of this form of pest management in tropical forestry. To achieve this, we first briefly consider the various types and aspects of the biogeography of tropical forest insect pests.

Tropical Forest Insect Pests: Types, Origin and Distribution

In the tropical highlands and lowlands, plantations have tended to be developed more rapidly in those countries/regions where the supply of natural tree products either is poor or has been exhausted through deforestation. Significant examples of this include eastern and southern Africa and parts of Latin America (Gibson and Jones, 1977; Wood, 1991). Nowadays, however, the greatest area of plantation lies in Asia, where approximately 63% of all tropical plantations occur (Sargent and Bass, 1992). In some countries, native tree species, particularly hardwoods and some agroforestry trees, have been important in the development of plantations; several species are still planted extensively in some regions, particularly in Asia. Examples include teak *(Tectona grandis)* in Asia, *Terminalia* spp. in West Africa and mahogany (*Swietenia* spp.) in Central

America and the Caribbean. It is exotic tree species, however, that have been used the most in tropical plantations. These trees have been favoured over native species largely because of their fast growth rates. Pines and eucalypts are the most commonly planted species for industrial purposes and for local fuel and timber needs, and these account for approximately 70% of all plantations in the tropics (Evans, 1982). Furthermore, tree legumes within the genera *Leucaena, Acacia* and *Prosopis* are being extensively planted as multipurpose agroforestry trees throughout the tropics (Anon, 1985).

From an ecological point of view it is convenient to divide insect pests into groups according to the different stages of development of the tree in plantation silviculture (Bigger, 1988); these are pests of seedlings in nurseries, saplings, mature trees and logs. At the nursery stage, trees are small, have relatively little woody growth and are tightly packed into small spaces. This situation is similar to an agricultural crop and the majority of pests that attack this stage are opportunistic in nature, e.g. aphids, leaf-eating caterpillars and beetles, cutworms and termites. In the field, saplings are usually planted into fairly simple and unstable environments. It is at this stage, and until the plantation has formed a distinct canopy, that some of the most destructive pests occur. Saplings are prone to attack from opportunistic species and, as they grow older, also from more established forest pests. Important examples of the latter group include lepidopteran and coleopteran shoot borers and sap-sucking Homoptera. Mature trees are prone to attack from four groups of pests: cambium and wood feeders, seed feeders, leaf defoliators and sap suckers. All species within these groups are established tree specialists, for example, cerambycid wood borers, geometrid and lasiocampid defoliators, and scolytid and curculionid seed feeders. Logs are mostly attacked by specialised coleopteran borers that have developed various ways to digest the cellulose and lignin which make up wood; most of the pests are in the families Scolytidae, Curculionidae, Buprestidae and Cerambycidae.

The insect fauna associated with trees in their native range can be diverse. For example, over 6000 tree-feeding species have been recorded from East Africa (Karanja and Chenga, 1985). In most tropical regions the majority of insect pest problems arise because native insects of various feeding habits have either invaded plantations of native trees or, in some cases, have been able to extend their feeding range and exploit exotic trees. In some countries the number of major native insect pest species has been estimated. Examples include Thailand, 23 (Hutacharern, 1990); India, 14 (Nair and Mathew, 1990); and Pakistan, 11 (Chaudhry, 1990). Most of these pest complexes included members of the four ecological groups described above. The majority of problems caused by native insects are local in nature although a few species have managed to spread quite widely in some continents and have become regional pests.

Besides the problems of native pests, plantations in some regions of the tropics have been invaded by exotic insect pests. It is mostly plantations of exotic trees (pines and eucalypts) that have been affected by these pests although some native tree species have also been badly damaged by them. To date, most exotic pest invasions have taken place in eastern and southern Africa and in Latin America. In all regions of the tropics, however, exotic pests are far fewer in number than native pest species; Odera (1991), for example, lists 11 invasive species for eastern, central and southern Africa. Despite their relatively small number, many of these exotic pest species are highly polyphagous, very destructive and are either regional or worldwide in their distribution. Exotic invaders have, so far, included members from all four ecological groups of forest pests listed above. However, it is notable that a high proportion of the invaders are homopteran pests, particularly species from the super families Aphidoidea and Coccoidea.

Biological Control Projects

Traditionally in biological control, the introduction approach (i.e. the importation and release of specialised natural enemies from the area of origin of the pest) is the preferred method for exotic pests (see DeBach, 1964) whereas all approaches (introduction, inoculation and inundation) are used for native pests. One or more of these techniques are particularly suitable for pests of seedlings, saplings or mature trees. Here we review the different types of biological control that have been implemented against native and exotic tropical forest insect pests in turn.

Information about biological control projects was obtained in two ways. First, a search was made of the database BIOCAT (Greathead and Greathead, 1992). This database has been put together at the International Institute of Biological Control (IIBC) and contains published information (source, pest, agent and outcome) on all introductions to date of insect natural enemies against arthropod pests. In BIOCAT, every introduction of an agent species is treated as a separate record: thus in cases where several agents have been used against a particular pest species, BIOCAT will contain an equivalent number of records. Some of the limitations of the data set that BIOCAT is based on have been discussed by Greathead and Greathead (1992), and thus are not discussed here. Second, a more general search was made of CAB International's (CABI's) vast database on agriculture and forestry to locate projects on biological control involving other agents (e.g. pathogens) and techniques (e.g. augmentation projects involving native natural enemies).

Native Pests

For this group of pests it was found that the number of projects that have been implemented is small; on a worldwide basis probably not more than about 20 species seem to have been targeted. This is obviously only a very small proportion of the native pest spectrum worldwide. Despite the small number of projects that have been undertaken, most regions of the tropics seem to have been active in the use of biological control methods against native pests. Most projects have been directed at pests of saplings and mature trees.

The biological control projects that have been conducted can be conveniently divided into two groups:

1. The introduction of exotic insect and microbial agents.
2. The augmentation of native insect and microbial agents.

Very few introductions of exotic insect agents seem to have been made (Table 1). In Columbia, the geometrid defoliator *Oxydia trychiata* (Lepidoptera) has moved over from natural hardwood trees to plantations of exotic cypress where it has caused substantial damage. However, in 1975, an egg parasitoid, *Telenomus alsophilae* (Hymenoptera: Scelionidae), was imported from the USA, released, and brought the pest under control (Bustillo and Drooz, 1977). A number of biological control projects undertaken in the 1960s and 70s have been attempted against the mahogany shoot borer, *Hypsipyla grandella* (Lepidoptera: Pyralidae), in various Caribbean countries and in

Table 1. Introduction of agents against native tropical forestry insect pests

Agents	Pest	Tree	Country	Outcome
Insects				
Cedria paradoxa Wilkinson	*Eutectona machaeralis* (Walker)	Teak	India	Not known
C. paradoxa	*E. machaeralis*	Teak	Burma	Not known
Telenomus alsophilae (Viereck)	*Oxydia trychiata* Guenée	Cypress	Columbia	Successful control
Hymenopteran parasitoids	*Hypsipyla grandella* (Zeller)	Mahogany	Brazil and several Caribbean countries	Failed
Hymenopteran parasitoids	*Hyblaea puera* (Cramer)	Teak	India	Not known/failed
Hymenopteran parasitoids	*H. puera*	Teak	India	Not known/failed
Bacteria				
Bacillus thuringiensis Berliner	*Pachypasa capensis* (Linnaeus)	Pines	South Africa	Still being researched
B. thuringiensis	*Euproctis terminalis* Walker	Pines	South Africa	Still being researched
B. thuringiensis	*Dendrolimus punctatus* (Walker)	Pines	China	Still being researched?
Viruses				
Cytoplasmic polyhedrosis virus	*D. punctatus*	Pines	China	Still being researched

Brazil. Twelve parasitoid species have been collected from the more diverse natural enemy complex of *Hypsipyla robusta* (Moore) in India and have been tried against the pest. Most of the parasitoids failed to establish, a few species established but failed to control the pest, and in the remaining cases the results of the releases are unknown. The reasons for the failures of these projects are unknown, but only a small proportion of the parasitoids recorded from *H. robusta* have been tried (Cock, 1985). Similar attempts were made to control teak defoliators in India and Burma in the 1930s and 40s using parasitoids from India, but again the projects either failed or are unknown (Rao et al., 1971).

There also seem to be only two well-documented records of the augmentation of native insect natural enemies; both these projects have been undertaken in China and have involved the seasonal inoculative releases of parasitoids. In the first case (Table 2), inoculative releases of the bethylid *Sclerodermus guani* (Hymenoptera: Bethylidae) have been made for the control of the cerambycid borer *Semanotus sinoauster* (Coleoptera), a serious pest of the Chinese fir *(Cumminghamia lanceolata)* (Zhang et al., 1989). In the second case, inundative releases of the parasitoid *Trichogramma dendrolimi* (Hymenoptera: Trichogrammatidae) have been made against the widespread lasiocampid defoliator *Dendrolimus punctatus* (Lepidoptera) (Yan and Liu, 1992). In both cases the successful seasonal control of these pests is claimed.

Attempts at using microbial agents in the tropics against forest pests is still in its infancy. The focus, to date, has been on microbial agents that can be applied as biopesticides. South Africa and China (Table 1) are both researching the use of the bacterium *Bacillus thuringiensis* for the control of lasiocampid and lymantriid defoliators (Anon, 1993a, b); China is also investigating the use of a Japanese cytoplasmic polyhedrosis virus for the control of *D. punctatus* (Chen, 1992). Unfortunately, the cost of production of some of these microbes is sometimes too high for them to be economical to use (Chen, 1992; Anon, 1993b). However, recent advances in cheap production techniques for native microbial agents has opened up ways for these agents to be augmented in a practical and economic way (Table 2). In India methods are being investigated for utilising natural epizootics of a nuclear polyhedrosis virus of the teak defoliator, *Hyblaea puera* (Lepidoptera: Hyblaeidae), to control the pest in areas where the virus is absent (Nair, pers. commun.). These viruses can, for example, be applied by ground spraying crude aqueous suspensions of diseased insect larvae. This method has been effectively employed for the control of diprionid sawflies in Canada (Cunningham and De Groot, 1980). Similar work is being conducted in China for the control of lepidopteran defoliators (Anon, 1993b). Research on local fungal pathogens for the control of tropical forest insects is also being conducted in some countries; these pathogens can very often be cheaply produced using local raw materials. For example, in China, aerial applications of a local strain of *Beauveria bassiana* have been used to control outbreaks of *Dendrolimus punctatus*. A mortality of 42–92.9% of larvae in the field was achieved (Anon, 1993b). Furthermore, the fungal pathogen *Metarhizium anisopliae* is being investigated in Australia for the control of termites on eucalypts. Initial trials were not successful (Hänel and Watson, 1983), but a new, more pathogenic, isolate of the fungus has now been selected and is being field tested (Milner, 1992). Finally, there is one example where

Table 2. Augmentation of native agents against native tropical forestry insect pests

Agent	Pest	Tree	Country	Outcome
Insects				
Sclerodermus guani Xiao and Wu	*Semanotus sinoauster* Gressit	Chinese fir	China	Successful control
Trichogramma dendrolimi Matsumura	*Dendrolimus punctatus* (Walker)	Pines	China	Successful control
Fungi				
Beauveria bassiana (Bals.) Vuill.	*D. punctatus*	Pines	China	Successful control
Metarhizium anisopliae (Metsch.) Sorok.	Termites	*Eucalyptus*	Australia	Failed but still being researched
Viruses				
Nuclear polyhedrosis virus	*Hyblaea puera*	Teak	India	Still being researched
Nematodes				
Steinernema feltiae (Filipjev)	*Zeuzera multistrigata* Moore	*Casuarina*	China	Successful control

successful control has been achieved by the use of a nematode. In China, the carpenter worm, *Zeuzera multistrigata* (Lepidoptera: Cossidae), causes damage to *Casuarina* trees by boring into the bole of the tree. To control the moth, a water suspension of the nematode *Steinernema feltiae* is applied to the frass-ejecting holes made in the tree by the pest (Xiao, 1991).

In conclusion, the different techniques of biological control that have been implemented or are being researched for the control of native tropical forest pests can be considered encouraging. However, it seems that much work still needs to be done to enable insect agents to be properly utilised. Furthermore, initial work with exotic microbes suggests that production costs may limit the use of some species.

Exotic Pests

An examination of the data set in BIOCAT and additional literature indicated that biological control projects of exotic pests have only involved introductions of exotic insect natural enemies and these have been mostly against pests of saplings and mature trees. A summary of these introductions of agents taken from the BIOCAT database is shown in Table 3. The figures in Table 3 reflect the facts that some pests are present in more than one country and that, in some countries, several agent species have been introduced against one pest species. A high proportion of agent introductions have been made in Africa and the surrounding islands; in contrast, very few introductions have been made in Latin America. Of the 59 introductions, 20 (34%) have resulted in the establishment of the agent; this figure disregards whether or not the agent also brought about, or contributed to, the control of the pest in question.

Table 3. Introduction of insect agents against exotic tropical forestry insect pests

No. of countries	20
No. of pest species	17
No. of agent species imported	43
No. of separate introductions of agents of all species	59
No. of establishments	20

Data from BIOCAT: Greathead and Greathead (1992).

Of course, of more importance to the current analysis is the success rate of projects on a pest–country basis, i.e. whether or not a particular pest in a country has been successfully controlled by the introduction of one or more agent species. Table 4 shows that a total of 35 projects have been undertaken; of these, the outcome is unknown in a high proportion (31%) of cases. Where the outcome is known, approximately 62% of introduction projects can be counted as successful. Some examples of particularly successful introduction biological control projects against exotic tropical forestry pests are summarised in Table 5.

Table 4. Outcome of introduction projects against exotic pests on a pest–country basis

No. of projects	35
No. of successful projects	15
No. of unsuccessful projects*	9
No. of projects where state of pests (i.e. controlled or uncontrolled) is unknown	11
Percentage of successful projects where outcome is known	62.5

*Some agents may have established in these projects but not brought about control of the pests.

Data derived from BIOCAT: Greathead and Greathead (1992).

In an analysis of all BIOCAT records (agricultural and forestry), Greathead and Greathead (1992) have shown that the Homoptera have been the most

Table 5. Examples of successful introduction projects against exotic tropical forestry insect pests

Pest	Tree	Agent	Country	Reference
Cinara cronartii Tissot & Pepper	Pines	*Pauesia cinaravora* Marsh	South Africa	van Rensburg (1992)
Goniperus scutellatus Gyllenhal	Eucalypts	*Anaphes nitens* (Girault)	Kenya South Africa St Helena Madagascar Mauritius	Greathead (1971)
Orthezia insignis Browne	Ornamental trees	*Hyperasis patherina* (Fürsch)	Kenya Tanzania Uganda	Greathead (1971)
Pineus sp.	Pines	*Leucopis tapiae* Blanchard	Hawaii	Culliney et al. (1988)
Trachymela tincticullis Blackburn	Eucalypts	*Enoggera reticulata* Naumann	South Africa	Tribe (1992)

frequently targeted order for the introduction technique and it is within this order that most successes (on the basis of the number of cases where the introduction of an agent resulted in control) have been achieved. Unfortunately, the data set on introduction against tropical forest insect pests is not large enough to conduct a similar, meaningful analysis. Further examination of the data set indicates, however, that most introductions (Table 6) have been focused on pines, eucalypts and *Leucaena*. This is because tree species within these genera have been widely planted throughout the tropics and have, therefore, attracted more pest species than other tree genera. The insect agents used in introduction projects against tropical forest insect pests have mostly been species from the orders Hymenoptera and Coleoptera (Table 7); this is consistent with more general analyses of natural enemy introductions (Greathead and Greathead, 1992).

A summary of some less successful introduction projects is shown in Table 8; all cases concern homopteran pests. In the first three, successful control of the pest has been achieved in another part (or several other parts) of the world.

Table 6. Introduction of agents against exotic insects in relation to tree genera

Pines	17
Eucalypts	9
Leucaena	10
Other (some 7 genera)	23

Data from BIOCAT: Greathead and Greathead (1992).

Table 7. Agents used in introductions against tropical forestry insect pests

Order	No. of species	No. of introductions
Hemiptera	5	6
Neuroptera	1	5
Diptera	5	8
Coleoptera	14	25
Hymenoptera	14	20

Table 8. Examples of 'unsuccessful' introduction projects against exotic tropical forestry insect pests

Pest	Tree	Agent	Country	Reference	Comments on project
Heteropsylla cubana Crawford	Leucaena	*Curinus coeruleus* Mulsant	India	Jalahi and Singh (1989)	Try another agent? (parasitoids)
			Indonesia	Waterhouse and Norris (1987)	
Icerya purchasi Maskell	Pines	*Cryptochetum iceryae* Williston	Sao Tome	Greathead (1971)	Try another agent? (*Rodolia cardinalis* Mulsant)
			India	Rao et al. (1971)	
Orthezia insignis Browne	Ornamentals	*Hyperaspis patherina* (Fürsch)	Malawi	Greathead (1971)	Success/failure in dispute. Precise monitoring required.
Pineus ?boerneri Annand	Pines	*Leucopis* spp.	Kenya	Owuor (1991)	Agents successful elsewhere. New release method required?

Possible reasons for failure in the particular instances listed seem to include the selection of an inferior agent or an inadequate release method. In the case of the project against *Orthezia insignis* in Malawi, the actual success of the project is somewhat in dispute, largely because the impact of the agent, *Hyperaspis patherina*, was inadequately monitored (Greathead, 1971).

In summary it seems that the introduction approach for exotic tropical forestry pests has been a particularly successful strategy. An examination of 'failed' projects has indicated a number of reasons why these projects might have failed but none of the problems identified pose a constraint on the further use of the introduction technique. One shortcoming of past work, though, is the large number of projects where the results of the releases are unknown.

On a more global level, an attempt has been made to assess the results of the introduction approach in different types of environments. In this analysis, Hall and Ehler (1979) found that the establishment rate of agents (i.e. whether or not the agent brought about, or contributed to, the control of the pest) in stable environments (forests) was significantly higher than in unstable environments (vegetable or field crops). However, in a subsequent analysis, Hall et al. (1980) could find no evidence that the success rate of agents (i.e. considering only those cases where the agent controlled or satisfactorily contributed to the control of pests) was higher in stable versus unstable environments.

Challenges and Opportunities

On the basis of the brief reviews of tropical forest pests and biological control initiatives to date we will now consider the opportunities and challenges for biological control. First, we will do this in relation to the two major groups of pests (i.e. native and exotic) and then second, we will consider some more general points.

Native Pests

It was noted earlier that native pests of tropical plantation trees are extremely numerous in many parts of the tropics. In some regions, notably Asia, some species are regional in distribution and cause a vast amount of damage to their host trees. It is ironic, therefore, that so little work on biological control has been undertaken. Given that the different methods of biological control implemented against some of these pests show much promise, it is suggested that there is a vast opportunity to apply these techniques to other forestry pests throughout the tropics. The use of exotic insect agents for the control of native pests is, in itself, an under-exploited technique, but in principle has great potential (Carl, 1982). Clearly, though, more emphasis needs to be placed on agent selection. The opportunity for developing the use of local microbial agents (for example, fungal pathogens) also looks promising but given that these agents have to be mass produced before application, their use over large forested areas may be limited; they may have more potential for the control of pests of seedlings or pests of trees grown in small woodlots such as in agroforestry systems. Such an approach may also be useful for the control of exotic pests in these systems. Examples of native pests where urgent work on their biological control is needed include the teak defoliator *(Hyblaea puera),* the teak skeletoniser (*Eutectona machaeralis* Lepidoptera: Pyraustidae) and pine shoot borers (*Dioryctria* spp. Lepidoptera: Phycitidae) in Asia, and the pan-tropical mahogany shoot borers (*Hypsipyla* spp.) and termites (Isoptera: Macrotermitinae) of various species which are problematic throughout the tropics.

Workers on the biological control of native pests face several major challenges. First, there is an increasing need for biological control to be integrated with silvicultural and tree-breeding approaches to pest control; in other words, for biological control to become part of an integrated pest management (IPM) approach to pest problems. Reasons for this are as follows:

1. Very often different approaches to pest control run tangentially to one another which results in the generation of conflicting advice about which strategy should be best adopted for a particular pest problem.
2. Some silvicultural practices and some resistant tree types can be detrimental to insect natural enemies (Hubert et al., 1989; Speight and Wainhouse, 1989). For this reason alone, it is necessary to integrate research projects that focus on different techniques.
3. Some degree of resistance within a tree species, together with the right silvicultural practices and the introduction and/or augmentation of natural enemies, may provide acceptable levels of control where any one method alone is not effective by itself (Speight and Wainhouse, 1989).

Second, although introduction and augmentation strategies appear attractive for the control of native pests of tropical plantations, these activities are, nonetheless, reactive, i.e. action is only taken once a problem has developed. A better goal might be, however, to try to prevent the risks of native pest outbreaks occurring in the first place through the conservation of natural enemies. This subject has received little attention in forestry. Several studies have indicated that in natural, diverse forest systems, natural enemy complexes are species-rich and/or important in keeping tree-feeding insects in check (Hagen et al., 1971; Berryman, 1986). Forest insect outbreaks are common, however, in plantations or in natural forests where one species of tree dominates over a large area (Gray, 1972; Turnock et al., 1976; Gibson and Jones, 1977; Nair et al., 1986). This implies that in some of these 'simple' systems, important regulating components such as natural enemies are either missing or hindered in some way. In the case of natural enemies, important factors that may hinder their effectiveness might be lack of refuges or food for adults. That some silvicultural practices in some cases have been shown to be important in relation to natural enemy diversity and activity means that it will be crucial to take these practices into account in natural enemy conservation projects. The optimum time to do this would be at the planting stage when the most important decisions about silviculture (for example, which tree species to use, monoculture versus polyculture) are made.

Exotic Pests

Many opportunities exist for the further use of the introduction technique for the control of this group of pests. Some initiatives are already underway. For example, two regional pests of conifers in southern and eastern Africa, the cypress aphid, *Cinara cupressi,* and the pine woolly adelgid, *Pineus boerneri* (Homoptera: Adelgidae), are the subjects of a regional classical biological control being undertaken by IIBC (Murphy et al., 1994). Other examples include projects against the neem scale, *Aonidiella orientalis* (Newstead) (Homoptera: Diaspidae), in Nigeria and the leucaena psyllid, *Heteropsylla cubana,* in East Africa. However, much more remains to be done. For pantropical pests, insect agents that have been successfully employed in one region or continent could be transferred to other regions where the pest remains uncontrolled. For example, the wood wasp, *Sirex noctilio* Fabricius (Hymenoptera: Siricidae), has been successfully controlled in Australia by the use of a nematode and ichneumonid parasitoids (Berryman, 1986). *Sirex noctilio* is still, however, a major problem in many pine-producing countries in South America (Pedrosa-Macedo, 1990). Although some agents have been introduced into Brazil and Uruguay for trial (Vibrans, 1991), efforts need to be made to introduce all of the agents that are known to be important, otherwise the successful control of the wood wasp is unlikely to be achieved.

There are also several exotic pests which are excellent targets for biological control through the use of insect natural enemies but where no action seems to have been taken. The reasons for this are unclear, but one reason might be that the impact of these pests on their tree hosts has not been quantified. Examples of exotic pests include the Australian eucalyptus psyllid, *Ctenarytaina eucalypti* (Maskell) (Homoptera), in Africa (Kenya Forestry Research Institute, unpublished data), the North American scolytid bark beetles, *Ips calligraphus* (Germar) and *Ips grandicollis* Eichhoff (Coleoptera), that attack pines in Jamaica (Garraway, 1986), and the pyralid shoot borer, *Rhyacionia frustrana* (Comstock) (Lepidoptera), that originates from the eastern USA and attacks pines in Central America (Ford, 1986). All of these species, apart from *I. calligraphus,* have been or are currently the subjects of very promising biological control projects in temperate regions.

Another opportunity that may be appropriate to the introduction approach relates to the use of microbes. To date, the focus of introduction projects has been on the use of insect agents; mostly hymenopteran parasitoids and coccinellid beetles. However, recent research has demonstrated the potential of microbial agents for the control of insect and other pests. Some of these agents, e.g. entomophthoralis fungi, are particularly suitable for the introduction approach because they do not need to be mass cultured. These fungi may be useful against forest pests such as aphids or defoliators. Consideration should also be given to the possible augmentation of local microbes against exotic pests of seedlings.

A number of challenges exist which future introduction projects against exotic pests need to take into account. For example, although this technique has been very successful, an analysis of 'failed' projects has indicated that improvements in the success rate of projects might be made if greater effort were put into factors such as agent selection and the monitoring of releases. Pschorn-Walcher (1977), in a review of the introduction approach in forest insect pest management, argues that pre-introduction studies on agents for the control of these types of pests are particularly appropriate because of the complex nature of the structure and the diversity of the natural enemy complexes associated with forest insects. Besides this, the fact that the results of a high proportion of introduction projects are unknown suggests that a much greater effort needs to be channelled into the monitoring of releases.

In addition to these points, and as already discussed for native pests, there is an increasing need for the introduction approach to be integrated with silvicultural and tree-breeding approaches to pest control.

Some General Challenges

Besides the specific challenges mentioned above, we suggest that several general challenges face biological control in tropical forest insect pest management. First, although there is a widespread need and thus opportunity for the use of biological control in tropical forest insect pest management, these needs have to be linked with demand from foresters and forest policy makers. It has already been noted that active and well-resourced forest pest management programmes are lacking in many tropical regions. This is largely because of the lack of information on the impact that many pests and diseases have on plantation trees. Most plantation species have long crop cycles, and it is difficult to measure losses in growth attributable to pests that accumulate over long periods. Thus, there is a clear need to promote pest impact and tropical forest pest management such that more active projects on biological control can be undertaken.

Second, there is the continuing and increasing need for biological control practitioners to ensure that agents for introduction projects (insects or microbes) do not pose any risk to the environment (Waage and Greathead, 1988). To date, no unforeseen problems seem to have occurred in insect biological control in tropical forestry. However, in view of the biological control activity against exotic pests, especially over recent years, and the increased public concern over the environment, the screening of all exotic agents is an absolute must for all biological projects. Clearly, the screening of agents needs to be scientifically based to avoid time and resources being wasted on investigating the extremely unlikely agents–host/prey relationships. As no clear protocols exist on screening, the Food and Agriculture Organisation of the United Nations, in collaboration with organisations such as IIBC and in consultation with national agricultural programmes worldwide, are currently drawing up a set of guidelines for the screening, introduction and use of exotic agents. Finally, an equally important and closely related topic to this relates to the potential conflicts of interest between weed and insect pest biological control projects. A good example of this arose in the 1980s in Asia and in Australasia. In these regions, the multipurpose agroforestry tree *Leucaena leucocephala* is attacked by the exotic psyllid pest *Heteropsylla cubana*. Although some promising parasitoids have been identified for the control of the psyllid, some countries are concerned that their introduction will interfere with a weed biological control project where another *Heteropsylla* sp. is being used to control the neotropical *Mimosa invisa* Martius, a weed of plantations (Waterhouse and Norris, 1987). This type of problem presents a very complex challenge not only to biological control workers but also to agriculturists and foresters in general.

Conclusion

Tropical plantations large and small are important to the economies of many countries and to the livelihoods of rural people. In many instances, the plantations have been established or developed with the support of international funding and thus cheap and efficient ways must be found to help protect these man-made forests against the invasions of insect and other pests. On the basis of general considerations and an examination of the records of the use and outcome of biological control in tropical forestry, we suggest that this method of control is appropriate for the management of many native and exotic insect pests. However, there is a need in some instances to integrate biological control with other methods of control but for native pests there is also a need to look more closely at the conservation of natural enemies such that pest management for this group of pests becomes more of a proactive rather than a reactive exercise.

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References

Anonymous (1985) Nitrogen Fixing Tree Association, Waimanalo, Hawaii, USA, *Annual Report*.

Anonymous (1993a) Plant Protection Research Institute, Pretoria, South Africa, *Annual Report 1992/93*, p. 11.

Anonymous (1993b) A general introduction to the research achievements on the major forest insects in China. Report, Chinese Academy of Forestry, Beijing, China, 8 pp.

Belt R. van den and Napompeth B. (1992) Leucaena psyllid comes to Africa. *Agroforestry Today* October–December, 11–12.

Berryman A. A. (1986) *Forest Insects.* Plenum Press, New York and London. 279 pp.

Bigger M. (1988) *The Insect Pests of Forest Plantation Trees in the Solomon Islands.* Overseas Development Natural Resources Institute, Chatham, UK. 190 pp.

Bustillo A. E. and Drooz A. T. (1977) Co-operative establishment of a Virginia (USA) strain of *Telenomus alsophilae* on *Oxydia traychiata* in

Columbia. *J. Econ. Entomol.* 70, 767–770.

Carl K. P. (1982) Biological control of native pests by introduced natural enemies. *Biocontr. News Info.* 3, 191–200.

Chaudhry M. I. (1990) Priorities in forest entomological research in Pakistan, pp. 245–250. In *Science in Forestry: IUFRO's Second Century.* Proceedings, Division 2, IUFRO XIX World Congress, Montrèal, Canada, 5–11 August 1990. Canadian IUFRO World Congress Organising Committee, Montrèal, Canada.

Chen C. (1992) A general survey using cytoplasmic polyhedrosis virus to control masson pine caterpillar *Dendrolimus punctatus* in China. Report, Chinese Academy of Forestry, Beijing, China. 112 pp.

Ciesla W. M. (1991) Cypress aphid, *Cinara cupressi,* a new pest of conifers in eastern and southern Africa. *FAO Plant Prot. Bull.* 39, 82–93.

Cock M. J. W. (Ed.) (1985) *A Review of Biological Control of Pests in Commonwealth Caribbean and Bermuda up to 1982.* Technical Communication No. 9 of the Commonwealth Institute of Biological Control. Commonwealth Agricultural Bureaux, Slough, UK. 218 pp.

Cunningham J. C. and De Groot P. (1980) *Neodiprion lecontei* (Fitch) redheaded pine sawfly (Hymenoptera: Diprionidae), pp. 323–329. In *Biological Control Programmes against Insects and Weeds in Canada* (Edited by J. S. Kelleher and M. A. Hulme). Commonwealth Agricultural Bureaux, Slough, UK.

Culliney T. W., Beardsley J. W. Jr. and Drea J. J. (1988) Population regulation of the Eurasian pine adelgid (Homoptera: Adelgidae) in Hawaii. *J. Econ. Entomol.* 81, 142–147.

DeBach P. (Ed.) (1964) *Biological Control of Insect Pests and Weeds.* Chapman and Hall, London. 844 pp.

Evans J. (1982) *Plantation Forestry in the Tropics.* Clarendon Press, Oxford, UK. 432 pp.

Evans J. (1986) Plantation forestry in the tropics—Trends and prospects. *The Int. Tree Crops J.* 4, 3–15.

Ford L. B. (1986) The Nantucket pine-tip moth. *Turrialba* 36, 245–248.

Garraway E. (1986) The biology of *Ips calligraphus* and *Ips grandicollis* (Coleoptera: Scolytidae) in Jamaica. *Canadian Entomol.* 118, 113–121.

Gibson I. A. S. and Jones T. (1977) Monoculture as the origin of major forest pests and diseases, especially in the tropics and southern hemisphere. In *Origin of Pests, Parasites, Disease and Weed Problems* (Edited by J. M. Cherrat and G. R. Sagar). Blackwell Scientific Publications, Oxford, UK.

Gray B. (1972) Economic tropical forest entomology. *Annu. Rev. Entomol.* 17, 313–354.

Greathead D. J. (1971) *A Review of Biological Control in the Ethiopian Region.* Technical Communication No. 5 of the Commonwealth Institute of Biological Control. Commonwealth Agricultural Bureaux, Slough, UK. 162 pp.

Greathead D. J. (1986) Parasitoids in classical biological control. In *Insect Parasitoids,* pp. 290–318. In *13th Symposium at the Royal Entomological Society of London* (Edited by J. K. Waage and D. J. Greathead). Academic Press, London, UK.

Greathead D. J. and Greathead A. H. (1992) Biological control of insect pests by insect parasitoids and predators: The BIOCAT database. *Biocontr. News Info.* 13, 61–68.

Hagen K. S., van den Bosch R. and Dahlsten D. L. (1971) The importance of naturally occurring biological control in the western United States, pp. 253–293. In *Biological Control.* Proceedings of an AAAS symposium on biological control, Boston, Massachusetts, December 30–31, 1969 (Edited by C. B. Huffaker). Plenum Press, London, UK.

Hall R. W. and Ehler L. E. (1979) Rate of establishment of natural enemies in classical biological control. *Bull. Entomol. Soc. Am.* 25, 280–282.

Hall R. W., Ehler L. E. and Bisabri-Ershadi B. (1980) Rate of success in classical biological control of arthropods. *Bull. Entomol. Soc. Am.* 26, 111–114.

Hänel H. and Watson J. A. L. (1983) Preliminary field tests on the use of *Metarhizium anisopliae* for the control of *Nasutitermes exitiosus* (Hill) (Isoptera: Termitidae). *Bull. Entomol. Res.* 73, 305–313.

Hebert C., Cloutier C. and Regnierre J. (1989) Factors affecting the flight activity of *Winthemia fumiferanae* (Diptera: Tachinidae). *Environ. Entomol.* 19, 293–302.

Hutacharern C. (1990) Priorities for forest insect research in Thailand, pp. 251–258. In *Science in Forestry: IUFRO's Second Century.* Proceedings, Division 2 IUFRO XIX World Congress, Montrèal, Canada 5–11 August 1990. Canadian IUFRO World Congress Organising Committee, Montrèal, Canada.

Jalali S. K. and Singh S. P. (1989) Release and recovery of an exotic coccinellid predator *Curinus coeruleus* (Huls.) on subabul psyllid, *Heteropsylla cubana* Crawf. in India. *J. Insect Science* 2, 158–159.

Karanja M. K. and Chenga F. M. (1985) Forest Insects of Kenya: An Annotated List. Unpublished report, Kenya Agricultural Research Institute, Forest Research Department, Muguga, Kenya, 643 pp.

Milner R. J. (1992) Selection and characteristics of *Metarhizium anisopliae* for control of soil insects in Australia, pp. 200–207. In *Biological Control of Locusts and Grasshoppers.* Proceedings of a workshop, International Institute of Tropical Agriculture, Cotonou, Bénin, 29 April–1 May 1991(Edited by C. J. Lomer and C. Prior). CAB International, Wallingford, UK.

Murphy S. T., Chilima C. J., Cross A. E., Abraham Y. J., Kairo M. T. K., Allard G. B. and Day R. K. (1994) Exotic conifer aphids in Africa: Ecology and biological control, pp. 233–242. In *Individuals, Populations and Patterns in Ecology* (Edited by S. R. Leather, A. D. Watt, N. J. Mills and K. F. A. Walters). Intercept, Andover, UK.

Nair K. S. S. and Mathew G. (1990) Priorities in forest entomological research in India, pp. 279–284. In *Science in Forestry: IUFRO's Second Century.* Proceedings, Division 2 IUFRO XIX World Congress, Montrèal, Canada, 5–11 August 1990. Canadian IUFRO World Congress Organising Committee, Montrèal, Canada.

Nair K. S. S., Mathew G., Mohanados K. and Menon A. R. R. (1986) A study of insect pest incidence in natural forests. Unpublished research report No. 44, Kerala Forest Research Institute, Peechi, Kerala, India, 28 pp.

Odera J. (1991) Pernicious exotic pests affecting forests and forest products in eastern, central and southern Africa, pp. 99–105. In *Exotic Aphid Pests of Conifers: A Crisis in African Forestry.* Proceedings of a workshop, Kenya Forestry Research Institute, Muguga, Kenya, 3–6 June 1991. Food and Agriculture Organisation of the United Nations, Rome, Italy.

Owuor A. L. (1991) Exotic conifer aphids in Kenya, their current status and options for management, pp. 58–63. In *Exotic Aphid Pests for Conifers: A Crisis in African Forestry*. Proceedings of a workshop, Kenya Forestry Research Institute, Muguga, Kenya, 3–6 June 1991. Food and Agriculture Organisation of the United Nations, Rome, Italy.

Pedrosa-Macedo J. H. (1990) Protection of Forests in the Tropics: Regional Priorities for Latin America. Unpublished report presented at IUFRO's XIX congress, Montréal, Canada, 5–11 August 1990, 8 pp.

Pschorn-Walcher H. (1977) Biological control of forest insects. *Annu. Rev. Entomol.* 22, 1–22.

Rao V. P., Ghani M. A., Sankaran T. and Mathur K. C. (1971) *A Review of the Biological Control of Insects and Other Pests in South-East Asia and the Pacific Region.* Technical Communication No. 6 of the Commonwealth Institute of Biological Control. Slough, UK; Commonwealth Agricultural Bureaux. 49 pp.

Rensburg N. J. van (1992) The black pine aphid: A success story. *Plant Prot. News* 28, 5–6.

Sargent C. and Bass S. (Eds) (1992) *Plantation Politics.* Earthscan, London, UK. 191 pp.

Speight M. R. and Wainhouse D. (1989) *Ecology and Management of Forest Insects.* Clarendon Press, Oxford, UK. 374 pp.

Tribe G. D. (1992) Neutralisation of the eucalyptus tortoise beetle. *Plant Prot. News* 29, 5.

Turnock W. J., Taylor K. L., Schroder D. and Dahlsten D. L. (1976) Biological control of pests of coniferous forests. In *Theory and Practice of Biological Control* (Edited by C. B. Huffaker and P. S. Messenger). Academic Press, London, UK.

Vibrans A. (1991) Zur biologischen Bekanpfung der Holwespe (*Sirex noctilio* F.) in Brasilien. *Forstarchiv* 62, 97–99.

Waterhouse D. F. and Norris K. R. (1987) *Biological Control: Pacific Prospects.* Inkata Press, Melbourne, Australia. 454 pp.

Waage J. K. and Greathead D. J. (1988) Biological control: Challenges and opportunities. *Phil. Trans. R. Soc. London,* B 318, 111–128.

Wood P. J. (1991) Forestry in Africa: An overview, pp. 19–22. In *Exotic Aphid Pests of Conifers: A Crisis in African Forestry.* Proceedings of a workshop, Kenya Forestry Research Institute, Muguga, Kenya, 3–6 June 1991. Food and Agriculture Organisation of the United Nations, Rome, Italy.

Xiao G. (Ed.) (1991) *Forest Insects of China.* China Forestry Publishing House, Beijing, China. 1362 pp.

Yan J. and Liu H. (1992) A review of development of studies on utilising parasites and predators of forest pests in China. *Shaami Forest Sci. Technol.* 2, 24–28.

Zhang L., Sung S., Huang H., Li X. and Qui L. (1989) Biological control of a wood borer in China. *IPM Practitioner* (XI), 5–7.

Biocontrol in Coffee Pest Management

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Abstract—Biocontrol of coffee pests has been attempted in many areas of the world with little success. Limiting factors to successful implementation of biocontrol include poor taxonomic information on the target pest and its host plant(s); inadequate studies on the biological and ecological requirement of potential agents; lack of consideration of the total pest complex and the farming system; conflict between pest control priorities and excessive use and reliance on synthetic chemical pesticides.

Integrated pest management (IPM) is a multidisciplinary approach to pest control that can lead to improved environmental conservation, increased food and cash income to coffee farmers and reduced pest pressure and losses in coffee. The possible components for sustainable IPM in coffee pests include classical biocontrol, use of biopesticides, judicious use of selective and environmentally friendly synthetic pesticides, use of plant varieties resistant to pests, cultural practices and quarantine. The potential and limitations of the IPM approaches in coffee systems are discussed.

Key Words: coffee pests, synthetic pesticides, biocontrol, IPM

Introduction

Coffee is one of the most valuable export crops of the third world countries, and Africa alone produces 30% of all exported coffee. Among the major factors limiting increased coffee production worldwide are losses due to pest damage, although most of the economic pests are indigenous to the producing countries except for a few which include the coffee berry borer, coffee leaf rust and the coffee green scales (Waller, 1981; Anon, 1982; Waterhouse and Norris, 1989; Murphy and Moore, 1990). Losses due to coffee pests (insects, diseases, nematodes and weeds) are estimated to be 13% worldwide (Bardner, 1978) with more serious losses occurring in Africa, the home of *Coffea* spp. The world distribution of the major pests of coffee is summarised in Table 1. It may be difficult to quantify losses due to different pests worldwide because coffee is grown under wide agro-ecological and management practices, thus affecting the economic pest status of the same pest in different countries. For example, the coffee berry borer, *Hypothenemus hampei* Ferrari, a notorious pest of coffee worldwide (Table 1), has been reported to cause up to 80% damage in Uganda, 5–20% in Ivory Coast, 84% in Congo, 96% in Tanzania, 90% in Malaysia, 60–80% in Brazil (Waterhouse and Norris, 1989) and 80% in Kenya (Masaba, 1994, unpublished report). The coffee berry disease (CBD), *Colletotrichum coffeanum* = *kahawae* Waller & Bridge, a major pest of coffee in East Africa, causes 90% crop loss on arabica coffee in Tanzania and up to 20% loss in Kenya (Masaba, 1991; E. Koinange, 1994 pers. commun.).

In Africa, coffee under smallholders (60 % of the export crop in Kenya) is often intercropped with a variety of

Table 1. Pests (insects, diseases and nematodes) of coffee and their global distribution. Note that:$^{++}$ (indicates effective control measures); and^{+} (control measures not effective); ? (control status not clear)

Pest	Country	Economic status	Origin	Year of introduction	Current control measures & status
Coffee berry borer *Hypothenemus hampei* (Coleoptera: Scolytidae)	All African coffee growing countries	Major	Indigenous		Chemical^{+}/cultural^{+} indigenous natural enemies
	Middle East	Major	Exotic	?	?
	Asia	Major	Exotic	?	?
	Central America	Major	Exotic	1983	Chemical^{+}/biocontrol^{++}
	South America	Major	Exotic	1913	Chemical^{+}/biocontrol^{++}
	Pacific	Major	Exotic	1963	Chemical?/biocontrol?
African coffee leaf miner: *Leucoptera meyricki* (Ghesq.) (Lepidoptera: Lyonetiidae)	Tanzania, Kenya, Uganda, S. Africa, Zambia, Malawi, Central Afri. Rep.	Major	Indigenous		Chemical^{+}
Neotropical coffee leaf miner: *L. coffeela* (Guer)	Madagascar, Reunion, Costa Rica, El Salvador, Guatemala, Honduras, West Indies, Bolivia, Colombia, Equador, French Guiana, Peru, Surinam, Venezuela	?	Indigenous		Chemical?
L. caffeina (Wash.)	Kenya, Tanzania, Malawi Zambia	Minor	Indigenous		Chemical

Contd.

Table 1. Contd.

Pest	Country	Economic status	Origin	Year of introduction	Current control measures & status
Antestia bugs: *Antestiopsis* spp., (Hemiptera: Pentatomidae)	Botswana, Kenya, Malawi, Tanzania, Uganda, Zambia, Zimbabwe	Major	Indigenous		Chemical^{+}/cultural^{+}
White stemborer: *Anthorea leuconotus* Pasc. (Coleoptera: Lamiidae)	Sri Lanka, China, Formosa, Java, Malaya, Phillipines, Loocho Is., Vietnam, Madagascar, Mauritius, Reunion, Caroline Is., Mariana Is., Guam,	?	Indigenous		Chemical^{+}/cultural^{+}?
	Tanzania, Kenya	Minor			
Citrus mealybug *Planococcus citri* (Risso) (Hemiptera: Coccidae)	Kenya	Minor	Indigenous		?
	India	Major	Indigenous		Biocontrol^{++}
Kenya mealybug *P. kenyae* (Le Pelley)	Kenya	Minor	Exotic	1911	Biocontrol^{++}
Green coffee scales *Coccus* spp. (Hemiptera: Coccidae)	Kenya	Minor	Indigenous		?
	India	Major	Indigenous		
	Papua New Guinea	Major	Exotic	1982?	Biocontrol^{++}
	Cuba	Major	Exotic	?	
Coffee leaf rust *Hemileia vastatrix*	All African coffee growing countries	Major	Indigenous		Chemical^{++}/resistant varieties^{++}

Contd.

Table 1. Contd.

Pest	Country	Economic status	Origin	Year of introduction	Current control measures & status
(Berk. & Broome) (Basidiomycotina: Uredinales)	All Latin American countries	Major	Exotic	1970s	
	Yemen	Minor	?		
Coffee berry disease *Colletotrichum coffeanus = kahawae*	Kenya	Major	Indigenous		Chemical[++]?/cultural[+]/? resistant varieties?
Sp. nov. (Waller & Bridge)	Tanzania	Major	Exotic	1960s?	Chemical[++]?
	Uganda	Major	?		Chemical[++]?
Coffee nematode *Pratylenchus coffeae* (Zimmerman)	Congo, Egypt, Madagascar, Malawi, Nigeria, Uganda, Zaire, Zimbabwe	Major	Indigenous		?
	India				Resistant robusta root stocks[++]
	Java	?			

companion crops (food crops, fruit trees, shade trees and fodder plants) mainly to optimise the micro-economy of the farm. This sort of intercropping would influence the pest complex and pest pressure on the coffee. In contrast to the African situation, in many parts of Latin America, coffee is grown as monoculture; in Colombia for example, it is not uncommon to find a small farm of 1–2 ha with 5000 coffee trees/ha and only occasional plantain or other fruit trees (P. Baker, pers. observ.). For many farmers in Latin America, coffee is their only source of income and hence pest infestation can cause great alarm.

Pesticides are widely used for coffee pest control worldwide. In Kenya, for example, chemical control of coffee pests accounts for 30% of the total costs of production (Masaba, 1991) and is the major factor reducing the net returns from coffee sales. The bulk of the chemicals used in Kenya are fungicides targeted against the CBD and coffee leaf rust, with some insecticides to control the major insect pests (antestia, coffee berry borer and the leaf miner).

However, pesticides are becoming less popular because of a number of constraints. First, pesticide prices are increasing annually, whereas coffee prices have fallen or remained static until recently (probably temporarily). For example, in Kenya the cost of chemical control of coffee rust in terms of coffee yield increased from one 60 kg bag/ha to four during the decade between the mid 1970s and 1980s (Waller, pers. observ.), thus putting chemical control of coffee pests far beyond the means of many farmers. Second, increased consumer awareness and demand for environmental conservation and low pesticide residues in food is forcing farmers and policy makers to search for alternative pest control methods. Third, some countries are having to deal with new pest problems some of which were traditionally regarded as minor pests e.g. the coffee leaf miner, *Leucoptera meyricki*, in Tanzania and Kenya, which is now a major economic pest in both countries. *Leucoptera* is believed to be a resurgent pest due to excessive use of pesticides targeted against the major diseases in the area (Abasa, 1975; Nyambo, 1993 unpublished). Fourth, the most widely used pesticides are not compatible with other cheap effective pest control strategies, e.g. most of the copper-based fungicides are known to be toxic to many potential natural enemies of coffee pests including pathogen antagonists (Swynnerton et al., 1948; Robinson, 1964; Masaba, 1991). This may have contributed significantly to the failure of biocontrol efforts. Fifth, the continuing spread of the coffee insect pests and diseases (e.g. CBD across Africa and coffee rust and the berry borer to the New World) add to the pressure to develop appropriate IPM strategies in new areas. Last, in some countries the coffee pest complex needs to be addressed from the farming systems approach in order to be able to formulate economically acceptable, sustainable and viable pest control strategies.

For many years, biological control of pests has been used as the best alternative to chemical pest control, but with varied results. Its potential in coffee agroecosystems, either alone or as a complement to other pest control tactics, needs to be reappraised.

Biocontrol in Coffee Pests

Biocontrol (biological control) is the use of natural enemies (parasites, predators, pathogens), either exotic or indigenous, to control pests. The literature on attempts to use classical biocontrol on coffee pests is immense and shows the importance attached to the role of natural enemies in coffee pest management. Table 2 gives a summary of the global attempts of classical biocontrol in coffee pests to date. It is evident that biocontrol has been used to control both indigenous and exotic pests. To date, about 50% of all attempted classical biocontrol has been on indigenous pests. Out of 20 cases (Table 2), 25% have been reported as successful.

What are the lessons from these attempts and how do they fit into the future of biocontrol of coffee pests?

The Kenya Coffee Mealybug, *Planococcus kenyae*

The successful biological control of *Planococcus kenyae* (Le Pelley) in Kenya from 1938 onwards was spectacular and opened the way for further biocontrol attempts in coffee pests. The first serious outbreak of *P. kenyae* on coffee occurred in 1924 in the Ruiru and Thika areas in Kenya and efforts to search for its natural enemies were initiated. However, it was not until 1938 that effective natural enemies were discovered, after many years of research and introductions of the wrong natural enemies.

Analysis of the case shows that this occurred for the following reasons (Abasa, 1975); 1—The pest was misidentified. Between the years 1911–1935 the pest was known as *P. lilacinus*. 2—The country of origin of *P. kenyae* remained unknown for years for it was widely believed to be indigenous to Southeast Asia as a result of the misidentification. After careful study (Abasa, 1975), the correct taxonomy and country of origin of the pest was established to be Uganda from where it was introduced in Kenya without its natural enemies. Even when the appropriate natural enemies had been identified, introduced, established and were considered effective, there were cases of poor control in some areas attributed to the presence of ants. Banding of the coffee trees with ant repellent plus pruning practices improved the efficacy of the introduced biocontrol agents.

The Coffee Green Scales, *Coccus* spp.

The coffee green scales, *Coccus viridis* Green and *C. celatus* (De Lotto) were accidentally introduced to Papua New Guinea with coffee planting material from East Africa in the 1980s (Anon, 1982). After the pest was correctly identified a search for effective natural enemies was carried out in Kenya, the country of origin, before these were imported to Papua New Guinea (Noyes, 1988; Murphy, 1991). Successful introduction and subsequent control of the coffee green scales in Papua New Guinea was achieved after a combination of spot application of ant deterrent around coffee trees and the release of *Metaphicus baruensis* in affected areas (Masamdu, 1989).

The Coffee Berry Borer, *Hypothenemus hampei*

Perhaps the most favoured coffee pest for biocontrol attempts worldwide is the coffee berry borer, but only a few of the attempted efforts have been successful (Table 2). In their review on biological control of the pest in different parts of the world, Waterhouse and Norris (1989) give the following as the major stumbling blocks:

1—Misidentification of species of *Hypothenemus* and misinterpretation of the relative roles of various 'host plants' which complicates quarantine procedures and control activities. *Hypothenemus hampei* has been observed to feed and breed on a number of alternative host plants but this has not been given serious consideration in relation to the management of the pest on coffee. For this reason they recommend a thorough

Table 2. Summary of biocontrol of coffee pests in the major coffee producing countries to date

Pest	Country	Status	Year of outbreak	Biocontrol agent used	Control status	Reference
The Kenya mealybug, *Planococus kenyae* (Le Pelley)	Kenya	Exotic	1924	*Anagyrus kivuensis* (Compere) & *A. beneficians*	Successful	Greathead (1971) Abasa (1975)
Citrus mealybug, *Planoccoccus citri* (Risso)	India	Indigenous	?	*Leptomastix dactylopii* (How) & *Cryptolaemus montrouzieri*	Successful	Prakasan (1987) Reddy et al. (1993)
White waxy scales *Ceroplastes (Gascardia) brevicauda* (Hill)	Kenya	Indigenous	1944	*Scuttellista cyanea* (Mots) & *Diversinervus elegans* (Silv) (indigenous n.e.)	Successful	Abasa (1975)
Coffee leaf miner *Leucoptera meyricki* (*coffeella* Guer) (Ghesq.) & *L. caffeina* (Wash)	Kenya	Indigenous	1920/54	*Zagromosoma variegatum* var. *afra: Pediobius coffeicola* (Ferr); *Achrysocharis ritchie* (Ferr.); *Parahormius leucoptera* (Nixon); *Pheidole liengmei;*	Unsuccessful	Abasa (1975)
				Miraz insularis (Mues)	Unsuccessful	Greathead (1971)
	Tanzania	Indigenous	1950	?	Unsuccessful	Greathead (1971)

Contd.

Table 2. *Contd.*

Pest	Country	Status	Year of outbreak	Biocontrol agent used	Control status	Reference
Antestia bug *Antestiopsis* spp.	Kenya	Indigenous	1917 1921 1928	*Corioxenus antestiae* (Strepsiptera); *Bogosia rubens* (Vill.)	Establishment unconfirmed Unsuccessful	Greathead (1971) Abasa (1975)
	Tanzania	Indigenous	?	*B. rubens*	Established but no control	Greathead (1971)
	Uganda	Indigenous	?	*C. antestiae* & *B. rubens*	Established but no control	Greathead (1971)
Coffee berry borer *Hypothenemus hampei* (Ferr.)	Kenya	Indigenous	1928	*Prorops nasuta* (Waterst); *Heterospilus coffeicola* (Schmied)	Control doubtful	Greathead (1971) Abasa (1975) Murphy and Moore (1990)
	Uganda	Indigenous	1908	*P. nasuta* & *H. coffeicola*	Control doubtful	Greathead (1971)
	Brazil	Exotic	1929	*P. nasuta*	Established, still considered important	Greathead (1971) Murphy and Moore (1990)
	Indonesia	Exotic	?	*P. nasuta* & *Cephalonomia stephanoderis*	Unsuccessful	Murphy and Moore (1990)
	Sri Lanka	Exotic	?	*P. nasuta* & *H. coffeicola*	Unsuccessful	Murphy and Moore (1990)

Contd.

Table 2. Contd.

Pest	Country	Status	Year of outbreak	Biocontrol agent used	Control status	Reference
	Peru	Exotic	?	*P. nasuta*	Unsuccessful	Murphy and Moore (1990)
					Failed to establish	Waterhouse and Norris (1989)
	Jamaica	Exotic	?	*P. nasuta*	Did not establish	Waterhouse and Norris (1989) P. Baker (unpub.)
	Equador	Exotic	1981	*Beauveria bassiana*	?	Kein-Koch (1990)
				P. nasuta	Established	Waterhouse and Norris (1989) Murphy and Rangi (1991)
				C. stephanoderis	Established	P. Baker (unpub.)
	Colombia	Exotic	1988	*P. nasuta* & *C. stephanoderis*	Established	P. Baker (unpub.)
	Mexico	Exotic	?	*P. nasuta* & *C. stephanoderis*	? Established & successful	Murphy and Moore (1990) Murphy and Rangi (1991) P. Baker (unpub.) Barrera et al. (1990)
	Java	Exotic	1923	*P. nasuta* & *H. coffeicola*	Established but died out	Greathead (1971)

Contd.

Table 2. Contd.

Pest	Country	Status	Year of outbreak	Biocontrol agent used	Control status	Reference
Green scales *Coccus viridis* (Green) & *C. celatus* (De Lotto)	Papua New Guinea	Exotic	1982?	*Metaphycus baruensis* sp.n.	Successful	Masamdu (1989)
C. viridis	Seychelles	Indigenous	1933	Entomophagus fungi, *Cephalosporium lecanii* &	Successful	Greathead (1971)
				Pseudomicrocera henningsii (Koord)	Unsuccessful	
Star scales *Asterolecanium* sp.	Sao Tome	?	1960?	*Coccidoxenus portoricensis* (Crawf)	Successful	Greathead (1971)
Coffee rust *Hemileia vastatrix*	Mexico	Exotic	?	*Verticillium lecanii*	?	Carrion (1988)
	Brazil	Exotic	1970	*V. lecanii* & *V. leptobactrum*	Unsuccessful	Waller (1981) Eskes et al. (1991)

review of true hosts of *H. hampei* to be able to formulate appropriate and effective IPM control measures.

2—The relative economic significance of *Hypothenemus* in the pest complex which may determine the nature and magnitude of control practices. This may be the case in East Africa where although the pest causes heavy losses to coffee, pest control efforts are targeted towards CBD and the coffee leaf rust, rendering the biological control attempts against *Hypothenemus* unsuccessful. The copper-based fungicides used to control the two major diseases are known to be toxic to a wide range of natural enemies including hymenopteran insects (Masaba, 1991), and hence the need to review the pest complex and control strategies.

3—Unfavourable environment for the natural enemies brought about by poor cultural practices. Proper pruning and removal of leftover berries at the end of the harvest should facilitate the impact of the natural enemies. However, most farmers are not practising this because it is labour intensive.

The Coffee Leaf Miner, *Leucoptera* sp.

In East Africa, the coffee leaf miner, *Leucoptera meyricki*, is an indigenous pest which attained economic importance in Kenya and Tanzania in the early 1950s (Swynnerton et al., 1948; Greathead, 1971; Abasa, 1975) mainly due to excessive use of copper-based fungicides to control coffee leaf rust and CBD in addition to the use of a wide spectrum of insecticides against other major insect pests in coffee. The pesticides are toxic to a wide range of the indigenous natural enemies and this has enabled the leaf miner to attain its current pest status (Crowe, 1964; Masaba, 1991). To effect good control of this pest a complete evaluation of the overall pest complex and control strategies is required. The *Leucoptera* situation in Kenya and Tanzania is a clear case of conflict between pest complex control priorities and incompatibility of control approaches.

In summary, the major factors limiting the success of many of the biocontrol attempts to date are inadequate taxonomy of the pest and its host range, poor information on its origin, lack of consideration of the overall pest complex and crop management practices.

Future Outlook

The IPM Approach: Potential and Limitations

Integrated pest management (IPM) is a flexible multidisciplinary pest management approach that utilises a combination of biological, genetical, cultural, physical and chemical techniques to hold pest populations below economically damaging levels. It is an approach that aims to encourage judicious use of chemical pesticides and other artificial pest controls to reduce pest losses to crops on a continuous basis, at low cost and with minimum hazard to the environment and non-target organisms.

Farming Systems Research Approach

Coffee is grown under different agro-ecological and management practices and the pest complex is often influenced by these two major factors. In East Africa for example, intercropping coffee with food crops and trees is widely practised (Njoroge and Kimemia, 1993; Nyambo, pers. observ.) whereas in Latin America, coffee is almost virtually grown as a monocrop. Even when coffee is not intercropped, shade trees are often used. Pest control research recommendations often consider individual pest problems in coffee forgetting the implications to the farmer and the other crops intercropped with it. Njoroge and Kimemia (1993) reported that in Kenya coffee is intercropped with grain legumes, cereals, tuber crops, fruit trees and shade trees. The authors further point out that farmers practice intercropping because they need to maximise land use, a fact that applies to many smallholder situations. This means that farmers divide their time and other inputs between coffee and the other crops. For this reason there is a need to look at the coffee farming system and the pest complex and its implications for the farm economy so as to be able to develop economically sound, acceptable and sustainable pest management practices.

The Potential and Limitations of Natural Control by Indigenous Natural Enemies

The insect pest and disease complex occurring on coffee is subject to a range of natural biocontrol systems. Much of the damage caused by pests on cultivated coffee is due to a disturbance of this natural biocontrol balance caused either by a direct reduction in populations of natural enemies and antagonistic micro-organisms or to the cultural conditions under which coffee is grown favouring pests without a corresponding increase in the activities of natural biocontrol agents. The many cultural practices undertaken on commercial coffee all effect this balance and the use of pesticides has the greatest effects. Yet our knowledge of these effects is still very limited particularly of their mechanisms, interactions and dynamics. Only by acquiring this knowledge can we manipulate the components of the system to produce practical integrated pest management.

The widespread occurrence of natural enemies of arthropod pests is well recorded and it is now known that natural biocontrol systems operate against the major pathogens of coffee as well (Masaba, 1991; Masaba and Waller, in press). Recent studies of leaf domatia of coffee in Queensland, Australia (O'Dowd, 1994) has provided evidence that domatia are a good refugia of predatory and fungivorous mites that have the potential to control fungal pathogens and some arthropod pests on coffee leaves. These can substantially limit the impact of diseases and insect pests in certain conditions but their removal or disturbance can increase pest levels. It has long been known in Kenya that the incidence of CBD on unsprayed coffee can be less than that on sprayed coffee, especially if fungicide applications are poorly timed. This is because the use of fungicides for disease control reduces the activity of these natural systems which operate through the antagonistic effects of the natural microflora growing on the surfaces of coffee plants (Masaba and Waller, in press). Hyperparasitic fungi of *Hemileia vastatrix* substantially reduce the sporulation of coffee rust lesions in humid areas and thereby restrict the rate of epidemic development. The existence or the effect of these natural biocontrol systems only becomes apparent when they are disturbed or removed, e.g. as a side-effect of pesticides on non-target organisms.

Antagonistic microflora act at several points during the life cycle of *Colletotrichum kahawae* to reduce the incidence of CBD; they reduce the survival and sporulation of the pathogen on coffee twigs and dead berries; restrict the germination of and subsequent infection by spores; and induce or activate resistance mechanisms in young berries. Several components of the microflora have been identified which have these effects and the challenge now is to determine how these can be increased. Possibilities include the use of antagonistic microflora as biopesticides and the adoption of cultural practices which naturally favour an increase in the microflora, e.g. selected intercropping with appropriate plant species may well help to increase the biodiversity of microflora, on coffee and thereby enhance its antagonistic effects against both insect pests and diseases.

The Potential and Limitations of Classical Biocontrol

To date classical biocontrol in coffee pests has had few successful results (Table 2). This has been partly due to lack of appreciation of the pest complex and the role of farming systems in pest control strategies particularly where pesticides are commonly used on other crops in the system. This needs to be addressed properly before biocontrol attempts are considered. Another important factor is the need for proper taxonomy of the target pest and its alternative host plants. The lesson from the case of *P. kenyae* is a good demonstration of how much time and resources could have been saved in terms of funding and other resources had the pest been identified correctly from the beginning. Together with this is the need for proper studies on the biology and ecological requirements of the identified potential biocontrol agent. The ecological requirement of a potential agent may be very crucial to the success of a classical biocontrol attempt in coffee agrosystems. A good example is the classical biocontrol of gorse, an exotic weed in New Zealand, with an exotic species of phytophagous mite, *T. lintearius.* The mite was first released in New Zealand in 1989. Post-release studies revealed that the strain of *T. lintearius* released was better established in the warmer, drier parts than in the cooler, wetter areas of New Zealand. Following these observations, searches were conducted in the cool, wet areas off the west coast of Spain and Portugal for biotypes of *T. lintearius* which are likely to be better adapted to similar ecological conditions to the wet-cool areas of New Zealand. The mites were released and have established well in these areas (Hill, 1994, pers. commun.); and hence the need for proper studies of ecological requirement of a potential agent.

The perceived danger that some arthropod natural enemies can spread major coffee diseases in an area and therefore could pose phytosanitary risk is a subject which needs further research. Work done by Nemeye et al. (1990) has provided some evidence to show that *Heterophilus coffeicolla,* a potential biocontrol agent of *H. hampei* could transmit the coffee berry disease. This shows the need for strict quarantine and sanitation in the importation of arthropod natural enemies to minimise such risks. However, there is no reason to suppose that the addition of exotic natural enemies or the enhancement of existing ones will have any untoward effects in diseases, indeed because of the positive interactions known to occur between insect pest damage and disease incidence any factor which reduces the former will tend to reduce the latter.

The Potential and Limitations of Augmentation (Biopesticides etc.)

Ideally, a good biopesticide should be selective and environmentally safe. However, depending on the farming system, the possibility of residues and contamination of non-target crops, e. g. leafy vegetables cannot be ruled out, and this needs careful evaluation.

The availability of effective formulations and cost-effective application techniques is an area that needs investment, particularly in the developing countries. International collaboration may be required in research and development of the appropriate technology. In Colombia, a programme to develop *Beauveria bassiana* as a component of IPM for the coffee berry borer to reduce dependency on thiodan is underway (Prior, pers. commun.). *Beauveria bassiana*, an indigenous entomopathogen, has been shown to be a potential biocontrol agent for coffee berry borer (Moore and Prior, 1988) but research is needed to develop effective formulations and application technology before its potential can be fully exploited (Prior, pers. commun.).

The development of biopesticides for control of pathogens from the microflora growing on the coffee surfaces has definite potential. Indications from the studies on microflora interactions with CBD in Kenya (Masaba and Waller, in press) is that some fungal species could readily be cultured and applied to coffee to give control but the commercial reality of this approach needs much more investigation. It is also very likely that organisms pathogenic or antagonistic to arthropod pests occur naturally on coffee, e.g. *B. bassiana*, which could have potential for biopesticides but there has been no concerted effort to investigate this.

Biopesticides may have to be used as a complement to synthetic chemical pesticides to effect adequate control of a particular pest. In such a situation, compatibility with synthetic pesticides would be desirable, as it is often possible to schedule both into a spray programme. Although biopesticides may be selective, and environmentally safe, careful use is essential to prolong their effectiveness in the field. As with chemical pesticides, the potential of the target pest developing resistance to a particular strain after continuous use should not be overlooked. Already there is evidence from Hawaii and Japan that *Plutella xylostella*, a pest of brassicas, has developed resistance to strains of *Bacillus thuringiensis* (Tabashnik et al., 1992; Tanaka, 1992).

Work has already been initiated in an attempt to control *Hemileia vastatrix* with strains of *Bacillus thuringiensis* (Roveratti et al., 1989) and *Verticillium lecanii* (Carrion, 1988; Eskes et al., 1991) and *Beauveria bassiana* strains against the berry borer in Colombia, which is a positive move towards development of alternatives to synthetic chemical pesticides.

Natural Products

The use of natural products to control coffee pests is perhaps the least researched and used approach. This could be because traditionally coffee is not intercropped with non-crop plants. However, work done in Indonesia has shown that some weed plants e.g. *Tagetes patula* have good nematocidal effect against the nematode, *Pratylenchus coffeae* (Saleh et al., 1971). This needs further research before the potential of such plants can be realised by farmers particularly in IPM strategies.

The Potential and Limitations of Breeding and Selecting for Host Plant Resistance to the Major Pests of Coffee

Breeding and selecting for resistance to the major pests of coffee has been given limited emphasis, with only a few reported cases in the literature. Resistance to diseases is the favoured option for control of all plant pathogens and has been very successful in many cases especially on annual crops. The use of resistance on perennial crops has been much more restricted because of both the nature of these crops and their economies (Waller, 1988). The main problem with resistance has often been its lack of 'durability'—the resistance is overcome by the emergence and spread of new more virulent pathogen races. Long term breeding programmes for control of coffee rust in Brazil and Colombia have produced varieties of coffee with complete resistance to all coffee rust races and which has so far proved to be durable. Output from these programmes have been used in Kenya to combine resistance to CBD and coffee leaf rust with high quality, and this has resulted in the release of Ruiru 11, a variety which has resistance to both diseases (Walyaro et al., 1984; Masaba, 1994, unpublished). Complete and durable resistance to CBD may be difficult to achieve because of the nature of the pathogen, but even partial resistance would be a useful component to include in an IPM package. In Côte d'Ivoire, hybrid coffee cultivars of high quality, high yielding, vigorous growth and resistant to coffee leaf rust and the beetle, *Xyleborus morstatti,* have been selected and released to farmers (Capot, 1972). Thus there is a potential to breed and select for cross-resistance to several pest problems while maintaining major commercial qualities. In South India, robusta coffee rootstocks have been successfully used to control *Pratylenchus coffeae* (Palanichamy, 1973). There are also reports of coffee cultivars tolerant to *H. hampei* in Côte d'Ivoire (Koch, 1973). All these examples show the high potential of host plant resistance in coffee pest management. However, conflict between the commercial quality requirements and pest control priorities may prevent the release of a variety with high levels of resistance or tolerance to a target pest. The availability of the relevant breeding technology, e.g. tissue culture techniques in developing countries, may be a limiting factor in breeding for host plant resistance. However, if well funded, traditional methods of breeding are very effective.

The Role and Limitations of Synthetic Chemical Pesticides

Synthetic chemical pesticides will continue to play a role in coffee pest management strategies. To optimise the benefits of pesticide use farmers should be educated and encouraged to use them properly and judiciously. Some of the major limiting factors to heavy reliance on synthetic pesticides have been listed above. Added to this is the high potential of some pests to develop resistance to some of the cheap and easily available chemical pesticides, e. g. *L. meyricki* in Tanzania has developed resistance to the cheap OP insecticides after many years of use (Bardner and Mcharo, 1988). In New Caledonia, *H. hampei* has shown high levels of resistance to endosulfan and cross-resistance to organochlorines (Brun et al., 1994), thus forcing the coffee industry to search for alternative control methods. Already in Colombia researchers are trying to develop *B. bassiana,* an indigenous entomopathogen, for use against *H. hampei* as an alternative to endosulfan. Other such situations are likely to develop unless deliberate moves are taken to search for alternative methods to chemical pesticide control.

Apart from the problems noted earlier concerning the use of fungicides for CBD control, the rapid development of resistance by *C. kahawae* to the systemic MBC-based fungicides used in the 1970s in Kenya resulted in a shift back to the use of captofol as the standard chemical. However, this was shown to increase the severity of bacterial blight which is prevalent in some areas of Kenya so that copper-based fungicides, with all the potential disadvantages of broad-spectrum fungicide/bactericide, are now commonly used particularly now that captofol has been discontinued because of potential health risks. Application of fungicides still remains the primary method of disease control on coffee in most of Africa and in many other coffee producing areas. There is an urgent need to reduce this both on economic and environmental grounds and the incorporation of other disease control components into the system to produce a workable and durable IPM strategy must be a major objective of current research and development in the coffee sector.

A major aim in the development of IPM measures against diseases must be to develop a package of mutually supportive strategies. Techniques involving cultural methods and the enhancement of natural antagonists which disrupt the pathogen life cycle will enhance the effectiveness and durability of resistance by reducing disease pressure and pathogen variability. There may still be a need to use pesticides in some situations but selective compounds which are applied in minimal effective doses on the appropriate target and at carefully selected stages during the disease cycle should have minimal disruptive effects on natural biocontrol systems.

Quarantine

The need to restrict the movement of planting material and unprocessed coffee beans to minimise spreading of damaging pests to new areas should be re-examined. Strict legislation was able to keep India free from coffee berry borer until the late 1980s (Chacko, 1978; Kumar et al., 1990). However, possibly due to laxity on the enforcement of the quarantine legislation, *H. hampei* entered India where it was reported on coffee for the first time in Tamil Nadu in February 1990 (Kumar et al., 1990). By the end of 1991 the pest had spread to Karnataka and Kerala, two major coffee growing areas of India (Krishnamoorthy-Bhat, 1991). In the same year the coffee berry borer was reported to be resistant to endosulfan (Agnihothrudu, 1991). Despite this fact, the value and potential of quarantine in coffee pest management should be emphasised as part of IPM strategy where and when appropriate.

Environmental Impact of Classical Biocontrol

The pests of coffee, notably insects, diseases and nematodes, are closely adapted to the *Coffea* spp. The natural enemies are, likewise, host specific or nearly so, and therefore providing only specific natural enemies are chosen for introduction, the probability of environmental damage is remote. The successful control of *P. kenyae* in Kenya with *Anagyrus* spp. from Uganda since 1938 to date is a good example of the long term benefits of classical biocontrol in coffee when host specific natural enemies are used.

As noted earlier, the perceived danger that some arthropod natural enemies can spread major coffee diseases should not be taken as a major deterrent to the use of classical biocontrol. On the contrary, this should be a warning for those involved in classical biocontrol so that they practice high quality standards to minimise the risks.

The problems of long term use of chemical pesticides have already been discussed in detail above. Successful introduction of appropriate biocontrol-based IPM is likely to reduce the environmental problems.

Conclusions

Biocontrol ought to be very important for coffee pest management because the coffee tree provides a stable crop over many years, thus giving time for natural enemies and the pest populations to establish equilibrium levels. However, biocontrol by itself may not be the answer to coffee pest management in all the different coffee agroecosystems. Moreover, there is high potential to develop effective, economically sound, and sustainable coffee pest management practices even for the notorious pests by making the existing agents work better with other methods developed through IPM. This is achievable through a better understanding of the farming systems, the pest complex in totality, the socioeconomics of the coffee farmer and the development of appropriate IPM technologies. Biocontrol-centered IPM should be the future path towards improved environmental conservation, increased food and cash income, and reduced pest pressure and losses in coffee.

References

Abasa R. O. (1975) A review of the biological control of coffee pests in Kenya. *E. A. Agric. For. J.* 40, 292–299.

Agnihothrudu V. (1991) More on coffee berry borer, *Hypothenemus hampei.* Resistance to endosulfan. *Indian Coffee* 55, 7–8.

Anonymous (1982) Coffee research in Papua New Guinea. *Trop. Pest Manage.* 28, 310.

Bardner R. (1978) Pest control in coffee. *Pesticide Science* 9, 458–464.

Bardner R. and Mcharo E. Y. (1988) Confirmation of resistance of the coffee leaf miner, *Leucoptera meyricki* Ghesq. (Lepidoptera, Lyonetiidae) to organophosphate insecticide spray in Tanzania. *Trop. Pest Manage.* 34, 52–54.

Barrera J. F., Moore D., Abraham Y. J., Murphy S. T. and Prior C. (1990) Biological control of the coffee berry borer, *Hypothenemus hampei* in Mexico and possibilities for further action. *Brighton Crop Protection Conference 1990,* pp. 391–396.

Brun L. O., Marcillaud C., Gaudichon V. and Suckling D. M. (1994) Cross-resistance between insecticides in coffee berry borer, *Hypothenemus hampei* (Coleoptera: Scolytidae) from New Caledonia. *Bull. Ent. Res.* 84, 175–178.

Capot J. (1972) Coffee improvement in the Ivory Coast: "Arabusta" hybrids. *Café, Cacao, Thé* 16, 3–18.

Carrion G. (1988) Studies on the biological control of coffee rust by *Verticillium lecanii* in Mexico. *Micologia Neotropical Applicada,* 1 79–86.

Chacko M. J. (1978) Control of certain devastating pests of coffee. *Indian Coffee* 42, 265–268.

Crowe T. J. (1964) Coffee leaf miner in Kenya. II—Causes of the outbreaks. *Kenya Coffee* 299, 223–231.

Eskes A. B., Mendes M. D. L. and Robbs C. F. (1991) Laboratory and field studies on parasitism of *Hemileia vastatrix* with *Verticillium lecanii* and *V. leptobactrum. Café, Cacao, Thé.* Inst. Agronomico de Campinas. Campinas SP, Brazil 35(4), 275–282.

Greathead D. J. (1971) A review of biological control in the Ethiopian Region. *CAB Technical Communication* No. 5, CIBC.

Kein-Koch C. (1990) Natural regulation factors and classical biological control of coffee berry borer, (*Hypothenemus hampei* Ferrari) in Ecuador, *No. 2. 331–334.* In *Integrated Pest Management in Tropical and Subtropical Cropping Systems '89,* held on 8–15 Feb. 1989 Bad Durkheim, Germany, GTZ Plant Protection Project, Ecuador.

Koch V. J. M. (1973) Abundance of *Hypothenemus hampei* Ferr., the coffee berry borer, in relation to its food-plant and its parasite, *Cephalonomia stephanoderis* Betrem, in the Ivory Coast. *Medelingen-Landbouwhogeschool-Wageningen No. 16,* 84 pp.

Krishnamoorthy-Bhat P. (1991) The coffee berry borer in India, pp. 56–57. In *Resumenes*. I Reunion Intercontinental sobre Broca del Cafe; 17–22 de Noviembre de 1991, Tapachula, Chiapas, Mexico (Edited by J. F. Barrera, A. Castillo, J. Gomez, E. Malo and F. Infante).

Kumar P. K. V., Prakasan C. B. and Vijayalakshmi C. K. (1990) Coffee berry borer, *Hypothenemus hampei* (Coleoptera: Scolytidae). First record from India. *Journal of Coffee Research* 20, 161–164.

Masaba D. M. (1991) The role of saprophytic surface microflora in the development of coffee berry disease, *Colletotrichum coffeanum,* in Kenya. PhD Thesis University of Reading, 241 pp.

Masaba D. M. (1994) Coffee Insect Pests in Kenya and Coffee Diseases in Kenya. CRF P. O. Box 4 Ruiru. Kenya (unpublished).

Masaba D. M. and Waller J. M.(in press) Factors influencing microflora on coffee surfaces. *Ann. Appl. Biol.*

Masaba D. M. and Waller J. M.(in press) The potential for biological control of coffee berry disease *Colletotrichum kahawae* using epiphytic microflora. *Ann. Appl. Biol.*

Masamdu R. (1989) Factors influencing the effectiveness of *Metaphycus baruensis* Noyes (Hymenoptera: Encyrtidae) parasitising *Coccus* spp. (Hymenoptera: Coccidae) on coffee in Papua New Guinea. *PNG Coffee* 8(2), 89–91 Kuk Agric. Res. Station PO Box 339 Mount Hagen, Papua New Guinea.

Moore D. and Prior C. (1988) Present status of biocontrol of the coffee berry borer, *Hypothenemus hampei*. *Brighton Crop Protection Conference-Pests and Diseases* 1119–1124.

Murphy S. T. (1991) Insect natural enemies of coffee green scales (Hemiptera: Coccidae) in Kenya and their potential for biological control of *Coccus celatus* and *C. viridis* in Papua New Guinea. *Entomophaga* 36, 519–529.

Murphy S. T. and Moore D. (1990) Biological control of the coffee berry borer, *Hypothenemus hampei* (Ferrari) (Coleoptera, Scolytidae): Previous programmes and possibilities for the future. *Biocontrol News and Information* 11, 107–117.

Murphy S. T. and Rangi D. K. (1991) The use of the African wasp, *Prorops nasuta* for the control of the coffee berry borer, *Hypothenemus hampei,* in Mexico and Ecuador: The introduction programme. *Insect Sci. Applic.* 12, 27–34.

Nemeye P. S., Moore D. and Prior C., (1990) Potential of the parasitoid *Heterspilus prosopidis* (Hymenoptera: Braconidae) as a vector of plant-pathogenic *Colletotricum* spp. *Ann. Appl. Biol.* 116, 11–19.

Njoroge J. M. and Kimemia J. K. (1993) Current intercropping observations, and future trends in arabica coffee, Kenya. *Outlook on Agriculture* 22, 43–48.

Noyes J. S. (1988) *Metaphycus baruensis* sp. n.(Hymenoptera: Encyrtidae) parasitic in green scales, *Coccus* spp. (Hemiptera: Coccidae) on coffee in Kenya. *Bull. Ent. Res.*, 78, 131–134.

Nyambo B. T. (1993) The management of coffee leaf miner, *Leucoptera* spp. (Lyonetiidae: Lepidoptera) in northern Tanzania: Past, present and future possibilities. Internal Report to the Commissioner. Research and Training, Ministry of Agric. Tanzania Dec. 1993.

O'Dowd D. J. (1994) Mite association with the leaf domatia of coffee, *Coffea arabica,* in north Queensland, Australia. *Bull. Entomol. Res.* 84, 361–366.

Palanichamy K. (1973) Nematode problems of coffee in India. *India Coffee* 37, 99–100.

Prakasan C. B. (1987) Biological control of coffee pests. *Journal of Coffee Research* 17, 114–117.

Reddy K. B. and Bhat P. K. (1993) Effect of seasonal augmentation of *Leptomastix dactylopii* How. on *Planococcus citri* (Risso). *Journal of Coffee Research,* Central Coffee Research Inst. Coffee Res. Station, 577, 117 Chikmagular District, Karnataka, India.

Robinson J. B. D. (1964) A handbook on arabica coffee in Tanzania, pp. 142–152. Published by the Tanganyika Coffee Board.

Roveratti D. S., Teixeira A. R. R. and Moraes W. B. C. (1989) *Bacillus thuringiensis* —A new perspective for an induced protection to coffee rust. *Journal of Phytopathology* 126, 149–159.

Saleh M. (et al.) (1971) Preliminary results from a trial on the biological control of nematodes in coffee plantations in Java, Indonesia. *Budidaja Kopi-tjoklat.* Vol. IV, 8 pp.

Swynnerton R. J. M., Bennet A. L. B. and Stent H. B. (1948) All about 'KNCU' Coffee, pp. 63–75. Published by the Moshi Native Coffee Board PO Box 132 Moshi, Tanganyika.

Tabashnik B. E., Finson N., Schwartz J. M., Caprio M. A. and Johnson M. W. (1992) Diamondback moth resistance to *Bacillus thuringiensis* in Hawaii, pp. 175–183. In *Diamondback Moth and Other Crucifer Pests.* Proceedings of the 2nd International Workshop Taiwan, Taiwan 10–14 Dec. 1990 (Edited by N. S. Talekar).

Tanaka H. (1992) Occurrence of resistance to *Bacillus thuringiensis* in diamondback moth, a result of trials for integrated control in a watercress greenhouse, pp. 165–173. In *Diamondback Moth and other Crucifer Pests.* Proceedings of the 2nd International Workshop Taiwan, Taiwan 10–14 Dec. 1990 (Edited by N. S. Talekar).

Waller J. M. (1981) The recent spread of some tropical plant diseases. *Trop. Pest Manage.* 27, 360–362.

Waller J. M. (1988) New development in integrated disease management in tropical plantation crops. *Proc. Brighton Crop Protection Conference-Pests and Diseases 1988,* 297–305.

Walyaro D. J., van der Vossen H. A. M., Owuor J. B. O. and Masaba D. M. (1984) New varieties to combat old problems in arabica coffee production in Kenya, pp. 146–151. In *Proceedings of CAB's First Scientific Conference Arusha,* Tanzania 12–18 Feb., 1984 (Edited by D. L. Hawksworth).

Waterhouse D. F. and Norris K. R. (1989) Biological control: Pacific prospects. Supplement 1. *Hypothenemus hampei* (Ferrari) *ACIAR. Canberra 1989,* pp. 57–75.

Banana Weevil: Ecology, Pest Status and Prospects for Biological Control

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Abstract—The banana weevil (*Cosmopolites sordidus* Germar) evolved in Asia and is now distributed in all major banana growing regions. This paper briefly reviews what is known about the weevil's ecology and pest status. Prospects of control, including use of natural enemies, is also discussed. Emphasis is on recent work conducted in East Africa. Pest status of the weevil is controversial; few data are available which quantify levels of attack and resulting yield loss. Nevertheless, the weevil is considered a pest on plantain (*Musa* AAB) in West Africa and Latin America, on highland bananas (*Musa* AAA-EA) in East Africa and on various bananas in Asia, Australia and the Pacific. Early attempts at classical biological control included the release of generalist predators and met with little success. More recent work has focused on endemic natural enemies, entomogenous fungi, entomophagous nematodes and secondary host association. Currently, there is renewed interest in conducting searches for natural enemies in Asia. Prospects for a complete success using classical biological control are limited by the weevil's biology; however, partial control by natural enemies could be integrated into a broader control strategy.

Key Words: *Cosmopolites sordidus, Musa* spp., plantains, classical biological control

Introduction

Musa Production Systems

Edible bananas (*Musa* spp.) comprise a genetically diverse crop encompassing a range of diploids, triploids and tetraploids (Stover and Simmonds, 1987) with a variety including dessert, cooking and brewing bananas. These now constitute important staple and/or commercial crops in sub-Saharan Africa, Latin America, Asia, the Pacific and Australia. Bananas originated in South and Southeast Asia from two wild progenitors *Musa acuminata* (donor of A genome) and *Musa balbisiana* (donor of B genome), and have been spread throughout the humid tropics (Stover and Simmonds, 1987). Secondary centres of crop diversity exist in East Africa (highland cooking bananas, unique to the region) and West Africa (plantains) (Stover and Simmonds, 1987).

Banana production systems range from kitchen garden (e.g. plantains in Nigeria) to low input stands on small farms (e.g. highland cooking bananas in Uganda) to intensively managed plantations (e.g. export bananas in Central America). Stand longevity is influenced by management levels, biotic pressures and abiotic constraints: Well managed banana stands often persist for 30 or more years, even under low input conditions (e.g. Uganda). In these situations, an extended harvest period ensures food and income throughout the year. Moreover, bananas and plantains reduce soil erosion on steep slopes and are principal sources of mulch for maintaining and improving soil fertility (INIBAP, 1986).

Shifts in banana and plantain production systems are clear in both

East and West Africa. In Uganda, declining soil fertility and pest pressure are the driving forces leading to cultivar shifts (from traditional AAA-EA cooking bananas to AB and ABB brewing bananas) and/or abandonment of the crop (in favour of sweetpotato and cassava) in traditional banana growing areas (e.g. Luwero, Iganga, Mukono, Mpigi and Kamuli districts) (Gold et al., 1993). Similar shifts have been occurring in Burundi, Rwanda and the Bukoba district of Tanzania (INIBAP, 1986; Bosch et al., 1995). At the same time, biotic and abiotic constraints have jointly contributed to plantain decline leading to treatment of plantain as a biennial crop in much of West Africa (Swennen, 1984; INIBAP, 1988a).

In both East and West Africa, deteriorating production has discouraged farmers from expending management effort in highland banana or plantain systems. In Uganda, highland bananas are often under-managed while brewing bananas are neither mulched, weeded, desuckered or deleafed. In Ghana, ratoon crops receive little attention and are soon abandoned (P. Schill, pers. commun.). Instead, the limited resources available to the farmer are often directed to other crops. Such low levels of crop management may exacerbate pest pressure (Ackland, 1971; Ostmark, 1974).

Banana and plantain production constraints include a pest complex (weevils, nematodes and diseases) which causes serious yield losses and shortens plantation life (Swennen et al., 1984; INIBAP, 1986; Sebasigari and Stover, 1988; Gold et al., 1993). Pest status, in turn, is influenced by genome group. In Africa, for example, the banana weevil, *Cosmopolites sordidus* Germar, is considered a primary production constraint of highland cooking bananas and plantains but not of dessert or brewing bananas. As such, it has been reported as the major biotic constraint to banana production in eastern Africa (Persley and de Langhe, 1987) and either the first or second (after black sigatoka) most important plantain pest in West Africa (cf. INIBAP, 1988a).

In Uganda, Tanzania, and Ghana, farmers have identified weevils as a major factor contributing to banana or plantain production decline. However, causal factors were frequently confused and damage by nematodes and pathogens was often attributed to weevils (Gold et al., 1993; Schill, pers. commun.). Nevertheless, Ugandan diagnostic survey results suggest that banana weevil is an important pest of highland cooking bananas at mid-elevations (Gold et al., 1994a).

Resource-poor African farmers are often confronted with a complex of problems (pests, diseases, soil fertility) which are beyond their means for management (Gold et al., 1993). This suggests that low input systems, suffering from soil and other stresses, are more vulnerable to additional yield losses to banana weevil; in other words, weevil problems may be worse in situations where the farmer has the lowest capacity to respond.

Banana Weevil Pest Status and Ecology

Banana Weevil Biology

The banana weevil displays a classical "k" selected life cycle (Pianka, 1970) with long life span and low fecundity. Adults are free living (not confined to the banana plant) and may live for two or more years (Froggatt, 1925; N.D. Rukazambuga and C.S. Gold, unpubl. data). The weevils commonly feed on crop debris and may survive for extended periods without feeding (Froggatt, 1923; Simmonds, 1966). However, they commonly die within 72 hours when maintained on dry substrates. This suggests that they are extremely sensitive to soil moisture.

Banana weevil adults are seldom encountered on the soil surface in farmers' fields. Instead, they are occasionally found in post-harvest residues (e.g. spent pseudostems) or at the base of leaf sheaths, although most often they are encountered in traps made from post-harvest residues. Greater trap catches in the rainy season (pers. observ.) suggest reduced activity and possible burrowing behaviour during dry periods. In drum experiments, banana weevils were observed to burrow 50 cm or more.

Egg production is low with oviposition estimated from 1 to 2.7 eggs per week (Cuille, 1950; Delattre, 1980; Arleu and Neto, 1984; Koppenhofer, 1993a) and 10 to 270 in the lifetime of the insect (Cuille, 1950; Arleu and Neto, 1984; Viswanath, 1977; Castrillon, 1989). In pot trials, Koppenhofer (1993a) found egg distribution on highland banana plants to be 33% in crown area, 5% superficially in base of roots, 29% inside of abandoned tunnels, 22% in remaining parts of rhizome and 11% in base of leaf sheaths.

In contrast, under field conditions in Uganda, most oviposition is near ground level, primarily in leaf sheaths at pseudostem base; maximum depth of eggs was 5 cm below the soil surface (Gold and Abera, unpubl. data). Preliminary data suggest that oviposition and egg density (per unit surface area) is greater on older plants than peepers and young suckers. Nevertheless, there is evidence of greater larval survival in younger plants (Schmitt, 1993).

Banana weevil larvae bore in the corm, stem and pseudostem and represent the insect's most damaging stage. The larval stage lasts 5 to 8 instars (Cendana, 1922; Beccari, 1967; Viswanath, 1977; Arleu and Neto, 1984; Schmitt, 1993). Eclosion occurs at oviposition sites in pseudostems from which most larvae quickly migrate to the rhizome. Damage from early instars tends to be in the top of the rhizome while older larvae moved throughout the corm (C.S. Gold and A. Abera, unpubl. data). Attack, averaged across plants, is evenly distributed throughout the corm although tunnelling may be highly clumped on individual plants. Larval feeding in the stem and pseudostem is less common and may reach more than 1 m above the ground. The larvae may also move through the rhizome from the mother plant into newly developing suckers. The pupal stage and teneral adult period is within the banana plant.

Studies on banana weevil developmental rates (reviewed by Schmitt, 1993; Traore et al., 1993) show wide variability in stage duration: 4 to 36 days for eggs, 12 to 165 days for larvae, 1 to 4 days for prepupae, 4 to 30 days for pupae and 24 to 220 days from egg to adult. Under tropical conditions, however, an immature period of 1 to 2 months is probably most common (Seshu Reddy, 1986; Bakyalire and Ogenga-Latigo, 1992; Schmitt, 1993). The wide variability in reported developmental periods most likely reflects differences in environmental conditions (particularly temperature) and, possibly, existence of biotypes. Most studies were done under ambient conditions without recording temperature. In addition, Schmitt (1993) suggests that relative humidity, cultivar, age of plant, food quality and population density may also influence developmental rates.

Mesquita et al. (1983) and Schmitt (1993) examined egg eclosion at two different temperatures; however, data obtained from these studies are insufficient to describe the complete relationship between temperature and development of the banana weevil. In contrast, Traore et al. (1993) studied egg development at four temperatures: They found a developmental threshold of 11.4° C and a thermal requirement of 96 degree-days.

Dissemination of banana weevils is predominantly through infested planting material. The weevils seldom, if ever, fly and dispersal by walking is limited. Gold and Bagabe (1994) found that movement of adult weevils was limited although some marked individuals moved more than 30 m in five days while Delattre (1980) recorded a maximum movement of 60 m in five months. Therefore, movement of suckers carrying eggs, larvae and, occasionally, adults into new fields offers primary entry points for infestation of new stands. With low reproductive rates, population buildup is slow and problems are more likely to be encountered in ratoon crops.

Weevil Damage

Banana weevil larval galleries weaken the plant and provide entry point for secondary pests. Larval tunnelling contributes to plant death (most common in suckers), a weakened root system, stunting (through disrupted nutrient transport), premature leaf drop, delayed maturation, reduced bunch size, snapping and toppling. Larval exit holes provide entry points for ants and invasion by fungal pathogens which accelerate destruction and decomposition of rhizome tissues. Moreover, weevil attack may render banana plants more susceptible to leaf spots and other stresses. Finally, weevil attack may affect followers, including the number and vigour of suckers and the proportion of water suckers. However, the different possible physiological mechanisms of yield loss remain in need of quantification.

Weevil damage levels may be influenced by timing of attack, extent of tunnelling, site of attack, depth of penetration into the corm, degree of secondary attack by pathogens and ants, presence of other stresses and host plant tolerance. Most often, damage is greater in older stands as weevil populations build up over time.

Pest Status: Distribution, Incidence and Severity

The banana weevil is presumed to have evolved in Asia from which it has spread to all of the world's major banana growing regions (Neuenschwander, 1988). Data on the weevil's pest status (e.g. distribution, incidence, severity, yield loss) in its area of origin is sparse (c.f. Waterhouse, 1993; Valmayor et al., 1994). For example, scattered reports of weevil problems in South India (Viswanath, 1977), Thailand (Nanthachai, 1985) and Indonesia (Kusomo and Sunaryono, 1985) are not supported by population or yield loss data and lack confirmation. Nevertheless, Waterhouse (1993) suggests that banana weevil is an important pest in Malaysia and of moderate importance elsewhere in the region (Table 1). An understanding of weevil pest status and population dynamics in Asia is critical for the development of a classical biological control programme.

In Africa, Latin America and Australia, banana weevil pest status is controversial. Ostmark (pers. commun.), for example, believes that banana weevil is unimportant in well-managed Cavendish plantations in Central America and elsewhere. Yet banana weevil has been considered a major biotic constraint in Africa (Persley and de Langhe, 1987; INIBAP, 1988a; Gold et al., 1993), Asia and the Pacific (Valmayor et al., 1994) and Latin America (Mesquita et al., 1984; Pena et al., 1993; Schmitt, 1993).

Table 1. Banana weevil pest status in its presumed centre of origin in Southeast Asia

	Pest Importance⁺	Data on incidence	Data on yield loss
Burma	?	–	–
Thailand	+	+	–
Laos	?	–	–
Cambodia	+	–	–
Malaysia	+++	–	–
Vietnam	++	–	–
Brunei	++	–	–
Indonesia	++	–	–
Philippines	++	–	–
India	+	–	–
Sri Lanka	++	–	–

+++Important, ++Moderately important, + Present.

⁺Sources: Viswanath (1977), Geddes and Iles (1991), Waterhouse (1993).

In eastern Africa, pest problems presented by the banana weevil are relatively recent in origin. The weevil achieved pest status in the 1970s, more than 70 years after being introduced (E. B. Karamura, pers. commun.) with severe outbreaks occurring in Uganda and Tanzania during the 1980s (Sengooba, 1986). At the same time, the region has witnessed shifts from cooking (AAA-EA) to beer (AB, ABB) bananas and replacement of bananas by annual crops. Weevils are believed to be an important factor in this process (Gold et al., 1993). However, the pest status of the weevil/nematode complex has never been clearly defined and the biotic and abiotic factors which influence infestation levels and yield losses remain poorly understood.

Disappearance of highland cooking bananas from traditional growing areas in central Uganda has led to concern that the underlying processes may recur across the entire banana zone, thereby threatening the food security of the region (Gold et al., 1993). For this reason, the International Institute of Tropical Agriculture (IITA) and the Ugandan National Banana Research Programme (UNBRP) have undertaken an intensive three year study including rapid rural appraisals and multiple visit surveys of selected growing sites. Methodology for weevil and nematode assessment are described in Gold et al. (1994b). Survey results complement data on weevil and nematode incidence and severity from single visit surveys within the region (Walker et al., 1984; Sengooba, 1986; Sebasigari and Stover, 1988; ISAR/CIRAD/UNR, 1989; Sikora et al., 1989; Musabyamana, 1993; Bosch et al., 1995).

In Uganda, highland cooking bananas still predominate although introduced brewing (Kayinja, Kisubi) and dessert bananas (Ndizi) now constitute about 20% of production (Table 2). Plantains (AAB) and highland bananas (AAA-EA) were more susceptible to banana weevil attack than bananas of other genome groups. Bogoya (AAA) demonstrated peripheral damage similar to highland cultivars but penetration into the central cylinder was limited. Introduced beer types (AB, ABB) were relatively resistant with little peripheral damage and limited penetration into the corm (Table 2).

Banana weevils were found throughout the major banana regions

Table 2. Banana weevil damage on different banana genome groups in diagnostic surveys of Ugandan banana-based cropping systems; January–November 1993

Genome group	Banana type	Distribution			Weevil damage	
		Sites	Farms	Proport. (%)	PCI	Inner (%)
AAA-EA	Matooke	24	120	76	7.3[b]	34[b]
AAA	Bogoya	24	75	2	6.2[b]	23[c]
AAB	Plantain	20	51	2	11.9[a]	48[a]
AB	Ndizi, Kisubi	24	110	12	2.4[c]	14[c]
ABB	Kayinja	22	80	8	3.6[c]	24[c]

Source: Gold et al. (1994a).

in southern Uganda (Gold et al., 1994a). In general, weevil damage to highland cultivars (AAA-EA) was most severe between 1000–1300 masl although considerable variability existed at each elevation level. Neither adult weevils nor related larval corm damage were observed at the two high elevation sites, Kabale and Kapchorwa, suggesting an elevation threshold of about 1700 masl.

The data suggest different levels of susceptibility to weevil attack among highland cultivars (Table 3). For example, the cultivars Nasaba and Kisansa displayed weevil damage scores two to three times as high as those for Mbwazirume and Nakitengu while degree of penetration into the central cylinder was highest for Nakitembe, Namwezi and Musakala. However, cropping systems and management practices were complex and cultivar profiles may be related to farm objectives and levels of management. For example, Mbwazirume was quite common on farms in regions with high levels of management and commercial objectives (e.g. Masaka, Mbarara). In contrast, Nasaba was often grown on small farms with limited inputs (e.g. Luwero). Therefore, screening trials will be necessary to confirm cultivar resistance/tolerance to banana weevils.

Table 3. Banana weevil and nematode damage scores on 11 common highland banana cultivars in Uganda

Cultivar	Banana weevil	
	PCI[1]	Inner[2] (%)
Nasaba	14.8	26
Kisansa	9.8	27
Namwezi	9.3	30
Nfuuku	9.3	24
Musakala	8.7	33
Nabusa	7.7	25
Nakitembe	7.2	29
Kibuzi	6.0	23
Nakabululu	5.6	21
Nakyetengu	5.2	18
Mbwazirume	4.9	20

[1] PCI: Percentage coefficient of infestation (0–20).

[2] Inner: Percent of damage in central cylinder.

Source: Gold et al. (1994a).

Integrated Control Strategies for Banana Weevil

Control Options

Research results suggest that no single control strategy will be likely to provide complete control for banana weevil. Therefore, a broad integrated pest management (IPM) approach might provide the best chance for success in controlling this pest. The components of such a programme would include habitat management, biological control, host plant resistance and (in some cases) chemical control (Table 4).

Table 4. Possible components of banana weevil *(Cosmopolites sordidus)* integrated pest management programme

1. Habitat management
Planting material
Cropping systems
Agronomic practices
Post-harvest residues
Trapping

Considerations
  Efficacy of methods
  Costs/availability of planting material
  Farmer adoption

2. Biological control
Exotic insects
Endemic insects
Secondary host association
Biopesticides

Considerations
  Availability/efficacy of natural enemies
  Costs/delivery systems/persistence of biopesticides

3. Host plant resistance
Genome groups

Considerations
  Mechanisms of resistance
  Priority in breeding programme
  Farmer acceptance

4. Insecticides
Chemicals
Botanicals

Considerations
  Cost/availability
  Efficacy
  Resistance
  Non-target effects

Habitat Management

Habitat management offers a first line of defense against herbivores (Altieri and Letourneau, 1982) by creating an environment which reduces pest movement, promotes plant vigour and pest tolerance, and/or is unfavorable to pest buildup. For banana weevil, habitat management includes use of clean planting material, selection of cropping systems and improved agronomic practices to promote plant vigour, management of post-harvest residues and trapping.

Clean Planting Material

Infested planting material provides the principal entry point of banana weevils and nematodes into newly planted fields. Use of clean planting material reduces initial weevil numbers and, thereby, retards population buildup. Tissue culture plants offer one means of assuring pest-free planting material although production capacity, costs and means of dissemination are limiting factors. Alternatively, paring the corm removes most eggs and exposes damage of heavily infested plants which may then be rejected. Hot water treatment (20 minutes at 55° C) further reduces weevil numbers by killing larvae within the corm (Stover and Simmonds, 1987): In Uganda, hot water treatment of highland banana corms killed 32% of weevil larvae (C.S. Gold and A. Abera, unpubl. data).

In areas with high land pressure, as is common in the East African highlands, farmers often use planting material to gap fill existing (infested) fields or for new plots adjacent to declining stands. Such planting scenarios may offset the advantages provided by use of weevil-free planting material. Incorporation of a biological control agent such as *Beauveria bassiana* or endophytic fungi provide promising avenues for research. Careful deployment of *Bacillus thuringiensis* genes might also offer another possible method of control although implementation of such a strategy must consider the insect's ability to develop resistance in transgenic plants. IITA, in collaboration with the University of Bonn and Katholiecke University, Leuven is currently developing research programmes in these areas.

In contrast, farmers in Ghana continually plant new, isolated stands of plantain. Here, the use of locally available, low-cost methods for disinfecting planting material offers an excellent means of reducing initial weevil numbers and retarding population buildup. Preliminary studies in East and West Africa show that many farmers do not readily accept these methods because of labour bottlenecks, lack of confidence and/or increased vulnerability to feeding by goats. Often farmers do not fully understand the weevil's life cycle and also believe that removal of roots is detrimental to plant establishment and development. IITA, UNBRP, and the University of Ghana are currently studying reinfestation rates under different planting scenarios as well as using a participatory research approach to explore factors influencing farmer adoption of methods for cleaning planting material.

Cropping Systems and Agronomic Practices

Diversified agroecosystems, including intercrops, often support lower herbivore load than corresponding monocultures (Altieri and Letourneau, 1982; Risch et al., 1983). These reductions have been attributed to increased efficacy of natural enemies (Root, 1973; Sheehan, 1986) or differences in "resource concentration" among cropping systems (Tahvanainen and Root, 1972). Differences in host plant location, immigration and emigration rates (e.g. tenure time) (Bach, 1980; Risch, 1981; Risch et al., 1983), host plant quality (Gold et al., 1990), and micro-environments (Risch, 1981) may contribute to lower herbivore levels.

Applicability of intercropping systems for control of banana weevil may be limited. Cropping systems effects on weevil levels would most likely be through changes in host plant quality and/or microclimates (i.e. factors influencing soil moisture). To date, there is little evidence of effective natural enemies against banana weevils in African banana-based cropping systems whose action might be enhanced by crop diversification. At the same time, the insect's limited mobility suggests that intercropping will have minimal effect on banana weevil immigration and emigration rates or tenure time.

The influence of cropping systems (e.g. intercropping and mulching) on banana weevil has been investigated by Uronu (1992), Price (1993) and Rukazambuga et al. (1994). In Tanzania, a series of intercropping trials failed to produce viable crop mixtures which would lower weevil numbers without coincident drastic effects on yield: Sweetpotato/banana intercrops supported lowest weevil numbers and damage but also displayed poorest banana performance (fewer suckers, retarded growth, delayed maturation, reduced yield) (Uronu, 1992). Thus, reduced weevil load did not compensate for the detrimental effects of intercrop competition. Maize and bean intercrops had limited effect on banana weevil levels and host plant growth. It appears that sweetpotato influenced weevil numbers by effects on host plant condition; plots with poorly growing banana supported fewer weevils.

In Uganda, Rukazambuga et al. (1994) studied the effects of cropping systems on host plant growth, weevil number and related damage. Treatments included banana/millet intercrops (stressed), controls, manured bananas, manured + mulched bananas (vigorous). Weevils were released at a rate of 20 per plant and free to move between plots. Four months after release, weevil numbers were highest in mulched plots (19 weevils per plant in mulched plots, 12 per plant in manured plots, 10 per plant in controls and 9 per plant in banana/millet intercrops) reflecting either aggregation or reduced mortality in mulched systems. However, damage levels were similar in all treatments while banana growth and yields were greatest in mulched plots. The likely mechanism is that mulching and increased canopy cover resulted in better soil moisture retention which favoured weevil buildup.

It is widely believed that banana weevil problems are exacerbated by poor management or other stresses (Ackland, 1971; Stover and Simmonds, 1987; Greathead et al., 1989; Gold et al., 1993). This would imply that well managed stands (e.g. healthy planting material, adequate spacing, desuckering, weeding, mulching) influences weevil levels and/or plant tolerance of weevil attack. Nevertheless, few data are available to demonstrate relationships between crop management, weevil levels and plant tolerance to pest attack. Surveys in East Africa have demonstrated up to threefold differences in weevil damage among neighbouring farms (Sebasigari and Stover, 1988; Gold et al., 1994a); followup studies are currently being undertaken by IITA and UNBRP to determine which sets of factors may be responsible for differences in weevil levels. In Rukazambuga et al.'s (1994) study, however, overall damage to stressed (e.g. intercropped) and vigorously growing (e.g. mulched) plants was similar although penetration into the central cylinder was greater in more vigorous plants. Nevertheless, the advantages afforded by mulches on banana growth rates more than offset any increase in weevil damage.

Post-Harvest Residues

The Uganda agricultural extension service widely recommends field sanitation as a means of reducing banana weevil attack. Specifically, farmers are encouraged to remove post-harvest residues by digging out old corms and cutting up harvested pseudostems to remove alternate breeding sites for the weevil. Indeed, some cultivars are much more susceptible to post-harvest attack (Treverrow et al., 1991; Gold and Bagabe, 1994; Vittayaruk et al., 1994). However, such methods are labour intensive and not widely adopted by farmers in Uganda (Gold et al., 1993). Moreover, there is no evidence to demonstrate the influence of post-harvest residue management on banana weevil population dynamics and damage to growing plants: It is possible that residues draw weevils away from standing plants and, in their absence, would concentrate attack on maturing bananas. IITA has initiated studies on the role of post-harvest residues in weevil population dynamics (IITA, 1994).

Trapping

Trapping methods most commonly include use of post-harvest residues which attract adult weevils; most often, traps involving rhizome material are more attractive to weevils than those composed only of pseudostems. Trapping may be used as a means of monitoring weevil numbers (Delattre, 1980; Cardenas and Arango, 1987), establishing action thresholds (Mitchell, 1978; Ambrose, 1984), controlling weevils (Schmitt, 1993; Seshu Reddy et al., 1993, Bosch et al., 1995), and/or providing a delivery system for entomopathogenic fungi and nematodes (Castineiras et al., 1991; Bakyalire, 1992; Treverrow, 1994).

Use of weevil traps as a means of controlling banana weevils remains controversial (INIBAP, 1988b). In Tanzania, trapping has been adopted by some farmers and is believed to exert effective control of banana weevils (Seshu Reddy et al., 1993; Bosch et al., 1995) although quantitative data on farmer adoption and weevil dynamics are not yet available. In Uganda, however, trapping following release of marked weevils in on-station experiments suggested trapping efficiency can range from 5 to 35% dependent on weevil density, number of traps, and soil moisture conditions. However, under farmer conditions, only 20 to 25% of marked weevils could be recaptured through intensive trapping (2 pseudostems per mat, replaced every three days for one month). Additionally, such levels of trapping are not feasible for most farmers who do not have the available labour or trapping material.

Biological Control

Classical biological control of banana weevil in Africa may be possible. Introduced pests, unimportant in native habitats, often reach damaging levels when released for the control of co-evolved natural enemies. The banana weevil appears to fit this pattern although there is some belief that the weevil might reach pest status in parts of Asia (see Table 1) (Waterhouse, 1993). Nevertheless, exploration for banana weevil natural enemies in Asia followed by selection, quarantine and release of suitable species could establish an herbivore equilibrium below economic thresholds. Successful biological control, once established, is permanent and inexpensive. At the same time, augmentation of existing (endemic) natural enemies may also contribute to control of herbivore pests. Both require little or no input on the part of farmers; occasionally, farming practices might be manipulated to enhance the efficacy of exotic and/or endemic natural enemies.

In contrast, fungal antagonists or entomopathogenic nematodes may be applied as biopesticides with concomitant production and delivery costs. Questions of field persistence and frequency of application would need to be considered.

Possibilities and considerations for classical biological control of banana weevil have been reviewed by Greathead (1986), Waterhouse and Norris (1987), Neuenschwander (1988), Greathead et al. (1989), Kermarrec et al. (1993) and Koppenhofer (1993b,c) while Schmitt (1993) provides a partial list of arthropod natural enemies. Koppenhofer et al. (1992) and Koppenhofer (1993b) studied endemic natural enemies of the weevil in Kenya while colonies of endemic species of ants have been manipulated for control of banana weevil in Cuba (Roche, 1975; Roche and Abreu, 1982; Castineiras et al., 1991). Based on the weevil's biology, Greathead et al. (1989) give a 30% chance for a complete success in biological control.

By means of its secluded life cycle, the banana weevil is protected against many potential natural enemies. Banana weevil adults, although free living, are protected by a thick, heavily sclerotised cuticle and (to date) is not known to support parasitoids. The existence of such parasitoids can only be determined from extensive surveys. Nevertheless, within the Curculionidae, parasitism of adults is uncommon (Clausen, 1978). The only reported predator on the adult stage is the toad, *Bufo marinus* (Dawl, 1985).

The egg, larval and pupal stages all occur within the host plant or post-harvest residues; those in residual plant material following harvest are more vulnerable to predation as the plant tissues break down. The weevil eggs are placed superficially within the host but are at low density and occasionally below the soil surface. The damaging larval stage lives in galleries within the banana corm which makes them largely inaccessible to parasitoids and opportunistic predators. In Uganda, the only insects found in larval galleries within living plants were ants (pers. observ.). This suggests that the most likely natural enemies would either be specialised parasitoids or generalist (opportunistic) predators feeding on eggs or in post-harvest residues. As with adults, no parasitoids have been yet identified from banana weevil eggs or larvae.

Exotic Natural Enemies

Cursory searches for natural enemies over restricted geographical ranges (primarily Indonesia) in the weevil's centre of origin have identified a number of generalist predators which are most effective in decomposing banana tissues (Clausen, 1978; Waterhouse and Norris, 1987; Neuenschwander, 1988; Koppenhofer et al., 1992). These have provided the basis for a number of biological control attempts. Thirty-nine releases of limited material resulted in 12 cases of establishment (none in Africa) with limited impact on weevil levels (Table 5) (Waterhouse and Norris, 1987). Greathead et al. (1989) suggests that partial control may have been achieved in Fiji and Jamaica but that none of the predators were given adequate trial in Africa.

It is possible that additional foreign exploration, concentrating on hitherto unexplored habitats on the southeast Asian mainland will turn up more suitable natural enemies. For example, inventories of difficult, yet potentially more effective egg parasitoids has only been attempted once, without success (Froggatt, 1923).

Neuenschwander (1988) suggests that the egg stage may be the stage most vulnerable to natural enemies. Of particular interest would be the possible existence of egg parasitoids. Success in establishment and efficacy of egg parasites (if they exist) would be affected by population density, oviposition sites and exposure of eggs. In an experiment using highland bananas planted in drums, Koppenhofer et al. (1992) concluded that only 58% of the eggs were accessible to predators. Under Ugandan field conditions, however, we found most eggs in leaf sheaths at the base of the pseudostem

Table 5. Introductions of natural enemies for biological control of *Cosmopolites sordidus* (1913–1959)

Insect	Attempts	Establ.	Location established
Plaesius javanus	23	8	Fiji Islands
P. laevigatus	1	1	Cook Island
Dactylosternum abdominale	1	0	
D. hydrophiloides	4	2	Australia, Jamaica
Hololepta quadridentata	6	1	Saint Vincent
Hololepta sp.	3	0	
Chrysophilus ferruginous	1	0	
Total	39	12	

Source: Waterhouse and Norris (1987).

where they would be vulnerable to both predators and parasitoids (Gold and Abera, unpubl. data). It is also likely that conditions of high mat would lead to a greater percentage of eggs placed at or near the soil surface and, therefore, more vulnerable to potential egg parasites.

Endemic Natural Enemies

Koppenhofer et al. (1992) and Koppenhofer (1993b,c) identified 10 endemic natural enemies of banana weevil in Kenya (Table 6). In potted experiments, these predators were able to bring about reductions of up to 44%; most of this was attributed to egg predation. However, low predator density in the field, difficulties encountered in rearing and preference for decaying host material suggest that these natural enemies have limited potential in controlling banana weevils or preventing damage (Koppenhofer, 1993c; Koppenhofer and Schmutterer, 1993).

Table 6. Endemic predators of banana weevil in Kenya

	Habitat	Stage attacked	Control potential
Thyreocephalus interocularis	P S	L P	No
Hesperus sparisor	R P S	E L	?
Hister sp.	R P S	E	?
Hololepta striaditera	P S	E L P	?
Dactylosternum abdominale	R P S	E L	Limited
Abacetus sp.	R P S	E L	?
Eutochia sp.	R P S	E	Limited
Labia sp.	R P S	E	?
Labia borelli	P S	E L	No
Euborellia annulipes	R P S	E L	Limited

R: Rhizome
P: Pseudostem
S: Stem

E: Egg
L: Larvae
P: Pupae

Source: Koppenhofer et al. (1992), Koppenhofer (1993b,c).

In Cuba, colonies of ants *(Tetramorium guinensee and Pheidole megacephala)* have been manipulated through movement of queens into new banana plantations for the control of banana weevil (Roche, 1975; Roche and Abreu, 1982; Castineiras et al., 1991). These have been reported to have brought about substantial control (75–85%) within two years of release.

Varela (1993) encountered 40 species of ants, including *P. megacephala*, during a survey of Tanzanian banana plantations. Her data on efficacy of ants as predators of banana weevil are preliminary and inconclusive but suggest that this area warrants further study. However, one ant, *Ondontomachus troglodytes*, is believed by many farmers to be a pest and has been identified by farmers as a key production constraint in Uganda (Gold et al., 1993). This species is believed to enlarge existing weevil galleries and to remove soil from the base of the plant, thereby exposing the roots. Nevertheless, this species is predacious and likely attacks banana weevil while causing little direct damage.

Secondary Host Association

With the possible exception of ants, known predators of banana weevil have demonstrated limited potential for controlling this pest. At the same time, parasitoids of the insect are unknown. In this context, Neuenschwander (1988) has suggested that natural enemies of closely related hosts may offer promise for efficient secondary associations. The first step of such a programme would be to demonstrate host acceptance and successful development in the laboratory. If this occurred, the parasitoid would have to be tested against other potential hosts prior to release. Finally, a successful parasitoid would have to be capable of locating a new host under field conditions.

In this context, IITA imported *Anaphes victus,* parasites of carrot weevil eggs (*Listronotus oregonensis* and *L. texanus*), into Benin from Canada and Texas for evaluation of its potential for using banana weevil as a secondary host. Under laboratory conditions, banana weevil eggs were accepted for oviposition; the *A. victus* successfully completed development but was unable to emerge, presumably due to the small portion of the egg contents which had been consumed. However, the parasite was successfully reared on eggs of a factitious host, the water hyacinth weevil *(Neochetina eichhorniae).*

Entomogenous Fungi

The use of entomopathogens provides a promising, yet untested, means of control against banana weevil in Africa. Entomogenous fungi, *Beauveria bassiana* and *Metarhizium anisopliae,* have gained considerable attention as a potential control for weevils (Boethel and Eikenbarry, 1979; Gotwald and Tedders, 1984). *Beauveria bassiana* and *M. anisopliae* have different ecological requirements which determine the environmental conditions under which they are most effective (J. E. Pena, pers. commun.). An understanding of the environmental requirements of different pathogen strains can help determine the types of programmes in which they can be most suitably employed.

Recent work in East Africa by Kaaya et al. (1993) and Nankinga (1994) have demonstrated high mortality rates of banana weevil when exposed to strains of *B. bassiana* and *M. anisopliae* in the laboratory. Kaaya et al. (1993) found both species killed nearly 100% of third instar larvae although only *B. bassiana* was effective against adults with LT_{50} ranging from 8–25 days; *M. anisopliae* failed to kill 50% of adults. Chains of *B. bassiana* and *M. anisopliae* hyphae invaded the insect's haemocoel and muscle tissues and destroyed tracheal taenidia and fat bodies. When the dead weevils were kept in a moist environment, they quickly developed surface growths of mycelia and conida suggesting mycosis can spread to other insects.

Higher adult mortality was observed when pathogens were applied topically than when applied to a substrate; moreover, mortality rates were influenced by both fungal species and strain (Table 7a) and by spore dosage (Nankinga, 1994). At low spore doses, mortality rates of females was 1.5 to 4 times that for males while at high doses females and males were killed in even numbers (Table 7b,c).

While many strains of *B. bassiana* and *M. anisopliae* have been demonstrated to kill high percentages of banana weevils in the laboratory, few researchers have tested these pathogens under field conditions. The use of fungal pathogens as biopesticides may have limited applicability under African conditions where production and distribution costs may be prohibitive. Therefore, studies on

Table 7. Influence of fungal pathogen species and strain on banana weevil adult mortality

A. Speed of action

	Pathogen strain		
	KB/91/3	KB/91/4	KM/92/8
Source	*C. sordidus*	*C. puncticolis*	Soil
Mortality 3 days	25%	3%	0
Mortality 21 days	99%	96%	40%

B. Influence of dose on female mortality

Spores/ml	KB/91/3	KB/91/4	KB/91/5
$3.35 * 10^7$	96%	96%	99%
$3.35 * 10^6$	83%	79%	90%
$3.35 * 10^5$	40%	46%	37%
$3.35 * 10^4$	17%	9%	28%

C. Influence of dose on male mortality

Spores/ml	KB/91/3	KB/91/4	KB/91/5
$3.35 * 10^7$	91%	94%	94%
$3.35 * 10^6$	39%	51%	49%
$3.35 * 10^5$	20%	29%	9%
$3.35 * 10^4$	11%	7%	9%

Source: Nankinga (1994).

delivery systems, field persistence and dissemination from one weevil to another represent critical areas of study.

In a preliminary study, Nankinga (1994) applied spore suspensions of two isolates of *B. beauveria* at a concentration of 1.12×10^7 spores/ml directly to weevils or to substrates that were then exposed to weevils. Direct application to weevils (5 minute immersion or spray) resulted in mortality ranging from 56 to 69%. In contrast, only 6 to 19% of weevils died following exposure to substrates (pseudostem traps and/or soil) receiving applications of *B. bassiana* spores. Unless the pathogen is spread from one weevil into the population, the use of traps as a delivery system provides little advantage over simply trapping the insects, a strategy of questionable value.

Trap efficiency or other delivery systems could be enhanced by use of semiochemicals to attract banana weevils to sources of inoculum. A clear limitation is that adult weevils are soil-borne insects where wind speeds are negligible, thus reducing the potential attractant range of semiochemicals. Both kairomones and male aggregation pheromones are known to exist (Budenberg and Ndiege, 1993; Budenberg et al., 1993 a,b) but these have only been demonstrated to be effective over a few centimetres. Nevertheless, Treverrow (1994) has demonstrated aggregation of adults at sites of cuts in harvested rhizomes suggesting that longer range stimuli are available.

Entomopathogenic Nematodes

Entomopathogenic nematodes (*Steinernema* spp. and *Heterorhabditis* spp.) have been tested against banana weevils in Australia and the Pacific (Parnitski et al., 1990; Treverrow et al., 1991; Treverrow, 1993, 1994), Puerto Rico (Figueroa, 1990), Florida (Pena et al., 1993), and Brazil (Schmitt, 1993).

Parnitski et al. (1990) found that banana weevils were resistant to many strains of entomopathogenic nematodes. Additionally, those strains which performed well in Tonga were not necessarily those which were effective in Australia, suggesting the presence of weevil biotypes. As a result, indigenous nematodes may be most effective against banana weevil due to coevolution with local biotypes and preadaption to local environmental conditions (Schmitt, 1993). Schmitt (1993) was able to obtain four strains of *S. carpocapsae* from Brazilian soils which provided adequate kills of banana weevils in laboratory tests.

In addition to Schmitt's work, Figueroa (1990) and Pena et al. (1993) were also able to effect high mortality rates of banana weevils in petri dish and greenhouse trials; however, Pena et al. (1993) were unable to reduce weevil levels following soil applications to experimental plots.

In Australia, field testing of entomopathogenic nematodes has produced positive results (Treverrow et al., 1991; Treverrow, 1994). Applications to rhizomes were found preferable to ground sprays which requires production of high levels of nematodes and did not appear to work. Baits were applied in cuts made in residual rhizomes only thereby preventing mechanical damage to growing plants. These included bored holes, transverse slices or cutting out and replacing a cone-shaped piece with use of a desuckering gauge. Such cuts proved very attractive to adult weevils; both the transverse slices and the cone-shaped holes provided thigmotactic stimuli which increased weevil tenure time at baited sites (Treverrow et al., 1991; Treverrow, 1994). Attack of larvae also occurred where cuts intersected with larval galleries. However, the number of available harvested plants at any one time limits the number of applications using this method; moreover, protection is oriented towards reducing weevil levels in a field rather than directly protecting growing plants, *per se,* against attack.

Nematodes were released at monthly intervals from October to May in polyacrylamide gels to prevent drowning in water which collected in rhizome cuts. The nematodes persisted for 50 days although how long they remained infective is not clear. At the same time, mineral oil was added to baits to cause the weevils to lift their elytra, thus exposing the spiracles (Treverrow, 1994).

Nematode baits performed consistently as well or better than insecticides; however, given low costs of insecticide treatments, baits may not be competitive except where requirement for no insecticide use (Treverrow, 1994).

Use of entomopathogenic nematodes has not been studied in Africa. Limitations for these agents are similar to those for *B. bassiana* and *M. anisopliae*: production and distribution technology and costs, availability of delivery systems and required frequency of application may determine how appropriate these agents are in the African context.

Host-Plant Resistance

Host plant resistance potentially offers a safe and long-term intervention strategy for banana weevil control for resource-limited farmers in Africa (Ortiz et al., 1995). However, breeding bananas is a tedious and slow process influenced by low seed set and the long duration of the crop. Nevertheless, breeding successful resistance in plantains against black sigatoka has been achieved in West Africa (Vuylsteke et al., 1993). As of yet, host plant resistance to banana weevil has not been a high priority for banana and plantain breeding programmes.

Preliminary information on cultivar or genome group susceptibility to banana weevil has been provided by Sen and Prasad (1953), Ittyeipe (1976), Haddad et al. (1979), Mesquita et al. (1984), Pavis (1993), Pavis and Minost (1993), Seshu Reddy and Lubega (1993), Gold et al. (1994), Ortiz et al. (1995). Of banana's two wild progenitors, *Musa acuminata* is considered susceptible to banana weevil while *M. balbisiana* is not (Mesquita et al., 1984). However, plantains (AAB) are generally considered the most susceptible group while highland bananas are also considered highly susceptible (Gold et al., 1994). At the same time, Cavendish and Gros Michel are moderately susceptible and AA diploids, Kayinja (ABB), Sukali Ndizi (AB) and Kisubi (AB) are considered resistant (Gold et al., 1994). Of note, however, is that results are not fully consistent across studies. Additionally, weevil pest status may be influenced by timing and site of attack as well as extent of tunnelling.

In Uganda, highland bananas showed a threefold difference among cultivars in levels of weevil attack; at the same time, penetration into the central cylinder also varied among cultivars (Table 3) (Gold et al., 1994). Factors influencing levels of attack are not yet clear although degree of penetration into the central cylinder was also affected by site (e.g. environment), weevil level and host plant condition.

Levels of weevil attack may be influenced by host-plant attractivity (oviposition rates), larval success and larval developmental rates. High quality hosts may promote quicker development (shorter generation time) and result in more fit (e.g. fecund) females. Mesquita et al. (1984) and Seshu Reddy and Lubega (1993) found larval development to vary among cultivars but differences could not be generalised to genome groups. Pavis (1993) and Pavis and Minost (1993) found a negative correlation between rhizome hardness and infestation levels. However, Ortiz et al. (1995) found no relationship between hardness and weevil attack in segregating full- and half-sib euploid hybrids.

Chemical Control

Insecticides have been widely tested and recommended for control of banana weevil (Batchelder, 1954; Bullock and Evers, 1962; Anon, 1974; Vilardebo et al., 1974; Foreman and Rawle, 1977; Ittyeipe and Smith, 1979; Nogueira et al., 1983; Robalino et al., 1983; Sengooba, 1986). Chemical control has the advantage of being fast acting and providing the farmer with an active tool against the pest. In contrast, cultural controls which require removal of harvested corms is labour intensive and damaging to followers on the same mat. In commercial farms in Latin America and Australia, insecticides are affordable and may be competitive with other means of control (e.g. entomopathogenic nematodes) (Treverrow, 1994).

In Africa, however, pesticides may be beyond the means of most resource-poor, small farmers. Nevertheless, many farmers in Uganda indicated a desire to use chemicals against banana weevil if prices could be made more affordable (Gold et al., 1993). In practice, only a few farmers in commercial growing zones (e.g. Masaka district) used chemical insecticides (e.g. carbofuran, carbosulfan, primicid, ethoprophos) in banana fields. However, many of the same farmers who claimed that they had no access to or could not afford pesticides in banana, routinely applied chemicals to horticultural and other annual cash crops, suggesting that insecticide use was more a question of economics than access and information. Still, national programmes in East Africa remain highly interested in using chemicals as a means of controlling banana weevil in spite of economic limitations and the potential of the weevil to develop resistance (INIBAP, 1992).

Insecticide resistance in banana weevil has been documented in Australia (Kelly, 1966; Swain and Corcoran, 1973; Wright, 1974; Shanahan and Goodyear, 1974; Edge, 1974; Edge et al., 1975; Collins et al., 1991) and Latin America (Foreman, 1976; Mitchell, 1978; Mello et al., 1979; Sampaio et al., 1982) for a range of chemicals including cyclodienes (BHC), organochlorines (dieldrin), organophosphates (prothiophos, chlorpyrifos, pirimiphos-ethyl and ethoprophos) and carbamates (carbofuran). Cross resistance has also been demonstrated (Collins et al., 1991).

Banana weevil outbreaks in key banana production zones in Uganda (e.g. Rakai and Masaka districts) and in the mid 1980s were attributed to resurgence following use of dieldrin (Sengooba, 1986). More recently, we have found resistance of banana weevils to dieldrin and furadan in Masaka district, Uganda (Gold and Bagabe, unpubl. data).

In addition to the potential problems common in pesticide use (resistance, resurgence, non-target effects), the opportunity for misuse is always common in tropical environments where information dissemination is limited. In Uganda, for example, farmers often applied dieldrin at lower than recommended doses or at wrong delivery sites (e.g. on pseudostems) while other farmers used the chemical as a fertiliser without cognisance of its insecticidal properties (Sengooba, 1986).

Conclusions

Pest status of the banana weevil remains controversial in Africa. A clearer understanding of economic thresholds as well as factors influencing distribution and severity will be necessary to focus control attempts in areas where weevils are, in fact, limiting factors. In Uganda, for example, extension workers often recommend labour intensive cultural controls to farmers where weevils do not appear to be a problem. In these cases, farmers' limited resources might be better directed towards other constraints.

At present, no intervention strategy appears to offer a complete solution to controlling banana weevils. Therefore, a broad integrated pest management strategy, combining habitat management, biological control, host plant resistance and (in restricted cases) chemical control appears to be the best approach.

Habitat management, including use of clean planting material, destruction of post-harvest residues and use of agronomic practices promoting plant vigour, may play a major role in retarding weevil invasion buildup and damage in farmers' fields. The effects of these interventions on weevil population dynamics and damage thresholds need elucidation. Additionally, socioeconomic studies will be necessary for developing an understanding of farmer adoption of cultural controls.

Biological control agents, including exotic natural enemies from the weevil's source of origin, endemic natural enemies within Africa, secondary host associations, entomogenous fungi and entomopathogenic nematodes, may contribute to weevil control. Whereas the weevil is an exotic pest in Africa and of questionable pest status in its area of origin, further exploration for natural enemies in Asia is warranted. A partial success, in concert with other interventions, may bring the weevil below damaging levels. To date, effective endemic natural enemies within Africa are not available although the Cuban experience using ants suggests that work in this area is merited.

The use of fungal pathogens and/or entomopathogenic nematodes are a high priority for research. Development of adequate delivery systems, including semiochemical attractants, will be critical to application of these agents. Production and distribution costs will also be a concern. At the same time, incorporation of pathogens into clean planting material may provide one of the better avenues of control.

Host-plant resistance would require an extensive breeding programme and represents a long-term strategy. Nevertheless, resistance, in concert with habitat management, may offer a first line of defense against banana weevils. Mechanisms of resistance need to be elucidated. Moreover, concerns include the length of time required for a banana breeding programme and adoption of hybrids in systems (e.g. Uganda) already supporting as many as 17 cultivars in one acre stands.

Chemical controls provide farmers with an immediate response to weevil attack. However, costs largely limit this strategy to commercial farmers. In addition to non-target effects, the weevil is capable of developing resistance to a wide array of compounds.

Finally, upstream research including determination of possible semiochemicals for use in biopesticide delivery systems, treatment of clean planting material with antagonistic endophytic fungi and the possible use of *Bacillus thuringiensis* genes should be pursued.

References

Ackland J. D. (1971) *East African Crops.* FAO. Longman, Singapore. 252 pp.

Altieri M. A. and Letourneau D. K. (1982) Vegetation management and biological control in agroecosystems. *Crop Protection* 1, 405–430.

Ambrose E. (1984) Research and development in banana crop protection (excluding sigatoka) in the English speaking Caribbean. *Fruits* 39, 234–247.

Anonymous (1974) New insecticides effective against banana weevil borer. *Banana Bulletin* 38, 4–5.

Arleu R. J. and Neto S. S. (1984) Broca da bananeira *Cosmopolites sordidus* (Germ., 1824) (Coleoptera: Curculionidae). *Turrialba* 34, 359–367.

Bach C.E. (1980) Effects of plant density and diversity on the population dynamics of a specialist herbivore, the cucumber beetle, *Acalymma vittata* (Fab.). *Ecology* 61, 1515–1530.

Bakyalire R. (1992) Aspects of the biology, behaviour and ecology of the banana weevil *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae) in Uganda. Unpublished MSc thesis. Makerere University. 118 pp.

Bakyalire R. and Ogenga-Latigo M. (1992) Aspects of life cycle and behavior of the banana weevil *C. sordidus*. In *Recent Contributions to Banana Entomology Research in*

Uganda (1990–1992) (Edited by M. Ogenga-Latigo). Makerere University, Kampala, Uganda.

Batchelder C. H. (1954) Experimentos con insecticidas para combatir el picudo negro (*Cosmopolites sordidus* Germ.) en las plantaciones de abaca. *Turrialba* 4, 88–93.

Beccari F. (1967) Contributo alla conoseenza del *Cosmopolites sordidus* Ger. (Coleoptera: Curculionidae), Parte I–II. *Riv. Agr. Subtrop. Trop.* 61, 51–93 and 131–150.

Boethel D. and Eikenberry R.D. (1979) *Pest Management Program. Deciduous Trees and Nuts.* Plenum Press, New York. 156 pp.

Bosch C., Lorkeers A., Ndile M.R. and Sentozi E. (1995) Diagnostic survey: Constraints to banana productivity in Bukoba and Kaleba Districts, Kagera Region, Tanzania. Tanzania/Netherlands Farming Systems Research Project, Lake Zone. Working Paper No. 8. ARI Maruku, Bukoba, Tanzania.

Budenberg W. J. and Ndiege I. O. (1993) Volatile semiochemicals of the banana weevil, pp. 75–86. In *Biological and Integrated Control of Highland Banana and Plantain Pests and Diseases. Proceedings of a Research Coordination Meeting* (Edited by C. S. Gold and B. Gemmill). IITA, Ibadan.

Budenberg W. J., Ndiege I. O. and Karago F. W. (1993a) Evidence for volatile male-produced pheromone in banana weevil *Cosmopolites sordidus*. *J. Chem. Ecol.* 19, 1905–1915.

Budenberg W. J., Ndiege I. O., Karago F. W. and Hansson B. S. (1993b) Behavioral and electro-physiological responses on the banana weevil *Cosmopolites sordidus* to host plant volatiles. *J. Chem. Ecol.* 19, 267–277.

Bullock R. and Evers C. (1962) Control of the banana root borer (*Cosmopolites sordidus* Germar) with granular insecticides. *Trop. Agric.* 39, 109–113.

Cardenas R. and Arango L. G. (1987) Control del picudo negro *Cosmopolites sordidus* (Germar 1824) del platano *Musa* AAB (Simmonds) mediante practicas culturales. *Cenicafe* 38, 50–61.

Castineiras A., Cabrera T., Calderon A., Lopez M. and Lujan M. (1991) Lucha biologica contra *Cosmopolites sordidus* (Germar), pp. 423–428. In *Recontres Caraibes en Lutte Biologique* (Edited by C. Pavis and A. Kermarrec). INRA, Paris.

Castrillon C. (1989) Plagas del cultivo del platano. In *Curso de Actualizacion sobre Problemas Sanitarios en Platano* (Edited by ICA). La Dorada, Colombia. 54 pp.

Cendana S. M. (1922) The banana weevil. *Philippines Agric.* 10, 367–376.

Clausen C. P. (1978) *Introduced Parasites and Predators of Arthropod Pests: A World Review.* USDA Agricultural Handbook 480. 545 pp.

Collins P. J., Treverrow N. L. and Lambkin T. M. (1991) Organophosphorous insecticide resistance and its management in the banana weevil borer, *Cosmopolites sordidus* (Germar) (Coleoptera:Curculionidae), in Australia. *Crop Protection* 10, 215–221.

Cuille J. (1950) Recherches sur le charancon du bananier. *Inst. Fr. Agric. Col. Ser. Tech.* 225 pp.

Dawl N. M. (1985) Insect pest management in banana, pp. 100–105. In *Banana and Plantain Research and Development* (Edited by B. E. Umali and C. M. Lancitan). ACIAR and PCARRD, Los Baños.

Delattre P. (1980) Recherche d'une methode d'estimation des populations du charancon du bananier, *Cosmopolites sordidus* Germar (Col. Curculionidae). *Acta Oecologica: Oecol. Applic.* 1, 83–92.

Edge V. E. (1974) Cyclodiene–BHC resistance in *Cosmopolites sordidus* (Germ.) (Coleoptera: Curculionidae) in New South Wales, Australia. *Bull. Entomol. Res.* 64, 1–7.

Edge V. E., Wright W. E. and Goodyear G. J. (1975) The development and distribution of dieldrin resistance in banana weevil borer, *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae) in New South Wales. *J. Aust. Ent. Soc.* 14, 165–169.

Figueroa W. (1990) Biocontrol of the banana root borer weevil, *Cosmopolites sordidus* (Germar), with steinernematid nematodes. *J. Agric. Univ. Puerto Rico* 74, 15–19.

Foreman P. (1976) Investigation into the resistance of the banana weevil borer (*Cosmopolites sordidus* Ger.) to dieldrin (1971–1972), pp. 26–27. In *Annual Report 1973,* Jamaica Banana Board, Research and Development Department.

Foreman P. and Rawle A. (1977) Effectiveness of seven insecticidal compounds against the banana weevil borer (*Cosmopolites sordidus* Germar) 1971–1972, pp. 79–80. In *Annual Report 1973,* Jamaica Banana Board, Research and Development Department.

Froggatt J. L. (1923) The banana weevil borer IV. *Queens. Agric. J.* 21, 369–378.

Froggatt J. L. (1925) The banana weevil borer (*Cosmopolites sordidus*). *Queens. Agric. J.* 24, 558–593.

Geddes A. M. W. and Iles M. (1991) *The Relative Importance of Crop Pests in South Asia.* Natural Resources Institute Bulletin No. 39. 102 pp.

Gold C. S., Altieri M. A. and Bellotti A. C. (1990) Direct and residual effects of short duration intercrops on the cassava whiteflies *Aleurotrachelus socialis* and *Trialeurodes variabilis* in Colombia. *Agric., Ecosyst. Environ.* 32, 57–67.

Gold C. S., Ogenga-Latigo M. W., Tushemereirwe W., Kashaija I. and Nankinga C. (1993) Farmer perceptions of banana pest constraints in Uganda: Results from a rapid rural appraisal, pp. 3–24. In *Biological and Integrated Control of Highland Banana and Plantain Pests and Diseases. Proceedings of a Research Coordination Meeting* (Edited by C. S. Gold and B. Gemmill). IITA, Ibadan.

Gold C. S. and Bagabe M. I. (1994) Banana weevil (*Cosmopolites sordidus*) infestation of cooking and beer bananas in adjacent stands in Uganda. In *African Crop Science Conference* (In press).

Gold C. S., Speijer P. R., Karamura E. B. and Rukazambuga N. D. (1994a) Assessment of banana weevils in East African highland banana systems and strategies for control, pp. 170–190. In *Proceedings of Banana Nematode/Borer Weevil Conference.* Kuala Lumpur, 18–22 April 1994 (Edited by R. V. Valmayor, R. G. Davide, J. M. Stanton, N. L. Treverrow and V. N. Roa). INIBAP, Los Baños.

Gold C. S., Speijer P. R., Karamura E. B., Tushemereirwe W. K. and Kashaija I. N. (1994b) Survey methodologies for pest and disease assessment in Uganda. *African Crop Science Journal* (In press).

Gotwald T. R. and Tedders W. T. (1984) Colonization, transmission and longevity of *Beauveria bassiana* and *Metarhizium anisopliae* (Deuteromycotina: Hypomycetes) on pecan weevil larvae (Coleoptera: Curculionidae) in the soil. *Environmental Entomology* 13, 557–560.

Greathead D. J. (1986) Opportunities for biological control of insect pests in tropical Africa. *Rev. Zool. Afr.* 100, 85–96.

Greathead D. J., Cock M. J. W. and Girling D. J. (1989) Draft report on a consultancy for IITA to assess the potential for biological control of pests of the African food crops: maize, sorghum, rice, plantain, cowpea, sweet potato and cassava. Mss 74 pp. IITA, Cotonou.

Haddad O., Surga J. R. and Wagner M. (1979) Relacion de la composicion genomica de las Musaceas con el grado de attracion de adultos y larvas de *Cosmopolites sordidus* G. (Coleoptera: Curculionidae). *Agron. Trop.* 29, 427–428.

IITA (1994) Plant Health Management Division Annual Report for 1993.

INIBAP (1986) *A preliminary study of the needs for banana research in Eastern Africa* INIBAP doc. EA-001e. Montpellier. 98 pp + appendices.

INIBAP (1988a) *Plantain in Western Africa: Proposal for a Regional Research and Development Network.* INIBAP, Montpellier. 68 pp + appendices.

INIBAP (1988b) *Nematodes and the Borer Weevil in Bananas: Proceedings of a workshop held in Bujumbura, Burundi, 7–11 December 1987,* Montpellier.

INIBAP (1992) *Regional Network for Eastern Africa: Proceedings of the Regional Advisory Committee Meeting, Kampala, Uganda, 23–25 September 1991.* 34 pp.

ISAR/CIRAD/UNR (1989) Enquete diagnostic sur la culture bananière en Prefecture Kibungo, Rwanda. 3 Volumes. CIRAD/IRFA.

Ittyeipe K. (1976) Studies on the host preference of banana weevil borer *Cosmopolites sordidus* Germ. (Coleoptera -Curculionidae). *Fruits* 41, 375–379.

Ittyeipe K. and Smith H. (1979) Control of banana borers and nematodes with insecticidal/nematicidal compounds, pp. 317–338. In *Memorias de la IV reunion.* Seccion tecnica IV-A-Entomologia. ACORBAT.

Kaaya G. P., Seshu Reddy K. V., Kokwaro E. D. and Munyinyi D. M. (1993) Pathogenicity of *Beauveria bassiana, Metarhizium anisopliae* and *Serratia marcescens* to the banana weevil *Cosmopolites sordidus. Biocontrol Science and Technology* 3, 177–187.

Kelly D.S. (1966) Control of dieldrin resistant banana weevil borer. Queensland Dept. of Mining Industries. Unpubl. Mss. 7 pp.

Kermarrec A., Sirjusingh C., Mauleon H., Pavis C. and Sarah J. L. (1993) Biological control of weevils and whitegrubs in the Caribbean: A review, pp. 155–170. In *Biological and Integrated Control of Highland Banana and Plantain Pests and Diseases. Proceedings of a Research Coordination Meeting* (Edited by C. S. Gold and B. Gemmill). IITA, Ibadan.

Koppenhofer A. M. (1993a) Observations on egg-laying behaviour of the banana weevil, *Cosmopolites sordidus* (Germar). *Entomol. Exp. Appl.* 68, 187–192.

Koppenhofer A. M. (1993b) Search and evaluation of natural enemies of the banana weevil, pp. 87–96. In *Biological and Integrated Control of Highland Banana and Plantain Pests and Diseases. Proceedings of a Research Coordination Meeting.* (Edited by C. S. Gold and B. Gemmill). IITA, Ibadan.

Koppenhofer A. M. (1993c) Egg predators of the banana weevil, *Cosmopolites sordidus* (Germar) (Col.: Curculionidae) in Western Kenya. *J. Appl. Entomol.* 116, 352–357.

Koppenhofer A. M. and Schmutterer H. (1993) *Dactylosternum abdominale* (F.) (Coleoptera: Hydrophilidae): A predator of the banana weevil. *Biocontr. Sci. Technol.* 3, 141–147.

Koppenhofer A. M., Seshu Reddy K. V., Madel G. and Lubega M. C. (1992) Predators of the banana weevil, *Cosmopolites sordidus* (Germar) (Col.: Curculionidae) in Western Kenya. *J. Appl. Entomol.* 114, 530–533.

Kusomo S. and Sunaryono H. (1985) Status of banana production in Indonesia, pp. 35–38. In *Banana and Plantain Research and Development* (Edited by B. E. Umali and C. M. Lancitan). ACIAR and PCARRD, Los Baños.

Mello E. J., Mello R. R. H. and Sampaio A. S. (1979) Resistencia ao aldrin em rocas de bananeira *Cosmopolites sordidus* Germ. do litoral paulista. *Biologico* 45, 249–254.

Mesquita A. L. M. and Alves E. J. (1983) Aspectos da biologia da broca-do-rizoma em diferentes cultivares de bananeira (*Cosmopolites sordidus*, *Musa acuminata*). *Pesquisa Agropecuaria Brasileira* 18, 1289–1292.

Mesquita A. L. M., Alves E. J. and Caldas R. C. (1984) Resistance of banana cultivars to *Cosmopolites sordidus* (Germar 1824). *Fruits* 39, 254–257.

Mitchell G. (1978) The estimation of banana borer population and resistance levels. *Tech. Bull. 2* 34 pp. WINBAN, St Lucia.

Musabyamana T. (1993) Methodologie de l'enquete diagnostic bananae au Rwanda, pp. 37–46. In *Biological and Integrated Control of Highland Banana and Plantain Pests and Diseases. Proceedings of a Research Coordination Meeting* (Edited by C. S. Gold and B. Gemmill). IITA, Ibadan.

Nankinga M.C. (1994) Potential of indigenous fungal pathogens for the biological control of the banana weevil, *Cosmopolites sordidus* (Germar), in Uganda. Unpublished MSc thesis. Makerere University. 95 pp.

Nanthachai P. (1985) Banana production and research programs in Thailand, pp. 45–51. In *Banana and Plantain Research and Development* (Edited by B. E. Umali and C. M. Lancitan). ACIAR and PCARRD, Los Baños.

Neuenschwander P. (1988) Prospects and proposals for biological control of *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) in Africa, pp. 54–57. In *Nematodes and the Borer Weevil in Bananas: Proceedings of a workshop* held in Bujumbura, Burundi, 7–11 December 1987 (Edited by INIBAP). INIBAP, Montpellier.

Nogueira S. B., de Lima J. O. G. and Manica I. (1983) Effeito de alguns insecticidas alcoois e ester aplicados em iscas contra as brocas de bananeira, *Cosmopolites sordidus*, *Metamasius ensirostris* e *Metamasius inequalis* (Coleoptera: Curculionidae). *Agronomia Sulriograndense* 19, 15–34.

Ortiz R., Vuylsteke D., Dumpe B. and Ferris R. S. B. (1995) Banana weevil resistance and corm hardness in *Musa* germplasm. *Euphytica* (in press).

Ostmark H. E. (1974) Economic insect pests of bananas. *Annu. Rev. Entomol.* 19, 161–176.

Parnitski P. F., Treverrow N., Bedding R. A. and Sikora R. A. (1990) Susceptibility of adults of the banana weevil borer *Cosmopolites sordidus* to 32 species and strains of *Heterorhabditis* and *Neoaplectana*. *Abstracts from the Second International Entomology Congress*: 121–122.

Pavis C. (1993) Etude des relations

plante–insecte chez le charancon du bananier *Cosmopolites sordidus*, pp. 171–181. In *Biological and Integrated Control of Highland Banana and Plantain Pests and Diseases. Proceedings of a Research Coordination Meeting* (Edited by C. S. Gold and B. Gemmill). IITA, Ibadan.

Pavis C. and Minost C. (1993) Banana resistance to the banana weevil borer *Cosmopolites sordidus*: Role of pseudostem attractivity and physical properties of the rhizome, pp. 129–142. In *Breeding Banana and Plantain for Resistance to Diseases and Pests* (Edited by J. Ganry). CIRAD, Montpellier.

Pena J. E., Duncan R. and Martin R. (1993) Biological control of *Cosmopolites sordidus* in Florida, pp. 124–139. In *Biological and Integrated Control of Highland Banana and Plantain Pests and Diseases. Proceedings of a Research Coordination Meeting* (Edited by C. S. Gold and B. Gemmil). IITA, Ibadan.

Persley G. J. and Langhe E. A. de (Eds) (1987) *Banana and Plantain Breeding Strategies. Proceedings of an International Workshop* held at Cairns, Australia 13–17 October 1986. ACIAR and INIBAP, Canberra 187 pp.

Pianka E. R. (1970) On r- and k-selection. *Amer. Nat.* 104, 592–597.

Price N. S. (1993) Preliminary weevil trapping studies in Cameroon, pp. 57–67. In *Biological and Integrated Control of Highland Banana and Plantain Pests and Diseases. Proceedings of a Research Coordination Meeting* (Edited by C. S. Gold and B. Gemmill). IITA, Ibadan.

Risch S. J. (1981) Insect herbivore abundance in tropical monocultures and polycultures: An experimental test of two hypotheses. *Ecology* 62, 1325–1340.

Risch S. J., Andow D. and Altieri M. A. (1983) Agroecosystem diversity and pest control: Data, tentative conclusions and new research directions. *Environmental Entomology* 12, 625–629.

Robalino G., Roman J. and Cordero M. (1983) Efecto del nematicida-insecticida oxamil aplicado al suelo y a las axilas de las hojas del bananero. *Nematropica* 13, 135–143.

Roche R. (1975) Comunicacion preliminar sobre la hormiga *Tetramorium guineense* para el control biologico del picudo negro del platano. *Rev. de Agricultura, Cuba* 8, 35–37.

Roche R. and Abreu S. (1982) Dispersion de la hormiga *Tetramorium guineense* (Mayr) (Hymenoptera: Formicidae). *Cienc. de la Agricult.* 13, 122.

Root R. B. (1973) Organization of a plant-arthropod association in simple and diverse habitats: The fauna of collards (*Brassica oleracea*). *Ecological Monographs* 43, 95–124.

Rukazambuga N. D., Gold C. S. and Gowen S. R. (1994) Banana weevil–host plant (*Musa* EA-AAA) interactions in East Africa highlands banana systems. In *African Crop Science Conference* (In press).

Sampaio A. S., Myazaki I., Suplicy Filho N. and Oliveira D. A. (1982) Broca da bananeira—*Cosmopolites sordidus* (Germar 1824) (Coleoptera: Curculionidae) resistente ao aldrin e sue controle com insecticidas sistemicos aplicados no solo. *Biologico* 48, 91–98.

Schmitt A. T. (1993) Biological control of the banana weevil (*Cosmopolites sordidus* (Germar)) with entomogenous nematodes. Unpublished PhD thesis. U. Reading. 210 pp.

Sebasigari K. and Stover R. H. (1988) Banana diseases and pests in East

Africa: Report of a survey in November 1987. INIBAP, Montpellier.

Sen A. C. and Prasad D. (1953) Pests of banana in Bihar. *Indian J. Entomol.* 15, 240–246.

Sengooba T. (1986) Survey of banana pest problem complex in Rakai and Masaka districts, August 1986: Preliminary trip report. Mss. 10 pp. Uganda Ministry of Agriculture, Kawanda Research Station.

Seshu Reddy K. V. (1986) Some biological observations on the banana weevil, p. 4. In *Sixteenth Annual Report of the International Centre of Insect Physiology and Ecology* (ICIPE), Nairobi, Kenya.

Seshu Reddy K. V., Koppenhofer A. M. and Uronu B. (1993) Cultural practices for the control of banana weevil, pp. 140–146. In *Biological and Integrated Control of Highland Banana and Plantain Pests and Diseases. Proceedings of a Research Coordination Meeting* (Edited by C. S. Gold and B. Gemmill). IITA, Ibadan.

Seshu Reddy K. V. and Lubega M. C. (1993) Evaluation of banana cultivars for resistance/tolerance of the weevil *Cosmopolites sordidus* Germar, pp. 143–148. In *Breeding Banana and Plantain for Resistance to Diseases and Pests* (Edited by J. Ganry). CIRAD, Montpellier.

Shanahan G. J. and Goodyear G. J. (1974) Dieldrin resistance in *Cosmopolites sordidus* in New South Wales, Australia. *J. Econ. Entomol.* 67, 446–447.

Sheehan W. (1986) Response by specialist and generalist natural enemies to agroecosystem diversification: A selective review. *Environmental Entomology* 15, 456–461.

Sikora R. A., Bafokuzara N.D., Mbwana A. S. S., Oloo G. W., Uronu B. and Seshu Reddy K. V. (1989) Interrelationship between banana weevil, root lesion nematode and agronomic practices, and their importance for banana decline in the United Republic of Tanzania. *FAO Plant Prot. Bull.* 37, 151–157.

Simmonds N.W. (1966) *Bananas.* 2nd Edition. Longman, London.

Stover R. H. and Simmonds N. W. (1987) *Bananas.* 3rd Edition. Longman, London. 468 pp.

Swaine G. and Corcoran R. (1973) Laboratory tests against banana weevil borer suspected of being resistant to dieldrin. *Queensland J. Agric. and Anim. Sci.* 30, 73–77.

Swennen R. (1984) A physiological study of the suckering behaviour in plantain (*Musa* cv AAB). Dissertationes de Agricultura No. 132. Faculty of Agriculture, Catholic University of Louvain. 180 pp.

Swennen R., Wilson G. F. and Decoene D. (1988) Priorities for future research on the root system and corm in plantains and bananas in relation with nematodes and the banana weevil, pp. 91–96. In *Nematodes and the Borer Weevil in Bananas: Proceedings of a workshop* held in Bujumbura, Burundi, 7–11 December 1987 (Edited by INIBAP). Montpellier, France.

Tahvanainen J. O. and Root R. B. (1972) The influence of vegetational diversity on the populational ecology of a specialized herbivore, *Phyllotreta cruciferae* (Coleoptera: Chrysomelidae). *Oecologia* 10, 321–346.

Traore L., Gold C. S., Pilon J. G. and Boivin G. (1993) Effects of temperature on embryonic development of banana weevil *Cosmopolites sordidus* Germar (Coleoptera:Curculionidae). *African Crop Sci. J.* 2, 111–116.

Treverrow N. (1993) An integrated management program for banana weevil borer. Final Report. HRDC.

Project Number: Fr/0012/RO. 40 pp.

Treverrow N. (1994) Control of the banana weevil borer, *Cosmopolites sordidus*, with entomopathogenic nematodes, pp. 124–138. In *Proceedings of Banana Nematode/ Borer Weevil Conference*. Kuala Lumpur, 18–22 April 1994 (Edited by R. V. Valmayor, R. G. Davide, J. M. Stanton, N. L. Treverrow and V. N. Roa). INIBAP, Los Baños.

Treverrow N., Bedding R. A., Dettman E. B. and Maddox C. (1991) Evaluation of entomopathogenic nematodes for control of *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae), a pest of bananas in Australia. *Ann. Appl. Biol.* 119, 139–145.

Uronu B. E. M. A. (1992) The effect of plant resistance and cultural practices on the population densities of banana weevil *Cosmopolites sordidus* (Germar) and on banana yield. Unpublished PhD dissertation. Kenyatta University. 216 pp.

Valmayor R. V., Davide R. G., Stanton J. M., Treverrow N. L. and Roa V. N. (Eds) (1994) *Banana Nematodes and Weevil Borers in Asia and the Pacific*. INIBAP, Los Banos, Philippines. 28 pp.

Varela A. M. (1993) Report on a trip to Bukoba and Muleba districts (Kagera region) to assess the possibility for biological control of banana weevil with ants. NDCP. Dar es Salaam. Mss. 15 pp.

Vilardebo A., Beugnon M., Melin P., Lecoq L. and Aubert B. (1974) Chlordecone et autres insecticides dans la lutte contre le charancon du bananier *Cosmopolites sordidus* Germar. *Fruits* 29, 267– 278.

Viswanath B. N. (1977) Studies on the biology, varietal response and control of banana rhizome weevil, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae). Unpubl. PhD Bangalore, India.

Vittayaruk W., Wattanachaiyingcharoen W., Chuaycharoen T. and Wattanachaiyingcharoen D. (1994) Status of weevil borer problems affecting banana in Thailand, pp. 106–114. In *Proceedings of Banana Nematode/Borer Weevil Conference.* Kuala Lumpur, 18–22 April 1994. (Edited by R. V. Valmayor, R. G. Davide, J. M. Stanton, N. L. Treverrow and V. N. Roa). INIBAP, Los Baños.

Vuylsteke D. R., Swennen R. L. and Ortiz R. (1993) Development and performance of black sigatoka-resistant tetraploid hybrids of plantain (*Musa* spp., AAB group). *Euphytica* 65, 33–42.

Walker P. T., Hebblethwaite M. J. and Bridge J. (1984) Project for banana pest control and improvement in Tanzania: A report to the Government of Tanzania: Final Report. TDRI. 129 pp.

Waterhouse D. F. and Norris K. R. (1987) *Biological Control: Pacific Prospects*. Inkata Press, Melbourne. 454 pp.

Waterhouse D. F. (1993) *The Major Arthropod Pests and Weeds of Agriculture in Southeast Asia.* ACIAR, Canberra. 141 pp.

Wright W. (1977) Insecticides for the control of dieldrin- resistant banana weevil borer, *Cosmopolites sordidus* Germar. *Aust. J. Exp. Agric. and Anim. Husb.* 17, 499–504.

Biological Control in Sugarcane

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Abstract—Biological control attempts against sapsucker, soil insect and stemborer pests of world sugarcane is reviewed. Successes and failures are related to the biologies of the sugarcane pests themselves, and to the period of association between sugarcane and its most important pests in the different regions of the world. The use of classical biological control in sugarcane is discussed in the context of its effect on indigenous insect faunas.

Key Words: biological control, sugarcane, natural enemies, entomopathogens, soil pests, stalkborers, sap suckers

Introduction

The origin of sugarcane has been the subject of much study and speculation. It is thought that varieties of *Saccharum officinarum* L. originated in Melanesia. The ancestral form is thought to be wild *S. robustum* of New Guinea and adjacent islands, where it has been grown in native gardens since time immemorial (Pemberton and Williams, 1969). Modern cultivated varieties of sugarcane have been derived from two wild ancestors, *S. robustum* from Melanesia, and *S. spontaneum* from East Africa and the southern part of Asia including islands of S.E. Asia and Melanesia (Stevenson, 1965).

In contrast to the origin of sugarcane, insect pests of sugarcane are characteristically of more limited geographical distribution. The regional character of sugarcane pests, their host-plant relationships, the presumed origins of cultivated sugarcanes and the close botanical affinity of these with wild canes and grasses of other genera, lead to the conclusion that sugarcane insects are generally local insects that have adopted sugarcane as a host consequent to its cultivation (Pemberton and Williams, 1969). However, with the expansion of the sugarcane industry, the distribution of local insects has increased because of transportation of plant material between countries. The pest fauna of any region is thus a mixture of indigenous and alien species. On oceanic islands, the latter predominate because the limited, insular faunas of islands have provided few agricultural pests, and the former are more common on continents.

Because of the various origins of sugarcane pests, classical biological control has been practised. However, as many sugarcane pests are indigenous, other biological control approaches have also been followed. These include augmentation of natural enemies, and the new association approach (Hokkanen and Pimentel, 1989). This review will detail the successes or otherwise of these approaches.

Materials and Methods

The data obtained has come from the recently held second sugarcane entomology workshop of the International Society of Sugarcane Technologists (ISSCT). Various authors were asked to review insect pests of their regions, to structure their talks around the insects biologies, relate these to reasons why they became pests, and to why control measures worked or did not. The presentations are published in the workshop proceedings.

Insect pests were divided into those living in soil, sap suckers and stalkborers. The world sugarcane growing industry was divided into geographical areas as follows: Africa and the Mascarene islands; Southeast Asia; India and Pakistan; Australia, Indonesia and the Pacific islands; South America; Central America and the Caribbean islands; and North America. This review will follow the same format, with the different insect groups forming the major divisions, and geographical locations the minor ones. This would also serve to illustrate the local nature of the major and minor pests in the world sugarcane industries. Only the data on biological control has been extracted, but reference to the proceedings will reveal that cultural and integrated control have also been very successful pest control options.

Results

Sugarcane Sap Suckers

These insects generally belong to the Hemiptera and Homoptera, and feed on the sap of leaves, stems and roots. Heavy infestations on any part of the plant cause yellowing and browning of leaves and plant stunting because of sap removal. Honeydew secreted by these insects onto leaves is often attacked by sooty mould, which further reduces photosynthetic activity. Many sap suckers are disease vectors and as such need to be controlled in sugarcane. The species currently recognised as being of major concern are shown in Table 1. Species of minor importance are listed in the references given in Table 1. The majority of these are under biological control, as are all the sap suckers in Australia (Allsopp, 1994).

Africa and Associated Islands

Table 1 lists the major pests in this category, and the numbers of exotic and indigenous natural enemies found on them.

The delphacid *Perkinsiella saccharicida* Kirkaldy, from the Australasian region, and the diaspid *Aulacaspis tegalensis* (Zehntner) from Southeast Asia are the only major exotic sap sucker pests recorded in Africa and the Mascarene islands. The majority of other species listed by Carnegie (1994)

Table 1. The major sugarcane sap sucking pests in Africa and the Mascarene islands, and the numbers of exotic and indigenous natural enemies used in biological programmes against them

	Number of natural enemy species	
Host	Exotic	Indigenous
P. saccharicida (from Carnegie, 1994)	0	4
A. tegalensis (from Greathead, 1994)	5	25
N. viridis (from Carnegie, 1994)	1	5
S. icerya (from Carnegie, 1994)	0	Numerous indigenous parasitoids and predators
M. sacchari (from Carnegie, 1994)	0	3

and Greathead (1994) are indigenous to this area. *Parkinsiella saccharicida* is, however, kept under control by indigenous egg parasitoids collected in Swaziland and South Africa. These are *Anagrus* sp. (Mymaridae) and *Ootetrastichus pallidipes* Perkins (Eulophidae). *Gonatopus* sp. (Dryinidae) has also been recorded as a parasitoid, but is itself heavily parasitised by *Cheiloneurus* sp. (Encyrtidae) (Carnegie 1994). Thus in this case, no introductions of natural enemies from the pests area of origin were needed.

Biological control of *A. tegalensis* has been attempted in East Africa and Mauritius. Predatory Coccinellidae and parasitoids were tried at various estates in East Africa (see Greathead, 1994). The coccinellid *Rhyzobius lophanthae* (Blaisdell), imported from Mauritius where it was the most abundant predator, was effective at Arusha Chini Estate, Tanzania. However, at Ramisi Estate in Kenya it failed to establish. Other coccinellids were not as effective, but indigenous species had some favourable impact. The indigenous parasitoids *Coccobius* spp. (Aphilinidae) and *Adelencyrtus miyari* Tachikawa (Encyrtidae) were hyperparasitised by *Tetrastichus* sp., therefore exotic parasitoids were sought and *Aphytis* spp. (Aphilinidae) imported and released. It is not known if they are established in East Africa (Greathead 1994).

In Mauritius, the coccinellid *Sticholotis madagassa* Weise was imported from Reunion Island, where it is an important predator of *A. tegalensis*. However, there is no evidence that its incidence in Mauritian cane increased after the introductions. Attempts to introduce *Chilocorus schioedtei* Mulsant and *C. distigma* (Fabricius) (Coccinellidae) from East Africa failed. Of the parasitoids which were introduced 2 became established, *Coccobius seminotis* (Silvestri) from Uganda and *Aphytis mytilaspidis* Le Baron from Java, and contributed to the reduction of infestations of *A. tegalensis* (Greathead, 1994). This is one of the few examples of classical biological control successes in sugarcane.

Numicia viridis Muir (Tropiduchidae) is indigenous to southern Africa, and became an economic pest in 1962. However, its indigenous egg parasitoids *Ootetrasticus beatus* Perkins (Eulophidae) and *Oligosita* sp. (Trichogrammatidae) became established in sugarcane and by the early 1970s had reduced populations of *N. viridis* to below pest proportions. Other indigenous parasitoids recorded were *Dryinus* sp. and *Lestodryinus* sp. (Dryinidae). *Epipyrops* sp. (Epipyropidae) was found when populations of *N. viridis* were high (Carnegie, 1994). Introduction of the egg predators, *Tytthus* spp. (Miridae), from Mauritius were unsuccessful (Carnegie 1994).

Saccharipulvinaria (Pulvinaria) iceryi (Signoret) (Coccidae) was originally described from sugarcane in Mauritius and Reunion. Control measures are ecological and aim at encouraging the action of the numerous indigenous predators and parasitoids (Carnegie, 1994).

Melanaspis sacchari Zehntner (Aphididae) is a cosmopolitan species which occasionally occurs in large numbers in African countries. Outbreaks are normally controlled by indigenous biological control agents which include syrphid flies, the braconid *Lysiphlebus testaceipes* Cress and several coccinellid beetles.

Southeast Asia

Table 2 lists the effective parasitoids and predators of the sugarcane sap suckers of Southeast Asia. No importations are mentioned by Suasaard and Charernsom (1994). They do in addition list the natural enemies of minor importance.

Table 2. The effective indigenous natural enemies of the most important sap sucking sugarcane pests in Southeast Asia

Host	Indigenous	Comments
Phaenacantha saccharicida (from Suasa-ard and Charernsom, 1994)	**Encyrtidae**	
	Oencyrtus malyensis Ferriers	Locally occurring parasitoid
	Chrysopidae	
	Chrysopa sp.	Effective predator
	Ankylopteryx sp.	Local predator
Perkinsiella saccharicida	**Mymaridae**	
	Anagrus obtabilis Perkins	Effective parasitoid
	A. freguens Perkins	Effective parasitoid
	Eulophidae	
	Tetrastichus beatus (Perkins)	Effective parasitoid
	T. formosanus	Local parasitoid
	Dryinidae	
	Pseudogonatopus hospes Perkins	Effective parasitoid
A. tegalensis	**Encyrtidae**	
	Adelencyrtus miyarai Tachikawa	Effective parasitoid
	A. mayurai Subba Rao	Effective parasitoid
	Coccinellidae	
	Cybocephalus binotatus Grouville	Effective predator
	Chilocorus circumdatus Gyllenhal	Effective predator
	C. nigritus Fabricius	Effective predator
	Menochilus sexmaculatus (Fabricius)	Effective predator
	Coccinella transversalis (Fabricius)	Effective predator
C. lanigera	**Aphilinidae**	
	Encarsia flavoscutellum Zehntner	Effective parasitoid
	Phycitidae	
	Thiallela sp.	Effective predator
	Coccinellidae	
	Menochilus sexmaculatus (Fabricius)	Effective predator
	Coccinella transversalis (Fabricius)	Effective predator
	Chrysopidae	
	Chrysopa basalis Walker	Effective predator
	Hemerobiidae	
	Eumiccromis santeri Esben-Peterson	Effective predator
R. maidis	**Aphelinidae**	
	Encarsia transvena Timberlake	Effective parasitoid
	Coccinellidae	
	Scymnus notescens (Blackb.)	Effective predator
	Chrysopidae	
	Chrysopa sp.	Effective predator
P. perpusilla	**Encyrtidae**	
	Cheiloneurus pyrillae Mani	Effective parasitoid
	Ooencyrtus papilionis Ashmead	Effective parasitoid
	Epiricania melanoleuca Fletcher	Effective parasitoid
A. barodensis	**Aphilinidae**	
	Encarsia ochai Viggiani	Effective parasitoid
	Azotus bimaculatus Khan & Shafee	Effective parasitoid
	Encyrtidae	
	Anagyrus saccharicola	Effective parasitoid
	Coccinellidae	
	Menochilus sexmaculatus Fabricius	Effective predator

Biological control is one of the major components of the Southeast Asian integrated pest management systems, and as such, much emphasis is placed on the conservation of natural enemies.

India/Pakistan

Table 3 lists the number of species of exotic and indigenous species used against the major sap sucking pests of sugarcane in India and Pakistan. Mohyuddin (1994a) gives a more complete list.

Table 3. The number of species of exotic and indigenous natural enemies used in biological control programmes against the major sap sucking sugarcane pests of India and Pakistan

	Natural enemies	
Host	Exotic	Indigenous
P. perpusilla (from Mohyuddin, 1994)	0	2
M. glomerata	7	0
A. barodensis	0	12

Pyrilla perpusilla (Walker) (Lophopidae) is endemic to South Asia and is a serious pest of sugarcane only. In India, biological control of this pest was achieved by distributing wire gauze cages containing field collected eggs which had been parasitised by an indigenous egg parasitoid *Parachrysocharis javensis* Crawford in heavily infested fields. The populations of this parasitoid were further conserved by having growers not burn their trash after harvest. If the trash is burnt, only 5% parasitism is recorded, compared to 80% if the trash is not burnt. This, along with the redistribution of the indigenous nymphal and adult parasitoid *Epiricania melanoleuca* Fletcher gave complete control without using insecticides (Mohyuddin, 1994).

A large number of natural enemies of *Melanaspis glomerata* (Green) (Aphididae) have been reported from this area, and augmentation of these is an important part of the IPM programme. In addition, the predators *Chilocorus cacti* L., *C. distigma* Klug, *C. schioedtei* Muls., *C. nigritus*, *Lindorus lophanthae* (Blaisd.), *Sticholotis madagassa* Weise and *Pharoscymnus horni* Weise (All Coccinellidae) were introduced from East Africa and Trinidad. Of these, only *C. cacti* and *S. madagassa* have become established (Mohyuddin, 1994).

Aleurolobus barodensis Mask. (Aleyrodidae) has occasionally been reported as a serious pest of sugarcane in this region. These outbreaks have been related to aerial spraying of pesticides against *P. perpusilla,* which killed many of the indigenous natural enemy complex of *A. barodensis* (Mohyuddin, 1994). In Pakistan the parasitoids include the aphilinids *Azotus delhiensis* Lal, *Eretmocerus* sp., *Prospaltella flava* Shafee, *P. udaipuriensis* Shafee; the eulophids *Euderomphale* sp. and *Tetrastichus* sp. and the platygasterid *Amitus aleurolobi* Mani. Indigenous predators include *Brumoides suturalis* (F.), *Catana parcesetosa* (Sic), *Oenopia sauzeti* Muls., *Scymnus* sp. and *S. nubilus* Muls. (all Coccinellidae) (Mohyuddin, 1994).

North and Central America

Table 4 lists the number of species of exotic and indigenous natural enemies of sugarcane sap sucking pests of North and Central America. Reagan (1994) provides an overview of the relatively few sap sucking pests in this area.

Sipha flava (Forbes) (Aphididae) has no effective parasitoids in this region. Naturally occurring coccinellids have not been adequate, nor has the introduced *Coelophora inaequalis* (F.) even though it is established. However,

Table 4. The number of species of exotic and indigenous natural enemies used in biological control programmes against the major sap sucking sugarcane pests of North and Central America

	Natural enemies	
Host	Exotic	Indigenous
S. flava (Forbes) From Reagan, 1994	1	Many
L. tabida	0	Many
P. saccharicida	1	2
S. saccharivora	3	3

various workers (cited by Reagan, 1994) have shown that various predators of *S. flava,* including coccinellids, were reduced for up to 10 weeks after applications of aldicarb in furrows. In addition, the use of fenvalerate as a foliar spray substantially suppressed certain predator groups (Reagan, 1994).

A mymarid egg parasitoid was introduced into Florida against *Leptodictya tabida* Herrich-Schaeffer (Tingidae), but it did not establish adequately. However, 5 indigenous coccinellid species and numerous spiders provide the most effective control (Reagan, 1994).

Biological control of *Perkinsiella saccharicida* Kirkaldy (Delphacidae) began showing success in 1907 with Australian introductions. By 1919 very successful releases of the egg predator *Tytthus mundulus* (Breddin) (Miridae) from Queensland were completed in Hawaii. In the 1980s this predator was introduced into Florida, with very limited success. However, an indigenous mirid predator, *T. parviceps* (Reuter) and an indigenous mymarid egg parasitoid, *Anagarus* sp. became established here and have reduced *P. saccharicida* populations substantially (Reagan, 1994).

During the 1960s, numerous biological control agents were imported from Jamaica in attempts to control *Saccharosydne saccharivora* (Westwood) (Delphacidae). These included the importation, rearing and release of the mymarid egg parasitoid *Anagarus armatus* Ashm., the reduviid *Zelus longipes* (L.) and the strepsipteran *Stenocranophilus quadratus* Pierce (Reagan, 1994). It is not known if these agents established, or if they are controlling the pest. However, indigenous natural enemies suppressing this pest include *Anagrus* sp., *Pseudogonatopus variistriatus* (Dryinidae) and 2 species of *Paracentrobia* (Trichogrammatidae), all egg parasitoids (Reagan, 1994).

Aeneolamia postica (Walker) (Cercopidae) and 2 other related species are serious pests in Mexico. Adults feed on plant foliage and the immature stages on plant roots (they will also thus be covered in the soil pest section). Extensive biological control efforts over a substantial period of time have met with little positive success. However, several fungi, including the genus *Metarrhizium* have shown promise in control programmes, and in the Caribbean, there is a major effort in the commercial production of *Metarrhizium* for control of *A. postica* (Reagan, 1994).

Sugarcane Soil Pests

The roots of sugarcane are attacked by species of Coleoptera, Isoptera, Diptera, Nematoda, Hemiptera and Homoptera. Generally, it is the immature stages which either feed on the root hairs, the roots and/or the basal portions of the stem. This feeding reduces sugarcane yields markedly. The effect of these pests on the crop can be found by reference to the papers cited in the following sections. This paper will not cover nematodes, although these organisms are covered in the cited papers.

Africa and Close Islands

Chemical control and suitable crop management have so far been the major control options used against soil pests in Africa. Biological control is only now being considered a serious control option because of development of resistance by insects to commonly used pesticides. Also, environmental groups are seriously questioning the use of pesticides.

The only scarabs (white grubs) exotic to this region are *Hoplochelus marginalis* (Melolonthidae) and *Phyllophaga smithi* (Melolonthidae) in Reunion and Mauritius. In a number of situations, a natural decline of white grubs has been observed. Rajabalee (1994) ascribed this to increased activity of indigenous entomopathogens. He cited the common occurrence of microsporidians in field collected larvae of *P. smithi* in Mauritius and *H. marginalis* in Reunion. A similar observation was made with the populations of *Heteronychus licas* (Dynastidae) in Swaziland.

Scoliid wasps are commonly found parasitising white grub larvae, but are not particularly effective (Rajabalee, 1994), and their presence is dependent on the presence of flowering food plants rich in nectar, e.g. *Eupatorium pallescens* in Mauritius and *Stachytarpha* sp. in Tanzania (Rajabalee, 1994). Predators include elaterid larvae and birds.

Rajabalee (1994) regards the most promising control method to be the use of entomopathogens. He cites the identification of 2 strains of *Beauveria brongnartii* collected from Madagascar which have been formulated into an effective biopesticide specific to *H. marginalis* on Reunion Island. He suggests further similar studies with strains of *Metarrhizium anisopliae,* and with *Cordeceps* sp. which is commonly found in Tanzania especially along irrigation canals. Recently, a unique isolate of *Bacillus thuringiensis* with a high lateral activity specific for scarabaeid beetles has been reported (Rajabalee, 1994).

Spiders of *Ammoxenus* spp. and *Diores* spp. are recorded as specialist termite predators in this region (Dippenaar, 1993), and it has been reported that *Metarrhizium anisopliae* is the most virulent fungal pathogen of termites and needs further developmental research (Rajabalee, 1994). However, none are effective by themselves.

Southeast Asia

Table 5 outlines the indigenous natural enemies collected from the major soil pests in Southeast Asia. These have been extracted from the list of Charernsom and Suasa-ard (1994) which also include some of the minor pests.

Charernsom and Suasa-ard (1994) list 3 species of Sphecidae parasitising 2 species of cricket. The parasitoid group most common on the white grubs were Scoliidae. Again, entomogenous fungi were commonly found, and a virus.

India/Pakistan

Sixty-one species of indigenous natural enemies, belonging to the Arachnida, Chilopoda, Insecta, Amphibia, Reptilia, Aves and Mammalia have been listed as attacking termites (Isoptera), none have been used for biological control (Mohyuddin, 1994b).

Fungal pathogens such as *Beauveria brongniartii* (Sacc.), *Penicillium* sp. and *Fusarium* sp. have also been reported from termites. These might prove useful after mass production and application techniques have been developed.

Table 5. The effective indigenous natural enemies of the most important soil-dwelling sugarcane pests in Southeast Asia

Host	Natural enemy	Comments
Brachytrypes portentosus Liest. (Field cricket)	**Sphecidae**	
	Sphex maxillosus Fabricius	Hymenopteran larval parasitoid—occurs naturally
Gryllotalpa africana Beauvois (African mole cricket)	**Sphecidae**	
	Larra luxonensis Rohwer	Hymenopteran larval parasitoid—occurs naturally
	L. bicolor Fabricius	As above
Lepidiota stigma Fabricius (sugarcane white grub)	Unidentified scoliid wasp	Hymenopteran larval parasitoid
	Metarrhizium anisopliae	Entomogenous fungus
Adoretes sinicus Burm. (Rose beetle)	**Scoliidae**	
	Campsomeris marginella billitonensis Tull	Hymenopteran larval parasitoid
	Typhiidae	
	Typhia sp.	Hymenopteran parasitoid
Anomala shanica Arrow	**Scoliidae**	
	C. annulata Fabricius	All are hymenopteran parasitoids
	C. phalerata Saussure	
	C. quadrifasciata Fabricius	
	Typhiidae	
	Typhia sp.	
	Histeridae	
	Hister sp.	
Oryctes rhinoceros Linnaeus	**Scoliidae**	
	C. luctuosa Smith	Hymenopteran larval parasitoid
	Elis romandi Saussure	As above
	Scolia azurea Chr.	As above
	S. oryctophaga Coquilet	As above
	S. ruficornis Fabricius	As above
	S. rufipes Smith	As above
	S. procer Ill.	As above
	Rhabdionvirus oryctes Huger	Virus
	Metarrhizium anisopliae	Entomogenous fungus
Xylotrupes gideon L.	**Scoliidae**	
	Campsomeris spp.	Hymenopteran larval parasitoid
	Scolia spp.	As above
	R. oryctes Huger	Virus
	Metarrhizium anisopliae	Entomogenous fungus
Sepiomus sp.	*Beauveria bassiana* (Balsamo & Vuillemin)	Entomogenous fungus

White grubs (Scarabaeidae) are not common in Pakistan, but in India 2 species of Scoliid wasp parasitoids, 2 carabid beetle predator species, 3 bird species and a toad have been recorded as natural enemies (Mohyuddin, 1994b).

Metarrhizium anisopliae Metch., *Beauveria bassiana* (Bals.), *B. brongniartii* (Sacc.), *Bacillus popilliae* (Dutky) and a nematode *Rhabditis* sp. are all naturally occurring entomopathogens, but none have been used on a large scale for the control of white grub (Mohyuddin, 1994b). However, some need further developmental work.

South America

Indigenous natural enemies have been collected from a number of white grub species in this region. However few attempts have been made to laboratory rear these (Ferrer, 1994). The most common parasitoids collected belonged to the genus *Campsomeris* (Hymenoptera: Scoliidae), and indigenous *Metarrhizium anisopliae* strains were found. Predators reported include lizards, frogs, domestic and wild birds and other vertebrates.

Paecilomyces liliacinus was used without success in Brazil against *Migdolus* (Cerambycidae). *Beauveria bassiana,* however, has been successfully used against *Sphenophorus levis.* Also in Brazil, several strains of *Neoplectana carpocapsae* were used against *Migdolus* without outstanding results (Ferrer, 1994).

Central America

In this region, the purely chemical approach of control is giving way to IPM systems after especially spittle bugs developed resistance to all classes of insecticide. There is increased emphasis on culturing *Metarrhizium anisopliae* for use in these situations (Falloon, 1994).

Table 6 lists the indigenous natural enemies recorded from soil pests in this region.

North America

Insect parasitic nematodes have been investigated as biological control agents against *Ligyrus subtropicus* (Blatchley) (Scarabaeidae), of which the indigenous *Steinernema glaseri* has been the most successful. Commercially available nematode species were not successful. Also, several nematode species tested against *Melanotus communis* Gyll. (Elateridae) were ineffective in laboratory tests (Sosa, 1994).

Australasia

In Australia, white grubs (Scarabaeidae) are parasitised by a variety of indigenous scoliid wasps and occasionally by dexiid flies. Nemistinids have been collected from pupae and tachinids from adults. Elaterids prey on eggs and larvae. All these agents, however, do not give economic control. In Indonesia, the scoliid wasps *Campsomeris* spp. are common, but do not give satisfactory control (Samoedi, et al., 1994).

Metarrhizium anisopliae occasionally causes heavy mortalities of these insects, and artificial production and distribution of this fungus is being researched in Australia. *Paraisaria* sp., another fungus occasionally causes epidemics in *Antitrogus rugulosus* Blackburn (Scarabaeidae) populations, but it is difficult to culture and has not been studied in detail. The bacterium *Bacillus popilliae* also reduces numbers of cane grubs dramatically. The spores of this bacterium are long lasting, but there is no method for the artificial production of the bacteria. Nematodes are another organism which sometimes cause heavy mortalities, but high production costs limit their use. In

Table 6. The effective indigenous natural enemies of the most important soil-dwelling sugarcane pests in Central America and the Caribbean islands

Host	Natural enemy	Comments
Aeneolamia flavilatera	**Syrphidae**	
	Salpingogaster nigra	Nymphal predator
	Trichogrammatidae	
	Oligosita giraulti	Egg parasitoid
	Mymaridae	
	Anagrus sp.	Egg parasitoid
	Eulophidae	
	Centrodora spp.	Egg parasitoid
	Metarrhizium anisopliae	Entomophagous fungus
Diaprepes abbreviatus	*Ignelater luminosus*	
	Platystasius citri	
	Scolopendra subspinipes	
	Tyranus dominicensis	
	Eulophidae	
	Tetrastichus sp.	
Phyllophaga smithi	**Scoliidae**	
	Campsomeris tricincta	
	C. trifasciata	
	Myzinum ephippium	
	M. haemorrhoidale	
	M. xanthonotum	
	Scolopendra spp.	
	Tiphia spp.	

Indonesia, *Metarrhizium* sp. is common on cane grubs, but its use as a control agent has not been investigated (Samoedi et al., 1994).

Immature stages of the dipterans *Inopus rubriceps* (Macquart) and *I. flavus* (James) (Stratiomyiidae) were attacked by parasitic wasps, *Metarrhizium anisopliae* and predators which eat the vulnerable pupae. It was suggested that heavy damage in cane resulted from the removal of its natural enemies by BHC, which was introduced for cane grub (Scarabaeidae) control (Samoedi et al., 1994).

Sugarcane stalkborers

Most stalkboring pests in sugarcane belong to the Lepidoptera, although some Coleoptera and Diptera also occur. It is generally the immature stages which damage the crop. They can bore into the growing shoot (top borers) of young and mature cane, into the stalk of mature cane (internode borers), and into the basal portion and/or rhizome of the sugarcane plant (root borers). Damage ranges from minimal to the complete loss of the crop. More information on the biological and crop loss aspects can be obtained from the references cited in the following sections.

Africa and the Mascarene Islands

In these areas, the stalkboring pests are lepidopteran, and belong to the families

Pyralidae and Noctuidae. Leslie (1994) lists species reported as pests. Table 7, however, lists only those regarded as major pests, as well as the exotic and indigenous natural enemies used in biological control programmes.

In addition to parasitoids, there are many indigenous predators in sugarcane fields, with mites and ants the most important against *E. saccharina* (Leslie, 1994).

Biological control of *Eldana saccharina* has been a major programme in South Africa. Twenty-three species of exotic egg, larval and pupal parasitoids of related borers from other world regions have been tested against *E. saccharina* in South Africa, without establishment being recorded. This has also happened with 4 parasitoids indigenous to *E. saccharina* from other parts of Africa. However, signs of establishment of 4 parasitoids normally found in the wetland hosts of this borer in S. Africa are evident on *E. saccharina* in sugarcane. These latter parasitoids are very effective against *E. saccharina* in the wetland sedge hosts of this borer, but are very scarce in sugarcane (Conlong, 1990). There has, however, not been a long association of *E. saccharina* with sugarcane, thus an effective natural enemy complex adapted to the sugarcane habitat has not yet evolved.

In situations where there has been a long association of a pest with sugarcane, e.g. *Sesamia calamistis*

Table 7. Exotic and indigenous natural enemies tested against major sugarcane stalkborers in Africa and the Mascarene islands

	Natural enemy		
Host	Exotic	Indigenous	Comments
Chilo sacchariphagus (from Leslie, 1994)	**Trichogrammatidae**		
	Trichogramma australicum		Egg parasitoid, not established on this host
	Braconidae		
	Cotesia flavipes		Larval parasitoid not established on this host
	Allorhogas pyralophagus		As above
	Eulophidae		
	Tetrastichus atriclavus		Pupal parasitoid, as above
	Ichneumonidae		
	Xanthopimpla stemmator		Pupal parasitoid, established, but not effective
	Trichospilus diatraeae		Pupal parasitoid, established, but not effective
		Ichneumonidae	
		X. citrina	Not established on this host
		Mermis sp.	Nematode affecting larvae, not established

Contd.

Table 7. Contd.

Host	Natural enemy		
	Exotic	Indigenous	Comments
Sesamia cretica (from Leslie, 1994)		**Scelionidae**	
		Platytelenomus hylas Nixon	Egg parasitoid, considered key mortality factor of eggs
		Predators (Coccinellids, ants, spiders)	Key mortality factors of neonate larvae
Chilo agamemnon (from Leslie, 1994)	**Trichogrammatidae**		
	Trichogramma evanescens		Mass releases led to this egg parasitoid being most effective control measure
Sesamia calamistis (from Leslie, 1994)	**Braconidae**		
	Cotesia sesamiae		Imported into Mauritius, established on larvae and became most important controlling factor
		Braconidae	
		Cotesia sesamiae	Indigenous to S. Africa, most important mortality factor of large larvae
		Ichneumonidae	
		Euvipio sp.	As above, contributes to mortality of large larvae
		Eulophidae	
		Pediobius furvus	As above, most important mortality factor of pupae
		Tachinidae	
		Dejeania bombylans	Occasional parasitoid of large larvae
Eldana saccharina (from Conlong, 1994)	**Trichogrammatidae**		
	Trichogramma pretiosum Riley		Field released, no recoveries
	T. braziliensis Ashmead		*E. saccharina* eggs unacceptable
	T. semifumatum Perkins		As above
	T. australicum Girault		Field released, recoveries while release in progress, no establishment
		(*T. evanescens* Westwood)	Field released, as above
	Trichogrammatoidea armigera		*E. saccharina* eggs unacceptable
	T. cryptophlebia Girault		As above

Contd.

Table 7. Contd.

	Natural enemy		
Host	Exotic	Indigenous	Comments
	Scelionidae		
	Telenomus sp.		As above
	Tachinidae		
	Sturmiopsis inferens Tns.		Did not accept target host
	Paratheresia claripalpis Wulp.		Field released, recoveries while releases in progress, no establishment
	Metagonistylum minense Tns.		Encapsulated by target host
	Palpozenilla diatraeae Tns.		Did not accept target host
	Lixophaga diatraeae Tns.		Did not accept target host
	Lydella sp.		As above
	Braconidae		
	Cotesia flavipes Cameron		Encapsulated by target host
	Allorhogas pyralophagus Marsh		Field released, recoveries while releases in progress, no establishment
	Rhaconotus roslinensis Lal.		Did not accept target host
	Macrocentrus prolificus Wharton		As above
	Digonogastra kimballi Kirkland		As above
	Ichneumonidae		
	Mallochia pyralidis Wharton		As above
	Xanthopimpla stemmator Thunb.		Field released, recoveries while releases in progress
	Meloboris sinicus		Did not accept target host
	Eulophidae		
	Tetrastichus howardi		Accepted *E. saccharina*, but never released because hyperparasitised beneficial parasitoids
		Trichogrammatidae	
		Trichogramma sp.	Field released, recoveries while releases in progress, no establishment
		Trichogrammatoidea eldanae Viggiani	As above

Contd.

Table 7. Contd.

Host	Natural enemy Exotic	 Indigenous	 Comments
		Scelionidae *Telenomus applanatus* Bin & Johnson	As above
		Tachinidae *Descampsina sesamiae* Mesnil	Encapsulated by *E. saccharina*
		Schembria eldana Barraclough	Parasitoid eggs not accessible to *E. saccharina* in sugarcane
		Bethylidae *Goniozus indicus* Ashmead (= *G. natalensis* Gordh)	Field released, obtained establishment for season while cane standing
		Braconidae *Bassus* sp. (=*Agathis* sp.)	Establishing on own accord in sugarcane
		Iphiaulax sp.	As above
		Ichneumonidae *Venturia* sp. (= *Chriodes* sp.)	Only found in indigenous host plants so far

Hamps., effective natural enemies are present, and *Cotesia sesamiae* is now an effective biological control agent in S. African sugarcane. This association has been used with success in a classical biological control exercise against *S. calamistis* in Mauritius.

Southeast Asia

Five lepidopterous borers have been recorded in Taiwan. These are discussed by Cheng (1994). Table 8 lists the 3 major borers and their indigenous natural enemies.

Twenty-five species of parasitoid and 14 predator species have been recorded as indigenous natural enemies of these borers in Taiwan. Mass propagation and release of the egg parasitoid *T. chilonis* reduced number of *T. schistaceana* Snellen (Olethreutidae), *P. venosatus* Walker (Pyralidae) and *C. infuscatellus* (Snellen) Kapur (Pyralidae). In addition, 16 exotic species have been introduced into Taiwan. Progeny of the larval parasitoids *Lixophaga diatraeae* Towns., *Isotoma javensis* Rohwer and *Sturmiopsis inferens* Towns. were recovered from fields after release. However, only *I. javensis* became established (Cheng, 1994).

Table 8. The indigenous natural enemies effective against the sugarcane stalk borers in Southeast Asia

	Natural enemy	
Host	Indigenous	Comments
Tetramoera (Argyroploce) schistaceana (from Cheng, 1994)	**Trichogrammatidae** *Trichogramma chilonis* Ishii	High egg parasitism indicates substantial control
Proceras venosatus (= Chilo sacchariphagus)	**Scelionidae** *Telenomus beneficiens* Zehntner	As above
Scirpophaga nivella	**Scelionidae** *Telenomus beneficiens* var. *elongatus* Ishida	As above

Australasian Region

In addition to the lepidopteran stalk borers, this region also has coleopteran borers. Three cerambycids have been recorded from Papua New Guinea (PNG) and its offshore islands, and a curculionid native to New Guinea and introduced to Australia, Fiji, Hawaii and other Pacific islands through infected cuttings. Kuniata (1994) has detailed all the borers of this region. Table 9 lists the major borers and their biological control agents.

Rhabdoscelus obscurus (Boisduval) (Curculionidae) has only one known indigenous natural enemy, *Lixophaga sphenophori* (Tachinidae). It is native to New Guinea and was introduced to Australia, Fiji and Hawaii. It has established in these areas, but is rare and not effective at controlling this

Table 9. The natural enemies used against sugarcane stalkborers in the Australasian region

	Natural enemy	
Host	Exotic	Indigenous
Rhabdoscelus obscurus (from Kuniata, 1994)	0	1 *Metarrhizium anisopliae*
Sesamia grisescens	0	7 Unidentified virus *Metarrhizium anisopliae*
Chilo sacchariphagus	0	10
C. terrenellus	0	10
C. infuscatellus	0	2
Tryporyza nivella	0	9
Barhytricha truncata	0	6

weevil. Strains of *Metarrhizium anisopliae* have been collected in Fiji and PNG which are being investigated as a bait for adult weevils (Kuniata, 1994).

Sesamia grisescens Walker (Noctuidae) is native to PNG and Indonesia. The indigenous natural enemies effective against this borer include the larval parasitoid *Cotesia flavipes* Cam. (Braconidae) (80% of 5–7th instar larvae parasitised), and the egg parasitoid *Telenomus* sp. (Scelionidae) (up to 18% of eggs parasitised). An eulophid pupal parasitoid, *Pediobius furvus* Gahan was imported from Kenya and has established and is giving good control (30% of pupae parasitised). In PNG all three parasitoids are being mass reared and released. Another indigenous parasitoid is *Enicospilus terebrus* Gauld (10% parasitism of full grown larvae), and the predators *Chelisoches terebrus* (F.) (Dermaptera), *Blaptostethoides* sp. (Anthocoridae) and the ants *Irridomymex* sp. and *Pheidole* sp. are common. An unidentified virus and a strain of *Metarrhizium anisopliae* have been isolated from field collected larvae (Kuniata, 1994).

The braconid larval parasitoids *C. flavipes* and *C. chilonis* and an unidentified tachinid fly are common on *Chilo terrenellus* Pagenstecher (Pyralidae). *Trichogramma plassivensis* Nagaraja, *T. chilotraeae* Nag.& Nagarkatti (Trichogrammatidae) and 2 species of *Telenomus* (Scelionidae) are important egg parasitoids. *Carphurus* sp. nr. *rubroanulatus* Motschul. (Col.: Melyridae) and *Chrysopa* sp. prey on egg masses. Combined parasitism/predation of up to 90% has been observed in PNG (Kuniata, 1994).

Eggs of *Chilo sacchariphagus* (Boj.) (Pyralidae) are preyed on by *Chrysopa* spp. and parasitised by *Telenomus* sp. (Scelionidae) and *Trichogramma* nr. *nana* (Zehnt.). Larval parasitoids include *C. flavipes, Campyloneurus erythrothorax* (Szepl.) (Braconidae), *Carcelia* sp. and *Diatraeophaga* sp. (Tachinidae). *Xanthopimpla stemmator* Thunb. and *Hormiopterus* sp. (Ichneumonidae) attack the pupae (Kuniata, 1994).

In Indonesia, *Chilo infuscatellus* Snellen (Pyralidae) is heavily parasitised by *Trichogramma* sp. (Trichogrammatidae) and tachinid flies. This borer has almost disappeared from their cane fields (Kuniata, 1994).

The top borer *Tryporyza (=Scirpophaga) nivella* (Fr.)(Pyralidae) has eggs parasitised by *Telenomus beneficiens* Zhnt. (Scelionidae), *Trichogramma* spp. (Trichogrammatidae) and *Tetrastichus schoennobii* Forr. (Eulophidae). Larval parasitoids include *Stenobracon trifasciatus* Szpl. (Braconidae) and *Cotesia* sp. (Braconidae). In Indonesia the larval/pupal parasitoids include *Elasmus zehntneri* Forr. and *Isotoma javensis* Rohw., but in low numbers. *Telenomus* sp. and *Stenobracon* sp. attack this borer in PNG (Kuniata, 1994).

The large moth borer *Barhytricha truncata* (Walker) is endemic to Australia. The larvae are parasitised by 2 small braconid wasps, including *C. flavipes*, 2 ichneumonids and a tachinid fly. The ant *Pheidole megacephala* is an aggressive predator of migrating larvae. The second generation of *B. truncata* is usually heavily parasitised, and damage therefore does not persist beyond December (Kuniata, 1994).

Discussion

Biological control using predators and parasitoids has been most successful on sugarcane sapsuckers, especially those that are exposed. Stalkborer biological control in sugarcane has been more difficult, because of the more cryptic nature of these organisms. However, considerable success has been achieved with egg parasitoids, especially on those stalkborers which lay their eggs in exposed positions. Control using larval parasitoids has been more difficult. Generally, those borers which have evolved with their larval parasitoids and sugarcane have been easier to control, than the borers which have more recently moved from another host onto sugarcane. The new association approach has worked spectacularly in the New World, when the Old World *Cotesia flavipes* was introduced to the New World stalk borers of the genus *Diatraea*. These borers are now well controlled by this parasitoid in much of the Americas and the Caribbean islands. However, in other situations this approach has not worked at all. Biological control of sugarcane soil pests has been least successful, because of the inaccessibility of the target organisms. It seems as though the use of indigenous microorganisms may provide the best biological control.

From the results presented it is evident that classical biological control against sugarcane pests has limited applicability, because most sugarcane pests are indigenous to their areas. Most success has been achieved by augmentation of indigenous natural enemies, and manipulation of the environment to encourage the foraging of parasitoids and predators. In many cases, indigenous natural enemies moved onto sugarcane pests on their own accord, and provided economic control of these.

Conclusions

Biological control in sugarcane has been most successful on sap-sucking pests. Stalkborers with stages of their life cycle accessible to natural enemies have also been successfully controlled with natural enemies. Biological control has not been successful on stalkborers with all of their life stages in cryptic positions, nor on those borers recently associated with sugarcane. The new association approach has been attempted many times, and has worked very efficiently once, with New World *Diatraea* sp. being controlled in sugarcane by the Old World *Cotesia flavipes*. The least success with biological control has been on soil insects, because of their very cryptic life style, long life cycles and a lack of suitable food plants for parasitoids in the sugarcane habitat.

The challenges facing biological control research against sugarcane pests involves the exploitation, by augmentation and/or habitat manipulation and conservation, of indigenous natural enemies and entomopathogens. Also, the 'new association' approach shows promise, but only if natural enemies are carefully selected.

References

Allsopp P. G. (1994) Australian sugarcane sapsuckers. In *Biology, Pest Status and Control Measure Relationships of Sugarcane Insect Pests* (Edited by A. J. M. Carnegie and D. E. Conlong). Proceedings of the Second Entomology Workshop of the International Society of Sugar Cane Technologists. S.A.S.A. Experiment Station. ISBN 1-874903-10-7.

Carnegie A. J. M. (1994) Sugarcane sucking insects (Homoptera): Africa and close islands. In *Biology, Pest Status and Control Measure Relationships of Sugarcane Insect Pests* (Edited by A.J.M. Carnegie and D. E. Conlong). Proceedings of the Second Entomology Workshop of the International Society of Sugarcane Technologists. S.A.S.A. Experiment Station. ISBN 1-874903-10-7.

Charernsom K. and Suasa-ard W. (1994) Pest status, biology and control measures for soil pests of sugarcane in South East Asia. In *Biology, Pest Status and Control Measure Relationships of Sugarcane Insect Pests* (Edited by A. J. M. Carnegie and D. E. Conlong). Proceedings of the Second Entomology Workshop of the International Society of Sugarcane Technologists. S.A.S.A. Experiment Station. ISBN 1-874903-10-7.

Cheng W. Y. (1994) Sugarcane stem borers of Taiwan. In *Biology, Pest Status and Control Measure Relationships of Sugarcane Insect Pests* (Edited by A. J. M. Carnegie and D. E. Conlong). Proceedings of the Second Entomology Workshop of the International Society of Sugarcane Technologists. S.A.S.A. Experiment Station. ISBN 1-874903-10-7.

Conlong D. E. (1990) A study of pest–parasitoid relationships in natural habitats: An aid towards the biological control of *Eldana saccharina* (Lepidoptera: Pyralidae) in sugarcane. *Proc. South African Sugar Technol. Assoc.* 64, 111–115.

Conlong D.E. (1994) A review and perspectives for the biological control of the African sugarcane stalkborer *Eldana saccharina* Walker (Lepidoptera: Pyralidae). *Agric., Ecosyst. Environ.* 48, 9–17.

Dippenaar A. J. (1993) Spiders associated with termites. *Proc. Ent. Soc. S. Afr.* 9, 23.

Falloon T. (1994) Pest status, biology and control of soil pests of sugarcane in Central America and the Caribbean. In *Biology, Pest Status and Control Measure Relationships of Sugarcane Insect Pests* (Edited by A. J. M. Carnegie and D. E. Conlong). Proceedings of the Second Entomology Workshop of the International Society of Sugar Cane Technologists. S.A.S.A. Experiment Station. ISBN 1-874903-10-7.

Ferrer W.F. (1994) Soil-inhabiting insect pests and nematodes that damage sugarcane in South America: Biology and control measures. In *Biology, Pest Status and Control Measure Relationships of Sugarcane Insect Pests* (Edited by A. J. M. Carnegie and D. E. Conlong). Proceedings of the Second Entomology Workshop of the International Society of Sugarcane Technologists. S.A.S.A. Experiment Station. ISBN 1-874903-10-7.

Greathead D. J. (1994) Sapsucking pests of sugarcane in East Africa. In *Biology, Pest Status and Control Measure Relationships of Sugarcane Insect Pests* (Edited by A. J. M. Carnegie and D. E. Conlong). Proceedings of the Second Entomology Workshop of the International Society of Sugar Cane Technologists. S.A.S.A. Experiment Station. ISBN 1-874903-10-7.

Hokkanen H. M. T. and Pimentel D. (1989) New associations in biological control: Theory and practice. *Can. Entomol.* 121, 829–840.

Kuniata L. S. (1994) Pest status, biology and control measures of sugarcane stalkborers in the Australian, Indonesian and Pacific Island sugarcane growing regions. In *Biology, Pest Status and Control Measure Relationships of Sugarcane Insect Pests* (Edited by A. J. M. Carnegie and D. E. Conlong). Proceedings of the Second Entomology Workshop of the International Society of Sugarcane Technologists. S. A. S. A. Experiment Station. ISBN 1-874903-10-7.

Leslie G. W. (1994) Pest status, biology and effective control measures of sugarcane stalk borers in Africa and surrounding islands. In *Biology, Pest Status and Control Measure Relationships of Sugarcane Insect*

Pests (Edited by A. J. M. Carnegie, and D. E. Conlong). Proceedings of the Second Entomology Workshop of the International Society of Sugarcane Technologists. S.A.S.A. Experiment Station. ISBN 1-874903-10-7.

Mohyuddin A. I. (1994a) Pest status, biology and control measures of sugarcane sap suckers in India and Pakistan. In *Biology, Pest Status and Control Measure Relationships of Sugarcane Insect Pests* (Edited by A. J. M. Carnegie and D. E. Conlong). Proceedings of the Second Entomology Workshop of the International Society of Sugarcane Technologists. S.A.S.A. Experiment Station. ISBN 1-874903-10-7.

Mohyuddin A. I. (1994b) Pest status, biology and control measures for soil pests on sugar cane in India and Pakistan.In *Biology, Pest Status and Control Measure Relationships of Sugarcane Insect Pests* (Edited by A. J. M. Carnegie and D. E. Conlong). Proceedings of the Second Entomology Workshop of the International Society of Sugarcane Technologists. S.A.S.A. Experiment Station. ISBN 1-874903-10-7.

Pemberton C. E. and Williams J. R. (1969) Distribution, origins and spread of sugarcane insect pests, pp. 1–9. In *Pests of Sugarcane* (Edited by J. R. Williams, J. R. Metcalfe, R. W. Mungomery and R. Mathes). Elsevier Publishing Company, Amsterdam.

Rajabalee A. (1994) Pest status, biology and control measures for soil pests of sugarcane (including nematodes) in Africa and close islands. In *Biology, Pest Status and Control Measure Relationships of Sugarcane Insect Pests* (Edited by A. J. M. Carnegie and D. E. Conlong). Proceedings of the Second Entomology Workshop of the International Society of Sugarcane Technologists. S.A.S.A. Experiment Station. ISBN 1-874903-10-7.

Reagan T. E. (1994) Pest status, biology and control measures of sugarcane sapsuckers in the North American sugarcane growing regions. In *Biology, Pest Status and Control Measure Relationships of Sugarcane Insect Pests* (Edited by A. J. M. Carnegie and D. E. Conlong). Proceedings of the Second Entomology Workshop of the International Society of Sugarcane Technologists. S.A.S.A. Experiment Station. ISBN 1-874903-10-7.

Samoedi D., Allsopp P. G. and Kuniata L. (1994) Pest status, biology and control measures for soil pests of sugarcane in the Australian, Indonesian and Papua New Guinean Regions. In *Biology, Pest Status and Control Measure Relationships of Sugarcane Insect Pests* (Edited by A. J. M. Carnegie and D. E. Conlong). Proceedings of the Second Entomology Workshop of the International Society of Sugarcane Technologists. S.A.S.A. Experiment Station. ISBN 1-874903-10-7.

Sosa O. (1994) Soil pests of sugarcane in North America. In *Biology, Pest Status and Control Measure Relationships of Sugarcane Insect Pests* (Edited by A. J. M. Carnegie and D. E. Conlong). Proceedings of the Second Entomology Workshop of the International Society of Sugarcane Technologists. S.A.S.A. Experiment Station. ISBN 1-874903-10-7.

Stevenson G. C. (1965) *Genetics and the Breeding of Sugarcane.* Longmans, London. 284 pp.

Suasa-ard W. and Charernsom K. (1994) Pest status, biology and effective control measures of sugarcane sapsuckers in South East Asia. In *Biology, Pest Status and Control Measure Relationships of Sugarcane Insect Pests* (Edited by A.

J. M. Carnegie and D. E. Conlong). Proceedings of the Second Entomology Workshop of the International Society of Sugarcane Technologists. S.A.S.A. Experiment Station. ISBN 1-874903-10-7.

Identifying Biocontrol Opportunities for Cowpea Pests

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Abstract—The feasibility of biological control against two major cowpea insect pests, the bean flower thrips *Megalurothrips sjostedti* Trybom and the pod borer *Maruca testulalis* Geyer, is assessed through the analysis of the factors responsible for their noxiousness. The study investigates the origin of the pest and compares the impact of biotic mortality factors on both cowpea and alternative host plants.

Megalurothrips sjostedti lacks efficient antagonists in Africa, whereas in Southeast Asia, species of the same genus are generally kept under control by eulophid parasitoids *Ceranisus* sp. Several antagonists of *M. testulalis* have been identified. Their impact, however, is not sufficient to prevent pest outbreak and subsequent damage to the crop. Based on taxonomic and ecological considerations, it is hypothesised that both pests are native to Southeast Asia. Hence, recommendations for foreign exploration of natural enemies are given.

Key Words: cowpea, *Megalurothrips sjostedti, Maruca testulalis,* natural enemies

Introduction

The bean flower thrips *Megalurothrips sjostedti* (Trybom) (Thysanoptera, Thripidae), and the pod borer *Maruca testulalis* Geyer (Lepidoptera, Pyralidae) are among the most serious pests of cowpea *(Vigna unguiculata* Walp.) in West Africa (overview by Singh et al., 1990).

In the past, host plant resistance combined with moderate chemical control was perceived as the most promising control option for cowpea pests (Singh et al., 1978; Jackai et al., 1985), while biological control received marginal attention only. A possible reason for not choosing biocontrol as a primary control option was the inefficacy of the numerous natural enemies already present in the cowpea agroecosystem (Jackai and Daoust, 1986; Singh et al., 1990). There was, in fact, "no clear evidence of a dominant role played by the parasites and predators of the major insect pests" (Singh et al., 1990). This argument, however, is valid only if we presuppose a long history of coevolution between the plant, the pests, and their natural enemies. Consequently, this assumption postulates that the key cowpea pests are indigenous to Africa: in fact, none of the important pests found on cowpea has ever been described as an exotic organism there. It is only recently that Tamò et al. (1993b), based on results from on-going ecological studies concerning *M. sjostedti,* started to question the presumed indigenous origin of this pest. This is in fact one of the most crucial questions in biocontrol. How can we conclude that biological control in cowpea is not efficient, because pest outbreaks are still very high in spite of the presence of a variety of natural enemies, if we do not know about the origin of the pest? If the pest is indeed of foreign origin, it is likely to have been introduced without the antagonists that keep its population under control in its native region. In its new environment, this introduced pest may be attacked by antagonists, which, however, are not efficient, because they primarily attack other organisms. Thus, what we have been describing as inefficient biocontrol in cowpea is most probably the unsuccessful attempt to control an exotic organism by poorly or non adapted natural enemies.

With this paper, we want to assess the opportunities for biological control interventions in cowpea. Hence, the origin of two pests under study is the first criterion which is used to evaluate the feasibility of biocontrol.

Now one can also argue that the impact of natural enemies on cowpea pests is low because the cowpea field is an unstable, short duration agro-ecosystem, and not because of their foreign origin. There is, in fact, a wide variety of alternative host plants which represent ecologically more stable environment for both the pest and the natural enemies, and where we could expect to find higher biotic mortality rates than on cowpea (Taylor, 1978; Tamo et al., 1993b). The presence, and particularly the efficacy of antagonists on naturally occurring alternative host plants is therefore considered as the second criterion to assess the feasibility of biocontrol. This gives us additional information whether the pest has closer interactions with a natural environment in which it is supposedly coevolved (probable indigenous origin), or whether the interactions are neutral and therefore similar to what we encounter in the cowpea field (probable exotic origin).

We consider this work as an important contribution towards identifying the causes of the imbalances responsible for pest outbreaks in cowpea, and incorporating biological control with compatible techniques for an ecologically sustainable pest management.

The Bean Flower Thrips *Megalurothrips sjostedti*

Megalurothrips sjostedti was recorded for the first time in East Africa on Mount Kilimanjaro in the flowers of an undescribed leguminous plant in 1905 (Trybom, 1908). Besides the African continent, this insect has never been recorded elsewhere (Palmer, 1987). At first glance, these two facts let suppose that *M. sjostedti* is of African origin. However, the recent revision of the taxonomy and of the worldwide species distribution of the genus *Megalurothrips* by the latter author (Palmer, 1987), although describing *M. sjostedti* as an African species, suggests its possible foreign origin. The first consideration regards the distribution of the different *Megalurothrips* species: while *M. sjostedti* is the only species of this genus present on the African continent, other six distinct species are uniquely found in tropical Asia. Following basic principles of evolution, one could conclude that, with great probability, the centre of origin of the genus *Megalurothrips* is tropical Asia. To strengthen this argument, *M. sjostedti* is the only species which is considered a very important crop pest in Africa, whereas none of the Asian species are important agricultural pests (Kalshoven and van der Vecht, 1950; Litsinger et al., 1978; Singh et al., 1990). Flower thrips have coevolved with their host plants as pollinators (Grinfel'd, 1959, cited by Lewis, 1973), and it would be surprising to find them as pests in their natural habitat. For example, *M. typicus*, the species which has been described as the most close to *M. sjostedti*, is a rarely collected species (Palmer, 1987), and is not present on commonly sampled legume flowers. Likewise, if present in Asia, *M. sjostedti* might be confined, e.g. by interspecific competition, to host plants of no agricultural importance, and might have never been sampled for this reason. As an example, while studying the seasonal flowering of the dipterocarp forest, Appannah (1993) recorded several flower thrips as major pollinators in the Malaysian rain forest. Among them, he collected specimens of *Megalurothrips*, which were not identified at the species level (Appanah, Forest Research Institute of Malaysia, 1994, pers. commun.).

Mortality inflicted by natural enemies is one of the most important factors regulating pest populations under tropical climates, and we would expect to find well adapted antagonists if M. *sjostedti* was of African origin. Although, the list presented in Table 1 shows a quite substantial number of natural enemies for *M. sjostedti,* as compared to antagonists known to attack other flower thrips (e.g. Lewis, 1973), the only quantitative data available for both parasitoids and pathogens indicate a negligible influence on the population dynamics of *M. sjostedti* (Tamò et al., 1993b). Mortality rates due to the activity of egg parasitoids of the genus *Megaphragma* (Hymenoptera: Trichogrammatidae), although reaching peaks above 30% on

Table 1. Natural enemies of *Megalurothrips sjostedti* [E: egg; L: larva; A: adult]

Organism	Stage affected	Country	Source
Parasitoids			
Hymenoptera			
Eulophidae			
Ceranisus menes	L	Benin	Tamò et al. (1993b)
Trichogrammatidae			
Megaphragma sp.	E	Benin	Tamò et al. (1993b)
Oligosita sp.	E	Benin	Tamò et al. (1993b)
Predators			
Acari			
Phytoseiidae			
Iphyseius sp.	E	Benin	Tamò et al. (1993b)
Coleoptera			
Coccinellidae			
Cheilomenes sulphurea	L	Benin	Tamò et al. (1993b)
Staphilinidae			
Paederus sabeus	L	Benin	Tamò et al. (1993b)
Hemiptera			
Anthocoridae			
Orius sp.	E, L	Nigeria	Matteson (1982), Rösingh (1980)
	L	Benin	Tamò et al. (1993b)
Pathogens			
Fungi			
Conidiobolus sp.	L	Benin	Tamò (unpublished data)
Entomophthora sp.	L	Nigeria	Salifu (1986)
Erynia sp.	L	Benin	Tamò (unpublished data)
Verticillum sp.	L	Benin	Tamò et al. (1993b)

cowpea and 53% on one alternative host plant, *Pueraria phaseoloides* (Leguminosae: Fabaceae), are inconsistent throughout the season and differ greatly from region to region. A reason for this inefficacy can be sought in the ephemeral character of *Megaphragma* sp., the smallest insects ever known, whose movements and survival on the host plant are greatly influenced by the surrounding microclimate. Also, *Megaphragma* spp. are known to be rather unspecific. They parasitise several thrips of the Terebrantia (Lewis, 1973), and *M. sjostedti* may not be the primary host.

The prospects for efficient control seem to be even less favorable for indigenous larval parasitoids of the genus *Ceranisus menes* (Tamò et al., 1993b). This parasitoid was first discovered in Benin Republic from *M. sjostedti* larvae found on an exotic shrub, *Tephrosia candida* (Leguminosae: Fabaceae). Further efforts to recover it from larvae feeding on cowpea remained largely unsuccessful. After having reared over 12,000 thrips larvae, we are now convinced that *C. menes* cannot recognise cowpea as a host plant for *M. sjostedti*. Also on naturally occurring alternative host plants, which represent a much more stable ecosystem than the cowpea field, the low parasitism rates (Table 2) indicate that *M. sjostedti* does not have efficient antagonists.

In the lab, experiments conducted in small rearing jars under no escape conditions revealed a parasitisation rate of about 15% only, indicating low host acceptance. Often, the parasitoid inside the attacked larva could not complete its life cycle (Tamò, unpublished data). All this suggests that the parasitoid is more likely to be associated with other thrips rather than with *M. sjostedti,* and that it is probably more attracted by *T. candida* than by cowpea or by native alternative host plants (see Table 2).

In Southeast Asia, the suspected area of origin of *M. sjostedti,* larval parasitoids of the genus *Ceranisus,* such as *C. femoratus* (Gahan), *C. vinctus* (Gahan) (Gahan, 1932; Fullaway and Dobroscky, 1934), and *C. menes* (Walker) (Chang, 1990) seem to play a major role in reducing the population of closely related thrips species such as *Megalurothrips usitatus* (Bagnall).

Experimental evaluations of the interactions between a hypothetical parasitoid, the larval population of *M. sjostedti,* and the yield of cowpea have been conducted using simulation models (Tamò et al., 1993a). Simulation results show that a parasitoid able to kill 35% of the larval population could already have a beneficial effect in the cowpea field.

Although *M. sjostedti* was recorded on the African continent 90 years ago, the above findings do not exclude its possible foreign origin. This hypothesis

Table 2. Parasitism rates of larvae of *Megalurothrips sjostedti* and *Maruca testulalis* collected on major alternative host plants in Benin (Tamò and Arodokoun, unpublished data)

Host plant	% larval parasitism *M. sjostedti*	 *M. testulalis*
Piliostigma thonningii	0.30	-
Lonchocarpus sericeus	1.71	1.87
Pterocarpus santalinoides	3.82	20.97
Tephrosia platycarpa	-	2.38

is further strengthened by the apparent lack of co-evolution in its natural environment, as indicated by the sometimes heavy damage on the flowering structures of alternative host plants, as well as the low parasitism rates on the same plants. It seems, therefore, crucial to search for *M. sjostedti* together with effective antagonists in Southeast Asia, particularly in areas with greater species diversity such as Indo-Malaysian region. At the same time, it is imperative to test the Southeast Asian parasitoids associated with different *Megalurothrips* spp. against *M. sjostedti* on cowpea, in order to assess their potential as possible biological control candidates.

Furthermore, detailed studies need to be carried out on entomopathogenous fungi attacking *M. sjostedti* and on their use as possible control agents.

The Pod Borer *Maruca testulalis* Geyer

Although, the first specimen of *M. testulalis* was found in Buenos Aires, Argentina (Geyer, 1832), the origin of this insect is uncertain (Waterhouse and Norris, 1987). *Maruca* is a small genus, comprising two other species only: *M. amboinalis* (Feld & Rog), and *M. nigroapicalis* (De Joannis). These two other species have been observed exclusively in the Indo-Malaysian and Tonkin area, the latter was never found again after the first description (Ghesquière, 1942). Also, the taxonomy of this genus is still unclear and needs to be revised. Taylor (1967) mentioned that for some time several species of the genus were considered as a complex, and later on they were all synonymised under the species *M. testulalis*.

More recently, the Indo-Malaysian region was given as the most probable area of origin of the genus *Maruca*, including *M. testulalis* (Munroe, 1993, Ottawa, Canada, pers. commun.). In this region, *M. testulalis* is known as a minor pest only (Kalshoven and van der Vecht, 1950). The same authors indicate a larval parasitoid, *Phanerotoma philippiniensis*, and a pupal parasitoid, *Bassus* sp. (see Table 3), as the natural enemies responsible for this low occurrence of the pest. In Africa, parasitism rates on cowpea are generally low, mostly between 5 and 15%, (e.g., Taylor, 1967; Okeyo-Owuor et al., 1991) and they cannot cope with pest population outbreaks. As for *M. sjostedti*, the parasitism rates are not significantly higher on naturally occurring alternative host plants (see Table 2) as compared to the above parasitism rates on cowpea. Again, this information could lead us to hypothesise that *M. testulalis* is an exotic pest in Africa, and thus become a target for classical biological control. The next logical step would be to test both the efficacy and specificity of *M. testulalis* parasitoids from Southeast Asia, and introduce the most promising ones into Africa. Still, the long list presented in Table 3 indicates that there are already many parasitoids in Africa, and we would need careful ecological studies before any releases are made. Also, Table 3 lists several parasitoids recorded from Africa, only a few from Asia, and none from South America where *M. testulalis* was first discovered. On the one hand, this reflects the fact that *M. testulalis* is economically more important in Africa as compared to other regions, and consequently was better investigated there. On the other hand, one could be tempted to conclude that *M. testulalis* is not a big problem in South America because it is kept under control by antagonists, whose identity is not known yet. Evidently, the actual knowledge about the regional distribution and importance of natural

Table 3. Parasitoids of *Maruca testulalis* [E: egg; L: larva; P: pupa; A: adult]

Parasitoid	Stage affected	Country	Source
Diptera			
Muscidae			
Musca domestica f *callara*	L	Nigeria	Taylor (1967)
Tachinidae			
Argyrophylax albincisa	L	Puerto Rico	Ghesquière (1942)
Pseudoperichaeta laevis	L	Nigeria	Usua and Singh (1979), Efueh (1991)
Thelairosoma palposum	L	Nigeria	Usua and Singh (1979), Ezueh (1991)
undetermined	P	Kenya	Okeyo-Owuor et al. (1991)
Hymenoptera			
Braconidae			
Agathis sp.	L	India	Vishakantaiah and Babu (1980)
Apanteles sp.	L	Puerto Rico	Ghesquière (1942)
	L	Kenya	Okeyo-Owuor et al. (1991)
Bassus sp.	P	Indonesia	Kalshoven and van der Vecht (1950)
Bracon sp.	L, P	Kenya	Okeyo-Owuor et al. (1991)
Braunsia sp.	L	Nigeria	Taylor (1967), Usua and Singh (1979), Ezueh (1991)
	P	Kenya	Okeyo-Owuor et al. (1991)
Cendria paradoxa	L	Fiji, Burma	Rao et al. (unpublished data)
Chelonus sp.	L	Kenya	Okeyo-Owuor et al. (1991)
Macrocentrus sp.	L	Benin	Arodokoun (unpublished data)
Microbracon thurberiphagae	L	Puerto Rico	Ghesquière (1942)
Phanerotoma sp.	L	India	Vishakantaiah and Babu (1980)
		Nigeria	Taylor (1967), Usua and Singh 1978)
P. philippiniensis	L	Indonesia	Kalshoven and van der Vecht (1950)
Chalcididae			
Antrocephalus sp.	P	Kenya	Okeyo-Owuor et al. (1991)
Brachymeria sp.	P	Benin	Adango (1994)
Eulophidae			
Tetrastichus sp.	L	Nigeria	Usua and Singh (1979), Ezueh (1991)
T. sesamiae	P	Kenya	Okeyo-Owuor et al. (1991)
Scelionidae			
Tepenomus sp.	E	Sri Lanka	Singh et al. (1978)
Trichogrammatidae			
Trichogrammatoidaea sp.	E	Benin	Tamò (unpublished data)

enemies of *M. testulalis* presents some gaps which need to be filled before making any final assumption concerning the chances of biocontrol. Following the recommendations of the taxonomist, it is necessary to test the efficacy of parasitoids from Southeast Asia. At the same time, one should keep in mind the unsuccessful attempts at biological control cited in Waterhouse and Norris (1987), and learn from the possible causes of these failures.

Among the natural enemies not included in Table 3 there are several pathogens (Otieno et al., 1983), and particularly a nuclear polyhedrosis virus which has been observed often on diseased larvae (Tamò, 1993, IITA, Cotonou, Benin, unpublished data), and needs further investigations.

We can conclude this paper with an open question, which arises as a consequence of our foreign origin hypothesis for the two pests under study. Anthropologists and historians have reported about intensive commercial and cultural exchanges between the east coast of Africa and tropical Asia, peaking around the first millennium A.D. (e.g., Hromnik, 1981), and still continuing in modern times. However, when and how exactly these pests might have been introduced into Africa can only be speculated about, although there is hope that molecular taxonomy may one day help to answer this question.

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References

Adango E. (1994) Inventaire des parasitoides de *Maruca testulalis* (Geyer) (Lepidoptera: Pyralidae) en culture du niebe *(Vigna unguiculata* L. Walp.) au sud-Benin. Université Nationale du Benin, Abomèy-Calavi, Benin. 96 pp.

Appannah S. (1993) Mass flowering of the dipterocarp forest in the aseasonal tropics. *J. Biosciences* 18, 457–474.

Chang N. T. (1990) *Ceranisus menes* (Walker) (Eulophidae: Hymenoptera), a new parasite of bean flower thrips, *Megalurothrips usitatus* (Bagnall) (Thripidae: Thysanoptera). *Plant Prot. Bull.* 32, 237–238.

Ezueh M. I. (1991) Prospects for cultural and biological control of cowpea pests. *Insect Sci. Applic.* 12, 585–592.

Fullaway D. T. and Dobroscky I. D. (1934) A new *Thripoctenus* parasite from the Philippines. *Proceedings of the 5th Pacific Scientific Congress Canada* 1933 5, 3439–3444.

Gahan A. B. (1932) Miscellaneous descriptions and notes on parasitic Hymenoptera. *Ann. Entomol. Soc. Am.* 25, 736–757.

Geyer (1832) *Crochiphora testulalis. Zuträge Samml. exot. Schmett.* 4, 12.

Ghesquière J. (1942) Catalogues raisonnés de la faune entomologique du Congo Belge: Lépidoptères, Microlépidoptères (2ème partie). *Annales du Musée du Congo Belge Serie III (II) Tome VII.*- 2, 121–240.

Grinfel'd E. K. (1959) The feeding of thrips (Thysanoptera) on pollen of flowers and the origin of assymetry in their mouthparts. (in Russian). *Ent. Obozr.* 38, 798–804.

Hromnik C. A. (1981) *Indo-Africa: Towards a New Understanding of the History of Sub-Saharan Africa.* Juta and Co. Ltd., Cape Town. 168 pp.

Jackai L. E. N. and Daoust R. A. (1986) Insect pests of cowpeas. *Annu. Rev. Entomol.* 31, 9–19.

Jackai L. E. N., Singh S. R., Raheja A. K. and Wiedijk F. (1985) Recent trends in the control of cowpea pests in Africa, pp. 233–243. In *Cowpea Research, Production and Utilization* (Edited by S. R. Singh and K. O. Rachie). John Wiley & Sons, Chichester.

Kalshoven L. G. E. and Vecht J. van der (1950) *De plagen van de culturgewassen in Indonesië*. 512 pp. Van Hoeve, La Haye.

Lewis T. (1973) *Thrips: Their Biology, Ecology, and Economic Importance*. Academic Press, London. 349 pp.

Litsinger J. A., Quirino C. B., Lumaban M. D. and Bandong J. P. (1978) Grain legume pest complex in rice-based cropping systems at three locations in the Philippines, pp. 309–320. In *Pests of Grain Legumes: Ecology and Control* (Edited by S. R. Singh, H. F. van Emden and T. A. Taylor). Academic Press, London.

Matteson P. C. (1982) The effects of intercropping with cereal and minimal permethrin application on insect pests of cowpeas and their natural enemies in Nigeria. *Trop. Pest Manage.* 28, 373–380.

Okeyo-Owuor J. B., Oloo G. W. and Agwaro P. O. (1991) Natural enemies of the legume pod borer, *Maruca testulalis* Geyer (Lepidoptera: Pyralidae) in small scale farming systems of western Kenya. *Insect Sci. Applic.* 12, 35–42.

Otieno D. A., Odindo M. O., Okeyo-Owuor J. B. and Sabwa D. M. (1983) Studies on legume pod borer, *Maruca testulalis* Geyer—VII. Field surveys on pathogenic micro-organisms. *Insect Sci. Applic.* 4, 211–215.

Palmer J. M. (1987) *Megalurothrips* in the flowers of tropical legumes: A morphometric study, pp. 480–495. In *Population Structure, Genetics and Taxonomy of Aphids and Thysanoptera* (Edited by J. Holman, J. Pelikan, A. G. F. Dixon and L.Weismann). The Hague, SPB Academic Publishing.

Rösingh C. (1980) Untersuchungen uber die Resistenz der Kuherbse, *Vigna unguiculata* (L.) Walp., gegen *Megalurothrips sjostedti* (Trybom) (Thysanoptera: Thripidae). PhD thesis, University of Hohenheim, Germany.

Salifu A. B. (1986) Studies on aspects of the biology of the flower thrips, *Megalurothrips sjostedti* (Trybom) with particular reference to resistance in host cowpea, *Vigna unguiculata* (L.) Walp. PhD thesis, Wye College, University of London, England.

Singh S. R., Jackai L. E. N., Dos Santos J. H. R. and Adalla C. B. (1990) Insect pests of cowpea, pp. 43–89. In *Insect Pests of Tropical Food Legumes* (Edited by S. R. Singh). John Wiley & Sons, Chichester.

Singh S. R., Emden H. F. van and Taylor T. A. (1978) The potential for the development of integrated pest management systems in cowpea, pp. 329–335. In *Pests of Grain Legumes: Ecology and Control* (Edited by S. R. Singh, H. F. van Emden and T. A. Taylor). Academic Press, London.

Tamò M., Baumgartner J. and Gutierrez A. P. (1993a) Analysis of the cowpea *(Vigna unguiculata* Walp.) agro-ecosystem in West Africa: II. Modelling the interactions between cowpea and the bean flower thrips *Megalurothrips sjostedti* (Trybom). *Ecological Modelling* 70, 89–113.

Tamò M., Baumgärtner J., Delucchi V. and Herren H. R. (1993b) Assessment of key factors responsible for the pest status of the bean flower thrips *Megalurothrips sjostedti* (Thysanoptera, Thripidae) in West Africa. *Bull. ent. Res.* 83, 251–258.

Taylor T. A. (1967) The bionomics of *Maruca testulalis* Gey. (Lepidoptera: Pyralidae), a major pest of cowpea in Nigeria. *J. West Africa Sci. Assoc.* 12, 111–129.

Taylor T. A. (1978) *Maruca testulalis:* An important pest of tropical grain legumes, pp. 193–200. In *Pests of Grain Legumes: Ecology and Control*

(Edited by S. R. Singh, H. F. van Emden and T. A. Taylor). Academic Press, London.

Trybom F. (1908) Physapoda 3, 1–22. In *Wissenschaftliche Ergebnisse einer Schwedischen~Zoologischen Expedition nach dem Kilimandjiaro, dem Meru, und den umgebenden Masaisteppen Deutsch-Ostafrica, 1905-1906* (Edited by Y. Sjöstedt).

Usua E. J. and Singh S. R. (1979) Parasites and predators of the cowpea pod borers, *Maruca testulalis* (Lepidoptera: Pyralidae). *Nigerian J. Ent.* 3,100–102.

Vishakantaiah M. and Babu C. J. J. (1980) Bionomics of the webworm, *Maruca testulalis* (Lepidoptera: Pyralidae). *Mysore J. Agric. Sci.* 14, 529–532.

Waterhouse D. F. and Norris K. R. (1987) *Biological Control. Pacific Prospects.* Melbourne, Inkata Press. 454 pp.

Haematophagus Arthropods as Vectors of Parasitic Diseases and their Population Management

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Anopheles Mosquitoes: Parasite–Vector Interactions, Host–Vector Interactions and Population Management

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Abstract—Although some *Anopheles* species are important in the transmission of filariasis and arboviruses, this genus of mosquitoes is rightfully known for its exclusive role as vector of the human and simian malarias. Malaria, and for that matter, the human filariases, are distributed essentially throughout the tropical and sub-tropical regions of the world. Malaria is responsible for significant morbidity and mortality, particularly among children in sub-Saharan Africa. In this area, estimates of symptomatic malaria range from one to five episodes per child per year, while deaths attributable to malaria are estimated at between 0.5 and 2.0 million annually. Malaria remains intractable throughout most of its range, in part due to the evolution of behaviours maximising contact of some *Anopheles* vectors with the human host while minimising the risk of mosquito mortality. Interactions between parasite and vector, and between vector and human host, influence disease transmission patterns while at the same time offering opportunities for the development of new intervention strategies. Population management of *Anopheles* vectors has become increasingly important with the rapid development of drug-resistant malaria strains. The recognition that disease caused by malaria may be dose as well as strain dependent has given impetus to vector control programmes, such as the use of insecticide-treated bednets, which can reduce morbidity, and perhaps mortality, due to malaria, while not markedly impeding the development of acquired immunity. Research on host immunisation with mosquito antigens has increased following the pronounced successes seen with this approach for controlling tick populations. This line of research may offer collateral benefits, as immunisation against vector-specific antigens has been shown to provide non-specific protection against the development of malaria infection in the mosquito. Genetic manipulation of *Anopheles* vectors of disease remains on the horizon, but has exciting potential, with several interesting avenues being explored to develop workable methodologies for inserting 'favorable' genes into vector genomes, ensuring the timely activation of these genes, and 'driving' them into the target vector population. However, ecological and ethical constraints on introducing genetically altered *Anopheles* remain formidable extra-technical barriers.

Key Words: *Anopheles* mosquitoes, malaria, population management, sub-Saharan Africa

Introduction

Insects and other arthropods transmit diseases caused by bacteria, viruses, helminths and protozoan parasites, including malaria. *Anopheles* mosquitoes are recognised vectors of pathogens from each of these groups, except the bacteria. Species of *Anopheles* are involved in the transmission of animal and human filariases (Rao, 1984). Although generally not as important as some species of culicine mosquitoes, *Anopheles* are known vectors of Bancroftian filariasis in East Africa and both Bancroftian and Brugian filariasis in Asia.

Responsibility for transmission of the other two important groups of human mosquito-borne diseases, viruses and malaria, is divided nearly uniformly between the major subfamilies of the Culicidae. With but one important exception, O'nyong nyong fever, culicine mosquitoes are responsible for transmission of the viruses responsible for human disease, while anopheline mosquitoes of the genus *Anopheles* transmit the human malarias. O'nyong nyong fever emerged out of Northern Uganda in 1959 and eventually spread throughout East Africa, including Kenya (Haddow et al., 1960). Disease was characterised by headache, fever, and severe joint and back pain but, fortunately, not by mortality. Both *Anopheles funestus* Giles and *An. gambiae* Giles were identified as vectors (Corbet et al., 1961; Williams et al., 1965), while no culicine species were implicated. More recently, *Anopheles* in various parts of the world have been shown to be associated with several arthropod-borne viruses. However, none of these viruses is known to cause serious human disease.

Anopheles mosquitoes are the exclusive vectors of human malaria. Worldwide, there are about 70 species of *Anopheles* which are known vectors of malaria (Rao, 1984) and this number will surely increase as more sibling species complexes are identified in this genus. Malaria is essentially restricted to the tropical and subtropical areas of the world, with more than 40% of the world's population at some level of risk (WHO, 1993). However, the burden of disease is not distributed evenly, and more than 90% of the estimated 0. 5 billion annual cases of clinical malaria occur in Africa, nearly all in sub-Saharan regions between the 20th parallels (WHO, 1993). Most malaria mortality also occurs in Africa with estimates ranging from 0.5 to 2 million deaths yearly (Greenwood, 1990; Greenwood et al., 1991), mostly in children under 6 years of age. Nearly all mortality is associated with *Plasmodium falciparum*, the most virulent of the 4 human malarias. This species predominates in Africa, East Asia, Oceania, and Amazonia while, elsewhere, it is of minor importance. The picture of malaria worldwide is one of deterioration, due largely to increasing resistance of the parasite to available drugs, and to the failure of vector control measures.

Parasite–Vector Interactions in the Life Cycle of Malaria

The life cycle of malaria is relatively complex, requiring passage of the parasite through several organ systems and two very different hosts. Malaria sporozoites may be injected into a human when an infected female attempts to take a blood meal, although in a substantial proportion of feeds, sporozoites will not be transmitted (Rosenberg et al., 1990; Beier et al., 1991a, b; Ponnudurai et al., 1991). Most sporozoites are probably not ejected into the blood, but rather into the skin, from which they disappear within two hours (Ponnudurai et al., 1991). Furthermore, although sporozoites may number in the tens of thousands in natural infections (Rosenberg et al., 1990; Beier et al., 1991b, c), on average very few are transmitted, usually on the order of 25 or less (Rosenberg et al., 1990; Beier et al., 1991a, b; Ponnudurai et al., 1991; Beier et al., 1992a; Habluetzel et al., 1992). Furthermore, a portion of ejected sporozoites may be reingested with the host's blood (Beier M. S. et al., 1992). Successfully transmitted sporozoites enter liver parenchymal cells where they develop and undergo a form of asexual replication called schizogony. Eventually, the schizonts burst, releasing thousands of merozoites into the bloodstream, whereupon they enter red blood cells (Bruce-Chwatt, 1985). Once inside the erythrocyte, parasites begin to grow by ingesting haemoglobin and other nutrients. Eventually, these growing trophozoites undergo schizogony on a more modest scale than that seen in the liver. The bursting of infected red blood cells is associated with the classic malaria paroxysm of chills and fever. Released merozoites infect other red blood cells. Eventually, some of them differentiate into a presexual form called a gametocyte of which there are two kinds, male and female. When a mosquito secures a bloodmeal from a gametocytemic human, the gametocytes differentiate into gametes inside the mosquito midgut where fertilisation occurs. The proportion of the human population which is infective to mosquitoes and the relative importance of different age group classes to transmission may vary widely among areas holoendemic for malaria (Muirhead-Thomson, 1957; Githeko et al., 1992; Boudin et al., 1993). The fertilised gamete or ookinete is the diploid stage, during which meiosis occurs. Cross fertilisation and recombination between different strains of the same species of malaria can occur (Walker-Jonah et al., 1992; Ranford-Cartwright et al., 1993), and may be responsible for differences in infection parameters, including virulence, among strains. Soon after fertilisation, the ookinete migrates through the peritrophic membrane and the midgut epithelium and attaches to the outer wall of the gut where it becomes an oocyst. Penetration of the peritrophic membrane appears to be mediated by an ookinete chitinase, as chitinase inhibitors block infection of the midgut (Shahabuddin and Kaslow, 1994). Intensities of ookinete and oocyst infection in field-collected African *Anopheles* are similar, suggesting that the transition between the two developmental states is very efficient in nature (Beier et al., 1992b). The oocyst develops and divides asexually into thousands of haploid sporozoites (Pringle, 1965; Rosenberg and Rungsiwongse, 1991), a portion of which make their way into the mosquito's salivary glands. Recent work suggests that a proportion of oocyst-positive mosquitoes may fail to develop a salivary gland sporozoite infection (Gamage-Mendis et al., 1993). Although the salivary glands may contain tens of thousands of sporozoites, apparently only those in the common salivary duct are capable of being ejected when a mosquito salivates prior to feeding (Beier et al., 1991a; Ponnudurai et al., 1991). Additionally, sporozoites do not appear to be delivered evenly in a steady stream of saliva, but rather in clumps (Li et al., 1992; Ponnudurai et al., 1991; Rosenberg, 1991), most of which are deposited into the skin (Ponnudurai et al., 1991). It is generally agreed that sporozoite-infected mosquitoes become less infective as sporozoites age (Boyd et al., 1936; Porter et al., 1954), and that the decrease in infectiousness is independent of mosquito age (Porter et al., 1954). While the drop in infectivity may be due partly to a loss of sporozoites after continuous blood and sugar feeding, it is likely that an age-dependent pathological process affecting the sporozoites themselves is of greater importance (Porter et al., 1954). The relationship between sporozoite load (total number of sporozoites in the salivary gland) and sporozoite inoculum is unclear. Most workers have found a correlation between these two parameters (Ponnudurai et al., 1989; Rosenberg et al., 1990; Beier et al., 1991a, b; Beier et al., 1992a), while others have found inoculum to be independent of load (Ponnudurai et al., 1991). This issue is important, as inoculum size is generally considered to be an important factor in determining the length of the incubation period in the host and severity of symptoms (Boyd, 1940;

Porter et al., 1954; Jeffrey et al., 1959; Greenwood et al., 1991), although this concept has recently been challenged (Lines and Armstrong, 1992). Regardless of whether high sporozoite loads are associated with larger inocula, an independent mechanism may be responsible for greater infectivity of sporozoites originating in heavily infected glands. Beier (1993) presented evidence of an inverse relationship between the amount of soluble circumsporozoite (CSP) antigen per salivary gland sporozoite, and sporozoite load. Apparently a feedback mechanism slows down secretion of CSP as sporozoite numbers increase in the glands. Since conserved CSP may provide individual sporozoites with higher energy reserves, inoculated sporozoites originating from a heavily infected gland may be more fit and "infective" (Beier, 1993). Malaria infection appears to be pathogenic to *Anopheles* in some cases, and to be completely benign in others. Apparently contradictory findings in the literature may reflect species-specific differences in susceptibility and pathology, and perhaps, artificially heavy oocyst infections in some laboratory studies. Higher mortality, in comparison to uninfected controls, has been reported for *An. stephensi* Liston infected with *P. berghei* (Gad et al., 1979), and *An. dirus* Peyton and Harrison infected with *P. cynomolgi* (Klein et al., 1982). However, other workers failed to find any effect of *P. falciparum* infection on longevity of laboratory (Robert et al., 1990) or field (Chege and Beier, 1990) populations of *An. gambiae*. Similarly, neither *P. falciparum* nor *P. vivax* infection had any effect on mortality of *An. tessellatus* Theobald (Gamage-Mendis et al., 1993). Since longevity is a major determinant of fitness, it is hard to see how susceptibility to malaria could be retained in a population in the face of such negative selection pressure.

The Interaction of *Anopheles* with the Human Host: Factors Affecting the Distribution of Mosquito Biting

Except for transfusion and needle-passaged malaria, transmission depends on the biting behaviour of *Anopheles* vectors. Several biotic and abiotic factors can influence biting behaviour and, consequently, the local distribution of malaria. In the following discussion of research on these factors, it should be borne in mind that there is some disagreement about the effect of these factors on biting.

Density of Potential Hosts

The number of people in a house has an effect on biting intensity per individual. Haddow (1942) demonstrated that more *Anopheles* females entered houses with many inhabitants than houses with few residents. However, an examination of his data reveals that although more mosquitoes were attracted into houses with larger numbers of inhabitants, the number of mosquitoes *per occupant* was lower than that seen in houses with less individuals. By extension, absolute malaria challenge per person is probably lower in houses with more residents.

Size of the Host

Muirhead-Thomson (1951) showed that female *An. albimanus* Wiedemann, *An. bellator* Dyar and Knab, and *An. aquasalis* Curry took a greater proportion of blood meals from adults than from children. Several workers have shown that *An. gambiae* are more likely to bite adults than children (Thomas, 1951; Boreham et al., 1978; Bryan and Smalley, 1978; Port et al., 1980) and that this difference is proportional to differences in the surface area of the respective hosts (Port et al., 1980). However, Clyde and Shute (1958) failed to find any size-related differences in biting by this species. Similarly, Burkot et al. (1988a) saw no selection for human host size by members of the *Anopheles punctulatus* Doenitz complex in Papua New Guinea.

Host Attractiveness

Little is known about differences in personal attractiveness among individuals to *Anopheles*. However, real differences may well have an important local effect on biting. In The Gambia, Lindsay et al., (1993) found significant differences in attractiveness among volunteers sleeping in experimental houses with veranda traps. Interestingly, individuals who attracted large numbers of mosquitoes into their houses were not necessarily fed on by those mosquitoes. Attractiveness may also be influenced by malaria infection in acutely ill persons with fever, if it can be shown that *Anopheles* respond to local temperature gradients. Other mosquitoes have been shown to be differentially attracted to test subjects with warmer skin (Smart and Brown, 1956). Recent advances allowing DNA 'fingerprinting' of the blood in engorged mosquitoes will help to evaluate the importance of personal attractiveness (Gokool et al., 1993; Hawley and Budowle, 1993).

Host Defensive Behaviour

Mosquito densities may influence host defensive behaviour, particularly in areas of intense biting pressure, such as those associated with some irrigation schemes. Feeding success by the mosquito *Culex nigripalpis* Theobald on birds was inversely correlated with mosquito density, and this effect was associated with levels of host defensive behaviour (Edman et al., 1972). Several studies have shown that blood meal size and feeding success are reduced when mosquitoes are offered unrestrained (i.e. defensively competent) hosts compared to when they have access to restrained hosts (Edman et al., 1974; Klowden and Lea, 1979; Waage and Nondo, 1982). Increased defensive behaviour is a determinant of the rate of interrupted feeding (Lenahan and Boreham, 1976; Davies, 1990), which in turn could influence transmission parameters. Interrupted feeding due to host defensive behaviour may increase the rate of multiple feeding in a vector population. In areas endemic for malaria, multiple host contacts may increase the chances for recombination events between different malaria strains (Davies, 1990). Alternatively, an increased rate of multiple feeding may actually reduce both mosquito to human and human to mosquito transmission by reducing either sporozoite inoculum size or the number of ingested gametocytes (Davies, 1990).

Host Infection Status

Infection of the host may influence feeding success, either by reducing or eliminating normal defensive behaviour in acutely sick hosts, or by parasite-mediated changes in host physiology, particularly haemostasis. Malaria caused a decrease in defensive behaviour in infected mice making them easier to feed on than uninfected mice (Day et al., 1983; Day and Edman, 1983). Furthermore, periods of increased feeding success of mosquitoes corresponded with periods of peak gametocytemia in the mice (Day and Edman, 1983). Malaria may also alter host haemostasis, affecting feeding proficiency of mosquitoes. In a rodent model, mosquitoes fed more rapidly on anaesthetised mice that were infected with *Plasmodium chabaudi* than on unanaesthetised mice which were uninfected, and this effect was attributed to a parasite-dependent thrombocytopenia in the host, affecting clotting time (Rossignol et al., 1985). Such an effect would appear to benefit both the parasite and the vector. Faster acquisition of blood would presumably reduce the chances of eliciting a host defensive response, which may drive away, or perhaps even kill, the mosquito. A field study in Papua New Guinea looked for evidence of such an effect in human malaria, but found that *Anopheles* did not feed preferentially on parasitemic versus non-parasitemic individuals (Burkot et al., 1989).

Vector Infection Status

There is an increasing body of evidence suggesting that parasites can modify the blood-feeding behaviour of the vector. Mosquitoes secrete a variety of compounds when salivating prior to blood feeding (Titus and Ribeiro, 1990; James and Rossignol, 1991). Among these are anti-haemostatic agents which maximise blood flow at the site of a bite. One of these, salivary apyrase, a salivary gland enzyme, appears to be critical to the blood-feeding success of some mosquito species. Salivary apyrase is injected when the mosquito probes the host, and acts by interfering with host haemostasis, by inhibiting platelet aggregation at the site of a bite (Ribeiro et al., 1984). This insures optimal blood flow by promoting the formation of a haematoma, resulting in the quick acquisition of a bloodmeal by the mosquito. *Aedes aegypti* (Linneaus) mosquitoes infected with *Plasmodium gallinaceum* probed on anaesthetised hosts for a longer time than did their uninfected counterparts, and this reduced feeding efficiency was associated with a loss of salivary apyrase activity due to sporozoite-induced salivary gland pathology (Rossignol et al., 1984). In different *Anopheles* species, salivary apyrase content was inversely correlated with the time needed to secure a bloodmeal (Ribeiro et al., 1985). Increased time spent probing on a host may elicit defensive reactions in response to an immediate hypersensitivity reaction (Ribeiro, 1988). Mosquitoes may fly off to look for another host, increasing the probability of multiple host contacts per gonotrophic cycle. Recently, Cupp et al. (1994) showed that *An. gambiae,* the major vector of malaria in Africa, also has substantial levels of apyrase, and a recent study suggests that feeding success of this species is also effected by malaria sporozoite infection (Wekesa et al., 1992). In that study, wild *An. gambiae* from western Kenya were captured while they attempted to feed on a human. Mosquitoes were then allowed to feed individually on an anaesthetised hamster, and behaviour was recorded for a ten minute period. The following morning mosquitoes were dissected and salivary glands were examined for the presence of sporozoites. Infected mosquitoes probed significantly more often and for a significantly longer time than did uninfected ones (Wekesa et al., 1992). Both responses may lead to interrupted feeding and an increase in multiple host contacts by infected mosquitoes, which could cause a local increase in malaria transmission. Alternatively, interrupted feeding and multiple host contacts may reduce malaria transmission by diluting sporozoite inocula per host contact, or multiple feeding may have no effect on transmission if most sporozoites are inoculated the first time a mosquito probes (Burkot, 1988). This appears unlikely, however, as Ponnudurai et al. (1991) found that equal numbers of sporozoites were inoculated into mouse skin before and after *Anopheles* feeding was interrupted.

A recent study provided strong

evidence that multiple host contacts by infected *Anopheles* do indeed, occur in the field, and that this results in increased malaria transmission. Workers in The Gambia examined the distribution of malaria genotypes among naturally infected humans. They looked at the genotypes of malaria infections in 17 pairs of children, each pair from a single house, and compared the frequency with which identical malaria genotypes occurred in the 17 pairs with the probability of occurrence of identical malaria genotypes, given the known genotype frequencies in the local area. Many more identical strains co-occurred in the same house than would be expected by chance alone, providing strong field evidence for multiple feeding by infected *Anopheles* (Conway and McBride, 1991).

How would multiple feeding by infected *Anopheles* impact on the equation for vectorial capacity, the most important element of MacDonald's (1957) mathematical description of malaria epidemiology?

The equation for the vectorial capacity of an *Anopheles* mosquito is;

$$\text{Vectorial capacity} = ma^2p^n/\text{-}\ln p$$

where;

m is the relative density of mosquitoes and is usually variable over seasons; it appears only once in the numerator, and is, therefore, a linear function.

a, sometimes called the man biting habit, is the product of the time between bloodmeals, usually determined by the rate of egg development, and the proportion of individuals of the species being considered which feed on humans. a appears twice in the equation because a mosquito must bite once to become infected and again to transmit sporozoites, the stage infective for humans. Thus, a is a squared function in the equation, carrying more weight than m.

p represents the odds that an individual mosquito will live through one day. p is an exponential function, raised to a power equal to n, the number of days it takes for the parasite to complete development in the mosquito (i.e. the extrinsic incubation period). Thus, the vectorial capacity of any *Anopheles* species is most sensitive to changes in p. As an example, assuming an extrinsic incubation period of 12 days (a realistic period for development of *P. falciparum* in a tropical *Anopheles* species), then if some factor is able to cause a decrease in p from 0.9 to 0.7, the odds of an individual mosquito living through one day has been reduced 22%. Yet, this apparently modest reduction yields a 20-fold decrease in vectorial capacity.

With respect to multiple feeding, then, by increasing the number of host contacts or attempted feeds, per gonotrophic cycle, there is an increase in a. Since a is a squared function, the local effect on transmission could be substantial, as suggested by the results of Conway and McBride (1991).

Availability of Alternative Host Species (Zooprophylaxis)

In cases where a vector is not exclusively anthropophilic in its feeding habits, the presence of alternative host species can reduce biting pressure on humans, affecting malaria distribution. This observation gave rise to the concept of zooprophylaxis, whereby potentially infective bites are deflected from humans to animals. In Africa, a good example of a target vector for such an approach to malaria control is *An. arabiensis* Patton, which takes a considerable proportion of its meals from cows, when they are present. For example, in western Kenya, where ca. 40% of *An. arabiensis* captured indoors will have fed on cattle (Petrarca et al., 1991), malaria infection rates of *An. arabiensis* are typically low, on the order of 1% or less (Taylor et al., 1990). In Malawi, the infection rate of this species over an entire year was 5.6%, no different than that seen in the same area for Africa's principal vector, *An. gambiae* (W. Hawley, pers. commun.). Among the Luo people of western Kenya, cattle are highly prized and ubiquitous, while in the area of Malawi studied, cattle were uncommon. Similarly, Schultz (1989), working in the Philippines, showed that the physical location of an alternative host (water buffalo) affected biting pressure on humans by *Anopheles.*

Personal Protection

Personal protection may be of critical importance in its effect on mosquito biting. Repellents reduce biting intensity (Gupta and Rutledge, 1994) and can be a very useful short term strategy to reduce contact with disease vectors. Untreated bednets have been shown to reduce spleen rates due to malaria (Bradley et al., 1986; Genton et al., 1994), and average spleen size and malaria prevalence (Genton et al., 1994). In Papua New Guinea, bednets reduced sporozoite and filarial rates in *Anopheles* mosquitoes, but had no effect on human malariometric parameters (Burkot et al., 1990). However, Genton et al. (1994) argued that the use of untreated bednets was problematic on both the individual and community levels, because bednet users had reduced levels of antibodies to two important malaria antigens suggesting a possible loss of immunological protection, and people who did not use bednets, but who lived in a house with those who did, were at higher risk of acquiring malaria and of having an enlarged spleen than non-users who lived with non-users.

Insecticide-treated bednets are very effective at reducing biting intensity on individual users (Lindsay et al., 1991; Miller et al., 1991; Lindsay et al., 1992). However, the results of community-based trials of insecticide-impregnated bednets for malaria control have been highly variable (Sexton, 1994). Insecticide-treated cotton curtains substantially reduce biting by *Anopheles* (Procacci et al., 1991), as do treated curtains made of locally available materials such as sisal and woven polypropylene sacks (Curtis et al., 1992).

Type of Housing

Housing construction may influence patterns of mosquito biting and, hence, malaria transmission. Work in Sri Lanka showed that malaria cases were more likely to be associated with poorly constructed houses (Gamage-Mendis et al., 1991). People who lived in houses with incomplete walls, or with walls and roofs made of palm leaves, experienced more malaria cases than those who lived in houses with complete walls and tile roofs. In The Gambia, Lindsay and Snow (1988) demonstrated that the incidence of symptomatic malaria was significantly lower in houses with closed eaves, the space between the top of a wall and the roof, than in houses with open eaves.

Effect of Local Topographical Features and House Placement

In the literature on malaria, large areas are characterised epidemiologically by their level of malaria endemicity. For example, western Kenya is referred to as holoendemic for malaria, with perennial transmission and increasing levels of age-specific immunity in the human population. However, when a holoendemic focus of malaria is examined on a micro-epidemiological level by measuring house to house variation in malaria challenge, profound differences in biting densities of *Anopheles* and, as a result, malaria challenge, become evident.

Figure 1 shows the distribution of *Anopheles* among 38 houses over 3 months during a malaria vaccine trial in 1990 in western Kenya. Biting intensity was related to local topographical features. In this area, seasonal streams were the most important *Anopheles* larval habitat. Most breeding of mosquitoes was in association with pools of water that remained after the intense rains ended. People living near seasonal streams were exposed to many more bites than those living in more hilly areas. Thus, topography was an important determinant of biting intensity, particularly when one considers that the area shown in Fig. 1 represents an altitudinal range of less than 65 metres and a total distance of only a few kilometres.

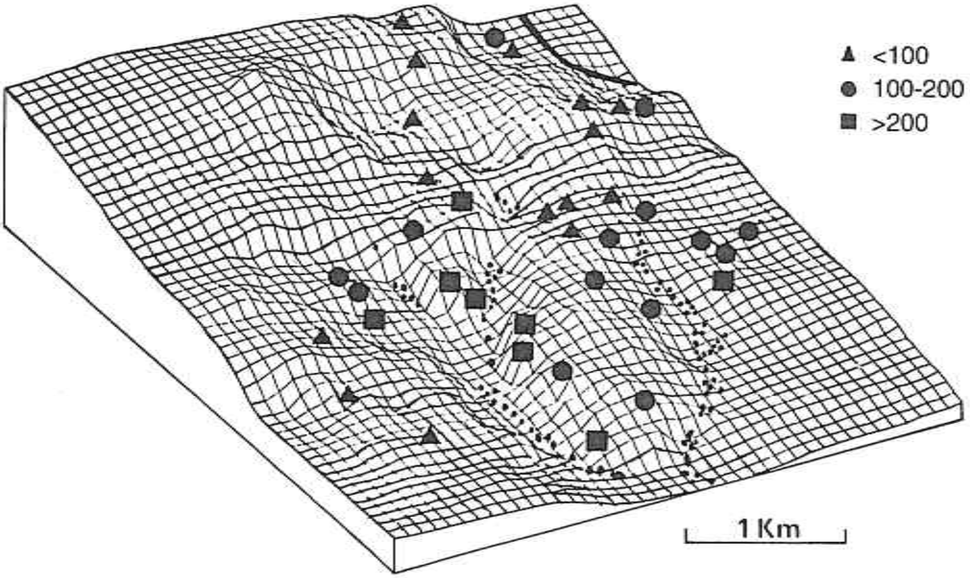

Fig. 1. Distribution of *Anopheles* females collected indoors over three months in 1990 in 38 houses in the Saradidi area of western Kenya. Small dots represent pools of water remaining along seasonal stream beds after the rains. The thick curved line represents the portion of a permanent stream that flowed through our study area.

Similar results were seen following more intense sampling during another study in 1993. Figure 2 shows the geometric daily mean number of infected *Anopheles* collected per day over 3 months from 22 houses in 5 closely situated villages. The total number of infected mosquitoes collected per house varied from a high of 193 to a low of 0, seen in two separate houses. Again, this variation occurred over very short distances. We assigned houses to one of two groups. Houses located within 20 m of an artificial pond and those less than 30 m in altitude above a stream bed were assigned to the group 'close to breeding site'. All other houses were assigned to the group 'far from breeding site'. Figure 3 shows that mosquito biting intensity was significantly related to distance from or

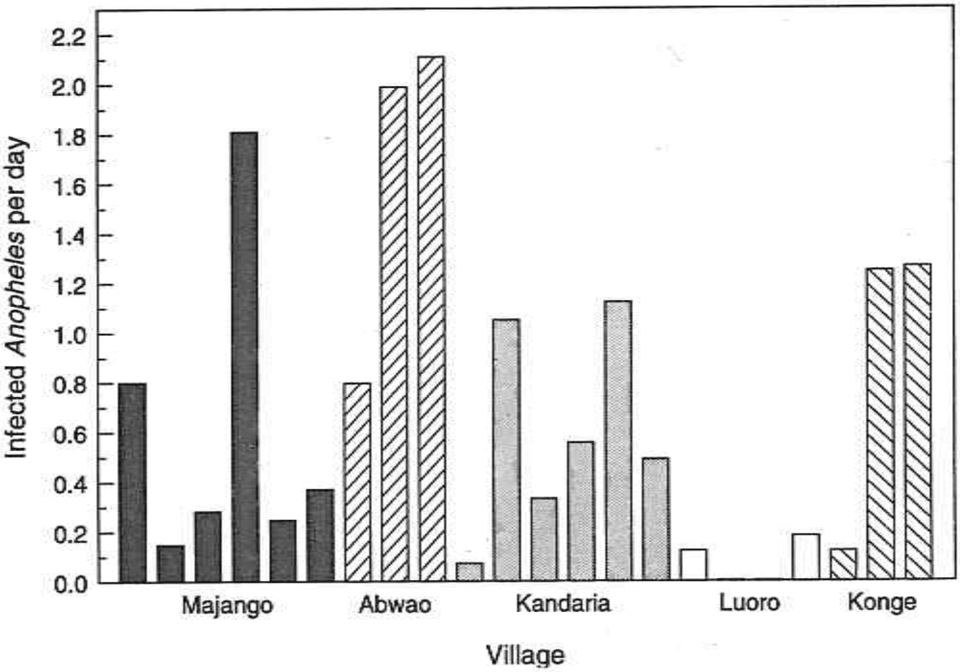

Fig. 2. Geometric daily mean number of infected *Anopheles* collected per day over three months in 1993 from 22 houses in 5 closely situated villages in western Kenya.

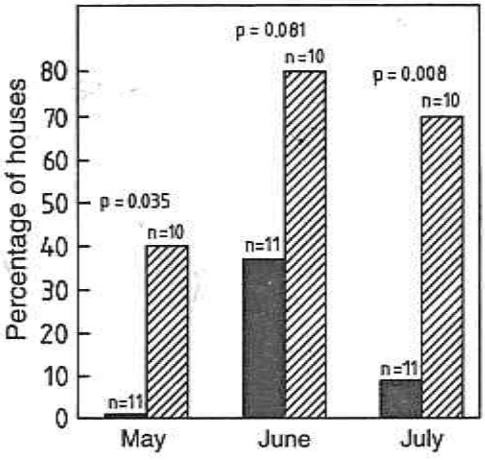

Fig. 3. Monthly percentage of houses with high densities of resting *Anopheles* females (greater than 5 per day). Striped bars (close to breeding site) represent houses located within 20 m of an artificial pond or less than 30 m above a stream bed. Solid bars represent all other houses (far from breeding site). Sample size is indicated above each bar. Results of Fisher's exact tests of monthly pairwise comparisons are indicated above each set of bars.

altitude above *Anopheles* larval habitats. Consequently, when the distribution of infected *Anopheles*, and by inference malaria challenge, is examined over short distances, we may find several levels of endemicity within a larger area characterised as classically holoendemic. This kind of data has serious implications for the design and interpretation of smallscale immunology and vaccine studies.

A few other studies have presented evidence for considerable variation in malaria over short distances. Burkot et al. (1987) and Burkot et al. (1988b) found substantial differences in entomological inoculation rates of malaria among villages located within a 22 km radius of Madang, Papua New Guinea, and these differences were reflected in the large variation in malaria incidence in humans (Cattani et al., 1986). In The Gambia, local variation in prevalence of malaria was seen by Bradley et al. (1986), and in prevalence and incidence of malaria by Greenwood (1989). Strickland et al. (1987) also found similar variation over short distances among four villages in Pakistan. The phenomenon of substantial variation within areas holoendemic for malaria may be more common than is recognised, depending on local differences in cultural practices, topographical features, innate genetic differences among ethnic groups, personal allocation of resources, and other, more obscure, causes.

Prospects for Control of *Anopheles* Vector Populations

In general, the malaria situation is deteriorating worldwide, largely a result of rapid selection for parasite resistance to drugs. As a result, attention has returned to developing methods for controlling vector populations, with scientific interest focusing on three distinct approaches to this problem; development of anti-vector vaccines, genetic manipulation of vector populations, and field interventions with existing technologies.

Immunisation with Mosquito Antigens

The concept of effecting immunologically mediated control of vector populations has been validated by recent successes against tick species (reviewed by Kay and Kemp, 1994). High levels of tick control due to increased mortality and reduced fecundity have been seen in tick populations fed on cattle immunised with homologous tick body parts. Similar research efforts directed against malaria vectors have been few with varying results. Dubin et al. (1948) found no effect on female *An. quadrimaculatus* Say which fed on rabbits immunised with homologous antigen. However, Alger and Cabrera (1972) reported increased mortality of *An. stephensi* after feeding on immunised rabbits, and feeding on rabbits immunised against *An. tessellatus* body parts reduced fecundity, but had no effect on mortality of *An. tessellatus* (Ramasamy et al., 1992). Ramasamy and Ramasamy (1990) found that *An. farauti* Laveran females which fed on immunised mice actually had lower mortality than that of controls. Billingsley (1994) has reviewed potential mosquito antigens being considered for vector and disease control. These include midgut enzymes, glycosylated molecules on midgut epithelium, which may be receptors for malaria parasites, midgut ATPases, and extracellular matrix molecules of the basal lamina (Billingsley, 1994). Billingsley (1994) also warned that, since mosquitoes imbibe very small quantities of blood compared to ticks, the antibody response to any antigen would need to be very strong in order to have a significant effect.

Interestingly, some studies have reported non-specific protection against malaria infection in mosquitoes fed on the blood of rodents immunised with mosquito body parts. *Anopheles farauti* females which fed on mice immunised with homologous mosquito midgut antigens developed less *P. berghei* oocysts than females which fed on infected, non-immunised mice (Ramasamy and Ramasamy, 1990). Recently, Lal et al. (1994) reported that immunisation of mice with *An. stephensi* midgut homogenates retarded oocyst and sporozoite development of *P. berghei* in mosquitoes which subsequently fed on mosquito immune sera. Multiple feeds increased this negative effect on malaria development. Such an effect could greatly reduce the vectorial capacity of an *Anopheles* species, since it increases the value of **n**, the extrinsic incubation period.

Manipulation of the Mosquito Genome

The development of sophisticated techniques in molecular genetics has given new life to the idea of genetic control of insect vectors. A few groups are working on manipulation of the mosquito genome with the aim of introducing deleterious genes into vector populations. The approach here is to find appropriate mechanisms for (1) identifying and cloning a favorable gene or genes (for example, refractoriness to malaria), (2) inserting the gene into the genome of the target mosquito, (3) identifying promoter gene sequences in the mosquito genome so that the introduced gene can be expressed, and (4) developing a mechanism for driving the gene throughout the target mosquito population (Besansky and Collins, 1992).

Although potential genes of *Anopheles* have been discussed as appropriate targets for genetic manipulation, none has so far been cloned. Targeting genes for refractoriness to malaria ('vector competence genes') may be difficult. Curtis (1994a) reviewed the work on development of *Anopheles* strains which are refractory to malaria infection. Unfortunately, in all of the systems analysed to date, refractoriness has been multifactorial, making identification, cloning, and insertion of several genomic elements necessary. Other possible strategies include manipulating genes which control mosquito development, enhancing mosquito immune system genes, corrupting insecticide resistance genes (Crampton et al., 1994), and introducing genes for zoophily (Curtis, 1994a). However, for some of these scenarios it seems likely that selective pressures would necessarily reverse any initial gains. One group is working on the novel approach of cloning and inserting, into the mosquito genome, mammalian genes coding for antibody production to mosquito-specific stages of the malaria parasite, the gametes and the ookinete (Crampton et al., 1994). This would provide an *Anopheles* population with an endogenous transmission blocking capability.

Transformation of the genome of intact mosquitoes has been accomplished. Foreign genes have been inserted into the mosquito genome and expressed by adult *Anopheles* (Miller et al., 1987). However, survivorship of transformed individuals was low. Additionally, transformation was accomplished using the pUChsneo vector system derived from *Drosophila melanogaster*, and integration of foreign DNA did not result from normal p-element behaviour (Crampton et al., 1994). Thus, other transforming systems must be developed before experimental transformation of *Anopheles* populations can be effectively accomplished, and the search is on for mosquito transposable genetic elements (Crampton et al., 1994).

Once cloned and inserted into the genome, favorable genes must be activated by endogenous promotor sequences in specific tissues. As yet, no promotors have been identified in the mosquito genome (Crampton et al., 1994). It must be said, however, that the attempt to identify a suitable promoter to activate anti-gamete or anti-ookinete antibody production by transfected mosquito midgut cells (Crampton et al., 1994) seems a particularly fruitful course of inquiry, since gametes enter the midgut with a bloodmeal, at a time when much physiological activity commences (e.g. peritrophic membrane production, secretion of midgut enzymes. etc.). If expression of the inserted genes could be linked to the same promotor sequences necessary for expression of the natural gene products involved in bloodmeal digestion, then the synchronisation required to make such a system work would be realised.

Finally, mechanisms must be found to drive the introduced gene(s) throughout the targeted mosquito population. Spielman (1994) has argued convincingly that, since populations of *Anopheles* are not normally regulated by density-dependent mechanisms, genes introduced into species of this genus will need a drive mechanism similar to the transposable p-element of *Drosophila*, to force the favorable genes throughout the target population. The *Drosophila* p-element has not proved a workable system in mosquito genomes, and p-element analogues are being sought in the Culicidae. Another possible drive mechanism involves the use of Rickettsia-like organisms in conjunction with introduced genes (Besansky and Collins, 1992; Curtis, 1992). Several insects, including mosquitoes, have such maternally-inherited symbionts, and this niche is apparently empty in the anophelines (Curtis, 1992). Crosses of infected females with uninfected males are viable but the reciprocal cross produces infertile females. Thus, infection is selected for in nature, and accompanying genes should be driven into the population. Spielman (1994), however, has pointed out the likelihood that introduced genes would soon become dissociated from the symbiont when uninfected males mate with fertile infected females.

Recently, Collins (1994) argued that the rapid pace of breakthroughs in molecular genetics makes it likely that none of these problems will prove intractable. Furthermore, Crampton et al. (1994) pointed out that the relatively small genome size of *Anopheles* makes species of this genus particularly good candidates for the kind of comprehensive genetic analysis that must precede effective manipulation of the germ line. However, even if the technical problems are solved, ethical constraints and ecological complexities may render such interventions impossible (Spielman, 1994). Among the problems is one that relates back to the equation for vectorial capacity. One target for genetic manipulation is the gene(s) which controls vector competence. For example, culicines are refractory to infection with primate malarias and the genetic basis for this deficiency could conceivably be transferred to an *Anopheles* population. However, anything less than total replacement of a vector population by a strain refractory to malaria transmission will simply reduce m, the relative density of vector-competent *Anopheles*, but m is the least sensitive component of the equation, and the one which will have the smallest impact on transmission (Spielman, 1994). Additionally, spatial heterogeneity in some vector populations would limit the rate of penetration of any introduced gene (Service, 1991). Wild *An. gambiae* populations show a relatively high degree of genetic isolation over short distances (McLain and Collins, 1989) which would probably necessitate several separate releases of transgenic mosquitoes.

Insecticide-Impregnated Bednets as a Malaria Control Strategy

Insecticide-treated bednets (IBN) for control of *Anopheles* populations are currently the major vector control initiative worldwide. Curtis et al. (1992) have rightly pointed out that IBN use is "...the most important advance in malaria vector control since the introduction of house spraying". Field trials of IBN efficacy have been undertaken in ca. 35 of the 103 countries with endemic malaria (Sexton, 1994), and IBN use is a part of the national malaria control programmes of China and The Gambia.

The rapid worldwide expansion in IBN use is a direct result of a change in the perception of the function of bednets from that of personal protection device to community protection (i.e. malaria control) strategy.

Do bednets work? To date, results from IBN trials have been varied, but this is hardly a surprise considering that they have been tested in areas comprising a wide range of malaria transmission characteristics. In general, these trials have shown that IBN use reduces morbidity and/or incidence, either accompanied by a reduction in prevalence (Sexton et al., 1990; Samarawickrema et al., 1992; Beach et al., 1993; Stich et al., 1994) or with no effect on prevalence (Coosemans et al., 1992; Luxemberger et al., 1994). One study in The Gambia demonstrated a reduction in child mortality (Alonso et al., 1991), prompting a substantial World Health Organisation initiative to assess IBN use for reducing overall child mortality. To date, bednets have produced these positive results without completely impeding the development of acquired immunity, which may be crucial in the event of a breakdown in IBN use. Insecticide-treated bednets also provide protection against bed bugs (Charlwood and Dagoro, 1989), which may be an important factor in gaining community acceptance for bednet use (Curtis, 1994b).

Bednet programmes are not without their problems however. One potential problem relates to the mode of action of permethrin. Permethrin is the pyrethroid in greatest use on bednets throughout the world, having lower mammalian toxicity than does deltamethrin, whose use is largely confined to China. Permethrin, as now constituted, has a major deterrent effect on house entry by *Anopheles* (Lindsay et al., 1991; Miller et al., 1991; Curtis et al., 1992; Lindsay et al., 1992). The deterrent effect is apparently due completely to volatile compounds in the carrier in which permethrin is dissolved (Lindsay et al., 1991). Permethrin also kills as a contact insecticide, but showed negligible aerial toxicity to *Anopheles* (Miller et al., 1991). Permethrin's primary effect is not, therefore, on mosquito mortality, which would lower $\boldsymbol{p}$ in the equation for vectorial capacity, but rather on the probability of locating a bloodmeal, which will decrease $\boldsymbol{a}$. From this perspective, permethrin provides a high level of personal protection to the user and also to those in his house who do not use bednets, but may provide little protection to non-IBN users in a community. Indeed, it is possible that mosquitoes deterred from entering a house with a permethrin-treated bednet may very well search elsewhere for a meal, which may increase malaria challenge to unprotected members of the community (Miller et al., 1991). Lindsay et al. (1992) examined this potential problem by looking at the effect of permethrin-impregnated bednets on behaviour of blood seeking *Anopheles*. Mosquitoes deterred from entering houses with permethrin-impregnated nets did not enter nearby IBN-free experimental houses. However, their experimental design used 6 houses in a single row parallel to a rice field breeding site. It seems reasonable to assume that deterred mosquitoes will search elsewhere for blood, although perhaps not in houses in the immediate vicinity of those with bednets. The epidemiological consequences of deterrency remain to be determined.

An important shortcoming of most IBN combinations is that washing significantly reduces their efficacy (Miller et al., 1991; Luxemburger et al., 1994). This is a particular problem in the many areas where cooking is done inside the house, and where, for aesthetic or hygienic reasons, users wish to keep bednets clean. Bednets also do not hold up in areas of consistently high humidity, lasting only about a year in Thailand (Luxemburger et al., 1994). Constant exposure to insecticides also may select for resistance in target vector populations. While no resistance to deltamethrin has been reported after more than 5 years of extensive testing in China (Curtis, 1994b) increased resistance to permethrin has been documented for *An. gambiae* in Kenya (Vulule et al., 1994).

Finally, bednet use may be constrained by social and cultural factors (Service, 1993). Bednet ownership and use is uncommon in endemic areas, particularly in Africa. Where it does occur, it is usually associated with high densities of pest mosquitoes. In order for a bednet programme to be self-sustaining in areas where biting pressures are not high enough to prompt widespread ownership of nets, malaria must be perceived by residents as a disease important enough to justify a commitment of their resources and time in an effort to combat it. Whether malaria is, in fact, perceived as such in areas of high endemicity is a question which has not received enough attention.

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References

Alger N. E. and Cabrera E. J. (1972) An increase in death rate of *Anopheles stephensi* fed on rabbits immunized with mosquito antigen. *J. Econ. Entomol.* 65, 165–168.

Alonso P. L., Lindsay S. W., Armstrong J. R. M., Conteh M., Hill A. G., David P. H., Fegan G., De Francisco A., Hall A. J., Shenton F. C., Cham K., and Greenwood B. M. (1991) The effect of insecticide-treated bednets on mortality of Gambian children. *The Lancet* 337, 1499–1502.

Beach R. F., Ruebush II T. K., Sexton J. D., Bright P. L., Hightower A. W., Breman J. G., Mount D. L. and Oloo A. J. (1993) Effectiveness of permethrin-impregnated bednets and curtains for malaria control in a holoendemic area of western Kenya. *Am. J. Trop. Med. Hyg.* 49, 290–300.

Beier J. C. (1993) Malaria sporozoites: Survival, transmission and disease control. *Parasitology Today* 9(6) 210–215.

Beier J. C., Beier M. S., Vaughan J. A., Pumpuni C. B., Davis J. R. and Noden B. H. (1992a) Sporozoite transmission by *Anopheles freeborni* and *Anopheles gambiae* experimentally infected with *Plasmodium falciparum*. *J. Am. Mosq. Cont. Assoc.* 8, 404–408.

Beier J. C., Copeland R. S., Mtalib R. and Vaughan J. A. (1992b) Ookinete rates in afrotropical *Anopheles* mosquitoes as a measure of human malaria infectiousness. *Am. J. Trop. Med. Hyg.* 47, 41–46.

Beier J. C., Davis J. R., Vaughan J. A., Noden B. H. and Beier M. S. (1991a) Quantitation of *Plasmodium falciparum* sporozoites transmitted *in vitro* by experimentally infected *Anopheles gambiae* and *Anopheles stephensi*. *Am. J. Trop. Med. Hyg.* 44, 564–570.

Beier J. C., Onyango F. K., Koros J. K., Ramadhan M., Ogwang R., Wirtz R. A., Koech D. K. and Roberts C. R. (1991b) Quantitation of malaria sporozoites transmitted *in vitro* during salivation by wild afrotropical *Anopheles. Med. Vet. Entomol.* 5, 71–79.

Beier J. C., Onyango F. K., Ramadhan M., Koros J. K., Asiago C. M., Wirtz R. A., Koech D. K. and Roberts C. R. (1991c) Quantitation of malaria sporozoites in the salivary glands of Afrotropical *Anopheles. Med. Vet. Entomol.* 5, 63–70.

Beier M. S., Davis J. R., Pumpuni C. B., Noden B. H. and Beier J. C. (1992) Ingestion of *Plasmodium falciparum* sporozoites during transmission by anopheline mosquitoes. *Am. J. Trop. Med. Hyg.* 47,195–200.

Besansky N. J. and Collins F. H. (1992) The mosquito genome: Organization, evolution and manipulation. *Parasitology Today* 8(6), 186–192.

Billingsley P. F. (1994) Approaches to vector control: New and trusted. 2. Molecular targets in the insect midgut. *Trans. R. Soc. Trop. Med. Hyg.* 88, 136–140.

Boreham P. F. L., Chandler J. A. and Jolly J. (1978) The incidence of mosquitoes feeding on mothers and babies at Kisumu, Kenya. *J. Trop. Med. Hyg.* 81, 63–67.

Boudin C., Olivier M., Molez J.-F., Chiron J.-P. and Ambroise-Thomas P. (1993) High human malarial infectivity to laboratory-bred *Anopheles gambiae* in a village in Burkina Faso. *Am. J. Trop. Med. Hyg.* 48, 700–706.

Boyd M. F. (1940) The influence of sporozoite dosage in *vivax* malaria. *Am. J. Trop. Med.* 20, 279–286.

Boyd M. F., Stratman-Thomas W. K. and Kicthen S. F. (1936) On the duration of infectiousness in anophelines harboring *P. falciparum. Am. J. Trop. Med.* 16, 157–158.

Bradley A. K., Greenwood B. M., Greenwood A. M., Marsh K., Byass P., Tulloch S. and Hayes R. (1986) Bed-nets (mosquito-nets) and morbidity from malaria. *The Lancet* Vol. II for July, pp. 204–207.

Bruce-Chwatt L. J. (1985) *Essential Malariology*. John Wiley and Sons, New York.

Bryan J. H. and Smalley M. E. (1978) The use of ABO blood groups as markers for mosquito biting studies. *Trans. R. Soc. Trop. Med. Hyg.* 72(4), 357–360.

Burkot T. R. (1988) Non-random host selection by anopheline mosquitoes. *Parasitology Today* 4, 156–162.

Burkot T. R., Garner P., Paru R., Dagoro H., Barnes A., McDougall S., Wirtz R. A., Campbell G. and Spark R. (1990) Effects of untreated bednets on the transmission of *Plasmodium falciparum, P. vivax* and *Wuchereria bancrofti* in Papua New Guinea. *Trans. R. Soc. Trop. Med. Hyg.* 84, 773–779.

Burkot T. R., Graves P.M., Cattani J. A. Wirtz R. A. and Gibson F. D. (1987) The efficiency of sporozoite transmission in the human malarias, *Plasmodium falciparum* and *P. vivax. Bull. WHO* 65(3), 375–380.

Burkot T. R., Graves P.M., Paru R. and Lagog M. (1988a) Mixed blood feeding by the malaria vectors in the *Anopheles punctulatus* complex (Diptera: Culicidae). *J. Med. Entomol.* 25(4), 205–213.

Burkot T. R., Graves P.M., Paru R., Wirtz R. A. and Heywood P. F. (1988b) Human malaria transmission studies in the *Anopheles punctulatus* complex in Papua New Guinea: Sporozoite rates, inoculation rates, and sporozoite densities. *Am. J. Trop. Med. Hyg.* 39(2), 135–144.

Burkot T. R., Narara A., Paru R., Graves P.M. and Garner P. (1989) Human host selection by anophelines: No evidence for preferential selection of malaria or microfilariae-infected individuals in a hyperendemic area. *Parasitology* 98, 337–342.

Cattani J. A., Moir J. S., Gibson F. D., Ginny M., Paino J., Davidson W. and Alpers M. P. (1986) Small-area variations in the epidemiology of malaria in Madang Province. *Papua New Guinea Med. J.* 29, 11–17.

Charlwood J. D. and Dagoro H. (1989) Collateral effects of bednets impregnated with permethrin against bedbugs (Cimicidae) in Papua New Guinea. *Trans. R. Soc. Trop. Med. Hyg.* 83, 261.

Chege G. M. M. and Beier J. C. (1990) Effect of *Plasmodium falciparum* on the survival of naturally infected afrotropical *Anopheles* (Diptera: Culicidae). *J. Med. Entomol.* 27, 454–458.

Clyde D. F. and Shute G. T. (1958) Selective feeding habits of anophelines amongst Africans of different ages. *Am. J. Trop. Med. Hyg.* 7, 543–545.

Collins F. H. (1994) Prospects for malaria control through the genetic manipulation of its vectors. *Parasitology Today* 10(10), 370–371.

Conway D. J. and McBride J. S. (1991) Genetic evidence for the importance of interrupted feeding by mosquitoes in the transmission of malaria. *Trans. R. Soc. Trop. Med. Hyg.* 85, 454–456.

Coosemans M., Wery M., Mouchet J. and Carnevale P. (1992) Transmission factors in malaria epidemiology and control in Africa. *Mem. Inst. Oswaldo Cruz.* 87, suppl. III, 385–391.

Corbet P. S., Williams M. C. and Gillett J. D. (1961) O'nyong-nyong fever: An epidemic virus disease in East Africa. IV. Vector studies at epidemic sites. *Trans. R. Soc. Trop. Med. Hyg.* 55(5), 463–480.

Crampton J. M., Warren A., Lycett G. J., Hughes M. A., Comley I. P. and Eggleston P. (1994) Genetic manipulation of insect vectors as a strategy for the control of vector-borne disease. *Ann. Trop. Med. Parasitol.* 88(1), 3–12.

Cupp E. W., Cupp M. S. and Ramberg F. B. (1994) Salivary apyrase in African and new world vectors of *Plasmodium* species and its relationship to malaria transmission. *Am. J. Trop. Med. Hyg.* 50, 235–240.

Curtis C. (1992) Making mosquitoes harmless. *Parasitology Today* 8(9), 305.

Curtis C.F. (1994a) The case for malaria control by genetic manipulation of its vectors. *Parasitology Today* 10(10), 371–374.

Curtis C. F. (1994b) Approaches to vector control: New and trusted. 4. Appropriate technology for vector control: Impregnated bednets, polystyrene beads and fly traps. *Trans. R. Soc. Trop. Med. Hyg.* 88,144–146.

Curtis C. F., Myamba J. and Wilkes T. J. (1992) Various pyrethroids on bednets and curtains. *Mem. Inst. Oswaldo Cruz.* 87, Suppl. III, 363–370.

Davies C. R. (1990) Interrupted feeding of blood-sucking insects: Causes and effects. *Parasitology Today* 6(1), 19–22.

Day J. F. and Edman J. D. (1983) Malaria renders mice susceptible to mosquito feeding when gametocytes are most infective. *J. Parasitol.* 69(1), 163–170.

Day J. F., Ebert K. M. and Edman J. D. (1983) Feeding patterns of mosquitoes (Diptera: Culicidae) simultaneously exposed to malarious and healthy mice, including a method for separating blood meals from conspecific hosts. *J. Med. Entomol.* 20, 120–127.

Dubin I. N., Reese J. D. and Seamans L. A. (1948) Attempt to produce protection against mosquitoes by active immunization. *J. Immunol.* 58, 293–297.

Edman J. D., Webber L. A. and Kale H. W. (1972) Effects of mosquito density on the interrelationship of host behavior and mosquito feeding success. *Am. J. Trop. Med. Hyg.* 21(4), 487–491.

Edman J. D., Webber L. A. and Schmid A. A. (1974) Effect of host defenses on the feeding pattern of *Culex nigripalpis* when offered a choice of blood sources. *J. Parasitol.* 5, 874–883.

Gad A. M., Maier W. A. and Piekarski G. (1979) Pathology of *Anopheles stephensi* after infection with *Plasmodium berghei berghei. Z. Parasitenkd.* 60, 249–261.

Gamage-Mendis A. C., Carter R., Mendis C., De Zoysa A. P. K., Herath P. R. J. and Mendis K. N. (1991) Clustering of malaria infections within an endemic population: Risk of malaria associated with the type of housing construction. *Am. J. Trop. Med. Hyg.* 45(1),77–85.

Gamage-Mendis A. C., Rajakaruna J., Weerasinghe S., Mendis C., Carter R. and Mendis K. N. (1993) Infectivity of *Plasmodium vivax* and *P. falciparum* to *Anopheles tessellatus:* Relationship between oocyst and sporozoite development. *Trans. R. Soc. Trop. Med. Hyg.* 87, 3–6.

Genton B., Hii J., Al-Yaman F., Paru R., Beck H.-P., Ginny M., Dagoro H., Lewis D. and Alpers M. P. (1994) The use of untreated bednets and malaria infection, morbidity and immunity. *Ann. Trop. Med. Parasitol.* 88(3), 263–270.

Githeko A. K., Brandling-Bennett A. D., Beier M., Atieli F., Owaga M. and Collins F. H. (1992) The reservoir of *Plasmodium falciparum* malaria in a holoendemic area of western Kenya. *Trans. R. Soc. Trop. Med. Hyg.* 86, 355–358.

Gokool S., Curtis C. F. and Smith D. F. (1993) Analysis of mosquito bloodmeals by DNA profiling. *Med. Vet. Entomol.* 7, 208–215.

Greenwood B. M. (1989) Impact of culture and environmental changes on epidemiology and control of malaria and babesiosis. The microepidemiology of malaria and its importance to malaria control. *Trans. R. Soc. Trop. Med. Hyg.* 83, Suppl., 25–29.

Greenwood B. M. (1990) Population at risk. *Parasitology Today* 6(6), 188.

Greenwood B., Marsh K. and Snow R. (1991) Why do some African children develop severe malaria? *Parasitology Today* 7(10), 277–281.

Gupta R. K. and Rutledge L. C. (1994) Role of repellents in vector control and disease prevention. *Am. J. Trop. Med. Hyg.* 50 (6), suppl., 82–86.

Habluetzel A., Merzagora L., Jenni L., Betschart B., Rotigliano and Esposito F. (1992) Detecting malaria sporozoites in live, field-collected mosquitoes. *Trans. R. Soc. Trop. Med. Hyg.* 86, 138–140.

Haddow A. J. (1942) The mosquito fauna and climate of native huts at Kisumu, Kenya. *Bull. Entomol. Res.* 33, 91–142.

Haddow A. J., Davies C. W. and Walker A. J. (1960) O'nyong-nyong fever: An epidemic virus disease in East Africa. I. Introduction. *Trans. R. Soc. Trop. Med. Hyg.* 54(6), 517–522.

Hawley W. A. and Budowle B. (1993) Amplified fragment length polymorphisms (AMP-FLPS) in mosquito bloodmeals used to identify individual hosts and detect multiple feedings. Abstract. *2nd International Symposium on the Forensic Aspects of DNA Analysis.* March 29–April 2, 1993.

James A. A. and Rossignol P. A. (1991) Mosquito salivary glands: Parasitological and molecular aspects. *Parasitology Today* 7(10), 267–271.

Jeffery G. M., Young M. D., Burgess R. W. and Eyles D. E. (1959) Early activity in sporozoite-induced *Plasmodium falciparum* infections. *Ann. Trop. Med. Parasitol.* 53, 51–58.

Kay B. H. and Kemp D. H. (1994) Vaccines against arthropods. *Am. J. Trop. Med. Hyg.* 50(6), suppl., 87–96.

Klein T. A., Harrison B. A., Andre R. G., Whitmire R. E. and Inlao I. (1982) Detrimental effects of *Plasmodium cynomolgi* infections on the longevity of *Anopheles dirus*. *Mosq. News* 42(2), 265–271.

Klowden M. J. and Lea A. O. (1979) Effect of defensive host behavior on the blood meal size and feeding success of natural populations of mosquitoes (Diptera: Culicidae). *J. Med. Entomol.* 15, 514–517.

Lal A. A., Schriefer M. E., Sacci J. B., Goldman I. F., Louis-Wileman V., Collins W. E. and Azad A. F. (1994) Inhibition of malaria parasite development in mosquitoes by anti-mosquito-midgut antibodies. *Infect. Immunol.* 62(1), 316–318.

Lenaham J. K. and Boreham P. F. L. (1976) Effect of host movement on multiple feeding by *Aedes aegypti* (L.) (Diptera, Culicidae) in a laboratory experiment. *Bull. Entomol. Res.* 66,681–684.

Li X., Sina B. and Rossingnol P. A. (1992) Probing behaviour and sporozoite delivery by *Anopheles stephensi* infected with *Plasmodium bergei*. *Med. Vet. Entomol.* 6, 57–61.

Lindsay S. W., Adiamah J. H. and Armstrong J. R. M. (1992) The effect of permethrin-impregnated bednets on house entry by mosquitoes (Diptera: Culicidae) in The Gambia. *Bull. Entomol. Res.* 82, 49–55.

Lindsay S. W., Adiamah J. H., Miller J. E. and Armstrong J. R. M. (1991) Pyrethroid-treated bednet effects on mosquitoes of the *Anopheles gambiae* complex in The Gambia. *Med. Vet. Entomol.* 5, 477–483.

Lindsay S. W., Adiamah J. H., Miller J. E., Pleass R. J. and Armstrong J. R. M. (1993) Variation in attractiveness of human subjects to malaria mosquitoes (Diptera: Culicidae) in The Gambia. *J. Med. Entomol.* 30, 368–373.

Lindsay S. W. and Snow R. W. (1988) The trouble with eaves; house entry by vectors of malaria. *Trans. R. Soc. Trop. Med. Hyg.* 82, 645–646.

Lines J. and Armstrong J. R. M. (1992) For a few parasites more: Inoculum size, vector control and strain-specific immunity to malaria. *Parasitology Today* 8(11), 381–383.

Luxemburger C., Perea W. A., Delmas G., Pruja C., Pecoul B. and Moren A. (1994) Permethrin-impregnated bednets for the prevention of malaria in schoolchildren on the Thai-Burmese border. *Trans. R. Soc. Trop. Med. Hyg.* 88, 155–159.

MacDonald G. (1957) *The Epidemiology and Control of Malaria.* Oxford Univ. Press, London.

McLain D. K. and Collins F. H. (1989) Structure of rDNA in the mosquito *Anopheles gambiae* and rDNA sequence variation within and between species of the *A. gambiae* complex. *Heredity* 62, 233–242.

Miller J. E., Lindsay S. W. and Armstrong J. R. M. (1991) Experimental hut trials of bednets impregnated with synthetic pyrethroid or organophosphate insecticide for mosquito control in The Gambia. *Med. Vet. Entomol.* 5, 465–476.

Miller L. H., Sakai R. K., Romans P., Gwadz R. W., Kantoff P. and Caon

H. G. (1987) Stable integration and expression of a bacterial gene in the mosquito *Anopheles gambiae*. *Science* 237, 779–781.

Muirhead-Thomson R. C. (1951) The distribution of anopheline mosquito bites among different age groups. A new factor in malaria epidemiology. *Brit. Med. J.* i. 1114–1117.

Muirhead-Thomson R. C. (1957) The malarial infectivity of an African village population to mosquitoes (*Anopheles gambiae*); a random xenodiagnostic survey. *Am. J. Trop. Med. Hyg.* 6, 971–979.

Petrarca V., Beier J. C., Onyango F., Koros J., Asiago C., Koech D. K. and Roberts C. R. (1991) Species composition of the *Anopheles gambiae* complex (Diptera: Culicidae) at two sites in western Kenya. *J. Med. Entomol.* 28, 307–313.

Ponnudurai T., Lensen A. H. W., Gemert G. J. A. van, Bensink M. P. E. Bolmer M. and Meuwissen J. H. E. Th. (1989) Sporozoite load of mosquitoes infected with *Plasmodium falciparum*. *Trans. R. Soc. Trop. Med. Hyg.* 83, 67–70.

Ponnudurai T., Lensen A. H. W., Gemert G. J. A. van, Bolmer M. G. and Meuwissen J. H. E. (1991) Feeding behaviour and sporozoite ejection by infected *Anopheles stephensi*. *Trans. R. Soc. Trop. Med. Hyg.* 85,175–180.

Port G. R., Boreham P. F. L. and Bryan J. H. (1980) The relationship of host size to feeding by mosquitoes of the *Anopheles gambiae* Giles complex (Diptera: Culicidae). *Bull. Entomol. Res.* 70, 133–144.

Porter R. J., Laird R. L. and Dusseau E. M. (1954) Studies on malarial sporozoites. ii. Effect of age and dosage of sporozoites on their infectiousness. *Exp. Parasitol.* 3, 267–274.

Pringle G. (1965) A count of the sporozoites in an oocyst of *Plasmodium falciparum*. *Trans. R. Soc. Trop. Med. Hyg.* 59(3), 289–290.

Procacci P. G., Lamizana L., Kumlien S., Habluetzel A. and Rotigliano G. (1991) Permethrin-impregnated curtains in malaria control. *Trans. R. Soc. Trop. Med. Hyg.* 85,181–185.

Ramasamy M. S. and Ramasamy R. (1990) Effect of anti-mosquito antibodies on the infectivity of the rodent malaria parasite *Plasmodium berghei* to *Anopheles farauti*. *Med. Vet. Entomol.* 4, 161–166.

Ramasamy M. S., Srikrishnaraj K. A., Wijekoone S., Jesuthasan L. S. B. and Ramasamy R. (1992) Host immunity to mosquitoes: Effect of anti mosquito antibodies on *Anopheles tessellatus* and *Culex quinquefasciatus* (Diptera: Culicidae). *J. Med. Entomol.* 29, 934–938.

Ranford-Cartwright L. C., Balfe P., Carter R. and Walliker D. (1993) Frequency of cross-fertilization in the human malaria parasite *Plasmodium falciparum*. *Parasitology* 107,11–18.

Rao T. R. (1984) Anophelines as vectors of human and animal diseases, pp. 92–107. In *The Anophelines of India*. Malaria Research Centre, Delhi Press, New Delhi.

Ribeiro J. M. C. (1988) How mosquitoes find blood, pp. 18–24. In *The Role of Vector-Host Interactions in Disease Transmission* (Edited by T. W. Scott and Grumstrup-Scott). Miscellaneous Publications of the Entomological Society of America. Lanham, Maryland.

Ribeiro J. M. C., Rossingnol P. A. and Spielman A. (1984) Role of mosquito saliva in blood vessel location. *J. Exp. Biol.* 108, 1–7.

Ribeiro J. M. C., Rossingnol P. A. and Spielman A. (1985) Salivary gland apyrase determines probing time in anopheline mosquitoes. *J. Insect. Physiol.* 31(9), 689–692.

Robert V., Verhave J. P., and Carnevale P. (1990) *Plasmodium falciparum* infection does not increase the precocious mortality rate of *Anopheles gambiae. Trans. R. Soc. Trop. Med. Hyg.* 84, 346–347.

Rosenberg R. and Rungsiwongse J. (1991) The number of sporozoites produced by individual malaria oocysts. *Am. J. Trop. Med. Hyg.* 45(5), 574–577.

Rosenberg R., Wirtz R. A., Schneider I. and Burge R. (1990) An estimation of the number of malaria sporozoites ejected by a feeding mosquito. *Trans. R. Soc. Trop. Med. Hyg.* 84, 209–212.

Rossingnol P. A., Ribeiro J. M. C., Jungery M., Turell M. J., Spielman A. and Bailey C. L. (1985) Enhanced mosquito blood-finding success on parasitemic hosts: Evidence for vector-parasite mutualism. *Proc. Natl. Acad. Sci.* 82, 7725–7727.

Rossingnol P. A., Ribeiro J. M. C. and Spielman A. (1984) Increased intradermal probing time in sporozoite-infected mosquitoes. *Am. J. Trop. Med. Hyg.* 33(1), 17–20.

Samarawickrema W. A., Parkinson A. D., Kere N. and Galo O. (1992) Seasonal abundance and biting behaviour of *Anopheles punctulatus* and *An. koliensis* in Malaita Province, Solomon islands, and a trial of permethrin impregnated bednets against malaria transmission. *Med. Vet. Entomol.* 6, 371–378.

Schultz G. W. (1989) Animal influence on human biting rates at a malarious site in Palawan, Philippines. *S. E. Asian J. Trop. Med. Publ. Hlth.* 20, 49–53.

Service M. W. (1991) Biotechnology and its potential use in *Anopheles* research and control. *Bull. Soc. Vector Ecol.* 16(1), 161–175.

Service M. W. (1993) Community participation in vector-borne disease control. *Ann. Trop. Med. Parasitol.* 87(3), 223–234.

Sexton J. D. (1994) Impregnated bednets for malaria control: Biological success and social responsibility. *Am. J. Trop. Med. Hyg.* 50(6), suppl., 72–81.

Sexton J. D., Ruebush II T. K., Brandling-Bennett A. D., Breman J. G., Roberts J. M., Odera J. S. and Were J. B. O. (1990) Permethrin-impregnated curtains and bednets prevent malaria in western Kenya. *Am. J. Trop. Med. Hyg.* 43, 11–18.

Shahabuddin M. and Kaslow D. C. (1994) *Plasmodium:* Parasite chitinase and its role in malaria transmission. *Exp. Parasitol.* 79, 85–88.

Smart M. R. and Brown A. W. A. (1956) Studies on the responses of the female *Aedes* mosquito. Part VII. The effect of skin temperature, hue and moisture on the attractiveness of the human hand. *Bull. Entomol. Res.* 47, 89–100.

Spielman A. (1994) Why entomological antimalaria research should not focus on transgenic mosquitoes. *Parasitology Today* 10(10), 374–376.

Stich A. H. R., Maxwell C. A., Haji A. A., Machano A. Y., Mussa J. K., Matteelli A., Haji H. and Curtis C. F. (1994) Insecticide-impregnated bed nets reduce malaria transmission in rural Zanzibar. *Trans. R. Soc. Trop. Med. Hyg.* 88, 150–154.

Strickland G. T., Zafar-Latif A., Fox E., Khaliq A. A. and Chowdhry M. A. (1987) Endemic malaria in four villages of the Pakistan province of Punjab. *Trans. R. Soc. Trop. Med. Hyg.* 81, 36–41.

Taylor K. A., Koros J. K., Nduati J., Copeland R. S., Collins, F. H. and Brandling-Bennett A. D. (1990) *Plasmodium falciparum* infection rates in *Anopheles gambiae, An. arabiensis,* and *An. funestus* in western Kenya. *Am. J. Trop. Med. Hyg.* 43, 124–129.

Thomas T. C. E. (1951) Biting activity of *Anopheles gambiae. Brit. Med. J.* 2, 1402.

Titus R. G. and Ribeiro M. C. (1990) The role of vector saliva in transmission of arthropod-borne disease. *Parasitology Today* 6(5),157–160.

Vulule J. M., Beach R. F., Atieli F. K., Roberts J. M., Mount D. L. and Mwangi R. W. (1994) Reduced susceptibility of *Anopheles gambiae* to permethrin associated with the use of permethrin-impregnated bednets and curtains in Kenya. *Med. Vet. Entomol.* 8, 71–75.

Waage J. K. and Nondo J. (1982) Host behaviour and mosquito feeding success: An experimental study. *Trans. R. Soc. Trop. Med. Hyg.* 76(1), 119–122.

Walker-Jonah A., Dolan S. A., Gwadz R. W., Panton L. J. and Wellems T. E. (1992) An RFLP map of the *Plasmodium falciparum* genome, recombination rates and favored linkage groups in a genetic cross. *Mol. Biochem. Parasitol.* 51, 313–320.

Wekesa J. W., Copeland R. S. and Mwangi R. W. (1992) Effect of *Plasmodium falciparum* on blood feeding behavior of naturally infected *Anopheles* mosquitoes in western Kenya. *Am. J. Trop. Med. Hyg.* 47, 484–488.

Williams M. C,. Woodall J. P., Corbet P. S. and Gillett J. D. (1965) O'nyong-nyong fever: An epidemic virus disease in East Africa. VII. Virus isolations from *Anopheles* mosquitoes. *Trans. Roy. Soc. Trop. Med. Hyg.* 59(3), 300–306.

World Health Organisation (1993) World malaria situation in 1991—Part 1. *Weekly Epidemiological Record* 68, 245–252.

Integrated Control of Malaria Vectors and Schistosomiasis Host Snails in a Rice Irrigation Scheme

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Abstract—Six villages within Lower Moshi Irrigation Scheme in Northern Tanzania were found to have high prevalence rates of malaria and bilharzia parasites. Among 2012 school children examined, 19.6% were found with *Plasmodium falciparum* and 62% with *Schistosoma haematobium.* Comparison of *S. haematobium* prevalence rates before and after the introduction of paddy cultivation in one village showed an increase of 139% over a four-year period.

Anopheles gambiae and *Culex quinquefasciatus* were the predominant mosquito species. Peak density periods for *An. gambiae* coincided with periods of rice transplantation and weeding. Laboratory and field experimental tests showed that *Bacillus thuringiensis* mixed with urea fertiliser effected high mortality rates on mosquito larvae. Predominant schistosomiasis host snails were *Bullunus pfeifferi* and *B. sudanica* found breeding in secondary and tertiary drains.

Key Words: malaria, schistosomiasis, bilharzia, mosquito, host snails, rice irrigation, Tanzania, *Plasmodium falciparum*, *Schistosoma haematobium*

Introduction

Malaria and schistosomiasis rank highest on the list of the five major tropical diseases, and are the leading causes of morbidity and mortality in most irrigation schemes in tropical countries. Malaria cases are estimated at 110 million per year, with annual world total deaths of one to two million (WHO, 1975). It is also estimated that schistosomiasis causes about 200,000 deaths per year globally (WHO, 1980). The disease is endemic in 74 countries with about 200 million people infected and 500 million at risk of acquiring infection (Mott, 1984).

Rice cultivation is closely associated with water-borne and water-related diseases including malaria and schistosomiasis. This results from irrigation activities requiring increased surface water, both in area and duration, throughout the year. Irrigation water in paddy fields creates favourable habitat for the breeding of malaria vectors while slow moving water in irrigation canals and drainage systems offer ideal breeding sites for schistosomiasis host snails. The two diseases are likely to encroach on new areas due to expected rapid expansion of irrigation schemes, most of which exclude health considerations during planning stages.

In tropical Africa, the most important vectors of malaria associated with irrigation schemes are the members of *Anopheles gambiae* complex, particularly *An. arabiensis* Patton and *An. gambiae s. str,* and in some cases *An. funestus* Giles.

Both urinary and intestinal schistosomiasis are endemic in Tanzania. The former, caused by *Schistosoma haematobium* is widespread along Lake Victoria and the coastal belt including the islands of

Zanzibar, while the latter caused by *S. mansoni* has a patchy distribution inland and is usually associated with irrigation (Bailey and Davis, 1970; Rugemalila, 1979). *Biomphalaria* snail species are the main hosts for *S. mansoni* while the snail host for *S. haematobium* belongs to the genus *Bulinus*.

Control strategies against malaria and schistosomiasis have usually been considered separately, even in irrigation schemes where both diseases are important. Under such circumstances, long term programmes involving community participation would be most practical and cost-effective if simultaneous intervention methods were instituted.

The present preliminary studies were aimed at collection of baseline data for a proposed malaria and schistosomiasis large-scale integrated control programme at Lower Moshi rice Irrigation Scheme.

Materials and Methods

The present studies were initially conducted during a period of 15 months (August 1990–October 1991). Subsequent longitudinal studies on malaria vectors dynamics were carried out between June 1993 and March 1994.

The study area consisted of four villages within Lower Moshi Rice Irrigation Scheme, namely Mabogini, Chekereni, Rau and Oria. The scheme which is based near Moshi town in Northern Tanzania received partial support from the Japanese Government and has been operational since 1986. The project area covers 2300 ha out of which 1100 ha is used for paddy cultivation. Two to three paddy planting seasons can be practised in the area depending on the amount of water available. Due to great constraint of water, a rotation system of paddy cultivation is common in the area, thus ensuring continuous transmission of malaria and schistosomiasis. The climate of the area is characterised by three seasons, namely long rains (March–May), dry (June–October) and short rains (November–February). Annual rainfall averages 590 mm while temperatures range between 21 and 26°C.

Determination of Disease Prevalance Rate

School children (6–15 years old) in each of the six villages were examined for malaria and schistosomiasis parasites. For malaria determination, thick and thin blood smears obtained by finger prick were stained with Giemsa and examined for parasites.

Schistosomiasis eggs were examined in stool and urine samples taken from the children according to methods described by Mott (1984).

Evaluation of Malaria Vectors and Schistosomiasis Host Snails

Adult mosquitoes from selected houses were sampled by man landing captures (MLC), pyrethrum spray catches (PSC) and window exit traps (WET) according to standard methodologies (WHO, 1975). Mosquito larvae were sampled periodically by dipping. Snail densities were estimated by standardised scooping from water canals, drains, field puddles and 'division boxes'.

Experimental Control of Mosquito Larvae by *Bacillus thuringiensis* Laboratory Tests

A serial dilution equivalent to enough *Bactis* to cover one plot (300 ml in 50 l water) was carried out using freshly collected water from mosquito breeding sites. It was calculated that 1.20 ml *Bactis* in 200 ml water was equivalent to *Bactis* applied at the recommended dose of 1.0 l/ha.

The following three experiments each with four replicate tests of 25 third-instar larvae each were carried out:

Bactis alone, *Bactis* + urea fertiliser (64 g/200 ml water) and urea fertiliser alone at three concentrations. Mortality rates were read at two hours and 24 h after exposure.

Field Tests

Dilution of *Bactis* was based on the recommended dose for field application (1.0–2.5 l/ha). According to normal practice in the scheme, one plot (0.3 ha) normally requires 50 l solution for full coverage. At a concentration of 1.0 l/ha 300 ml of *Bactis* was diluted with 50 ml water mixed with recommended amount of urea fertiliser (53 kg/ha or 16 kg/plot) and then applied with a knapsack sprayer.

Results

Disease Prevalence Rates

Prevalance rates of *Plasmodium falciparum* among 2012 primary school children ranged between 14.0% and 23.5% with mean of 19.6%. The highest rates were recorded at Oria (23.5%) and Mabogini (23.1%) primary schools (Table 1).

Schistosoma mansoni was the predominant schistosomiasis causative organism (Table 2) with prevalance rates ranging from 15.3% (Chekereni) to 77.1% (Rau). *Schistosoma haematobium* was found only in 0.9% of the children examined. Other major intestinal parasites observed among the

Table 1. Malaria parasite rates *(P. falciparum)* among school children in six villages within the Lower Moshi Irrigation area

Village	December 1990		August 1991	
	No. examined	% positive	No. examined	% positive
Mabogini	458	23.1	443	13.1
Chekereni	583	18.7	685	13.0
Oria	268	23.5	235	21.3
Rau	275	17.7	-	
Mtakuja	170	18.2	-	
Mvuleni	258	14.0	265	24.4

Table 2. Schistosomiasis prevalence rates among school children in six villages within the Lower Moshi Rice Irrigation area

Village	Population	No. examined	*S. mansoni* %	*S. haematobium* %
August –December 1990				
Mabogini	5226	458	54.8	3.7
Chekereni	3438	583	15.3	0
Oria	4320	268	66.1	0.4
Rau	3120	275	77.1	0
Mtakuja	3945	170	62.4	1.2
Mvuleni	7634	258	76.0	0.2
December 1986				
Mabogini		475	39.2	0
Chekereni		421	6.4	0

Table 3. Mosquito density estimated by pyrethrum-spray catch (PSC) and man-landing capture (MLC) in four villages within the Lower Moshi Irrigation area between July–August 1991

	Mean bites/person/night		Mean number/bedroom	
Village	*An. gambiae*	*Cx. quinqu.*	*An. gambiae*	*Cx. quinqu.*
Mabogini	96.5	6.5	113.8	25.4
Chekereni	2.0	6.2	8.3	3.5
Oria	77.2	12.9	25.8	13.1

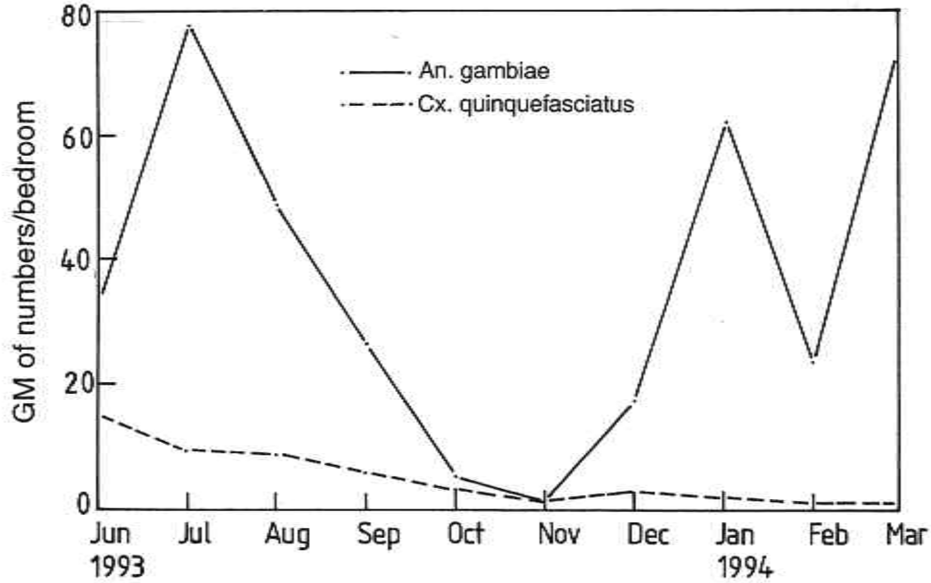

Fig. 1. Density fluctuations of *An. gambiae* and *Cx. quinquefasciatus* at Mabogini of the Lower Moshi Irrigation Scheme.

2012 children examined included *Ascaris lumbricoides* (10.5%), *Trichuris trichiura* (4.4%) and *Ancylostome* spp. (1.7%).

Entomological Results

Anopheles gambiae complex (predominantly *An. arabiensis*) and *Culex quinquefasciatus* were the predominant mosquito species in the Irrigation Scheme. Other minor species accounting for less than 1.0% included *An. funestus, An. pharoensis, Culex duttoni* and *Mansonia uniformis.*

Highest mosquito densities estimated by MLC and PSC during July and August 1991 were observed at Mabogini where irrigation in plots with young rice was being carried out (Table 3). Longitudinal studies involving mosquito sampling by WET and PSC carried out in four houses at Mabogini showed that peak *An. gambiae* complex density coincided with rice transplantation periods during July–August 1993 and January–March 1994 (Fig. 1). There were more *An. gambiae s.l.* collected by WET (53.7%) than by PSC (46.3%).

Snail Hosts

Two predominant snail hosts for *S. mansoni* namely *Biomphalaria pfeifferi* and *B. sudanica* were observed in tertiary drains, secondary drains and field drains. Respective mean numbers per scoop were 2.3, 0.7 and 0.3. Non-human host snails were found in very low numbers within tertiary and field drains. These included *Bullinus tropicus*, *B. forskalii*, *Lymnaea* spp. and *Lanistes* spp. Extensive sampling at various contact sites along both sides of an earth-lined main canal in Kahe/Oria settlement showed *Biomphalaria* spp. and *Bulunus* spp. densities ranging from 0.01 to 0.10 snails per scoop. Minor snail species included *Lanistes* spp. *Lymnaea* spp., *Cleopatra* spp. and *Melanoides* spp.

Bacillus thuringiensis **Tests**

Laboratory efficacy tests of *Bacillus thuringiensis* formulations *'Bactis S'* against *An. gambiae s.l.* larvae showed 100% kill even at half the concentration of the recommended dose. *Bactis* mixed with urea fertiliser gave the same results. In both cases, the experiment was terminated after two hours instead of the usual 24 h since all the test larvae had died by this time.

Experiments with urea fertiliser alone showed that an equivalent amount of 53 kg/ha normally applied in paddy field after weeding, caused 35.2% mortality rate within 24 h.

Smaller amounts of urea equivalent to 26.5 kg/ha did not cause larval mortality. With the field experiments, *Bactis* mixed with fertiliser caused high mortality rates on all mosquito larval species in the paddy fields within a period of less than 8 hours. Subsequent mosquito larval sampling within a period of one week revealed hardly any larvae.

Discussion and Conclusion

Peak mosquito abundance periods for *An. gambiae s.l.* were found to coincide with periods of rice transplantation and weeding. This period offered optional breeding conditions for *An. gambiae* complex, i.e. shallow open sun-lit ponds with unpolluted muddy water. Similar observations have been reported by several other workers, including Chandler and Highton (1976), and Lindsay et al. (1991). Rice irrigation can therefore be said to be closely associated with increased malaria vector densities as well as malaria transmission risk. However, there are some instances where incidences of malaria cases have declined after introduction of rice cultivation (Sharma and Mehrotra, 1980; Robert et al., 1985). Factors responsible for these anomalies are presently being investigated in this irrigation scheme.

The slight exophilic tendencies observed for *An. gambiae* complex is typical for *An. arabiensis* which so far has been identified as the only sibling species of the complex in this area. The predominance of *An. arabiensis* in upcountry irrigation schemes has been observed in several parts of Kenya and Tanzania (Mosha and Subra, 1982; Mosha et al., 1985; Mosha et al., 1992). However, the proportion of *An. gambiae* complex found existing in these previous studies was much higher than in the present studies. Lubega et al. (1977) also reported higher numbers of fed *An. gambiae* complex in veranda and window traps compared to numbers left inside of experimental huts at TPRI Magugu Field Station. The implication of these studies is that in rice irrigation schemes where *An. arabiensis* is the predominant species vector control programmes must adopt an integrated pest management (IPM) strategy involving both larvae and adult mosquito stages as well as various appropriate control methods.

Various control methods including the use of pyrethrum-impregnated materials, botanicals such as neem *(Azadirachta indica)* and *Ocimum* spp.

as well as pyrethroid acaricides applied on domestic animals have been found to reduce mosquito densities considerably in some of our study areas. Several other laboratory and field experiments have also confirmed the efficacy of *Bacillus thuringiensis* against mosquito larvae (Mikkola et al., 1982; Lacey et al., 1984). However, the present confirmation that *B. thuringiensis* can work equally well in the field when mixed with fertilisers is quite encouraging and suggestive of future possible use of this environmentally safe pesticide for malaria vector control under normal agricultural practice and involving community participation. *Bacillus thuringiensis* formulation can be mixed with fertilisers for application during recommended periods of tillering and panicles initiation which coincide with periods of peak mosquito breeding.

Whereas there is no strong association between increased irrigation and malaria, the same cannot be said for schistosomiasis. There is now ample evidence to show that increasing irrigation and water conservation have greatly increased schistosomiasis transmission potential in many parts of Africa. Observations carried out at Chekereni village prior to the introduction of the scheme in 1986 and after the implementation of the scheme in 1990, showed a marked increase of 139% *S. mansoni* prevalance rate, from 6.4 to 15.3%.

As for Mabogini village where irrigation had been operational before the first examination, there was an increase of 39.8%, i.e. from 39.2 to 54.8%.

Apart from schistosomiasis, two other important water-borne/water-related diseases identified included intestinal parasites and diarrhoeal diseases. The root cause of these diseases may be linked to complete lack of toilet facilities and poor public health education. Secondary and tertiary drains which were found to be the most favourable breeding sites for *S. mansoni* snail hosts serve as toilets and also as good pasture areas for grazing and collecting grass for animals.

The present studies have pointed out some areas of research which should receive special attention before implementation of a large-scale malaria and schistosomiasis control programme in the Lower Moshi Irrigation Scheme or in other similar projects. These include malaria vectors resting and biting habits, association between irrigation activities and malaria transmission and also sociological studies related to sanitation. The studies have demonstrated a cost-effective method of applying *Bacillus thuringiensis* for mosquito larvae control in rice irrigation schemes where fertiliser application is practised.

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References

Bailey D. R. and Davis A. (1970) The prevalence and intensity of infection with *Schistosoma haematobium* in primary school. *E. Afr. Med. J.* 47, 1–12.

Chandler J. A. and Highton R. B. (1976) The breeding of *Anopheles gambiae* Giles (Diptera: Culicidae) in rice fields in the Kisumu area Kenya. *J. Med. Entom.* 13, 211–215.

Lacey L. A., Urbina M. and Heitzman C. M. (1984) Sustained release formulations of *Bacillus* *thuringiensis* (H-14) and *Bacillus spheircus* for control of container breeding *Culex quinquefasciatus*. *Mosquito News* 44, 26–32.

Lindsay S. W., Wilkins H. A., Zielaer H. A., Daly R. J., Petrarca V. and Byass P. (1991) Ability of *Anopheles gambiae* mosquitoes to transmit malaria during the dry and wet seasons in an area of irrigated rice cultivation in the Gambia. *J. Trop. Med. Hyg.* 94, 313–324.

Lubega R., Obudho W. O. and Myamba J. B. (1977) Verandah trap hut assessment of mosquito coils perfumed with aggerbatti. *E. J. Med. Res.* 4, 31–37.

Mikkola A. R., Carlberg G. A., Vaara T. and Gyllenberg H. G. (1982) Comparison of inclusions in different *B. thuringiensis* strains. An electron microscope study. *FEMS Microbiol. Lett.* 13, 401–408.

Mosha F. W., Mutero C. and Haji J. J. (1985) Ecological studies on *Anopheles gambiae* complex sibling species in Kenya and Tanzania. *TPRI Misc. Report.*

Mosha F. W., Njau R. J. A. and Alfred J. (1992) Efficacy of Esbiothrin mosquito coils at community level in northern Tanzania. *Med. Vet. Entom.* 6, 44–46.

Mosha F. W. and Subra R. (1982) Ecological studies on *Anopheles gambiae* complex sibling species in Kenya I. Preliminary observations on their geographical distribution and chromosomal polymorphic inversions. WHO Unpublished Mimeograph, WHO/VBC/82.867.

Mott K. E. (1984) Schistosomiasis; A primary health care approach. *Wld. Hlth Forum* 5, 221–225.

Robert V., Gazin P. and Bondin C. (1985) La transmission du paludisme en zone de savane arborée et en zone rizicoles des enviros de Bobo Dioulasso (Burkina Faso). *Ann. Soc. Belg. Med. Trop.* 65(2), 201–214.

Rugemalila J. B. (1979) The impact of urinary schistosomiasis on the health of two community populations living in endemic areas in Tanzania. *Trop. Geogr. Med.* 31, 375–380.

Sharma V. P. and Mehrotra K. N. (1980) Malaria resurgence in India: A critical study. *Soc. Sc. Med.* 22(8), 835–845.

Snow W. F. (1979) The vertical distribution of flying mosquitoes (Diptera: Culicidae) near area of irrigated rice-fields in the Gambia. *Bull. Ent. Res.* 69, 561–571.

World Health Organisation (1975) *Manual on Practical Entomology in Malaria. Part II. Methods and Techniques.* WHO, Geneva.

World Health Organisation (1980) Epidemiology and control of schistosomiasis: Report of WHO Expert Committee, *Technical Report, Series 643,* Geneva.

Ixodid Ticks as Vectors of Parasitic Diseases and their Population Management with Special Emphasis on *Theileria parva* and *Rhipicephalus appendiculatus*

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Abstract—Although ixodid ticks are particularly important vectors of human diseases caused by viruses, rickettsia, spirochaetes and protozoa, all these infections can be considered accidental since no tick species is maintained by infesting humans. Other mammal and reptile species maintain ixodid ticks and therefore are the main hosts of tick-borne pathogens. The role and importance of ixodid ticks as vectors of livestock diseases is summarised. Because of the complexity of the interactions between ticks and tick-borne pathogens aspects of the relationships between *Theileria parva*, the causative organism of East Coast fever (ECF) of cattle and its main tick vector *Rhipicephalus appendiculatus*, is the subject of the rest of the review although the principles apply equally to other tick-borne diseases. The population dynamics of *R. appendiculatus* has a profound effect on the transmission of *T. parva* infection, which varies in different parts of its distribution range from southern Sudan to South Africa. A most important feature is behavioural diapause of adult *R. appendiculatus* in the southern part of its range controlled by photoperiod. This results in one generation of tick per annum occurring in southern Africa and up to three generations in equatorial eastern Africa where populations do not show diapause. As the transmission of *T. parva* is transstadial, transmission of *T. parva* to cattle tends to be seasonal in southern Africa but all the year round in eastern Africa. The interaction between *T. parva* and the tick is described and discussed in some detail. It is stressed that the life cycle of *T. parva* in the tick is very specific in that each intracellular stage infects a particular tick cell type. It appears that the environment within the tick is not necessarily ideal for development of the *Theileria* parasite as a very high proportion die. The epidemiology and control of ECF is discussed as well as attempts to model the population dynamics of the tick. The epidemiology of ECF are described and areas for further research suggested.

Key Words: ixodid ticks, tick-borne pathogens, *Theileria parva, Rhipicephalus appendiculatus,* tick population dynamics, parasite/tick interactions, epidemiology, modelling, control

Introduction

The Tick-Borne Disease Problem

Ixodid ticks, often known as hard ticks, are considered the second most important group of pathogen vectors for man and animals after the mosquitoes. Ixodid ticks are particularly important vectors of livestock diseases but are also important vectors of human pathogens (Sonenshine, 1993). In humans, tick-borne viruses (arboviruses) cause three main types of syndrome—systemic febrile illness, encephalitis and haemorrhagic fever. The majority of tick-borne viral agents are encephalitides in that they produce clinical responses in which encephalitis is the predominant feature. Examples are Russian spring-summer encephalitis, Central European encephalitis, Louping ill and Kyasanur Forest disease. Examples of haemorrhagic fevers are Crimean-

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*Deceased

Congo haemorrhagic fever and Omsk haemorrhagic fever while only a few tick-borne viruses produce a generalised, systemic infection such as Colorado tick fever. Human rickettsioses transmitted by ticks include Rocky Mountain spotted fever, tick typhus, Q-fever and ehrlichiosis. Lyme disease is a human infection caused by a tick-transmitted spirochaete *(Borrelia burgdoferi)* which is an emerging disease in many parts of the world. Ixodid ticks also transmit protozoa parasites such as *Babesia* to humans causing disease.

However, the primary hosts for ixodid ticks are livestock presenting a major health problem to them. Tick-borne diseases of domestic livestock occur on the world's major continents and they are particularly prevalent between latitudes 40°N and 32°S. Tropical theileriosis caused by a protozoa *Theileria annulala* is endemic in 11 countries in West Asia and North Africa, 9 countries in Asia as well as parts of southern Europe and nearly 280 million cattle are at risk from the disease. Theileriosis due to *T. parva* infection (East Coast fever) occurs in at least 11 African countries and approximately 24 million cattle are at risk (Mukhebi et al., 1992). Cowdriosis caused by a rickettsiosis, *Cowdria ruminantium* occurs in sub-Saharan Africa and the Caribbean and approximately 175 million cattle are at potential risk in Africa (Norval et al., 1992); and it also causes problems in sheep and goats. At least 500 million cattle are at risk to a babesiosis caused by protozoa of the genus *Babesia* and anaplasmosis caused by the rickettsioses *Anaplasma marginale* (de Vos, 1992).

What makes the ixodid ticks such good vectors of a wide variety of pathogens? A major reason must be due to their unique feeding behaviour. While most haematophagous arthropods take a short period to feed, ixodid ticks may take several days to weeks to complete engorgement on the host. The feeding process is highly complicated with 9 separate activities noted (Waladde and Rice, 1982). The end result is that most instars of ixodid ticks take in vast amounts of blood upto 200 times their unfed weight. The exception is the male tick which only imbibes 4 times its weight in blood. Hence, most tick instars imbibe a much larger amount of blood than other haematophagous arthropods, which increases their chance of becoming infected with the (tick-borne) pathogens.

If the different tick-borne diseases of livestock are considered in terms of their clinical symptoms, babesiosis and anaplasmosis cause anaemia, cowdriosis causes a complex syndrome involving neurological signs and theileriosis causes lympho-proliferation and anaemia. Cerebral babesiosis and theileriosis are relatively common disease syndromes caused by blockage of brain capillaries by infected host cells.

The vectors of tick-borne diseases in Africa are shown in Table 1. It can be seen that ticks of several genera are involved in the transmission of these parasites. The nature of the transmission cycle of different tick-borne pathogens varies: transstadially between different instars in *Theileria, Anaplasma* and *Cowdria;* intrastadially in the male tick in the case of *Anaplasma* and possibly *Cowdria;* and transovarially in the case of *Babesia*. These differences in transmission cycles affect the epidemiology of these parasites as does the population dynamics of the tick-vector (Dallwitz et al., 1987).

Wildlife components are often involved in the epidemiology of tick-borne diseases of livestock (Grootenhuis and Young, 1981). This is particularly apparent in eastern Africa where over 40 species of wild ungulates occur that act as hosts of vector tick species that

Table 1. *Theileria* species of cattle, their ixodid vectors and known distribution

Theileria species	Tick vectors	Distribution
Theileria parva (Theiler, 1904)	*Rhipicephalus appendiculatus* *Rhipicephalus zambeziensis* *Rhipicephalaus duttoni* *Rhipicephalus nitens*	Eastern, central and southern Africa
Theileria mutans (Theiler, 1906)	*Amblyomma variegatum* *Amblyomma gemma* *Amblyomma hebraeum* *Amblyomma cohaerens* *Amblyomma lepidum*	Western, eastern, central and southern Africa; Caribbean Islands
Theileria taurotragi (Martin and Brocklesby, 1960)	*Rhipicephalus appendiculatus* *Rhipicephalus pulchellus* *Rhipicephalus zambeziensis*	Eastern, central and southern Africa
Theileria velifera (Luhs, 1904) (Uilenberg, 1964)	*Amblyomma variegatum* and other *Hyalomma* species	Western, eastern, central Europe, Middle East, Asia including India
Theileria buffeli (Neveu Lemaire, 1912)	*Haemaphysalis* species	Europe, eastern Africa, Asia, including Japan and Australia
Theileria sergenti (Yakimov and Dekhterev, 1930)	*Haemaphysalis* species	Japan and Korea

also infest cattle (Young and Grootenhuis, 1985). Hence it is not surprising in Africa that livestock are subject to infestation with more species of tick-borne disease organisms than on any other continent. However, similar but smaller problems occur elsewhere. For example, in the Northern Territories of Australia, feral water buffalo maintain *Boophilus microplus* infestation and act as reservoirs of *Babesia bovis* and *B. bigemina* infections complicating control measures for this disease in cattle (Young, 1988). However, one important problem that still exists in several countries in Africa is *Theileria parva* infection emanating from the African buffalo *(Syncerus caffer)* populations which causes a highly fatal and distinct disease syndrome in cattle called Corridor disease (Young et al., 1988).

The economic impact of tick-borne diseases on livestock population takes several forms. The level of mortality can be high which produces an easily measurable economic impact. However, many animals may not die but suffer reduced productivity either due to the effects of acute or chronic infection. A great complication in Africa with a high prevalence of a variety of tick-borne diseases is that several of these may act in concert, hence making it difficult to quantify the effects of the different infections. Another aspect of economic impact of tick-borne disease which is difficult to cost is the exclusion of cattle of higher potential productivity from vast areas of Africa where they would not survive infection with various tick-borne pathogens. The control measures which are being used such as frequent acaricide application and drug treatment of clinical disease are also very expensive. In the case of East Coast fever the economic impact in Africa has been considered in some detail (Mukhebi et al., 1992).

This review will concentrate on the East Coast fever (ECF) problem in Africa, the biology and ecology of the main vector *Rhipicephalus appendiculatus* a three-host tick, the interaction between *Theileria parva* and the vector, epidemiology and modelling and new control measures. Many of the principles described could be applicable to other tick-borne diseases.

The Biology and Ecology of *Rhipicephalus appendiculatus*

The distribution of *R. appendiculatus* ranges between southern Sudan to the North and to Natal, South Africa in the South. It has been reported to infest cattle in Sudan, Uganda, Zaire, Rwanda, Burundi, Kenya, Tanzania, Zambia, Malawi, Zimbabwe, Mozambique, Swaziland and South Africa. *Rhipicephalus zambeziensis* is a southern African species which is distributed mainly in areas drier than those of *R. appendiculatus* and therefore extends the range of *T. parva* vectors. The role of *R. duttoni* in Angola in transmission of *T. parva* has yet to be fully explored. It is obvious that *R. appendiculatus* exists in a whole variety of different agroecological zones and there are similar agroecological zones particularly in Ethiopia which have not been infested (Norval et al., 1991). To a great extent the distribution of *R. appendiculatus* appears to have been influenced by cattle movements.

The studies on *R. appendiculatus* distribution show that the tick appears to move its range considerably from year to year dependent on the climate conditions prevailing. Examples are Karamoja in Uganda, Isiolo District and Coast Province of Kenya, Sukumaland in Tanzania, several areas in Zambia and the areas between high and low veld in Zimbabwe. These movements of the range of *R. appendiculatus* may be critical in the production of epidemic states which results in high mortality due to East Coast fever.

Two computer models have been used to study the differences between the potential and actual distribution of *R. appendiculatus*. CLIMEX, which was developed by Sutherst and Maywald (1985), is a model for comparing the relative potential for survival and development of population of poikilothermic animals at different times and places. The most important climatic components are temperature, which determines development rates (and may affect survival), and moisture, which usually has a direct influence on survival. CLIMEX uses meteorological data to estimate the responses of populations in terms of an annual ecoclimatic index (EI) which is measured on a scale between 0 (unfavourable) and 100 (highly favourable). EI is derived from a growth index (GI) which is an annual mean of weekly values that relate to development potential and moderated by four stress indices, heat stress (HS), cold stress (CS), dry stress (DS) and wet stress (WS).

Sutherst and Maywald (1985) used CLIMEX to predict the potential worldwide distribution of the ticks *Boophilus microplus*, *R. appendiculatus* and *A. variegatum*. Maywald and Sutherst (1985) used the model to make more detailed predictions of the distribution of *R. appendiculatus* in Africa which has been further refined by Lessard et al. (1990). Using annual meteorological data it may be possible to use CLIMEX to predict the annual range of *R. appendiculatus* so indicating the likely occurrence of large-scale East Coast fever outbreaks in susceptible groups of cattle. Norval and Perry (1990) showed that *R. appendiculatus* was able to become established in a normally unsuitable area of southern Zimbabwe (lowveld) during a seven-year wet cycle during which EI values indicated climatic suitability and that the tick disappeared in the four-year dry cycle that followed when the EI values returned to zero.

Another model which has been applied to *R. appendiculatus* has been BIOCLIM (Nix, 1986). A selection of geographical points throughout the distribution of *R. appendiculatus* and *R. zambeziensis* were taken and accompanying altitude data recorded. For each point BIOCLIM generates 24 climatic attributes and from these are derived a set of indices that summarises annual and seasonal mean conditions, extreme values and intra year seasonality. Initial results using BIOCLIM gave a good overall fit of known and potential distributions of *R. appendiculatus* and *R. zambeziensis* (Norval et al., 1992). However, the major limitation to this model at present is poor quality of the continental interpolated climatic database, which is being improved (Norval et al., 1992).

A striking feature of CLIMEX is that it predicts the distribution of *R. appendiculatus* in southern Africa much less efficiently than in eastern Africa. While in eastern Africa around Lake Victoria, the EI can reach 91–100, in Zimbabwe it reaches a maximum of between 11–20 (Lessard et al., 1990). This problem leads onto another subject, the seasonality of infestation of *R. appendiculatus* on-host throughout its range.

There is a basic difference in the seasonality of *R. appendiculatus* infesting hosts in eastern and southern Africa. This difference is seen in the many studies on the seasonal occurrence of *R. appendiculatus* throughout its range (Norval et al., 1992). Data is available from localities in Kenya, Uganda, Tanzania, Burundi, Malawi, Zambia, Zimbabwe and South Africa (Norval et al., 1992). Short and Norval (1981) compared the seasonal occurrence at eight climatically different localities in eastern and southern Africa to identify the factors responsible for its regulation. They concluded that the seasonal pattern is set by the adults which are active only under a specific set of climatic conditions (temperature and rainfall/humidity) and daylength. This subject has also been reviewed by Randolf (1993, 1994). The result of seasonality is that in central and southern Africa, the *R. appendiculatus* instars occur at different times of the year. Adults only become active in December and have a peak around February with subsequent peaks of larvae in April/May and nymphs in July/August. This results in inactivity in the adult population for about 5 to 6 months per year and results in one generation of ticks a year (Rechav, 1981; Short and Norval, 1981; Pegram et al., 1986). Berkvens (1991) working in Eastern Province of Zambia reported a rather different situation with the possibility of two adult peaks unlike the unimodal peaks evident further South. This did not occur every year but was dependent on the prevailing weather conditions.

The situation in eastern Africa is totally different. In favourable areas particularly in the Lake Victoria basin all instars are active all the year round and it has been estimated that up to 3 generations could occur a year (Branagan, 1973; Kaiser et al., 1982; Punyua et al., 1990). However, in areas which have unfavourable seasons this potential can be reduced to one generation per year (Yeoman, 1966; Newson, 1978) because the second generation of ticks may not survive during dessication sensitive stages such as oviposition, egg hatching and the resultant larval stages (Yeoman, 1966; Randolf, 1994).

This leads into two important behavioural characteristics of *R. appendiculatus,* namely diapause and quiescence. These two types of behaviour can explain differences in the seasonal occurrences of *R. appendiculatus* throughout its range. Both result in reduced activity which results in the tick not questing for the host. Quiescence is a reversible state of suppressed metabolism imposed by conditions beyond certain thresholds in temperature, moisture and nutrition (Tauber et al., 1986). Diapause on the other hand has been defined as a neurohormone mediated dynamic state of low metabolism which in this case involved altered or reduced behavioural activities (Tauber et al., 1986). Diapause occurs during genetically determined stages of metamorphosis and its full expression develops in response to a number of environmental stimuli that precede in favourable conditions. Once diapause has began, metabolic activity is supported even if conditions favourable for development prevail. In *R. appendiculatus* the first published study of the effect of photoperiod on the feeding behaviour of adult *R. appendiculatus* was a series of laboratory experiments conducted by Rechav (1981). He compared the feeding behaviour of adult *R. appendiculatus* from South Africa kept at short and long day photoperiods and found that the ticks fed more successfully after they had been held in an incubator with long photoperiod for 6 weeks.

Young et al. (in press) and Muzhawu et al. (in press) investigated the behaviour and feeding behaviour of adults of different *R. appendiculatus* populations from different parts of Africa in the laboratory and after exposure in the field found that eastern African populations of *R. appendiculatus* from Uganda and Kenya (4 stocks) showed no evidence of behavioural diapause in the laboratory when kept in the dark, short or long day photoperiod as judged by their ability to attach to hosts and their feeding performance. However, three stocks of *R. appendiculatus* obtained from Zambia and two stocks from Zimbabwe showed a marked difference in attachment and feeding behaviour under different daylengths. All these stocks showed a very slow attachment rate and poor feeding performance if they were kept in the dark or under short day photoperiod but had a greatly improved attachment and feeding performance if they were kept under long day photoperiod, indicating that the southern African stocks entered diapause in short day photoperiod condition but did not enter diapause if they were exposed to long day photoperiod. Three stocks of *Rhipicephalus zambeziensis* did not show any signs of diapausing behaviour under different photoperiods. If the southern African ticks were exposed to short day photoperiod and entered diapause, it took about 3 weeks at long day photoperiod to break diapause as judged by attachment rate and feeding performance.

In Kenya it was found that the tick stock in nylon mesh columns exposed to natural conditions showed a marked difference in behaviour. The Kenyan tick showed a high level of questing activity through the exposure period while those of the Zambia and Zimbabwean ticks was much lower indicating that they were in diapause. In the two years of exposure using this generation of ticks the Zambian and Zimbabwean ticks gave no indication that behavioural diapause was terminated. This was confirmed by application of ticks to rabbits at monthly intervals—the feeding performance of the Zambian and Zimbabwean ticks was much poorer than the Kenyan ticks.

In contrast, in Harare, Zimbabwe, the Kenyan ticks exposed to natural conditions in nylon mesh columns showed no evidence of diapause although they did appear to enter quiescence. The Zambian and Zimbabwean ticks did show evidence of diapause with reduced questing behaviour which broke several months after exposure in December. These observations were confirmed by feeding ticks on rabbits at monthly intervals and the Zimbabwean and Zambian ticks showed improved feeding behaviour after diapause broke in December. The daylength in Harare at the time of termination of diapause was at 1320 h. The Kenyan ticks showed similar feeding behaviour throughout.

These studies have important implication on understanding both the population dynamics of *R. appendiculatus* throughout its range and for the epidemiology of *T. parva* infection. It would appear there are 3 populations of *R. appendiculatus* as far as diapause is concerned: a northern equatorial population which will not enter diapause, an intermediate population in southern Tanzania, Malawi and Northern and Eastern Provinces of Zambia and southern population from Central and Southern Provinces of Zambia southward which shows strong diapause.

Behavioural diapause of *R. appendiculatus* adults ensures that the females feed on hosts and subsequently lay eggs during favourable periods of the year. The eggs are the stage most prone to dessication (Randolf, 1994) and due to the unimodal rainfall prevalent in southern Africa conditions for egg hatching would be unsuitable during most of the year. The eastern African ticks if introduced into southern Africa, would be unlikely to survive since they lack behavioural diapause and would feed and lay eggs during unfavourable condition (Norval et al., 1992). Daylength appears to be the factor which controls behavioural diapause but further work is required before it can be fully quantified.

Interactions between *Theileria parva* and *Rhipicephalus appendiculatus*

While the population dynamics of *R. appendiculatus* and other rhipicephalid vectors determines the transmission of *T. parva,* the presence of larvae, nymphae and adults infesting cattle determines the pattern of transmission. There are other complex interactions between *Theileria* and their tick vectors. The development cycle of *T. parva* within *R. appendiculatus* is complicated (Mehlhorn and Schein, 1984; Shaw and Young, 1994). An unknown proportion of piroplasms produced within erythrocytes of cattle are gametocytes (i.e. are potentially ineffective to ticks). It is evident that very few piroplasms ingested by susceptible tick stage, larvae or nymphae develop to the sporozoite stage, which infects cattle. A simple calculation is that 7 million piroplasms may be ingested by individual nymphae feeding on a *T. parva*-infected animal but from 0 to 700 salivary gland acini of the adult stage may become infected with *T. parva* kinetes. In fact, the infection in the salivary glands shows overdispersion or a negative binomial distribution in that few ticks may show high infection while most will have lower or no infection. Observations on the development of piroplasms in the gut of newly engorged nymphae show that vast numbers of piroplasms are destroyed after they are liberated from the lysed erythrocytes. However, this distribution is variable between individual ticks from a batch. As the piroplasms being destroyed are usually showing agglutination it is tempting to think that lectin-like substances or enzymes in the gut may be involved and that individual ticks vary in their gut lectin or in their gut enzymes activity. In some individuals large number of sexual stages can be produced and these ticks are considered to be individuals with ideal conditions in their guts for the development of the sexual stages.

The occurrence of sex in the development cycle of *Theileria* has been controversial for many years but this has now been resolved by studies on the morphology (Mehlhorn and Schein, 1984; Shaw and Young, 1994), on DNA concentration (Gauer et al., in press) and on sexual recombination (Morzaria et al., 1992). Like its relative *Plasmodium,* the sexual cycle is an obligatory one. The stages of *T. parva* in the cow and the sexual stages in the gut of a tick are haploid while the product of fusion, the zygote and the kinete are diploid. The reduction division of the parasite has not been recognised but is likely to occur when the kinete enters the salivary gland since the sporozoites again are haploid (Gauer et al., in press).

The microgamonts called the 'ray body' can be produced in large number in certain individual ticks within 1–3 days after the engorgement of the nymph dependent on the ambient temperature. The microgamete is formed from the ray bodies and the elongated parasite fuses with the larger macrogamete. The macrogamete does not appear to undergo such a complex development but just gets larger. The zygote, the product of fusion, then enters the gut epithelium of the nymphal tick. Again it may be possible that considerable mortality of parasites occurs during this process. The zygote is seen to grow and at a certain stage transforms into the kinete stage that appears to coincide with the moult of the nymphal tick. Another area of interest is the transformation of the zygote stage into the kinete which could possibly be under control of the same hormonal mechanisms which control tick moulting (Young and Leitch, 1980). The kinete is relatively large about 18 µm in length, is motile and has a relatively well-developed apical complex.

Rhipicephalus appendiculatus will survive for long periods in the field; its survival is dependent on prevailing conditions of temperature and moisture (Newson et al., 1984). The *T. parva* parasites within the salivary glands of ticks can also survive for long periods in the field which is often comparable to their tick host and is again dependent on climatic conditions (Young et al., 1983; Newson et al., 1984; Young et al., 1987; Ochanda, 1994).

The selection of cell type in salivary glands infected by the kinete is interesting. The salivary glands of adult female ticks are large bifid organs which consist of about 2200 acini although lying in haemocoel that are in close apposition to the gut of the tick (Ochanda, 1994). Bell (1980) has shown that salivary glands of *R. appendiculatus* do not appear to attract the kinetes. The kinetes do appear to selectively enter the salivary glands of type III acini and then a particular granular cell type, the 'e' cell (Fawcett et al., 1982; Shaw and Young, in press). A question which is important is whether the kinete recognises the 'e' cell by receptor sites or whether the entry is by chance. The salivary gland acini are covered with a thick basal lamina so it is unlikely that molecules specific for the surface of the 'e' can be recognised by the kinete through the lamina. From the study of the structure of the salivary gland the III acini are the distal acinar type and surround the outside of the salivary gland and the two 'e' cells in the Type III acini represent the largest outer surface area of the Type III acini. Hence even if the penetration of the salivary gland acini occurred randomly the parasite is likely to enter an 'e' cell. This selective infection of 'e' cells of Type III acini is broken down when very high infections occur in individual tick and development has been noted in Type II in the 'c' cells (Shaw and Young, in press). However, the development is often not fully completed in these cells. It is suggested when large numbers of kinetes are produced in the gut epithelium some of the migrating kinetes may by chance first encounter the more proximal Type II acini.

Recent studies (Ochanda, 1994) have compared the relative role of the different *R. appendiculatus* instars in transmission of *T. parva*. They found that nymphal/female transmission was the most efficient followed by nymphal/male transmission. Larval/nymphal transmission was much less efficient with up to twenty times lower numbers of nymphal acini infected than in adults on ticks feeding on cattle with acute infections. With stocks of *T. parva* causing mild infection such as Boleni from Zimbabwe very low infections or no infections developed in nymphal ticks and much higher infections developed in the adult ticks. Also nymphal/adult transmission is much more efficient than larval/nymphal transmission from cattle with the *T. parva* carrier state. Two reasons have been suggested for the less efficient transmission between larvae and nymphs; the smaller blood meal of the larvae which tends to be diluted with more tissue fluid due to small size of the mouth parts and the much fewer number of acini in the nymphal salivary gland (about 20 times less) compared to those of the adults (Ochanda, 1994). The male tick also has smaller numbers of Type III acini than the female tick (female mean No. 1736; male mean No. 1346). However it must be remembered that Short and Norval (1981) have indicated that the ratio of larvae, nymphae and adults feeding on hosts is 100, 10, 1 respectively so that larval/nymphal transmission may represent a more important source of infection than indicated by infection rate.

The development of the kinete stage into the sporozoites within the Type III acini 'e' cell (Fawcett et al., 1982; Fawcett et al., 1985) is particularly interesting in *T. parva*. Basically one kinete enters the cell and produces approximately 40,000 sporozoites which then initiate the infection of cattle during the feeding of tick. In most cases the development of the parasite in the salivary gland proceeds for a period but stops and the parasite mass becomes dormant. Under high ambient temperatures some of the parasites may complete sporogony in unfed ticks and are infective to cattle (Young et al., 1984). However, these sporozoites have a short life within the salivary gland. The majority of parasites complete development only when the infected instars attach to the host and start to feed. The parasite develops in a convoluted syncytium with an area called a labyrinth which does not contain parasite nuclei. The 'e' cell during parasite development becomes greatly engorged, loses its granular inclusion bodies and the host cell nucleus also becomes enlarged. When the sporozoites are formed they are released from the infected acini by a process similar to apocrine secretion in that the apical part of 'e' cell membrane is lost. The emission of the sporozoites into the salivary collection ducts has to be a trickle since the aperture of the valve in the Type II acinus is small (about 1 µm) in size similar to the size of the sporozoite (Shaw and Young, in press). There is no synchronisation of development and the infection of 'e' cells appears to be random throughout the length of the salivary glands. The rate of development in 'e' would appear to be dependent on the secretory level of individual Type III acini which is controlled by enervation (Shaw and Young, in press). It is believed that the cattle become infected by inoculation of sporozoites by feeding ticks into the dermis of the cow where they encounter target cells. The sequence of events is now studied *in vivo*.

The genetics of susceptibility of *R. appendiculatus* to *T. parva* infection has been studied recently. Ochanda (1994) found that certain stocks of *T. parva* were more efficiently transmitted by certain stocks of *R. appendiculatus* ticks. When different stocks of *T. parva* were used the efficiency of *R. appendiculatus* stocks as vectors could be different. This suggests that populations of *R. appendiculatus* in a particular area could have a powerful selection pressure on the *T. parva* strains transmitted in that area. In another study, Young et al. (in press) investigated the heritability of the susceptibility to infection with *T. parva* in *R. appendiculatus* using full sib families. It was found that heritability estimate reach upto 0.59 indicating that tick lines of high or low susceptibility could be produced through selection. Quite a high level of variance in infection was shown to be due to genetic factors and it would be of great interest to determine what these genetic factors are.

Hence the interaction between *T. parva* and its tick vector *R. appendiculatus* are very complex and it is only at this stage that they are beginning to be unravelled. One of the prime puzzles is to obtain a clear relationship between piroplasms, parasitaemia of animals and the infection levels developing in the ticks engorging on it. The pattern has been established to a certain extent. In animals showing piroplasms on day 11, the ticks feeding on them first become infected on day 13 and show a linear increase in infection level to day 17. After that the infections become variable but decrease after day 19 after infection.

New *in vitro* techniques of feeding *R. appendiculatus* nymphae on artificial membranes developed by Waladde et al. (1993) and Waladde et al. (in press) will allow some of these interactions to be investigated without feeding the ticks on cattle so removing the effects of tick/cattle interactions and the effects of a dynamic *T. parva* infection in animals.

Epidemiology and Modelling

Classical ECF has been reported to cause 95% mortality in cattle (Brocklesby et al., 1961). This is a misleading statement which has become established in the literature. Brocklesby and colleagues were referring to their experimental infections where they applied 10 experimentally infected *R. appendiculatus* adults which had fed as nymphae on acutely infected cattle. They were also using taurine breed cattle. In the field the challenge by infected ticks is very variable and it has been shown that the severity of ECF is dependent on level of challenge (Jarrett et al., 1969).

From the study of ticks it can be seen that the minimum infective unit is approximately 40,000 sporozoites produced in one infected 'e' cell but it cannot be determined how many of these would actually initiate infection during the process of tick feeding on a susceptible animal. It has been shown in several sites in Kenya that the infection rate of *T. parva* in field ticks is low, between 1 and 2% of adult ticks showing infection (Leitch and Young, 1981; Walker et al., 1981; Young et al., 1986). However, there are reports of infection rates being much higher in other areas. A complication is that *R. appendiculatus* can transmit more than one species of *Theileria*. For example *Theileria taurotragi* is an extremely widespread parasite of cattle and highly infective to *R. appendiculatus*. The parasite cannot be differentiated by conventional methods of staining the salivary glands but can be differentiated by ultrastructure and DNA and RNA probes (Fawcett et al., 1985; Bishop et al., 1994). Therefore the field challenge would appear to be much lower than has been used usually in the laboratory. An additional feature is that the local breeds of cattle particularly zebu from endemic areas are not as susceptible to disease as taurine or zebu cattle from non endemic areas (Barnett and Bailey, 1955).

The possible mechanisms producing a state of endemic stability has been reviewed by Young (1981). He suggested a combination of low infection rates in ticks, genetic resistance of cattle populations both to the development of ECF and tick infestation and maternal transfer of protective antibodies all contribute to a reduced *T. parva* challenge and low mortality in these areas as reported by Barnett and Bailey (1965) and Moll et al. (1984, 1986). Norval et al. (1992) and Perry et al. (1992) have attempted to refine the definition of the endemic states of ECF.

Natural endemic stability is found in areas of Africa where indigenous cattle are exposed to a continuous challenge throughout the year. This has been most clearly demonstrated in East African zebu cattle in the Lake Victoria basin region and highland and coastal eastern Africa where a bimodal rainfall occurs. Perry and Young (in press) put forward four key factors controlling the occurrence of epidemiological states. First, an ecological cline in which the climatic suitability for tick vectors within the tropical and subtropical regions of its distribution varies with rainfall and altitude. This gradient can be affected by differences in vegetation cover. Second, the host genetic cline in which pure bred taurine cattle raised under tick-free conditions are highly susceptible to disease; taurine cattle bred in tick-borne infection endemic area and some zebu breeds (such as Boran) raised in tick-free condition are moderately susceptible and zebu breeds raised in tick-borne infection endemic areas are of low susceptibility. Third, the feeding management cline which controls the exposure of hosts to different ecological conditions; this can range from no influence, where cattle are herded on natural pasture to complete influence where cattle are kept on concrete and fed on cultivated storage grasses, as in the small fodder zero-grazing units of eastern Africa. Fourth, tick control gradient where tick control ranges from highly effective regular application through to no tick control at all.

Modelling the distribution of *R. appendiculatus* has already been described. Other models have been developed for tick population dynamics. In 1980, Maywald et al. modified a model for *Boophilus microplus*, a one-host tick, developed by Sutherst and Dallwitz (1979) for three-host ticks called T3HOST. T3HOST has subsequently been adapted for *R. appendiculatus* and has been used to simulate the population dynamics of this species in Zimbabwe (Floyd et al., 1987a) and Burundi (Kaiser et al., 1988). The most important application of tick models in Africa could be their use in the design of cost-effective dipping strategies. Computer simulation allows predictions to be made of the effects of tick populations of a wide range of control strategies. The cost and benefits of these strategies can be assessed with input such as current control costs, current value of cattle products such as beef and milk and the damage coefficients (production losses per engorged tick) of the tick species involved.

Floyd et al. (1987b) have run simulations using the T3HOST model of strategic dipping regimes for the control of *R. appendiculatus* at Lake McIlwaine in the high veld of Zimbabwe. According to their predictions, the most effective 3-month period of intensive control would be one that started in December or January. This is the time of year when the adult stage is present on cattle and their control has a greater impact on the population size than control of other stages at other times of the year. More recently, Byrom (1990) has developed a population model for *R. appendiculatus* as part of a quantitative rule-based model for ECF called ECFXPERT. This model predicts the seasonal occurrence of *R. appendiculatus,* but cannot as yet be used to predict abundance as it omits host-related factors such as host density and the tick resistance of hosts. One problem with these models at present is that the effects of behavioural diapause have not been included which means the models are not accurate for southern Africa.

T3HOST model has also been used to simulate tick control strategies for indigenous Ankole cattle in Burundi (Kaiser et al., 1988). The study covered five ecological zones and considered the effects of 3 tick species, *R. appendiculatus, A. variegatum* and *B. decoloratus,* on beef and milk production. The simulations provided a reasonable estimate of the actual populations and, like Zimbabwe, the simulations indicated that the greatest reduction in the size of *R. appendiculatus* population could be achieved through the control of adults, the most cost-effective 3-month period of strategic dipping being predicted to be between December and February when the adults were most abundant. Hence, tick population models promise to be an effective tool for use in the design of strategies for tick control in Africa and should be further developed to provide a base for epidemiological models.

Models of theileriosis are few in number and have followed different approaches. A quantitative rule-based model of the dynamics of ECF has been recently developed (Gettinby and Byrom, 1989; Byrom, 1990) with a set of rules for modelling the *T. parva* life cycle. These comprise: primary rules, supported by published findings; test rules, which are those of conflicting literature reports which can be evaluated under different circumstances; and secondary rules which fill the gaps in published findings by a set of assumptions termed "expert opinion" by the authors. The model called ECFXPERT, contains an ECF model, a dipping model and a chemotherapy model in addition to the tick model already described earlier. The ECF model investigates the incidence of disease in cattle by modelling tick and parasite interactions. The model has several useful features but probably requires further refinement to be of practical use.

A second approach has been developed by Medley et al. (1993) using analytical models using a set of differential equations to model the transmission of *T. parva.* The model quantifies the transition between various classes of infection in a herd; susceptible to infection, incubating infection, primary acute infection in animals that will eventually die, primary acute infections in animals that will recover and recovered animals. These authors first attempted to model a situation of endemic stability using data from an endemic area of Kenya reported by Moll et al. (1986) in order to estimate the rate of infection under these circumstances, the consequences of manipulating infection by immunisation or breed change and the effect that the carrier state of *T. parva* has on the disease dynamics. The model largely conforms with our understanding of the behaviour of *T. parva* in an endemic area. This model is now being developed so that it will also predict the *T. parva* status in other ecological zones. One of the important roles of theileriosis models is to identify key variables required to predict the distribution and abundance in the cattle population in order that the appropriate diagnostic tools and minimum data sets can be developed.

Control Measures for *Theileria parva* and *Rhipicephalus appendiculatus*

The classical control method for *R. appendiculatus* and ECF has been the use of frequent applications of acaricides at intervals. The usual regimen for application recommended by chemical companies selling acaricide has been weekly intervals while farmers in trouble with ECF in Kenya, for example, will apply acaricide at twice weekly intervals. While *T. parva* transmission is often not seasonal in eastern Africa it can be seasonal in areas where long dry periods occur. On its own the use of acaricides is not an ideal way of controlling ECF. It is expensive, time-consuming, affects productivity and is potentially dangerous for the environment and for animal and human health. Strategic use of acaricides to kill the adult population of *R. appendiculatus*, if they are seasonal, would appear to be a better, cheaper and safer approach (Floyd et al., 1987b; Kaiser et al., 1988).

Even so there is need for adjunct methods of controlling ticks such as vaccines against *R. appendiculatus* and other economically important ticks in Africa and selection of genetically resistant cattle to tick infestation. Both approaches have been applied in Australia with some degree of success although the Australians only had to worry about one tick species on livestock, *Boophilus microplus* (Opdebeeck et al., 1992). Although both approaches have been investigated in Africa further investment would be required to obtain the required output. Many other approaches have been investigated for tick control such as the use of natural pesticidal products, parasitoids and changing the nature of pastures but none appear at this stage to be practical measures.

Prevention of ECF would appear to be an important approach which has received much attention in recent years. Immunisation against *T. parva* infection is possible and over the years a method known as infection and treatment has been developed. The sporozoite stage of *T. parva* is harvested from ticks and cryopreserved as a stabilate (Radley, 1981). This stabilate is then titrated in cattle groups to determine the immunogenic dose required. During immunisation the required dose is given to cattle simultaneously with oxytetracycline treatment. The animal develops an infection which is slowed down by the oxytetracycline treatment that allows the animal immune system to control the infection. This results in the animal becoming immune to the homologous challenge. However, there are problems with this technique. Some animals do not control the infection during immunisation and have to be treated and this requires expensive monitoring. Some stocks of *T. parva* of wide immunogenicity and lower pathogenicity have been recognised which could be useful for this immunisation method. Another problem is to provide immunisation stock of wide enough immunogenicity to protect against the diversity of the field challenge. This is particularly difficult where African buffalo are involved in the epidemiology of cattle theileriosis since they harbour strains of greater diversity than cattle. Nevertheless an initiative has been taken by FAO and other donors to implement infection and treatment immunisation in eastern, central and southern Africa.

At the same time ILRI is attempting to identify antigens associated with *T. parva* parasites which play a protective role. One such antigen has been identified, a circumsporozoite antigen p67, which in its recombinant form will protect cattle against *T. parva* challenge. The quest for other protective antigens is proceeding.

Over the last 20 years, chemotherapy agents effective against ECF, have been identified and developed for the market. These are parvaquone, buparvaquone and halofuginone. The use of these drugs, however, is only a measure of last resort since they are relatively expensive and their efficacy depends on the rapid diagnosis of the disease in the field which is not always possible.

It is clear that there is a potential for integrated control of ECF. However, before this can be achieved with confidence several of the developments mentioned above would have to become a reality. Another question is, When ECF is controlled how does one tackle other tick-borne diseases? This may not be difficult to achieve due to a reversage resistance to these diseases so that calves exposed to *Cowdria, Babesia* and *Anaplasma* may develop relatively mild infections and recover with the development of long-term immunity. This will, however, require a much clearer understanding of the epidemiology of tick-borne diseases of livestock than is available at present. With the use of new and improved technology becoming available, it is believed that the relevant intervention can be applied as required in different areas to control tick-borne disease of livestock more effectively.

References

Barnett S. F. and Bailey K. P. (1955) *East African Veterinary Research Organization Report,* 1952–53, 1954–1955. East African High Commission, Nairobi, pp. 51–74.

Bell L. J. (1980) Organ culture of *Rhipicephalus appendiculatus* with maturation of *Theileria parva* in tick salivary glands *in vitro. Acta Trop.* 37, 319–325.

Berkvens D. L. (1991) A study of the ecology of *Rhipicephalus appendiculatus* complex with special reference to the Eastern Province of Zambia. PhD thesis. Brunel University, Uxbridge.

Bishop R. P., Sohnpal B. K., Morzaria S. P., Dolan T. T., Mwakima F. N. and Young A. S. (1994) Discrimination between *Theileria parva* and *Theileria taurotragi* in the salivary glands of *Rhipicephalus appendiculatus* ticks using oligonucleotides homologous to ribosomal RNA sequences. *Parasit. Res.* 80, 259–261.

Branagan D. (1973) Observations on the development and survival of the ixodid tick *Rhipicephalus appendiculatus* (Neumann, 1901) under quasi-natural conditions in Kenya. *Trop. Anim. Hlth. Prod.* 5,153–165.

Brocklesby D. W., Barnett S. F. and Scott G. R. (1961) Morbidity and mortality rates in East Coast fever *(Theileria parva* infection) and their application to drug screening procedures. *Brit. Vet. J.* 117, 529–531.

Byrom W. (1990) Simulation models for investigating East Coast fever and other parasitic diseases. PhD thesis. University of Strathclyde, 189 pp.

Dallwitz M., Young A. S., Mahoney D. F. and Sutherst R. W. (1987) Comparative epidemiology of tick-borne diseases with special emphasis on modelling. *Int. J. Parasitol.* 17, 629–638.

De Vos A. J. (1992) Distribution, economic importance and control measures for *Babesia* and *Anaplasma,* pp. 3–12. In *Recent Development in the Control of Anaplasmosis, Babesiosis and Cowdriosis.* Proceedings of a Workshop held at ILRAD, Nairobi, Kenya, 13–15 May 1991 (Edited by T. T. Dolan). The International Laboratory for Research on Animal Diseases, Nairobi.

Fawcett D. W., Doxsey S. and Buscher G. (1982) Salivary glands of the tick vector of East Coast fever III. Ultrastructure of sporogony in *Theileria parva. Tissue Cell* 14, 183–206.

Fawcett D. W., Young A. S. and Leitch B. L. (1985) Sporogony in *Theileria* (Apicomplexa: Piroplasmida). A comparative ultrastructural study. *J. Submicros. Cytol.* 17, 299–314.

Floyd R. B., Maywald G. F. and Sutherst R. W. (1987a) Ecological models—2. A population model of *Rhipicephalus appendiculatus,* pp. 72–75. In *Ticks and Tick-Borne Disease* (Edited by R. W. Sutherst). ACIAR Proceedings No. 17. Australian Centre for International Agricultural Research, Canberra.

Floyd R. B., Sutherst R. W. and Maywald G. F. (1987b) Modelling tick management. Designing control strategies for *Rhipicephalus appendiculatus* using T3HOST, pp. 141–144. In *Ticks and Tick-Borne Disease* (Edited by R. W. Sutherst). ACIAR Proceeding No. 17, Australian Centre for International Agricultural Research, Canberra.

Gauer M., Mackenstedt U., Mehlhorn H., Schein E., Zapf F., Njenga E., Young A. and Morzaria S. (in press). Comparison of DNA measurements in different development stages of *Theileria annulata* and *T. parva. Parasitol. Res.*

Gettinby G. and Byrom W. (1989) The dynamics of East Coast fever: A modelling perspective for the integration of knowledge. *Parasitol. Today* 5, 68–73.

Grootenhuis J. G. and Young A. S. (1981) The involvement of wildlife in *Theileria* infections of domestic animals in East Africa, pp. 71–73. In *Advances in the Control of Theileriosis* (Edited by A. D. Irvin, M. P. Cunningham and A. S. Young). Martinus Nijhoff Publishers, The Hague.

Jarrett W. F. H., Crighton G. W. and Pirie H. W. (1969) *Theileria parva:* Kinetics of replication. *Exp. Parasitol.* 24, 9–25.

Kaiser M. N., Sutherst R. W. and Bourne A. S. (1982) Relationship between ticks and zebu cattle in southern Uganda. *Trop. Anim. Hlth. Prod.* 14, 63–74.

Kaiser M. N., Sutherst R. W., Bourne A. S., Gorissen L. and Floyd R. B. (1988) Population dynamics of ticks on Ankole cattle in five ecological zones in Burundi and strategies for their control. *Prevent. Vet. Med.* 6, 199–222.

Leitch B. L. and Young A. S. (1981) *Theileria* infection in *Rhipicephalus appendiculatus* collected in the field, pp. 53–65. In *Advances on the Control of Theileriosis* (Edited by A. D. Irvin, M. P. Cunningham and A. S. Young). Martinus Nijhoff Publishers, The Hague.

Lessard P., L'Eplattenier R., Norval R. A. I., Kundert K., Dolan T. T., Croze H., Walker J. B., Irvin A. D. and Perry B. D. (1990) Geographical information systems for studying the epidemiology of cattle diseases by *Theileria parva. Vet. Rec.* 126, 255–262.

Maywald G. F. and Sutherst R. W. (1985) *Users Guide to CLIMEX: Computer Programme for Comparing Climates in Ecology.* Commonwealth Science and Industrial Research Organization, Canberra, pp. 39–43.

Medley G. F., Perry B. D. and Young A. S. (1993) Preliminary analysis of the transmission dynamics of East Coast fever. *Parasitology* 106, 251–264.

Mehlhorn H. and Schein E. (1984) The piroplasms: Life cycle and sexual stages. *Adv. Parasitol.* 23, 37–103.

Moll G., Lohding A. and Young A. S. (1984) Epidemiology of theileriosis in the Trans-Mara Division, Kenya. Husbandry and disease background and preliminary observations on theileriosis in calves. *Prevent. Vet. Med.* 2, 801–831.

Moll G., Lohding A., Young A. S. and Leitch B. L. (1986) Epidemiology of theileriosis in calves in an endemic area of Kenya. *Vet. Parasitol.* 19, 255–273.

Morzaria S. P., Young J. R., Spooner P. R., Dolan T. T., Young A. S. and Bishop R. P. (1992) Evidence of a sexual cycle in *Theileria parva* and characterization of the recombinants, pp. 71–74. In *Proceedings of the First International Conference on Tick-Borne Pathogens at the Host Vector Interface.* Saint Paul, Minnesota, 15–18 September, 1992 (Edited by U. G. Munderloh and T. J. Kirtti). St Paul University of Minnesota.

Mukhebi A. W., Perry B. D. and Kruska R. (1992) Estimated economics of theileriosis control in Africa. *Prevent. Vet. Med.* 12, 73–85.

Muzhawu W., Mutapi F., Marstand M., Rusiwa S., Berkvens D. L., Norval R. A. I., Pegram R. G. and Young A. S . (in press) Behaviour of adults of *Rhipicephalus appendiculatus* stocks from Kenya, Zambia and Zimbabwe exposed to quasi-natural conditions in Zimbabwe. *Bull. Entomol. Res.*

Newson R. M. (1978) Life cycle of *Rhipicephalus appendiculatus* on the Kenyan Coast, pp. 46–50. In *Tickborne Disease and their Vectors* (Edited by J. K. H. Wilde). Centre for Tropical Veterinary Medicine, University of Edinburgh.

Newson R. M., Cheira J. W., Young A. S., Dolan T. T., Cunningham M. P. and Radley D. E. (1984) Survival of *Rhipicephalus appendiculatus* (Acarina: Ixodidae) and persistence of *Theileria parva* (Apicomplexa: Theileriidae) in the field. *Int. J. Parasitol.* 14, 483–489.

Nix H. (1986) A biogeographic analysis of Australian elapsid snakes, pp. 4–15. In *Atlas of Elapsid Snakes of Australia* (Edited by R. Longmore). Australia Flora and Fauna Series No. 7, Australian Government Publishing Service, Canberra.

Norval R. A. I. and Perry B. D. (1990) The introduction, spread and subsequent disappearance of the brown-ear tick *Rhipicephalus appendiculatus* from the southern low veld of Zimbabwe. *Exp. Appl. Acarol.* 9, 103–111.

Norval R. A. I., Perry B. D., Gebreal F. and Lessard P. (1991) East Coast fever: A problem of the future for the horn of Africa. *Prevent. Vet. Med.* 10, 163–172.

Norval R. A. I., Perry B. D. and Young A. S. (1992) *The Epidemiology of Theileriosis in Africa.* Academic Press, London.

Ochanda H. (1994) Factors affecting the population dynamics of *Theileria parva* in *Rhipicephalus appendiculatus*. PhD thesis, University of Warwick.

Opdebeeck J. P., Lee R. P., Wong J. Y. M. and Jackson L. A. (1992) Vaccination of cattle against *Boophilus microplus*, pp. 233–239. In *Proceedings of the First International Conference on Tick-Borne Pathogens at the Host Vector Interface.* Saint

Paul, Minnesota, 15–18 September, 1992 (Edited by V. G. Munderloh and T. J. Kurtii). St Paul University of Minnesota.

Pegram R. G., Perry B. D., Musisi F. L. and Mwanaumo B. (1986) Ecology and phenology of ticks in Zambia: Seasonal dynamics on cattle. *Exp. Appl. Acarol.* 2, 25–45.

Perry B. D., Deen S. L., Medley G. F., Morzaria S. P. and Young A. S. (1992) The ecology of *Theileria parva* infections in cattle and the development of endemic stability, pp. 290–296. In *Proceedings of the First International Conference on Tick-Borne Pathogens at the Host Vector Interface,* 15–18 September 1992 (Edited by U. G. Munderloh and T. J. Kurtti). St Paul University of Minnesota.

Perry B. D., Lessard P., Norval R. A. I., Kundert K. and Kruska R. (1990) Climate, vegetation and distribution of *Rhipicephalus appendiculatus* in Africa. *Parasitol. Today* 6, 100–104.

Perry B. D. and Young A. S. (in press) The role of epidemiology and economics in the control of tickborne diseases of livestock in Africa. *Prevent. Vet. Med.*

Punyua D., Yonow T., Newson R. M. and Gigon F. (1990) Studies of ticks in different ecological zones of Kenya, pp. 40–41. In *Seventeenth Annual Report 1989.* The International Centre of Insect Physiology and Ecology, Nairobi.

Radley D. E. (1981) Infection and treatment method of immunization against theileriosis, pp. 227–237. In *Advances in the Control of Theileriosis* (Edited by A. D. Irvin, M. P. Cunningham and A. S. Young). The Martinus Nijhoff Publisher, The Hague.

Randolf S. E. (1993) Climate, satellite imagery and seasonal abundance of the tick *Rhipicephalus appendiculatus* in Southern Africa: A new perspective. *Med. Vet. Entomol.* 7, 243–255.

Randolf S. E. (1994) Population dynamics and density dependent seasonal mortality induces of the tick *Rhipicephalus appendiculatus* in eastern and southern Africa. *Med. Vet. Entomol.* 8, 351–368.

Rechav Y. (1981) Ecological factors affecting seasonal activity of the brown ear ticks *Rhipicephalus appendiculatus,* pp. 187–192. In *Tick Biology and Control.* Proceedings of an International Conference held in Grahamstown 27–29 January, 1981 (Edited by G. B. Whitehead and J. D. Gibson). Tick Research Unit Rhodes University, Grahamstown.

Shaw M. K. and Young A. S. (1994) The Biology of *Theileria* species in ixodid ticks in relationship to parasite transmission. *Adv. Dis. Vector Res.* 10, 23–63.

Shaw M. K. and Young A. S. (in press) Differential development and emission of *Theileria parva* sporozoites from the salivary glands of *Rhipicephalus appendiculatus. Parasitology.*

Short N. J. and Norval R. A. I. (1981) Regulation of seasonal occurrences in the tick *Rhipicephalus appendiculatus* Neumann 1901. *Trop. Anim. Hlth. Prod.* 13, 19–26.

Sonenshine D. E. (1993) *Biology of Ticks.* Vol. 2, Oxford University Press, New York.

Sutherst R. W. and Dallwitz M. J. (1979) Progress in the development of a population model for the cattle tick *Boophilus microplus,* pp. 557–563. In *Proceedings of the 4th International Congress of Acarology 1974.*

Sutherst R. W. and Maywald G. F. (1985) A computerized system for matching climates in ecology. *Agric Ecosyst. Environ.* 13, 281–299.

Tauber M. J., Tauber C. A. and Musaki S. (1986) *Seasonal Adaptations of*

Insects. Oxford University Press, New York.

Waladde S. M. and Rice M. J. (1982) The sensory basis of tick feeding behaviour, pp. 71–118. In *Physiology of Ticks* (Edited by F. D. Obenchain and R. Galun). Pergamon Press, Oxford.

Waladde S. M., Young A. S., Mwaura S. N., Njihia G. M. and Mwakima F. N. (in press) Optimization of *in vitro* feeding of *Rhipicephahls appendiculatus* nymphae for *Theileria parva* transmission. *Parasitology*.

Waladde S. M., Young A. S., Ochieng' S. A., Mwaura S. N. and Mwakima F. N. (1993) Transmission of *Theileria parva* to cattle by *Rhipicephalus appendiculatus* adults fed as nymphae *in vitro* on infected blood through an artificial membrane. *Parasitology* 107, 249–256.

Walker A. R., Young A. S. and Leitch B. L. (1981) Assessment of *Theileria* infection in *Rhipicephalus appendiculatus* ticks collected in the field. *Zeitschrift für Parasitenkunde* 65, 63–69.

Yeoman G. H. (1966) Field vector studies of epizootic East Coast fever. I. A quantitative relationship between *Rhipicephalus appendiculatus* and the epizooticity of East Coast fever. *Bull. Epizoot. Dis. Afric.* 14, 5–27.

Young A. S. (1981) The epidemiology of theileriosis in East Africa, pp. 38–55. In *Advances in the Control of Theileriosis*. Proceedings of an International Conference held at ILRAD, Nairobi, Kenya 9–13 February 1981 (Edited by A. D. Irvin, M. P. Cunningham and A. S. Young). Martinus Nijhoff Publisher, The Hague.

Young A. S. (1988) Epidemiology of babesiosis, pp. 81–98. In *Babesiosis of Domestic Animals and Man* (Edited by M. Ristic). CRC Press, Boca Raton.

Young A. S., Dolan T. T., Mwakima F. N., Mwaura S. N., Njihia G. M., Muthoni M. W. and Dolan R. B. (in press) Estimations of heritability of susceptibility to infection with *Theileria parva* of the tick *Rhipicephalus appendiculatus*. *Parasitology*.

Young A. S., Groocock C. M. and Kariuki D. P. (1988) Integrated control of ticks and tick-borne diseases of cattle in Africa. *Parasitol.* 96, 403–432.

Young A. S. and Grootenhuis J. G. (1985) Influence of wild life on immunization of cattle against theileriosis in East Africa, pp. 104–109. In *Immunization against Theileriosis in Africa* (Edited by A. D. Irvin). International Laboratories for Research on Animal Diseases, Nairobi.

Young A. S. and Leitch B. L. (1980) A probable relationship between the development of *Theileria* species and the analysis of their tick host. *J. Parasitol.* 66, 356–359.

Young A. S. and Leitch B. L. (1981) Epidemiology of East Coast fever. Some effects of temperature on the development of *Theileria parva* in the tick vector, *Rhipicephalus appendiculatus*. *Parasitology* 83, 199–211.

Young A. S., Leitch B. L., Dolan T. T., Newson R. M., Ngumi P. N. and Omwoyo P. L. (1983) Transmission of *Theileria parva* by a population of *Rhipicephalus appendiculatus* under simulated natural conditions. *Parasitol.* 86, 255–267.

Young A. S., Leitch B. L., Morzaria S. P., Irvin A. D., Omwoyo P. L. and Castro J. J. de (1987) Development and survival of *Theileria parva parva* in *Rhipicephalus appendiculatus* exposed in the Trans-Mara Kenya. *Parasitol.* 94, 433–441.

Young A. S., Leitch B. L. and Mutugi J. J. (1984) Some factors controlling the stimulation of sporogony of *Theileria parva* in its tick vector *Rhipicephalus appendiculatus. Int. J. Parasitol.* 14, 97–102.

Young A. S., Leitch B. L., Newson R. M. and Cunningham M. P. (1986) Maintenance of *Theileria parva parva* infection in an endemic area of Kenya. *Parasitol.* 93, 4–16.

Young A. S., Mwakima F. N., Ochanda H., Norval R. A. I., Perry B. D., Dolan T. T., Berkvens D. L. and Pegram R. G. (in press) The importance of behavioural diapause of adult *Rhipicephalus appendiculatus* and *R. zambeziensis* ticks in its population dynamics in eastern, central and southern Africa. *Bull. Entomol. Res.*

Trypanosomiasis Management Using Baits: Some Implications of Tsetse Behaviour and Ecology

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Abstract—Several successful trials show that odour-baited targets, when appropriately managed, can rapidly control and eventually eradicate the savanna tsetse flies *Glossina morsitans* Westwood and *G. pallidipes* Austen. The technique works because of the fly's total reliance on blood for nutrition and because of its low birth rate—consequent on the adenotrophic viviparous reproductive system. It is remarkable that the approach is successful despite its reliance on killing only female flies, a large proportion of which is unavailable to targets on any particular day. Trap, and thus presumably target, catches of females are strongly biased in favour of older flies and there is a particular bias against teneral and immature flies. (This bias does mean, however, that infected flies have a higher probability of being killed than those which have not yet matured an infection.) Trap and target samples are also strongly biased in favour of flies which have not fed for at least 48 h—and in favour of flies which have recently deposited a larva. If baits were modified to attract the missing categories of flies—without prejudicing the numbers in the categories already being treated, then it would be possible to reduce the number of baits required per unit area, and/or the time required to achieve any given level of control. Moreover, the method would be more efficient if safe chemosterilants replaced insecticides so that the number of males treated becomes relevant. Ways of achieving these ends are discussed.

Key Words: tsetse, *Glossina,* control, baits, trapping biases, age, nutrition, pregnancy

Introduction

Sleeping sickness and nagana are the manifestations, in humans and livestock respectively, of pathological infection with protozoans called trypanosomes. The diseases are controlled directly by treatment with prophylactic or curative drugs, or indirectly by reducing populations of the tsetse flies *(Glossina* spp.) responsible for the cyclical transmission of trypanosomes. Tsetse flies have been successfully controlled and sometimes completely eradicated, over large areas, using habitat and/or game destruction, and ground or aerial spraying of insecticides. Jordan (1986) gives good examples of the successful applications of these methods, their limitations, and objections to their use.

The issues involved in the selection of a control method are complex and a complete discussion of them is beyond the scope of this paper. However, three considerations appear to be of overriding importance in current attitudes to tsetse control. First, most African countries are heavily dependent on aid donors for large-scale tsetse control efforts. Second, increased concern about environmental issues ensures that the donors will not fund projects where there is any question of using methods involving direct destruction of habitat or wildlife or which will result in insecticide pollution. Third, for various reasons, donors are not interested in funding long-term, high-cost, high-tech tsetse control operations. Rather they wish to see the development of methods which African governments and local communities are technically and financially capable of operating themselves.

Currently, these considerations make classical approaches to tsetse control unfashionable—at best. Attitudes have been further modified as a result of the emergence, over the past 15–20 years, of a viable alternative (in the shape of so-called 'bait technology') which meets donor concern about insecticide pollution, and destruction of wildlife and habitat. Bait technology is also a sufficiently simple method that it should, theoretically, allow much greater participation in control operations by the local people who expect to benefit from tsetse and trypanosomiasis control.

Terminology

In the following text the term 'trap' means a device designed to induce tsetse to enter a space from which they cannot escape. A 'target' ('ecrans' in the French literature) means a device which the flies are induced to touch—generally with a view to treating them chemically. If a trap, or a living animal, is sprayed with insecticide it is a target by the above definition. A 'refuge' is a device (Vale, 1971) designed to provide a dark, cool shelter which tsetse enter during the hottest times of the year when temperatures exceed c. 32°C. The flies are free to come and go, so that these are not traps as defined above—but flies already in the refuge can be trapped there simply by closing the entrance. Examples of a trap, a target and a refuge are shown in Fig. 1. The term 'bait' covers all systems designed to attract tsetse and concentrate them around a given point; again, generally with a view to catching or treating them chemically. By this definition traps, targets, refuges and insecticide-treated animals are all baits. An excellent review by Green (1994) gives a detailed account of the development and current status of bait methods of tsetse control. A much abbreviated version, covering only the main developments, follows below.

Bait Methods of Tsetse and Trypanosomiasis Control

Harris (1932) developed a trap which was used to kill enormous numbers of *G. pallidipes* Austen in Zululand, South Africa and gave hope that trapping could be used widely as a method of tsetse control. However, later trapping campaigns by Morris and Morris (1949) against other species of tsetse in other parts of Africa failed to achieve eradication and trapping as a control method fell into disfavour.

Two developments in the 1970s led to a reconsideration of this attitude. First, new and better traps were developed. Challier and Laveissière (1973) developed the biconical trap, initially as a sampling device, and later to give local relief from human trypanosomiasis by substantially reducing relatively isolated populations of tsetse. The traps could be used to catch the flies, or they could be treated with insecticide (Laveissière and Couret, 1981) so that a fly only had to land on the trap to be killed. In the latter case, however, there was little point in having a trap at all. Much simpler and cheaper 'écrans' (sheets of material suspended on simple frames) were developed (Laveissière and Couret, 1982). Initially, in West Africa when used against *G. m. submorsitans*, these targets did not appear to be as effective as the traps, but their efficacy has since been much improved due largely to work in Zimbabwe.

The Zimbabwean interest in bait technology was rekindled following the second development, which was Vale's (1974a) demonstration that the importance of odour in host location was greater than previously suspected.

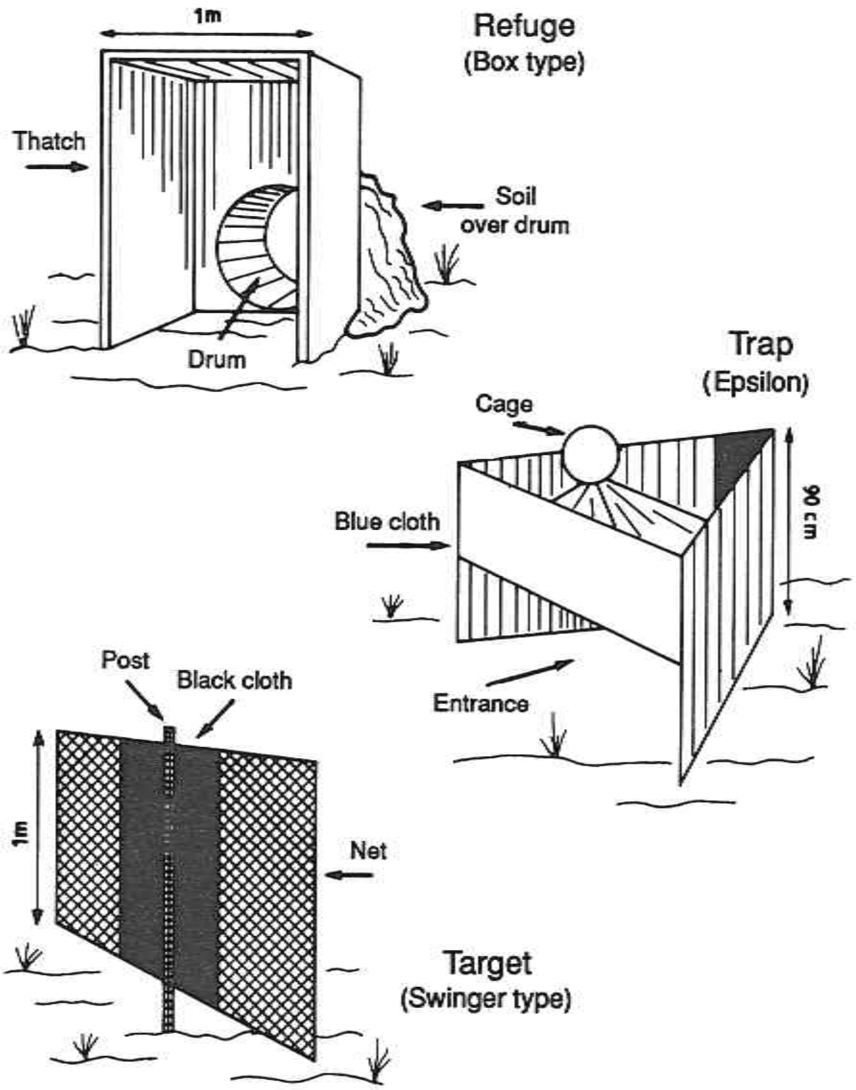

Fig. 1. A 'box' type artificial refuge (Vale, 1971), an epsilon trap, designed by G. A. Vale (Hargrove and Langley, 1990) and a 'swinger' target (Vale et al., 1988).

Hargrove (1977, 1980) developed traps which were more effective and efficient (Vale and Hargrove, 1979) for *G. m. morsitans* Westwood and *G. pallidipes* than previous devices. Traps baited with host odour caught more tsetse than unbaited traps, and catch increased with dose (Vale, 1974a; Vale and Hargrove, 1975; Hargrove and Vale, 1978) with no apparent upper limit (Hargrove et al., 1995).

It was appreciated from the outset that, despite the successes in West Africa against isolated pockets of forest tsetse, unbaited traps would be impractical tools against the more extensive savanna species. However, if the odours responsible for enhancing catches could be identified and used in synthetic form in combination with the traps, exciting new control techniques seemed feasible (Vale, 1974b; Hargrove and Vale, 1979). Flies could be caught in the trap or could be killed with insecticide on targets, in which case the effect would be measured basically by the numbers of females killed. Alternatively, they could be sterilised and released. The latter approach has a theoretical advantage if treated males mate with, and transfer sterility to, untreated females (Vale, 1974b; Langley and Weidhaas, 1986).

Once it was confirmed that carbon dioxide and acetone were important attractants for tsetse flies (Vale, 1974a, 1980) and an automatic sterilising device had been developed (Bursell, 1977) a field trial was carried out on Antelope Island, Lake Kariba, Zimbabwe (Vale et al., 1986). Automatic sterilisation and release, removal trapping and killing with odour-baited targets were all tried and all had demonstrable effects on the populations (Fig. 2). The most dramatic effects were obtained with the targets (baited only with acetone and octenol) used at a density of only 4 km^{-2}. These were estimated to be killing at most 2–9% a day of the female population (Vale et al., 1986) and resulted in eradication of the remaining tsetse in about 6 months (Fig. 2). A consideration of population dynamics is required to realise why this low level of treatment is so devastating, even for healthy tsetse populations.

Why Bait Methods Are So Effective against Tsetse

All tsetse of both sexes are obligate haematophages and the water requirements of the adult come, almost

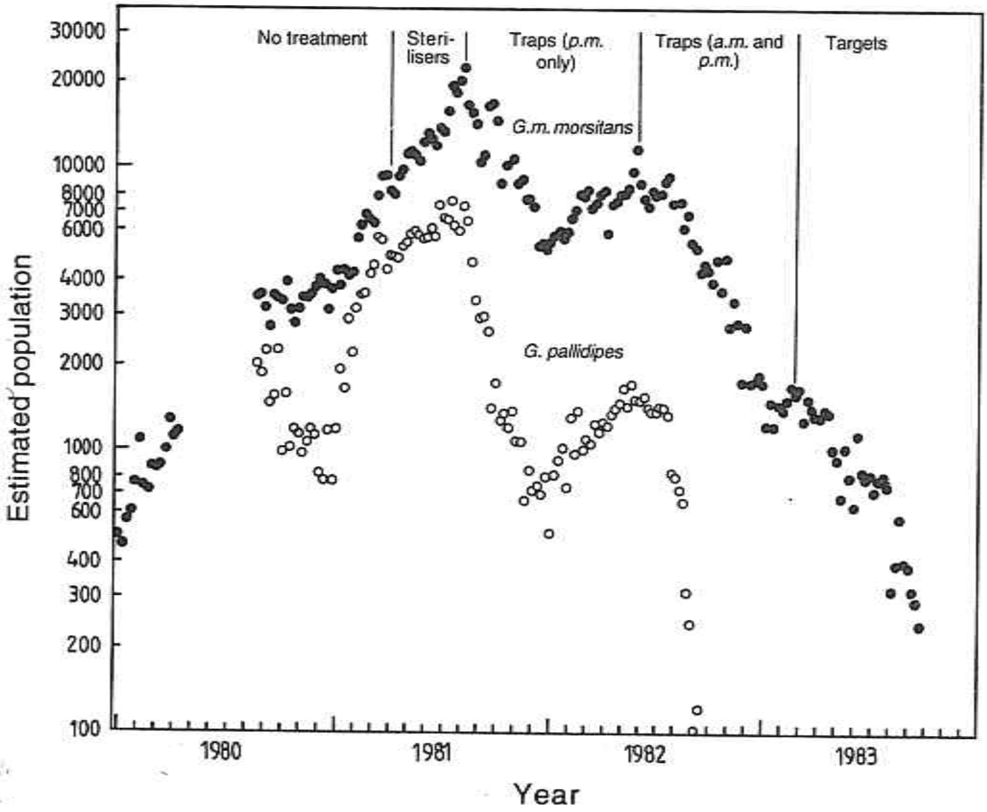

Fig. 2. Changes in populations of adult *G. m. morsitans* (dots) and *G. pallidipes* (circles) on Antelope Island, Lake Kariba, Zimbabwe.

incidentally, with the bloodmeal. Apart from this intake, the nature of tsetse flies makes them entirely independent of water. The adults do not drink it directly, nor do they take it in through the imbibition of nectar or any other plant juices. More importantly, the larva spends almost its entire life *in utero* and is then deposited on dry ground, under which it burrows, forms a hard shell around itself and pupates. It emerges about 4 weeks later as an adult— having not fed at all since deposition by its mother.

The effects of all this independence of water are twofold. Tsetse populations, unlike those of mosquitoes and tabanids, for instance, continue to reproduce through the long dry seasons typical of Africa's semi-arid regions; and the populations exhibit rather small fluctuations with season. On the other hand, the female fly must invest in the third-instar larva all of the energy and raw material required to support it until its first meal as a young adult. The immense implied load on the female means, naturally, that birth rates, and hence natural rates of increase, in tsetse populations are much lower than observed in most insect species. (Each female typically deposits just one larva every 9 days.) This carries with it the further implications that the natural death rate must be very low for positive growth rates and that, therefore, any small imposed additional mortality will have a relatively large effect.

To give some quantitative meaning to the above, note that, even under the most beneficial conditions, tsetse population growth rates (due to birth processes alone) could not possibly exceed 10^4 per annum even over short periods (Rogers, 1979; Hargrove, 1988) and would not generally be expected to exceed 10^3 per annum. In reality, when conditions are apparently ideal and populations are low, such that adverse density effects are expected to be minimised, maximum growth rates were closer to 10^2 than 10^3 (Vale et al., 1986; Turner and Brightwell, 1986) and were only maintained at these levels for a few months.

Hargrove (1988), using Leslie matrix projections, formalised Vale's unpublished rule of thumb that an imposed death rate of 1%/day on adult female tsetse would decrease the population by an order of magnitude (Fig. 3) in a year. Thus, if we were trying to control a very healthy population with a growth rate of 10^3 per annum and applying additional mortalities of 1, 2, 3 or 4% per day we expect the growth rate to decrease to 10^2, 10^1, 10^0 or 10^{-1} per annum respectively. Notice that, for killing rates of > 3% per day, the population which had formerly been

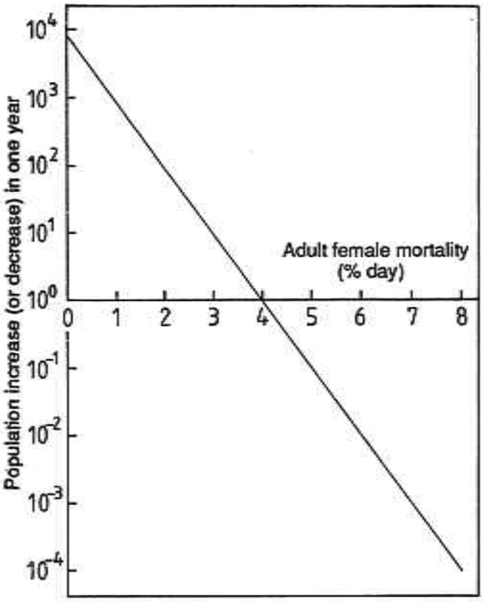

Fig. 3. The effect of changing adult female mortality on growth rates in tsetse. Redrawn from Hargrove (1988). The growth rate is defined here as the ratio of the numbers of flies present at the end of a year to those present at the beginning. A stable population thus has a growth rate of $10^0 = 1.0$.

growing at a rate close to the maximum theoretically possible, is now declining. For a 4% imposed death rate we expect 90% control in one year; for a 5% imposed death rate we expect 99% control in one year and so on.

If, as we calculate, we impose an additional mortality of up to 9% on female *G. pallidipes* when we deploy odour-baited targets at 4 km^{-2} we would expect even a very healthy population to decline by a factor c. $10^3/10^9 = 10^{-6}$ in one year. By the time targets were deployed on Antelope Island there were too few *G. pallidipes* to check this expectation. Better estimates are available from the first full-scale trial of odour-baited targets in a normal field situation (Vale et al., 1988) which was carried out in the c. 600 km^2 Rifa Triangle, Zambezi Valley, Zimbabwe.

In this case the population of *G. pallidipes* declined by a factor of between 10^{-4} and 10^{-5} during the first year of the trial (Fig. 4). This agrees moderately well with expectation given that the target density only reached 4 km^{-2} 5 months after the start of the trial; and that the area was subject to intense re-invasion pressure on one boundary. What was more surprising was the very rapid decline in the *G. m. morsitans* population, given the low estimated treatment rate. Possible reasons will become apparent below.

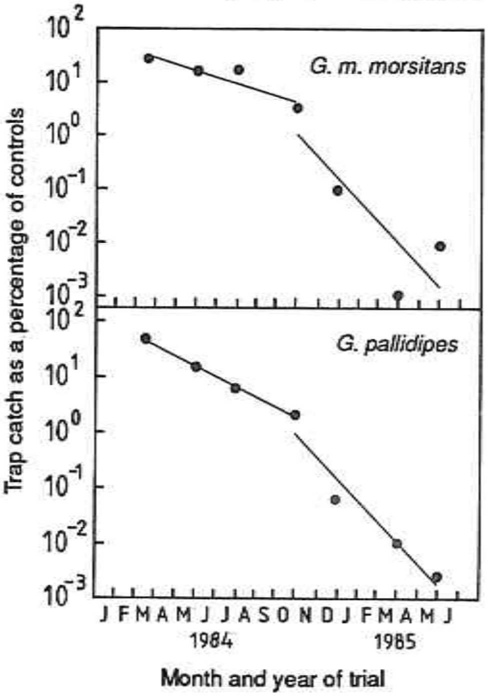

Fig. 4. Decline of tsetse populations in the Rifa Triangle, Zambezi Valley, Zimbabwe. Redrawn from Vale et al. (1988).

The Rifa Triangle has remained largely fly free now for 10 years, despite long periods (up to 18 months) when the targets were not maintained at full efficacy. Since that time a similar operation saw the eradication in 1986–1987 of a healthy population of *G. m. morsitans* from the 600 km^2 Umfurudzi Wildlife Area, again using odour-baited targets at 4 km^{-2} (Whittingham, unpublished). Targets were removed entirely by the end of 1988 and the area has remained fly free ever since. Elsewhere in our region, there has been a successful target-based campaign in the Western Province of Zambia (Willemse, 1991) in which *G. m. centralis* was eradicated from a 600 km^2 trial block near Kaanja on the west bank of the Zambezi, and from most of the surrounding 2000 km^2.

Could Do Better

The undeniable success of the operations detailed above does not imply that the problem of tsetse control has been solved. Green (1994) gives a preliminary discussion of where bait-based operations have run into problems. We are not presently in a position to provide an unequivocal resolution of these problems but, whatever they are, their solution must be made easier if we can improve the cost/effectiveness of our baits. This can be achieved if further attractants are identified, if we can make the targets physically smaller and cheaper without prejudicing their efficacy, if we use cheaper and/or longer lasting insecticides and if we can get away from the need to revisit and refurbish targets (Barrett, 1991).

An alternative, less obvious, approach arises from the realisation that a remarkably small proportion of the tsetse population is even *potentially* available to stationary baits on any particular day. The remainder of this article is devoted to a consideration of this problem and ways in which it could be overcome.

Where Have All the Young Flies Gone?

The problem is best illustrated by looking at the attributes of samples of female *G. pallidipes* taken from odour-baited epsilon traps (Fig. 5). Given the high efficiency of this trap for *G. pallidipes* these samples may be presumed to resemble those killed by odour-baited targets. What is striking, first, is the dearth of the youngest flies in the trap catch. Challier and Laveissière (1973) commented on the same feature when they first tested the biconical trap and it has since been accepted as commonplace for (stationary) trap and electric net samples (Vale and Phelps, 1978; Challier and Turner, 1985; Van Sickle and Phelps, 1988). Of course, the length of the first ovarian cycle is only c. 70% of later cycles (Hargrove, 1994) but, even allowing for this, this category is clearly under-represented in trap catches. It is standard practice, when attempting to estimate mortalities from ovarian age distributions, to ignore the flies in ovarian category zero for this reason (van Sickle and Phelps, 1988).

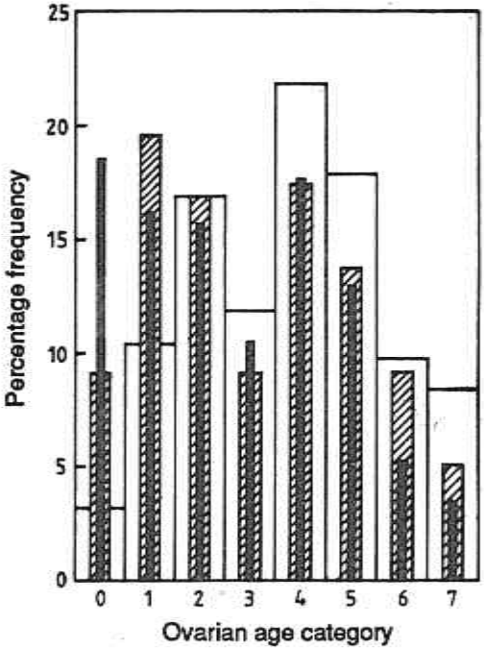

Fig. 5. Distributions of ovarian ages of samples of female *G. pallidipes* caught in odour-baited epsilon traps (open histogram), on an electric net mounted on the back of a Land Rover (hatched histograms), or in refuges (solid histograms). All flies sampled at Rekomitjie Research Station, October 1992.

It is implicitly assumed that all of the other age categories are equally represented. In fact, a rather complex argument developed over several papers; (Hargrove, 1990, 1991,1993) suggests that the probability of capturing a female fly actually increases in an approximately linear fashion over most of her life. This has some interesting theoretical implications regarding, for instance, the difficulties arising in estimating death rates from sample age structures and also the question of precisely why this bias should exist.

Of greater practical importance here, however, is the simple fact that the distribution of flies we are killing in traps is seriously skewed towards the geriatric end of the spectrum. Given that there does appear to be an aging effect in female tsetse (Hargrove, 1990) these old flies have a lower life expectancy (and therefore reproductive potential) than younger flies. We would thus prefer the distribution to be skewed quite the other way for maximum effect on the growth rate.

The bias does have one beneficial aspect. The prevalence of *Trypanosoma vivax* and *T. congolense* infections in female *G. pallidipes* shows that no infection is acquired before the age of c. 15 days and mature infections become more prevalent with age (Fig. 6) up to at least 60 days (Woolhouse et al., 1993). Thus, by killing older flies first we are at least removing the most infective part of the population. Nonetheless, the long-term decline in the growth rate would clearly be greater if it were drawn from the younger elements of the female population.

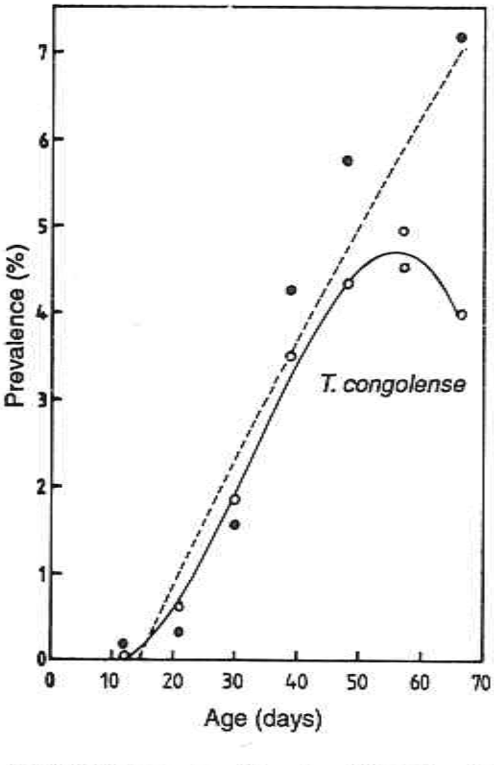

Fig. 6. The age-specific rates of infection of female *G. pallidipes* with *T. vivax* (dots) and *T. congolense* (circles). Flies trapped at Rekomitjie Research Station, September 1990–September 1991. Redrawn from Woolhouse et al. (1993).

The age distributions of flies caught on an electric net mounted on the back of a truck, or from artificial refuges, contain 1.5–6 times the proportion of category zero flies (see Fig. 5). The refuge catch approximates more closely the expected age distribution—particularly in the much higher proportion of category zero flies in the catch (see Fig. 5).

Slim Pickin's

The nutritional state of tsetse from stationary baits is strongly biased towards flies with low fat and haematin reserves (Vale and Phelps, 1978; Rogers, 1984; Randolph et al., 1991; Langley and Wall, 1990; Hargrove and Packer, 1993). Haematin levels suggest that <10% of male *G. pallidipes* caught in traps have fed in the previous 48 h (Fig. 7); males and females of the species caught on electric nets show the same dearth of high haematin flies (Langley and Wall, 1990). If flies feed every 2.5–3 days (Randolph et al., 1991; Hargrove and Packer, 1993) then roughly 33–40% of the population is expected to feed on any particular day and 66–80% should feed on one of two consecutive days. Once again, therefore, stationary baits have as a potential target on any particular day a relatively small portion of the population.

Refuges sample a broader spectrum of nutritional states. Figure 7 shows that about half of the sample had fed within the previous two days. Even this technique is biased against recently fed flies but the degree is considerably less severe than for odour-baited targets. Mobile baits, similarly, produce a larger number of better fed flies. Vale (1974a) found that 30% of female *G. m. morsitans* caught on mobile electric nets had traces of red or red-brown in the gut when this was smeared. These had also presumably fed within the previous

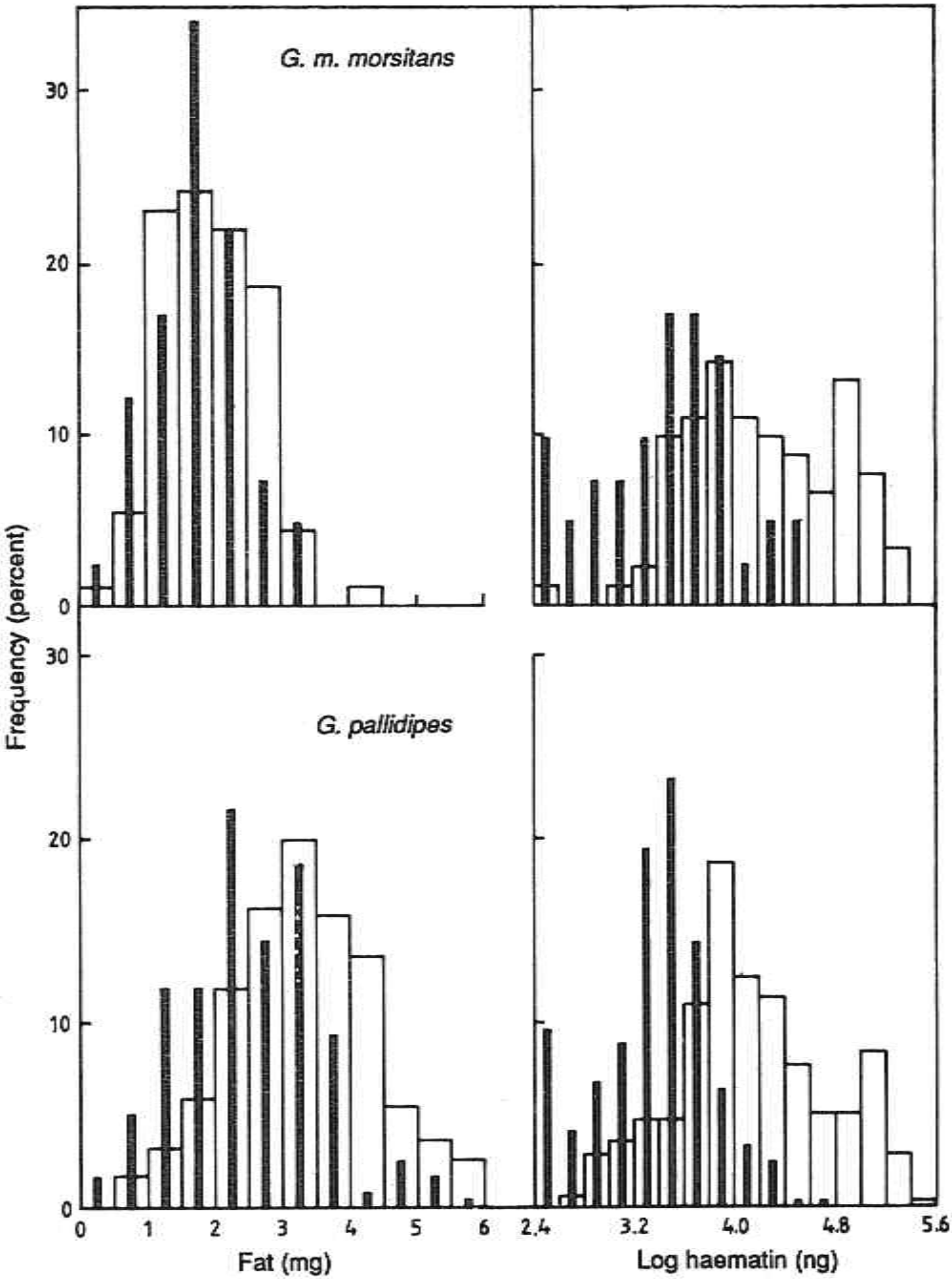

Fig. 7. Distributions of fat and log-haematin levels of samples of male *G. pallidipes* caught in odour-baited epsilon traps (solid histogram) or in refuges (open histogram). All flies sampled at Rekomitjie Research Station, September–November 1988. Redrawn from Hargrove and Packer (1993).

48 h. There is still a bias against recently fed flies, but it is not as severe as for odour-baited stationary devices.

Have Larva, Won't Travel

There are significant differences, too, in the distribution of pregnancy states of

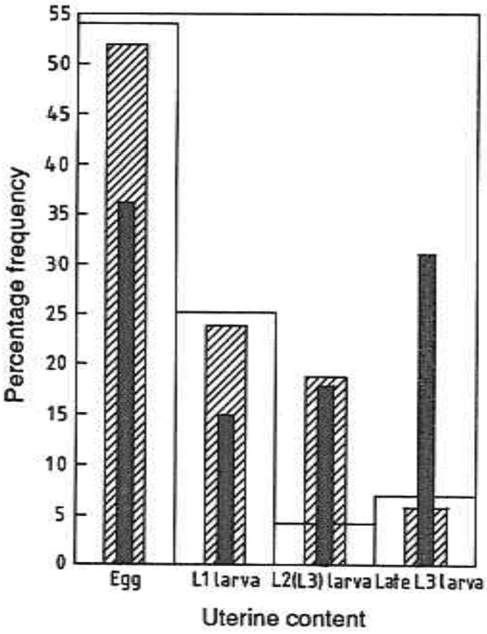

Fig: 8. Distributions of uterine contents of samples of female *G. pallidipes* caught in odour-baited epsilon traps (open histogram), on an electric net mounted on the back of a Land Rover (hatched histogram), or in refuges (solid histogram). All flies sampled at Rekomitjie Research Station, October 1992.

flies sampled using various methods. Samples from odour-baited traps and mobile electric nets are biased towards females with an egg, and against those with a late third-instar larva *in utero* (Fig. 8). This makes sense if, as expected, flies which have recently deposited a larva are 'hungry' and hence active (Brady, 1975) and if, as indicated by laboratory studies, heavily pregnant females show low levels of spontaneous flight activity (Brady and Gibson, 1983). Refuge samples, conversely, have elevated proportions of flies which are either heavily pregnant or have just deposited a larva and not yet ovulated, and fewer than expected flies with an egg *in utero*.

Mad Dogs

In addition to the above, there are also temporal differences in the responses of tsetse to various baits. The numbers of tsetse caught on odour-baited electric nets typically show a U-shaped pattern, modulated by temperature (Hargrove and Brady, 1992), with relatively few flies caught in the midday heat. Responses to refuges, naturally, show quite the opposite response (Fig. 9). Flies enter refuges at increased rates as temperatures increase during the morning (Vale, 1971).

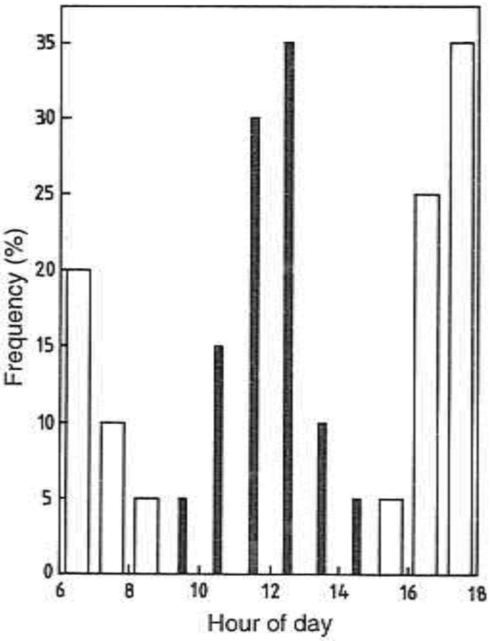

Fig. 9. Diurnal distribution of catches of *G. pallidipes* from odour-baited electric nets (open histogram) and from artificial refuges (solid histogram). Data from Vale (1971) and Hargrove and Brady (1992).

The Implications for Tsetse Control Strategies Using Bait Methods

The foregoing results illustrate that it is theoretically possible to augment the number of tsetse currently killed by odour-baited targets if we play on different aspects of fly behaviour. Ideally one would like to produce a single bait which attracts flies in more than one phase of behaviour. This is not as far-fetched as one might suppose. In a recent experiment Torr and Hargrove (in preparation) covered one of Vale's (1971) thatched 'box' refuges with phthalogen blue cloth such that it had the superficial appearance of a large F3 trap (Flint, 1985). The normal refuge catch (routinely made at 1400 h) was at least as high as that from a normal thatched refuge. However, tsetse also entered the blue refuge during the evening when flies are normally coming out of refuges and going into traps. What is probably implied is that tsetse may well enter appropriately sited traps in the middle of the day—but are not trapped at these times because the trap, once entered, does not offer the shade promised by its initial dark appearance. More work needs to be carried out to elucidate the detailed behavioural responses involved, but there is at least the possibility of developing a device which catches tsetse both in the feeding and in the 'refuge seeking' phases of behaviour.

It is less easy to see how one could combine the effects of mobile and stationary baits. However, in control areas where blood from livestock is an important component of the tsetse diet, the above results indicate that the combined use of odour-baited targets and insecticides applied to the livestock will produce baits which are complementary to each other in the classes of tsetse they are killing on any particular day.

An alternative, indirect, way of treating young females involves the sterilisation of males which then mate with young, virgin females which would not normally visit baits until later in their life cycle. Traditionally this approach has involved the treatment and release of laboratory bred males. Lately, however, chemicals have been developed which can be applied to traps or targets and which lead to the sterilisation of flies which contact them. Field trials have shown that impressive decreases in natural birth rates can result (Hargrove and Langley, 1990,1993). What has not been demonstrated thus far is an effective transfer of material from treated males to untreated females in the field.

Prospects

The reader may be asking why we *need* to improve bait technology. In view of the dramatic early successes, tsetse eradication, certainly in Zimbabwe, should be a formality. The technique is simple, easily understood and applied by field staff, no more expensive than ground spraying of DDT, and considerably cheaper (particularly in terms of foreign exchange) than ground spraying of deltamethrin or aerial spraying of any form (Barrett, 1991). We have the technology; surely we can finish the job?

In reality, the combined effects of transport, financial, administrative and sociological difficulties have ensured that target-based programmes have not always gone as well as they should. There are already examples of areas in Zimbabwe where targets have been deployed for more than 5 years and where tsetse populations have not been eradicated. There are many obvious reasons why there have been problems. On occasion targets are not optimally sited, they are not serviced at the required frequency, or they are stolen, the odours or insecticides are not available when they should be, and so on.

There are no grounds to suggest at this stage that there is anything intrinsically wrong with the approach. On the other hand, it is clear that further improvements in bait efficacy and simplicity are both desirable and necessary—particularly if the currently fashionable demand for implementation of bait technologies by local peasant communities is to be more than a trendy pipe dream.

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References

Barrett J. (1991) Cost analysis of odour-baited targets used for tsetse control in Zimbabwe, pp. 456–465. In *Twentieth Meeting of the International Scientific Council for Trypanosomiasis Research and Control,* Mombasa, Kenya, 1989. OAU/STRC, Nairobi.

Brady J. (1975) 'Hunger' in the tsetse fly: The nutritional correlates of behaviour. *J. Insect Physiol.* 21, 807–829.

Brady J. and Gibson G. (1983) Activity patterns in pregnant tsetse flies. *Physiol. Ent.* 8, 359–369.

Bursell E. (1977) Chemosterilisation of tsetse flies using a pressurised metepa aerosol. *Trans. Rhod. Sci. Assoc.* 58, 43–47.

Challier A. et Laveissière C. (1973) Un nouveau piège pour la capture des glossines (Glossina: Diptera, Muscidae) déscription et essais sur la terrain. *Cah. ORSTOM, Sér. Ent. Méd. Parasitol.* 11, 251–262.

Challier A. and Turner D. A. (1985) Methods to calculate survival rate in tsetse fly *(Glossina)* populations. *Ann. Soc. belge Méd. Trop.* 65, 191–197.

Flint S. (1985) A comparison of various traps for *Glossina* spp. (Glossinidae) and other Diptera. *Bull. Ent. Res.* 75, 529–534.

Green C. H. (1994) Bait methods for tsetse fly control. *Adv. Parasitol.* 34, 229–291.

Hargrove J. W. (1977) Some advances in the trapping of tsetse *(Glossina* spp.) and other flies. *Ecol. Ent.* 2, 123–137.

Hargrove J. W. (1980) Improved estimates of the efficiency of traps for *Glossina morsitans morsitans* Westwood and *G. pallidipes* Austen (Diptera, Glossinidae), with a note on the effect of the concentration of accompanying host odour on efficiency. *Bull. Ent. Res.* 70, 579–587.

Hargrove J. W. (1988) Tsetse: The limits to population growth. *Med. and Vet. Ent.* 2, 203–217.

Hargrove J. W. (1990) Age-dependent changes in the probabilities of survival and capture of the tsetse fly *Glossina morsitans morsitans* Westwood. *Insect Sci. Applic.* 11, 323–330.

Hargrove J. W. (1991) Ovarian ages of tsetse flies (Diptera: Glossinidae) caught from mobile and stationary baits in the presence and absence of humans. *Bull. Ent. Res.* 81, 43–50.

Hargrove J. W. (1993) Age-dependent sampling biases in tsetse flies *(Glossina).* Problems associated with estimating mortality from sample age distributions, pp. 549–556. In *Management of Insect Pests: Nuclear and Related Molecular and Genetic Techniques.* International Atomic Energy Agency, Vienna.

Hargrove J. W. (1994) Reproductive rates of tsetse flies in the field in Zimbabwe. *Physiol. Ent.* (in press).

Hargrove J. W. and Brady J. (1992) Activity rhythms of tsetse flies *(Glossina* spp.) (Diptera: Glossinidae) at low and high temperatures in nature. *Bull. Ent. Res.* 82, 321–326.

Hargrove J. W., Holloway M. T. P., Vale G. A., Gough A. J. E. and Hall D. J. (1995) Catches of tsetse flies *(Glossina* spp.) (Diptera: Glossinidae) from traps baited with large doses of natural and synthetic host odour. *Bull. Ent. Res.* 85 (in press).

Hargrove J. W. and Langley P. A. (1990) Sterilizing tsetse in the field: A successful field trial. *Bull. Ent. Res.* 80, 397–403.

Hargrove J. W. and Langley P. A. (1993) A field trial of pyriproxyfen-treated targets as an alternative method for controlling tsetse (Diptera: Glossinidae). *Bull. ent. Res.* 83, 361–368.

Hargrove J. W. and Packer M. J. (1993) Fat and haematin contents of male tsetse flies *Glossina pallidipes* and *G. m. morsitans* (Diptera: Glossinidae), caught in odour-baited traps and artificial refuges. *Bull. ent. Res.* 83, 29–46.

Hargrove J. W. and Vale G. A. (1978) The effect of host odour concentration on catches of tsetse flies (Glossinidae) and other Diptera in the field. *Bull. ent. Res.* 68, 607–612.

Hargrove J. W. and Vale G. A. (1979) Aspects of the feasibility of employing odour-baited traps for controlling tsetse flies (Diptera: Glossinidae). *Bull. ent. Res.* 69, 283–290.

Harris R. H. T. P. (1932) Some facts and figures regarding the attempted control of *Glossina pallidipes* in Zululand. *S. Afr. J. Sci.* 29, 495–507.

Jordan A. M. (1986) *Trypanosomiasis Control and African Rural Development.* Longman, London & New York.

Langley P. A. and Wall R. (1990) The implications of hunger in the tsetse fly *G. pallidipes,* in relation to its availability to trapping techniques. *J. Insect Physiol.* 36, 903–908.

Langley P. A. and Weidhaas D. (1986) Trapping as a means of controlling tsetse, *Glossina* spp. (Diptera: Glossinidae): The relative merits of killing and sterilisation. *Bull. ent. Res.* 76, 89–95.

Laveissière C. et Couret D. (1981) Essai de lutte contre les glossines riveraines à l'aide des ecrans et des pièges imprégnés d'insecticide. *Cah. ORSTOM, sér. Ent. méd. Parasitol.* 19, 271–283.

Laveissière C. et Couret D. (1982) Effet comparé des écrans et des pieges impregnes d'insecticide sur *Glossina m. submorsitans* dans les galeries forestières. *Cah. ORSTOM, sér. Ent. méd. Parasitol.* 20, 63–68.

Morris K. R. S. and Morris M. G. (1949) The use of traps against tsetse in West Africa. *Bull. ent. Res.* 39, 491–528.

Randolph S. E., Rogers D. J. and Kiilu J. (1991) The feeding behaviour, activity and trappability of wild female *G. pallidipes* in relation to their pregnancy cycle. *Med. Vet. Ent.* 5, 335–350.

Rogers D. J. (1979) Tsetse population dynamics and distribution: A new analytical approach. *J. Anim. Ecol.* 48, 825–849.

Rogers D. J. (1984) The estimation of sampling biases for male tsetse flies. *Insect Sci. Applic.* 5, 369–373.

Sickle J. van and Phelps R. J. (1988) Age distributions and reproductive status of declining and stationary populations of *Glossina pallidipes* Austen (Diptera: Glossinidae) in Zimbabwe. *Bull. ent. Res.* 78, 51–61.

Turner D. A. and Brightwell R. (1986) An evaluation of a sequential aerial spraying operation against *Glossina pallidipes* Austen (Diptera: Glossinidae) in the Lambwe Valley of Kenya: Aspects of the post-spray recovery and evidence of natural population regulation. *Bull. ent. Res.* 76, 331–349.

Vale G. A. (1971) Artificial refuges for tsetse flies (*Glossina* spp.). *Bull. Ent. Res.* 61, 331–350.

Vale G. A. (1974a) The responses of tsetse flies (Diptera: Glossinidae) to mobile and stationary baits. *Bull. Ent. Res.* 64, 545–588.

Vale G. A. (1974b) Tsetse control—A new method holds exciting prospects. *Tobacco Forum* 2, 19–23.

Vale G. A. (1980) Field studies of the response of tsetse flies (Glossinidae) and other Diptera to carbon dioxide, acetone and other chemicals. *Bull. ent. Res.* 70, 563–570.

Vale G. A. and Hargrove J. W. (1975) Field attraction of tsetse flies (Diptera: Glossinidae) to ox odour; the effects of dose. *Trans. Rhod. Sci. Assoc.* 64, 1–8.

Vale G. A. and Hargrove J. W. (1979) A method of studying the efficiency of traps for tsetse flies (Diptera: Glossinidae) and other insects. *Bull. ent. Res.* 69, 183–193.

Vale G. A., Hargrove J. W., Cockbill G. F. and Phelps R. J. (1986) Field trials of baits to control populations of *Glossina morsitans morsitans* Westwood and *G. pallidipes* Austen (Diptera: Glossinidae). *Bull. Ent. Res.* 76, 179–193.

Vale G. A., Lovemore D. F., Flint S. and Cockbill G. F. (1988) Odour-baited targets to control tsetse flies, *Glossina* spp. (Diptera: Glossinidae), in Zimbabwe. *Bull. ent. Res.* 78, 31–49.

Vale G. A. and Phelps R. J. (1978) Sampling problems with tsetse flies (Diptera: Glossinidae). *J. Appl. Ecol.* 15, 715–726.

Willemse L. (1991) A trial of odour baited targets to control *Glossina morsitans centralis* (Diptera: Glossinidae) in West Zambia. *Bull. ent. Res.* 81, 351–357.

Woolhouse M. E. J., Hargrove J. W. and McNamara J. J. (1993) Epidemiology of trypanosome infections of the tsetse fly *Glossina pallidipes* in the Zambezi Valley. *Parasitol.* 106, 479–485.

Crop Pests Biology

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Distribution of *Cicadulina* Leafhoppers and Maize Streak Virus Occurrence in Africa

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Abstract—Between 1982 and 1990, regular samplings of *Cicadulina* leafhoppers were analysed by the author from various climate zones in Nigeria, Togo and Cameroon and occasionally from Benin, Burkina Faso, the Ivory Coast, Burundi, Zaire, Zimbabwe, Zambia and Kenya. Quantitative and qualitative differences in species composition were observed between seasons and within a single growing season. *Cicadulina mbila* and *C. storeyi (triangula)* were the dominant species in major maize growing areas of West Africa in 1983, 1984, 1986 and 1987 and *C. similis* and *C. arachidis* in 1985. *Cicadulina ghaurii* was the dominant species in the rain forest zone during the greater part of the growing seasons studied in West Africa. Drastic changes in species composition at the beginning of the dry season indicated mass migration of *Cicadulina* leafhoppers from other zones into the forest zone. The dominant *C. ghaurii* species was replaced at that time by *C. mbila* or *C. storeyi* in various locations.

Cicadulina mbila and *C. storeyi* were the most widely distributed species in Zambia, and *C. mbila* and *C. latens* in Kenya in samples collected between 1987–1990 and 1989, respectively.

Maize streak virus (MSV) disease outbreaks in 1983 and 1984 were associated with long drought or irregular rains at the beginning of the growing season, especially in the savanna regions of West Africa. The high MSV incidence in 1986 in the forest and transition (forest/savanna) zone was attributed to the interruption of the dry season by regular rains between December and April, allowing farmers to start planting maize in February and March. Green grasses during the first season maintained the *Cicadulina* populations, which migrated in large numbers into early-planted maize fields. Bioassays showed that 0–15% of leafhoppers in samples collected in the first growing season and 0–23% in the second season were capable of infecting maize test plants with MSV. The high portion of *C. mbila* and *C. triangula* in the local *Cicadulina* populations was always correlated with a high level of MSV incidence on maize fields in all sampled locations. Maize growing areas with a high portion of *C. ghaurii, C. arachidis, C. similis* (West Africa) or *C. latens* and *C. vescula* (East Africa) always showed lower levels of maize streak virus infection. The importance of correct species identification of *Cicadulina* leafhoppers in the studies on MSV disease epidemics is strongly emphasised.

Key Words: *Cicadulina* leafhoppers, maize streak virus, Africa

Introduction

Cicadulina leafhoppers are widely distributed in Africa, Indian Ocean Islands, and in some parts of Asia and Australia. Some *Cicadulina* species have been identified as vectors of the maize streak virus and the mottle/chlorotic stunt virus in Africa (Storey, 1925; Guthrie, 1977; Rossel et al., 1980). Maize streak virus (MSV) disease is at present considered one of the most important factors reducing maize yield in Africa (Bock, 1974; Fajemisin et al., 1976; Rossel and Thottappilly, 1985). The severity of the disease is usually related to the age of the plant at the time of infection (van Rensburg and Kuhn, 1977). Plants infected before the 4–6 leaf growth stage develop the most severe symptoms. The disease is naturally erratic, like most virus diseases. Damage due to MSV can be insignificant in some years; but epidemics of the disease can devastate crops with yield losses up to 100%.

The MSV disease epidemics are noted from all over Africa south of the Sahara. In the past, the MSV was mainly recorded from low altitude zones; recently, however, high incidences have also been observed at higher altitudes (in some cases above 2000 m) in Cameroon, Zaire, Burundi, Zambia and Kenya. Because long term studies are lacking on MSV epidemics and *Cicadulina* leafhoppers' distribution and ecology on the geographical zone level in Africa, the reasons for the recent increased importance (especially in East Africa) are unknown.

According to the survey carried out in 1989 by the Ministry of Agriculture, Kenya, the MSV has caused considerable yield reduction in many parts of the Central Province. Many farmers did not harvest any maize that year. Overall, it was estimated that unless the situation is checked, it is likely to cause 50% crop loss in future years, equivalent to a shortfall of approximately 420,000 tons of maize valued at over K£ 60,000,000 (equivalent to US$ 3,000,000). Besides the economic effects on the population in the region, this magnitude of shortfall in maize supplies would create a serious strain in the entire economy (Anon, 1990).

Given the nature of the disease and the circumstances and constraints encountered by African farmers, it was recognised that the development of resistant varieties is the most appropriate and cost-efficient approach to controlling the disease (Fajemisin et al., 1985; Bjarnason, 1986). Development of simple and reliable screening techniques made progress possible (Soto et al., 1982; Dabrowski, 1984 a–c). The necessity of making further improvements in mass rearing and optimising the release of viruliferous leafhoppers for MSV resistance screening has recently forced researchers to conduct a wide range of laboratory and field observations and experiments on *Cicadulina* biology, behaviour and ecology (Dabrowski, 1985, 1987 a–d, 1989; Okoth et al., 1987 a,b).

In the past the basic information on *Cicadulina* ecology and its relation to MSV transmission has been generated with the focus on the role the leafhoppers play in the MSV epidemics under field conditions. The research in this area has been mainly carried out by Storey (1925 and 1936) in Kenya; Rose (1972, 1973 a–c, 1974, 1978) in Zimbabwe; van Rensburg (1982 a,b) in South Africa; Okoth and Dabrowski (1987); Okoth et al. (1987 a,b) in Nigeria and Dabrowski (1987 a–d) in Nigeria, Togo, Cameroon and Zimbabwe.

Valuable information on the systematics and taxonomy of *Cicadulina* has been provided in the revisions published by Ruppel (1965), van Rensburg (1983) and especially Webb (1987 a,b), who for the first time has included detailed descriptions of existing intraspecific variations in size, marking and colour of adult *Cicadulina* specimens and in the structure of the male genitalia. The intraspecific variations in the past led to incorrect species identification.

Distribution

The distribution of most *Cicadulina* species seems to be limited to fairly large regions within Africa, and most of those in the Middle East and Asia seem to have spread from Northern Africa (Ruppel, 1965; Rose, 1983; Okoth and

Dabrowski, 1987; Dabrowski, 1987c; Webb, 1987a). Rose (1983) divided *Cicadulina* species into three groups common to different regions of Africa: (a) northern and eastern Africa; (b) eastern and southern Africa; (c) western and southern Africa. He emphasised that species common to both North and South, or East and West are rare. This division based on the limited studies available at that time, has been generally confirmed by new findings of Okoth and Dabrowski (1987) and Dabrowski (1987 a–c) in West Africa; Okoth et al. (in press) in Kenya; Okech et al. (in press) in Zambia; Dabrowski (unpublished) in Zimbabwe, Burundi, Zambia, Zaire and Kenya. Webb (1987 a,b) has recently re-examined available collections and expanded the geographical distribution of some *Cicadulina* species.

Considering that *C. triangula* Ruppel should be synonymised with *C. storeyi* China (Webb, 1987a), this species as well as *C. mbila* (Naude) are the two most widely distributed species in Africa, being recorded in northern, western, eastern and southern regions, including Mauritius.

Occasionally, individual specimens are found far away from their major species distribution region, e.g., *C. chinai* Ghauri by Dabrowski in Nigeria (4 males in a sample of 232 at Ikene, 5 November 1986); *C. ghaurii* Dabrowski by Okoth et al. (in press) on Rusinga Island (Kenya) or by Webb (1987a) in samples collected from Ethiopia. Two males of *C. latens* Fennah in a sample of 65 *Cicadulina* leafhoppers were found at Eboko (Cameroon) on 25 October 1985; and at Ikenne (Nigeria) on 12 December 1986 (Dabrowski, unpublished). Recent regular collection of *Cicadulina* in six locations in Uganda revealed a presence of 11 species as follows: *C. storeyi; C.mbila; C. ghaurii; C. dabrowskii* Webb; *C. arachidis* China; *C. chinai* Ghauri; *C. niger* Ghauri; *C. bipunctata* (Melichar); *C. vescula* Ruppel; *C. latens* Fennah and *C. similis* China (W. W. Page, pers. commun.).

It should be emphasised that because regular ecological studies on *Cicadulina* leafhoppers have been restricted to only a few countries (Zimbabwe, Nigeria, Cameroon, Togo and recently Kenya, Zambia and Uganda), the distribution recorded above is far from complete.

Quantitative Changes in *Cicadulina* Population Density

Based on five-yearly regular sampling of *Cicadulina* leafhoppers collected by the author in various climatic zones in Nigeria and occasionally in Togo, Benin and Cameroon, quantitative and qualitative differences in population density and species composition were observed between consecutive seasons and within a single growing season.

The sizes of field populations of *Cicadulina* leafhoppers are mainly determined by the number of host grasses suitable for oviposition and development of nymphs. The suitability of vast areas of natural grasslands depends on rainfall patterns. In all the ecological zones sampled in West Africa, a generalised trend was observed that *Cicadulina* populations build up with the rains (Fig. 1). The number of leafhoppers caught was very low at the onset of the rains, generally rising and reaching its maximum before the rains finally stopped. The same observations were made for southern Africa (Rose, 1978).

During most of the growing season, *Cicadulina* leafhoppers were scarce on grasses, maize and pearl millet. The highest numbers of leafhoppers (34–136 adults/m^2) were always collected from the following grasses toward the end of the rainy season: *Digitaria, Brachiaria, Eleusine, Pennisetum* and *Polystachion.*

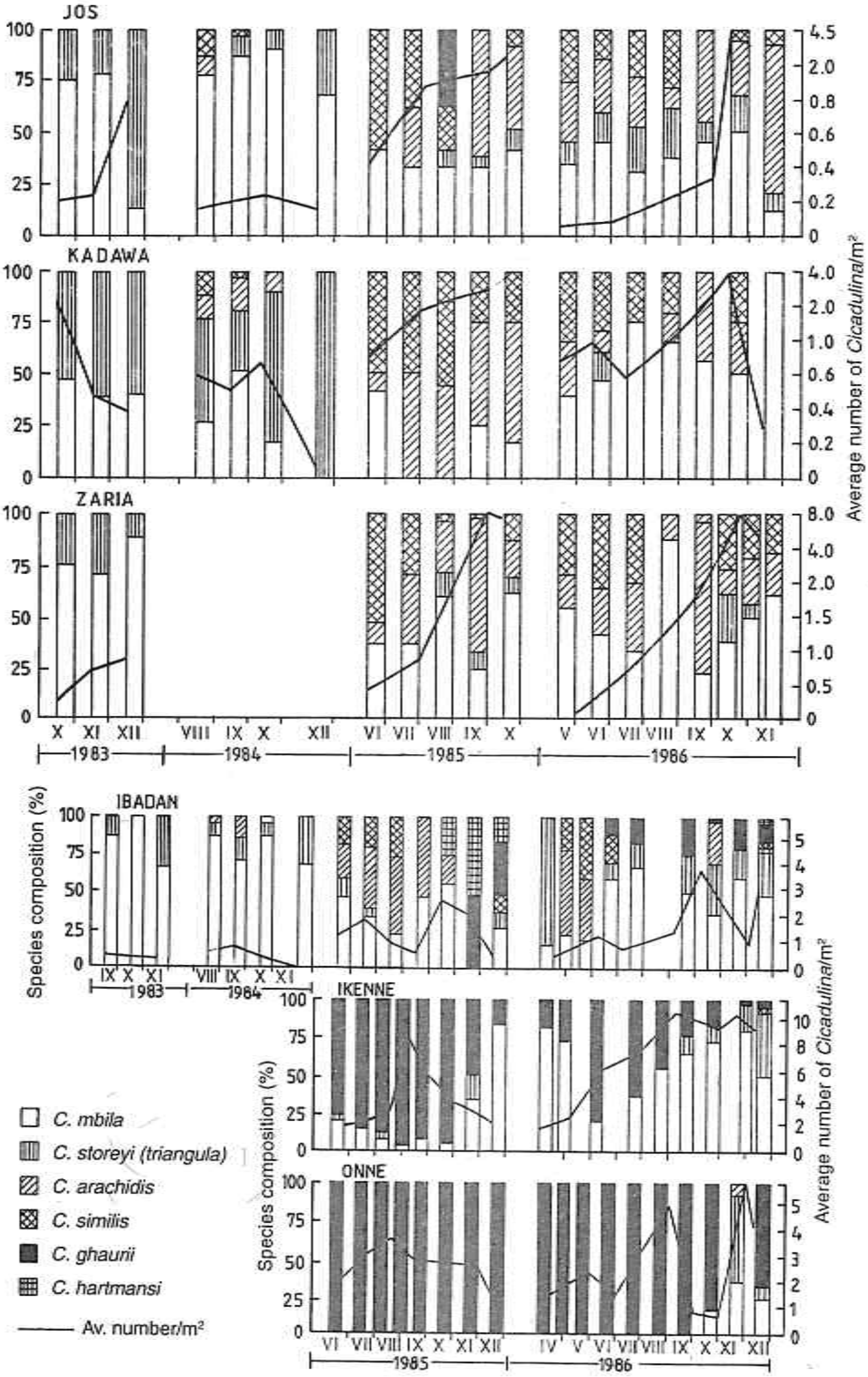

Fig. 1. Population dynamics and species composition of *Cicadulina* populations in selected major ecological zones in Nigeria between 1983 and 1986; Jos Plateau (1200–1400 m above sea level and 600–700 m above the surrounding Hausa Plain); Kadawa Irrigation Scheme near Kano; southern Sudan savanna; Zaria—northern Guinea savanna; Ibadan—derived savanna; Ikenne—rain forest; Onne—freshwater swamp.

Cicadulina adults tend to aggregate on young grasses rather than on extensive areas of maize, pearl millet and sorghum. The density fell progressively during the dry season and was low even on small irrigated areas covered by maize or preferred species of grasses. Probably the strong, dry, cold (or hot) harmattan winds from the Sahara affect the *Cicadulina* population in the Guinea savanna and some parts of the rain forest (Okoth and Dabrowski, 1987). The average population density of leafhoppers in the rain forest zone was always higher than on irrigated plots in the savanna zone. Generally, the population size was determined by the availability of young grasses for oviposition and feeding but weather conditions during the second part of the dry season modified those relationships. The general population density of leafhoppers in the wet forest zone never decreased below 0.5 adults/m^2 of grassland in comparison to the total absence of leafhoppers in the transitional part of the forest zone, Guinea savanna and Sudan savanna sampled by us.

In 1986 adult leafhoppers appeared on grasses and young maize plants earlier than in the previous years in the forest zone in Nigeria. The rainfall pattern in 1986 showed significant differences in comparison with previous seasons. The usual period of dry season in the rain forest zone (December–April) was interrupted by few rains, allowing farmers to start planting maize in February and March. Green grasses during the first season maintained the *Cicadulina* population, which migrated in large numbers into early-planted maize fields.

A sharp increase in the *Cicadulina* population density was always observed in November and December in the rain forest and deltaic swamp forest zones (Fig. 1), which may indicate mass migration activity of leafhoppers from the already dry areas of the adjacent Guinea savanna at that period.

Differences have been observed in the population density and leafhopper migration between grasses and maize crop in years with regular versus irregular rainfall distribution. Under regular rains, most farmers planted their maize field after the first rains. Maize crops developed parallel to grass growth. Most of the *Cicadulina* leafhoppers developed on grasses and only low migration was observed and this was restricted to the border rows of the maize. In years with irregular rainfall distribution, the first rains allowed grasses to start growing, but maize planting was delayed. A full generation of leafhoppers can develop on these grasses (a period of 4–5 weeks is needed for the development of a *Cicadulina* generation) before migrating into the maize field offering young plants (maize or newly germinated grass weeds) for feeding and oviposition. High populations of *Cicadulina* develop on fields with young maize crops, increasing the probability of MSV infestation (Fajemisin et al., 1986).

Qualitative Changes in *Cicadulina* Populations

Detailed ecological observations conducted in West Africa between 1983 and 1987 have shown that at least some species live undetected in low-density populations in seasonal grassland, and it is possible that high-density populations in favorable places with irrigated grasses and cereals are more readily noticed and sampled, for example, *C. hartmansi* Dabrowski in Ibadan, Nigeria (Dabrowski, 1987a,b).

Cicadulina species which did not previously dominate in a particular ecological zone during the growing season, suddenly appeared in high numbers at the end of the rainy season on young green grasses and late planted maize plants, indicating mass migration of leafhoppers at that time (Dabrowski et al., 1991).

Four species: *C. mbila, C. storeyi (triangula), C. arachidis* China and *C. similis* China were found in the rain forest, Guinea savanna and southern Sudan savanna in Nigeria and Cameroon (Figs 1 and 2). *Cicadulina mbila* was the predominant species, comprising 68.5% of the total number

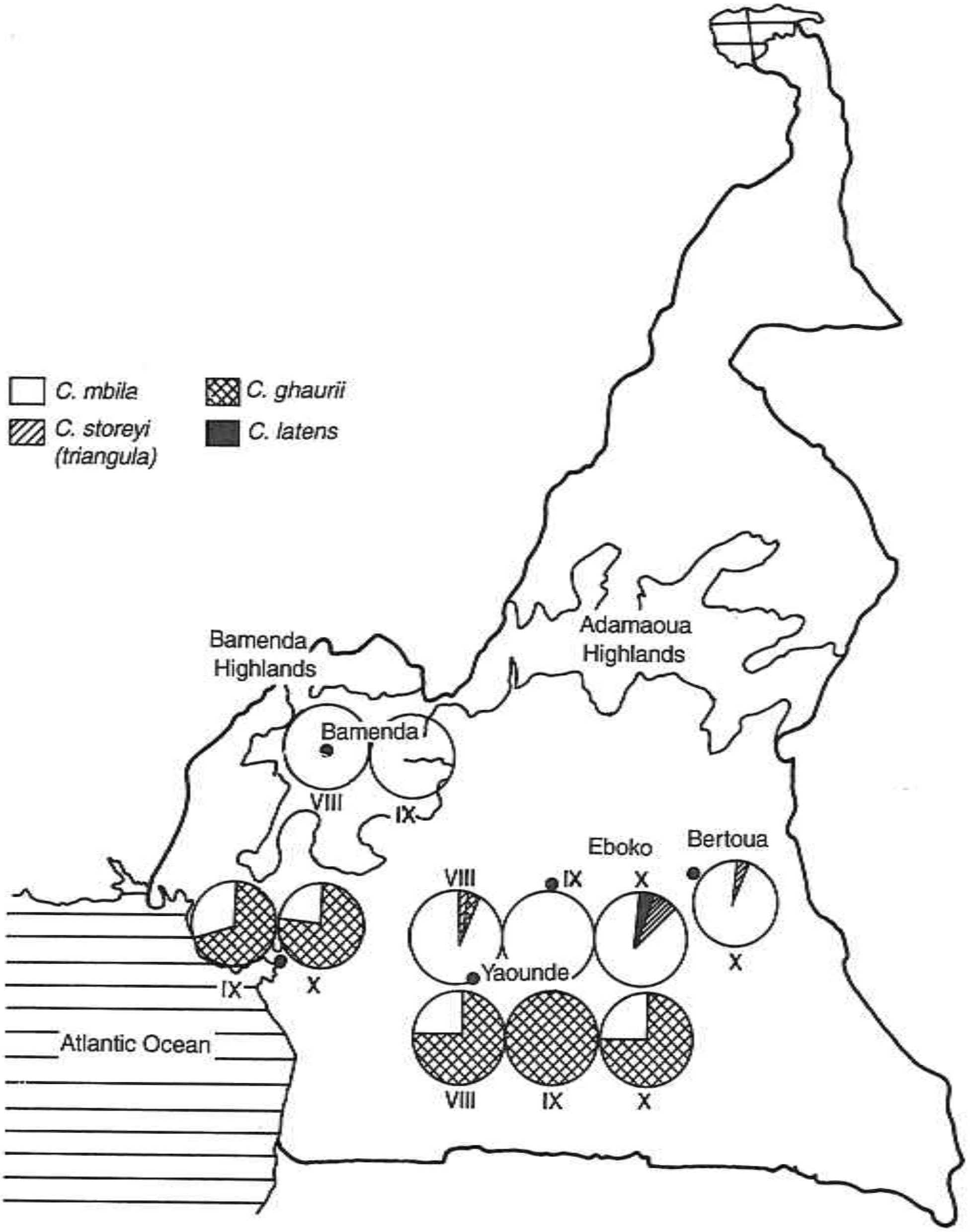

Fig. 2. Seasonal changes in *Cicadulina* population composition in four ecological zones in Cameroon in 1986: Bamenda highlands; Nanga and Bertoua—savanna; South of Yaounde forest; Douala—high rainfall forest (samples collected by Mr Ch. Njoh, identification by Z. T. Dabrowski).

of species collected in the 1983/84 and 1986/87 growing seasons. *Cicadulina mbila* occupies low- to mid - (800–1000m) altitude areas, but not areas where the daily temperature is higher than 28°C. In those areas of higher temperatures in West Africa, the portion of *C. storeyi* and/or *C. arachidis* rapidly increases. The percentage of *C. storeyi* increased from 17% in the transitional part of the rain forest to 60% in the warmer Sudan savanna. *Cicadulina arachidis* and *C. similis* never exceeded 15% of the total number of *Cicadulina* in 1983/84 but reached 60–80% in 1985/86 in some parts of West Africa. *Cicadulina ghaurii* was recorded as the predominant species in the high rainfall forest and swamp forest of Cameroon and Nigeria respectively (Figs 1 and 2) (also Dabrowski, 1987a,b; Dabrowski et al., 1991).

Extensive sampling of *Cicadulina* between August and November 1985 in various climatic zones in Nigeria showed the increase of the *C. arachidis* fraction between August and October–November in the Sudan savanna and the northern Guinea savanna (Fig. 3 *versus* a figure presented by Dabrowski, 1987c). Samples obtained at that time from Burkina Faso confirmed that *C. arachidis* was the dominant species in the dry and hot zones of West Africa.

Our regular observations conducted over two years in 1986 and 1987 in the swamp and high forest zones of Nigeria showed that the population composition of *Cicadulina* leafhoppers drastically changed with their rapid numerical increase at the beginning of the dry season (Nov–Dec). The fraction of *C. ghaurii*, the predominant species during the first (Feb–June) and second growing

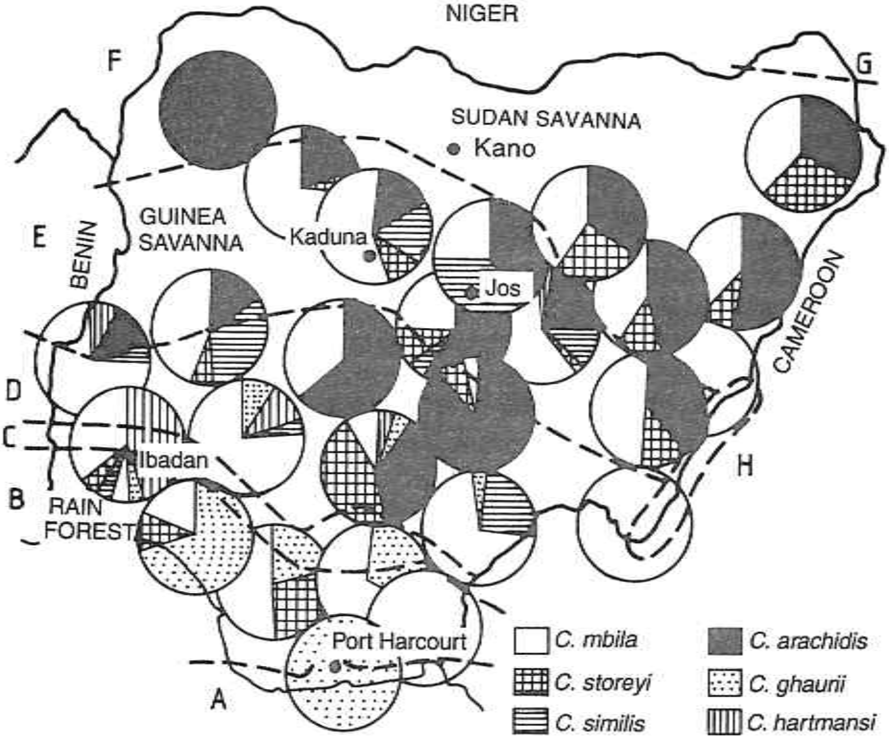

Fig. 3. Population composition of *Cicadulina* leafhoppers in October–November 1985 in various ecological zones in Nigeria: A—freshwater swamp; B—rain forest; C—transitional zone (rain forest/derived savanna); D—southern Guinea savanna; E—northern Guinea savanna; F—Sudan savanna; G—Sahel savanna; and H—montane vegetation.

season (Aug–Nov) was rapidly reduced in favour of *C. mbila*, *C. storeyi* and *C. arachidis*, which previously formed only a marginal portion of leafhoppers (see Fig. 1) and Dabrowski et al. (1991).

Field surveys conducted in Zambia during 1987/88; 1988/89 and in the 1990 growing seasons in some selected important maize growing areas showed that *C. mbila* and *C. storeyi* were the most widely distributed species, traversing the whole country (Fig. 4) (Okech et al., in press; and Dabrowski, unpublished). *Cicadulina similis* was found in Dundwa (near Choma) while *C. parazeae* Ghauri was found around Lusaka only. Samples collected on 23 March 1990 in Golden Valley contained 33.3–44.4% of *C. vescula* Ruppel. Generally, the population of leafhoppers was higher in the northern and central part of the country compared to the south. Higher densities of the *Cicadulina* in the South were only recorded at Chirundu where there is an irrigation scheme (Okech et al., in press). Webb (1987a) has reported only three species from Zambia: *C. mbila* (unverified record), *C. vescula* (new record) and *C. hastula* Van Rensburg collected from Shaangonbo, March Island.

In most of the areas surveyed by Okoth et al. (in press) in Kenya during the 1989 growing season, two species of *Cicadulina*, namely *C. latens* Fennah and *C. mbila* were the commonest (Fig. 5). *Cicadulina latens* seemed to occupy the cooler areas to the east of the Rift Valley, while *C. mbila* appeared to occur

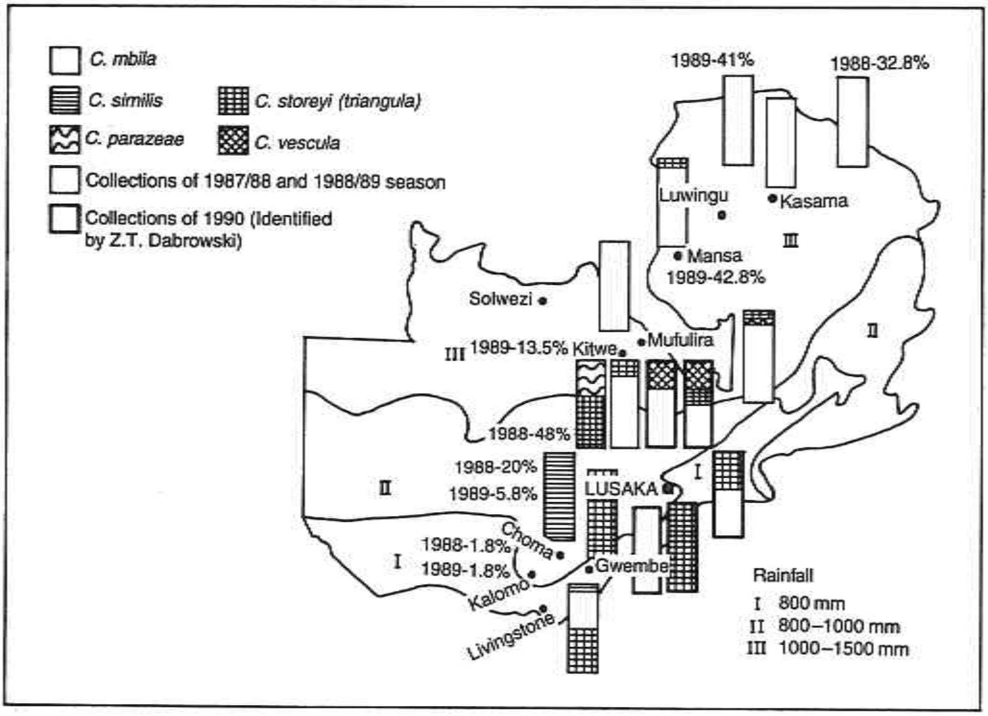

Fig. 4. *Cicadulina* leafhoppers distribution and MSV incidence in the main maize growing zones in Zambia (modified after Okech et al., in press and Dabrowski, unpublished).

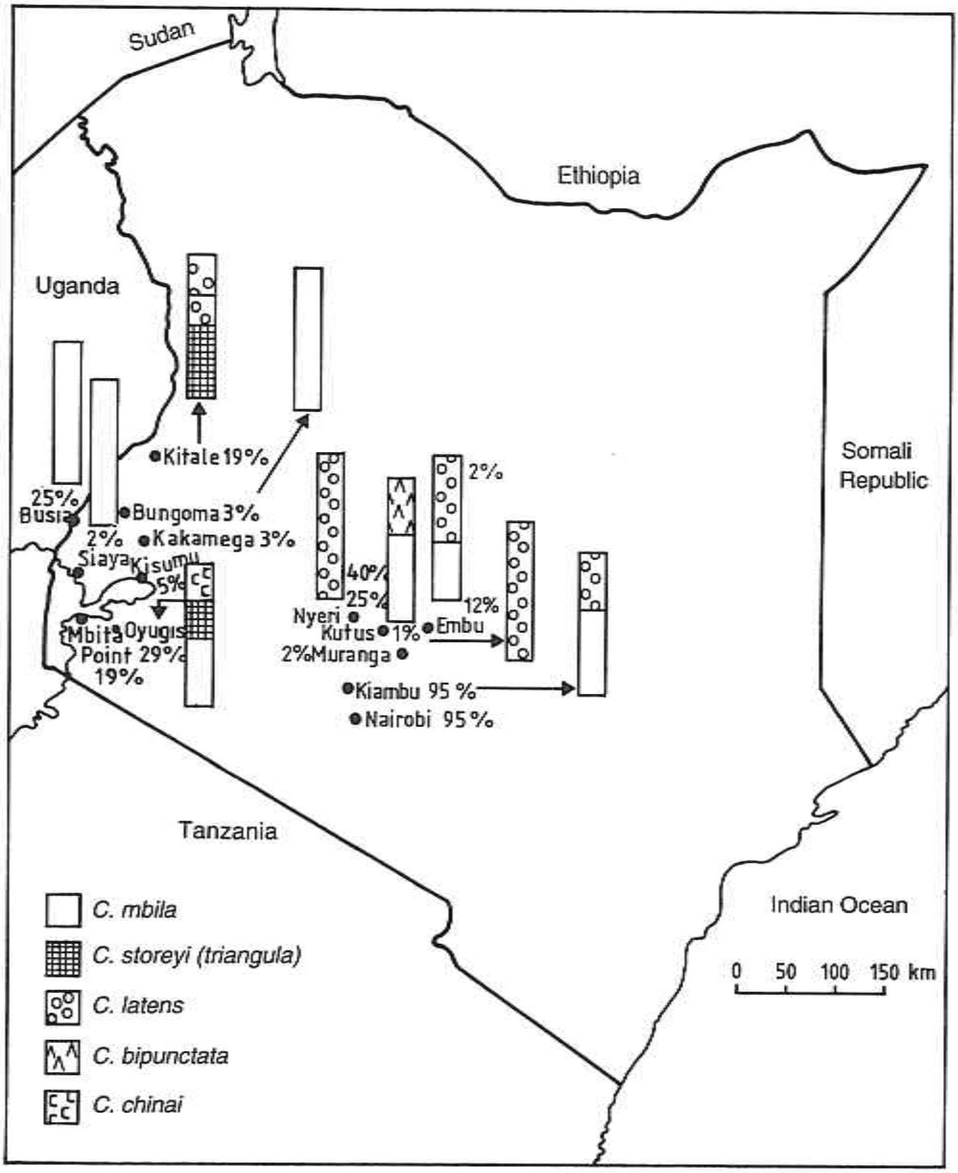

Fig. 5. *Cicadulina* leafhoppers distribution and MSV incidence in Kenya in 1989 (modified after Okoth et al., in press and Dabrowski, unpublished).

in the Lake Basin and western ecozones to the southwest. *Cicadulina chinai* and *C. storeyi* were probably the third and fourth most dominant species, sampled in areas as wide apart as the Lake Basin and Trans Nzoia. *Cicadulina bipunctata* (Melichar) was found in Kirinyaga District only and *C. ghaurii* in Siaya District, as a new record from Kenya (Okoth et al., in press).

Factors Associated with MSV Epidemics

Outbreaks of MSV disease are irregular. In some years, the disease can be insignificant, but in others it can devastate crops with high yield losses. Maize streak epidemics have been reported in Nigeria in 1966, 1971, 1973 and 1977 (Esenam, 1967; Fajemisin et al., 1976). Recent outbreaks of the disease in 1983, 1984 and 1986 are associated with drought conditions or irregular early rains, especially in the savanna regions of West Africa. Severe maize streak epidemics have also been reported from Zaire, Zambia, Angola and Mozambique (IITA, 1986), Zambia (Okech et al., in press); and Kenya (Okoth et al., in press).

In various ecological zones where maize is grown in Africa, streak is often observed on the minor season crop after the dry season that immediately follows the major season or in the late-sown crop during the major season.

The development of a streak epidemic is primarily governed by the availability of the leafhopper vectors and their relative rates of infectivity. These in turn are related to the factors affecting the growth of grasses as the natural host of the vector and the hosts of the virus (Rose, 1974). The weather conditions directly affect the growth of maize and perhaps its tolerance to MSV infection. It is the complexity of these interactions that has made the pattern of streak epidemics least understood. The direct and indirect effect of climatic factors on maize crops, grasses, *Cicadulina* vectors and the maize streak virus epidemics are summarised in Fig. 6 (Fajemisin et al., 1986).

One of the major factors responsible for MSV epidemics is a 'domestication'

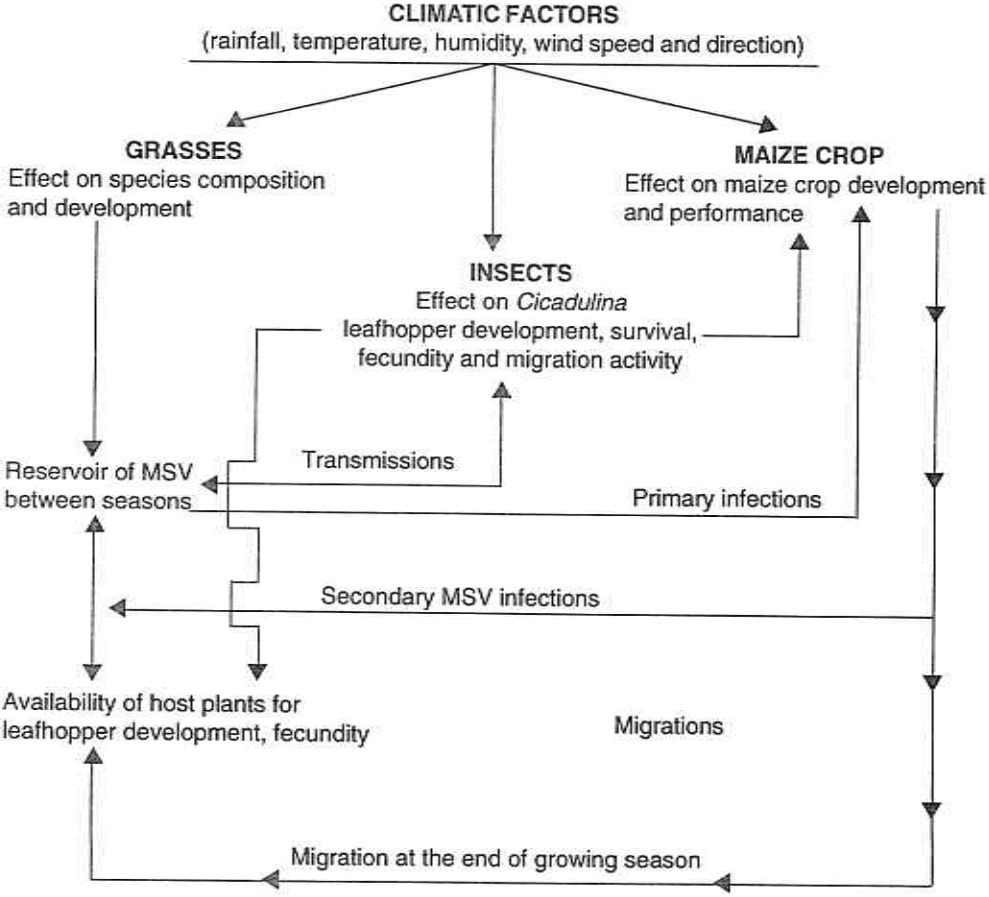

Fig. 6. Effects of climatic factors on the biotic components of the maize streak disease epidemics and their reciprocal interactions (after Fajemisin et al., 1986).

of the environment, e.g. conversion of grassland savanna into land used for agriculture; introduction of irrigation; extensive use of land with narrow breaks between/or overlapping two consecutive crops. It should be remembered that within the past 25 years, maize has become an increasingly popular crop in Africa. Since the drought of the early 1970s, maize has steadily been replacing sorghum and millet in the savanna zones. This is due to the relative ease in which maize is turned into food, and to the progress made in adapting the crop to the savanna through appropriately improved varieties and agronomic packages. The status of maize has therefore changed from that of a mere garden (backyard) crop to a plantation cash crop of hundreds of hectares, especially in the Guinea savanna zone of West Africa (Fajemisin et al., 1986). In the forest belt where two crops of maize can be grown in a year, the availability of an early-maturing and disease-resistant maize has made the growing of minor-season maize increasingly popular.

This encroachment of maize into non-traditional areas and seasons has ecological implications. It increases reserves of the streak virus and provides additional host food for leafhopper activities on maize and grasses. The preferred grass species for *Cicadulina* feeding or oviposition and harbouring MSV, e.g., *Eleusine, Brachiara, Rottboellia* or *Setaria,* often occur as weeds in agricultural fields rather than in a typical savanna grassland.

Another component of the changing agricultural practices in Africa with similar MSV epidemiological consequences is the introduction of large-scale irrigation facilities (Rose, 1978).

Okech et al. (in press) noted in Zambia, that generally the MSV incidence seems to be correlated with the rainfall pattern within the country. The northern part of the country with a high rainfall regime is more vulnerable to MSV outbreak than the drier southern part (Fig. 4). Rainfall in the North (region III) is high, and well-spread over a longer period than region I (South), stimulating constant growth of host grasses suitable for oviposition and development of *Cicadulina.*

The incidence of MSV assessed during the 1989 main growing season in three ecologically widely differing maize growing zones of Kenya showed the severe infection level in the highlands to the east of the Rift Valley, averaging 40% in Nyeri District and over 90% in Kiambu (Fig. 5). In Lake Basin, Western and Kitale areas, the incidence was generally low, with the average between 0.5–5%, although in Busia District it was 25% (Okoth et al., in press). According to the Kenya Agricultural Research Institute (1990), the current spate of the MSV disease began in 1988 and was particularly serious in Central Province and the Coast Province.

Under Zimbabwean conditions, the invasion flight of *Cicadulina* leafhoppers is prolonged through cold weather. This allows MSV to multiply in susceptible irrigated crops even though only low proportions (1–2%) of the grassland-originated populations of *Cicadulina* are infective. During the flight period, leafhoppers settle on the crops daily and stay for one to several days before leaving. The population is continuously changing, and as the leafhoppers have often come long distances from widely distributed sources, the leafhoppers and MSV-infected plants have a slightly aggregated dispersion throughout the entire crop. Over a period of eight or more weeks, a high proportion of crops become infected with virus, and these crops are sources of high density populations of infected leafhoppers when these mature after the end of the cold season, having developed from eggs laid by the shifting *Cicadulina* populations during the flight period. Rose (1978, 1983) emphasised that the common cause of streak disease in Zimbabwe is the planting of irrigated maize crops close to winter crops before these have been destroyed. Streak epidemics caused by the leafhoppers dispersing from drying grassland occur when an extra generation develops in the widespread grasslands and the wet season is extended through prolonged rains. The prolonged rains induce growth of new grasses suitable for oviposition at an unusual time of the year.

Patterns of streak infection in maize fields conform closely with the seasonal differences in *Cicadulina* distribution. Commonly, it is known that late planted maize is always more severely infected with MSV than early planted maize in West and East Africa. As previously shown, the density of leafhoppers also increases in the course of the growing season.

Regular observations over a five-year period on the percentage of naturally infected *Cicadulina* leafhoppers under field conditions carried out in the first and second growing seasons in various ecological zones in Nigeria did not indicate the direct correlation between MSV incidence on maize fields with total population density and the percentage of MSV-infected leafhoppers. In some areas of the forest zones, the leafhopper density reached a high level of 18–40 adults/m^2 with only 4–16% of MSV on maize and 3–10% of infected leafhoppers. The detailed analysis of all the factors showed that leafhopper species composition is the main factor responsible for low MSV incidence. *Cicadulina ghaurii* was the dominant species in the forest zone. The dominance of *C. mbila* and *C. storeyi* was always correlated with a high level of maize streak virus incidence on maize fields in all locations sampled between 1982 and 1987. Maize growing areas with a higher portion of *C. ghaurii*, *C. arachidis* and *C. similis* always showed lower levels of MSV.

The importance of a *Cicadulina* species in MSV epidemics has been confirmed by laboratory experiments conducted under controlled conditions. It was found that *Cicadulina* species vary in their efficiency in transmitting MSV (Dabrowski, 1987c). Around 44% of *C. storeyi* and *C. mbila* are capable of transmitting the virus, whereas only 8% of *C. arachidis* can do so. Therefore, the species composition of *Cicadulina* populations will directly affect the level of MSV infection on the maize crop. In 1983 and 1984 when there were MSV epidemics in Nigeria, the number of *C. arachidis* and *C. similis* was never higher than 15% of the total *Cicadulina* population, and *C. mbila* and *C. storeyi* were the dominant species in all sampled areas. On the other hand, *C. arachidis* was the predominant species in the Guinea savanna and Sudan savanna zones in Nigeria in 1985 when streak incidence was negligible.

Bioassays conducted under controlled conditions using *Cicadulina* specimens collected from various climatic zones in Nigeria also confirmed that leafhoppers collected later in the growing season are composed of a high fraction of insects which have already acquired MSV. There were no significant differences between MSV transmission by randomly selected populations of *C. mbila* and *C. storeyi* (=*triangula*) from western and southern Africa (Dabrowski, unpublished).

Practical Application of Basic Knowledge on *Cicadulina* Taxonomy, Biology and Ecology by National Agricultural Research Programmes in Africa

Realising the importance of streak virus control through releasing resistant maize cultivars, some African National Programmes have tried to develop their own *Cicadulina* colonies and MSV resistance breeding programmes. In most cases, these efforts have not been successful. National scientists have faced scientific and technical problems in the following areas:

- (i) Correct identification of *Cicadulina* specimens in numerous populations of leafhopper and planthopper species that always occur on grasses and cereals in Africa;
- (ii) Collecting a large number of live individuals of the proper species to start colonies;
- (iii) Handling the initial small population of *Cicadulina;*
- (iv) Enlargement and correct management of the colony to produce enough insects for field infestation.

These problems have already been addressed by development of a new and improved expertise in taxonomy, methods and techniques of rearing leafhoppers for streak resistance screening, and bioassays to monitor the percentage of viruliferous leafhoppers in populations used for screening (Dabrowski, 1989). Of special value has been the recent revision of *Cicadulina* species by Webb (1987a,b) who has provided good and clear illustrations of a broad range of intraspecific variations in the taxonomic structures used for species identification.

Correct species identification is a prerequisite in the study of the biology, behaviour and ecology of *Cicadulina* leafhoppers transmitting MSV. Such studies have been recently initiated by a number of maize national programmes in sub-Saharan Africa: Burkina Faso, Burundi, Cameroon, Ivory Coast, Kenya, Nigeria, Tanzania, Togo, Zaire, Zambia, Zimbabwe and Uganda. All of these programmes have faced the problem of species identification. It has been also shown that only some selected species of *Cicadulina* are suitable for mass rearing and MSV resistance screening. Significant differences in the ability to transmit MSV between *Cicadulina* species which are similar in their coloration (e.g. *C. mbila, C. similis* or *C. ghaurii*) underlines the importance of correct species identification based on the characters of the male genitalia.

References

Anonymous (1990) Farmers learn how to control maize disease. *Daily Nation,* February 14, 1990, Nairobi, Kenya.

Bjarnason M. (1986) Progress in breeding for resistance to the maize streak virus disease, pp. 197–207. In *A Proceedings of the First Eastern, Central and Southern Africa Regional Maize Workshop,* Lusaka, Zambia, March 10–17, 1985 (Edited by B. Gelaw). CIMMYT, Mexico DF.

Bock K. R. (1974) Maize streak virus. In *Description of Plant Viruses.* No. 133, 4 pp. Commonwealth Mycological Institute/Association of Applied Biologists.

Dabrowski Z. T. (1984a) Handling new *Cicadulina* colonies. *IITA Research Briefs,* 5(1), 2–4, Int. Inst. Tropical Agric., Ibadan, Nigeria.

Dabrowski Z. T. (1984b) Rearing *Cicadulina:* Technical methods, equipment needed. *IITA Research*

Briefs, 5(2), 2–3, Int. Inst. Tropical Agric., Ibadan, Nigeria.

Dabrowski Z. T. (1984c) Releasing *Cicadulina* for maize streak resistance screening. *IITA Research Briefs,* 5(3), 4–5, Int. Inst. Tropical Agric., Ibadan, Nigeria.

Dabrowski Z. T. (1985) The biology and behavior of *Cicadulina triangula* in relation to maize streak virus resistance screening. *Insect Sci. Applic.* 6, 417–424.

Dabrowski Z. T. (1987a) Two new species of *Cicadulina* China (Hemiptera: Euscelidae) from West Africa. *Bull. ent. Res.* 77, 53–56.

Dabrowski Z. T. (1987b) *Cicadulina ghaurii* (Hem.: Euscelidae): Distribution, biology and maize streak virus (MSV) transmission. *Zeitsch. angew. Ent.* 103, 489–496.

Dabrowski Z. T. (1987c) Comparative studies of *Cicadulina* leafhoppers in West Africa, pp. 35–39. In *Proc. 2nd Int. Workshop on Leafhoppers and Planthoppers of Economic Importance* Provo, Utah, USA, 28 July–1 Aug., 1986 (Edited by M. R. Wilson and L. R. Nault). CIE, London.

Dabrowski Z. T. (1987d) Some parameters affecting suitability of *Cicadulina* species for resistance screening to maize streak virus. *Insect Sci. Applic.* 8, 757–764.

Dabrowski Z. T. (1989) Procedures and techniques for rearing *Cicadulina* leafhoppers, pp. 84–93. In *Toward Insects Resistant to Maize for the Third World; Proceedings of the International Symposium on Methodologies for Developing Host Plant Resistance to Maize Insects.* CIMMYT, Mexico, DF.

Dabrowski Z. T., Nwilene F. and Kumar R. (1991) First regular observations on leafhoppers *Cicadulina* spp., vectors of maize streak viruses (MSV) in southeastern Nigeria. *Insect Sci. Applic.* 12, 249–261.

Esenam E. U. (1967) Some observations on the maize streak disease in western Nigeria. *Nigeria Agric. J.,* 3, 38–41.

Fajemisin J. M., Cook G. E., Okusanya C. and Shoyinka S. A. (1976) Maize streak epiphytotic in Nigeria. *Plant Dis. Reporter* 60, 443–447.

Fajemisin J. M., Dabrowski Z. T., Efron Y. and Kim S.K. (1986) Weather factors associated with recurring maize streak epidemics, pp. 267–276. In *Proc. Semin. on Agromet, and Crop Protection in the Lowland Humid and Sub-Humid Tropics,* Cotonou, Benin, 7–11 July 1986.

Fajemisin J. M., Efron Y., Kim S. K., Khadr F. H., Dabrowski Z. T., Mareck J. H., Bjarnason M., Parkinson V., Everett L. A. and Diallo A. (1985) Population and varietal development in maize for tropical Africa through resistance breeding approach, pp. 385–407. In *Breeding Strategies for Maize Production Improvement in the Tropics* (Edited by A. Brandolini and F. Salamini). FAO and Instituto Agronomico per L'Oltremare Firenze, Italy.

Guthrie E. J. (1977) Virus diseases of maize in East Africa, pp. 62–68. In *Proc. International Maize Virus Disease Colloqium and Workshop* (Edited by D. T. Gordon, L. R. Nault and L. E. Williams). Ohio Agricultural Research and Development Centre, Wooster.

International Institute of Tropical Agriculture (IITA) (1986) Solving the problem of maize streak virus: A research breakthrough to increase maize production in sub-Saharan Africa. An award-winning project paper submitted to TAG-CGIAR by IITA for the 1986 King Boudouin Award.

Kenya Agricultural Research Institute (KARI) (1990) Know and control maize streak disease. *Information Bulletin No. 1*, 4 pp.

Okech S. H. O., Neukermans L. M. R. M., Okoth V.A.O. and Chitekwele L. P. (in press) *Cicadulina* leafhopper species composition and incidence of maize streak virus (MSV) disease in selected agroecological regions of Zambia. *Insect Sci. Applic.*

Okoth V. A. O. and Dabrowski Z. T. (1987) Population density, species composition and infectivity with maize streak virus (MSV) of *Cicadulina* spp. leafhoppers in some ecological zones in Nigeria. *Acta Oecologia Applicata* 8, 191–200.

Okoth V. A. O., Dabrowski Z. T. and Emden H. F. van (1987a) Comparative biology of some *Cicadulina* species and populations from various climatic zones in Nigeria. *Bull. Ent. Res.* 77, 1–8.

Okoth V. A. O., Dabrowski Z. T., Thottapilly G. and Emden H. F. van (1987b) Comparative analysis of some parameters affecting maize streak virus (MSV) transmission of various *Cicadulina* spp. populations. *Insect Sci. Applic.* 8, 295–300.

Okoth V. A. O., Kalengesa D. M., Obara J. O. and Gethi M. (in press) *Cicadulina* species composition incidence of maize streak virus (MSV) disease in selected maize growing areas of Kenya. *Insect Sci. Applic.*

Rensburg G. D. J. van (1982a) Laboratory observations on the biology of *Cicadulina mbila* (Naude) (Homoptera: Cicadellidae), a vector of maize streak disease. (1) Effect of temperature. *Phytophylactica* 14, 99–107.

Rensburg G. D. J. van (1982b) Laboratory observations on the biology of *Cicadulina mbila* (Naude) (Homoptera: Cicadellidae), a vector of maize streak disease. (2) Effect of selected host plants. *Phytophylactica* 14, 109–111.

Rensburg G. D. J. van (1983) Southern African species of the genus *Cicadulina* China (Homoptera: Cicadellidae) with descriptions of new species. *Entomology Mem. Dep. Agric. Rep. S. Afr.* 57, 22 pp.

Rensburg G. D. J. van and Kuhn H. C. (1977) Maize Streak Virus. Department of Agriculture Technical Services, South Africa, Maize Series, No. E3, 1–4.

Rose D. J. W. (1972) Dispersal and quality in populations of *Cicadulina* species. *J. Anim. Ecol.* 41, 589–609.

Rose D. J. W. (1973a) A field study in Rhodesia on *Cicadulina* spp. vectors of maize streak disease. *Bull. Ent. Res.* 62, 477–495.

Rose D. J. W. (1973b) Laboratory observation on the biology of *Cicadulina* spp. with particular reference to the effects of temperature. *Bull. Ent. Res.* 62, 471–476.

Rose D. J. W. (1973c) Distance flown by *Cicadulina* spp. vectors of maize streak disease in Rhodesia. *Bull. Ent. Res.* 62, 497–505.

Rose D. J. W. (1974) The epidemiology of maize streak disease in relation to population densities of *Cicadulina* spp. *Ann. Appl. Biol.* 76, 199–207.

Rose D. J. W. (1978) Epidemiology of maize streak disease. *Annu. Rev. Ent.* 23, 259–282.

Rose D. J. W. (1983) The distribution of various species of *Cicadulina* in different African countries, frequency of their attack and impact on crop production, pp. 297–304. In *Proc. 1st Int'l Workshop on Leafhoppers and Planthoppers of Economic Importance.* Commonwealth Institute of Entomology, London, 4–7 October 1982.

Rossel H. W., Buddenhagen I.W. and Thottapilly G. (1980) Storey's maize mottle virus rediscovered. *IITA Research Briefs,* 1(22) 2–4. Int. Inst. Tropical Agric., Ibadan, Nigeria.

Rossel H. W. and Thottapilly G. (1985) *Virus Diseases of Important Food Crops in Tropical Africa.* IITA Publication Series, Ibadan, 61 pp.

Ruppel R. F. (1965) A review of the genus *Cicadulina* (Homoptera: Cicadellidae). *Mich. State Univ. Mus., Biol. Ser.* 2, 387–428.

Soto P. E., Buddenhagen I.W. and Asnani V. L. (1982) Development of streak virus resistant maize populations through improved challenge and selection methods. *Ann. appl. Biol.* 100, 639–646.

Storey H. H. (1925) The transmission studies of maize streak virus disease. *Ann. Appl. Biol.* 15, 1–25.

Storey H. H. (1936) Virus diseases of East African plants. IV. A survey of the viruses attacking the Gramineae. *E. Afr. Agric. J.* 1, 333–337.

Webb M. D. (1987a) Species recognition in *Cicadulina* leafhoppers (Hemiptera: Cicadellidae), vectors of pathogens of Gramineae. *Bull. Ent. Res.* 77, 683–712.

Webb M. D. (1987b) Distribution and male genetical variation in *Cicadulina bipunctata* and *C. bimaculata* (Homoptera: Cicadellidae), pp. 235–240. In *Proc. 2nd Int. Workshop on Leafhoppers and Planthoppers of Economic Importance* Provo, Utah, USA, 28 July–1 Aug., 1986 (Edited by M. R. Wilson and L. R. Nault). CIE, London.

IPM of Crop Borers on Food Crops

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Royal Veterinary and Agricultural University, Denmark
Convenor: *Dr K. V. Seshu Reddy*
ICIPE, Nairobi, Kenya

PLENARY LECTURE

Borer Strategy—Practical Implications and Scientific Challenge

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Abstract—Borer strategy is the strategy of herbivorous insects which involves boring deep into and establishment in host tissue during part of their lives. Typical borers live in pods (f. i. *Maruca testulalis*), fruits (f. i. *Cydia pomonella*), stalks (f. i. *Chilo* spp.), shoots (f. i. *Hypsipyla robusta*) and stems (f. i. Scolytidae), while superficial miners and gall inducers are excluded. Many holometabolous insects are borers but the majority are found in Pyralidae (Lep.) and Scolytidae (Col.). The focus of the present paper is borer strategy as related to herbaceous plants with primarily qualitative defence tactics. *Chilo partellus* and *Busseola fusca* relevant to the tropics are used as examples. Other Lepidoptera are also referred to while the interactions between Scolytidae and the quantitative defence of trees are excluded.

The life strategy of the borers includes a number of principally interesting steps: adult dispersal, host finding, acceptance of the host, oviposition, establishment and success of young larvae, stalk entering, stalk feeding and development, (diapause and) pupation. In most of these steps behavioural and physiological reactions to host plant properties are determinants of the success of the insect.

The practical implication of borer strategy is the occurrence in the world of a number of pests difficult to manage by traditional methods but offering opportunities for alternative ways of management. Such opportunities have been explored to some extent in the case of grass borers but a lot still needs to be done. A more systematic study is needed, with a potential for the development of better borer management systems. Such a study could include, among others, investigation of whether there is a coherence in the behavioural and physiological responses to the host plant chemicals, and the level of intra-specific variation present in such responses.

Key Words: borer strategy, herbaceous plants, *Chilo partellus, Busseola fusca*, tropics, borer management, stemborer

Introduction

Among the life strategies employed by herbivorous insects is the boring strategy. A borer may be defined as an insect which bores deep into normal tissue of its host plant and establishes itself there during a significant part of its life cycle. This definition excludes insects that have superficial associations with the host plants, such as leaf miners, miners in the surface of stalks of annual plants, or those that are gall inducers. Within the holometabolous insect orders, a number of well known species and families are borers. Among the Lepidoptera f.i., the tortricids *Cydia pomonella* (L.) and *Rhyacionia buoliana* Schiff. establish themselves during the major part of larval life in apples and pine shoots, respectively. In the Sesidae family larvae of some species establish in the trunks of hurt or stressed trees, while those of other species live inside the stems of biennial or perennial shrubs.

Among the well-known borers are the tropical species *Busseola fusca* (Fuller) and *Sesamia calamistis* Hamps., belonging to the Noctuidae family, and a number of tropical *Chilo* species and the European corn borer, *Ostrinia nubilalis* (Hb.), in the family Pyralidae. All these important borers utilise host plants within the grass family (Graminaceae). Among the Pyralidae, the cowpea pod borer, *Maruca testulalis* (Geyer), and the mahogany shoot borer, *Hypsipyla robusta* Moore, are also important in tropical Africa. In the order Coleoptera, the Scolytidae is worth mentioning as all members of this family are borers. Borers encounter two major problems during predation and particularly during entry into the tissue—host chemical defence and the physical barrier provided by the host tissue. There are important differences in host chemical defence strategies. Thus the defence encountered by stemborers in grasses and other annual and biennial plants is qualitative in nature whereas Scolytidae and *C. pomonella* encounter quantitative defence in their hosts. Perhaps the best known example of quantitative response to attacking insects is the increase in the flow of resins of many trees. In many plants, the concentration of toxic secondary plant products may increase in response to predation. With respect to physical barriers, the grass-living larvae of Pyralidae and Noctuidae as well as the larvae of *C. pomonella* and *R. buoliana* have to bore through the plant surface, while in the case of Scolytidae this is by the parental beetles. The boring through the plant surface appears to be one of the difficult steps for boring larvae, and many species first feed superficially on softer plant parts. Thus, the early instars of f.i. *C. suppresalis* and *B. fusca* first feed on leaves while *R. buoliana* first feeds on the soft basal parts of pine needles. Not until a later instar, often the third, do these insects become real borers.

The apparent difficulty in boring into host plants raises an important question: What are the advantages and disadvantages linked to the boring strategy and how are the disadvantages 'handled' by the insects. An obvious benefit of being a borer instead of just feeding and living on leaves is the protection conferred against weather and enemies. The stabilising effect of being connected to either perennials or grasses, also a major feature of most landscapes may be another benefit. The utilisation of these beneficial elements, however, requires a degree of specialisation by the insect as reflected by host plant selection of borers, most of which are oligophagous and some being virtually monophagous. Extremely few are polyphagous. This limitation in the utilisation of host plants imposes specific requirements on the insect including the need to overcome the plant defence mechanisms, whether qualitative or quantitative. This overview focuses on borer strategy as related to plants with qualitative defence. The widespread grass boring species *C. partellus* and *B. fusca* which are both important pests of sorghum and maize in Africa will serve as examples to elucidate the important steps of a typical borer life cycle and to highlight their implications for possible interventions and the scientific challenge these pose. The two species occur over very large areas often overlapping but not always so. The solely African *B. fusca* has few annual cycles and occurs mainly at moderate altitudes f.i. Zimbabwe (Blair, 1969) and Ethiopia (Gebre-Amlak, 1989) and the *C. partellus* which occurs in Asia and East Africa has approximately 5 annual cycles and is distributed at lower and warmer areas, f.i. Zimbabwe (Sithole, 1989).

Where relevant the other species will be mentioned for comparison.

Important Life Cycle Steps Related to Borer Strategy

The life cycle of the grass boring species in particular reference to *C. partellus* and *B. fusca* includes a number of steps of principal interest with respect to their life strategy (Fig. 1). These are: (1) adult dispersal, (2) host plant finding, (3) landing–1st acceptance, (4) staying –2nd acceptance, (5) oviposition–3rd acceptance, (6) (eclosion of eggs) establishment of young larvae, (7) stalk entering, (8) feeding and development, (diapause)–pupation in stalks. The degree of success of the insect depends on its behavioural and physiological reactions to physical and chemical properties of the host plant in all, or nearly all, of the steps elaborated below.

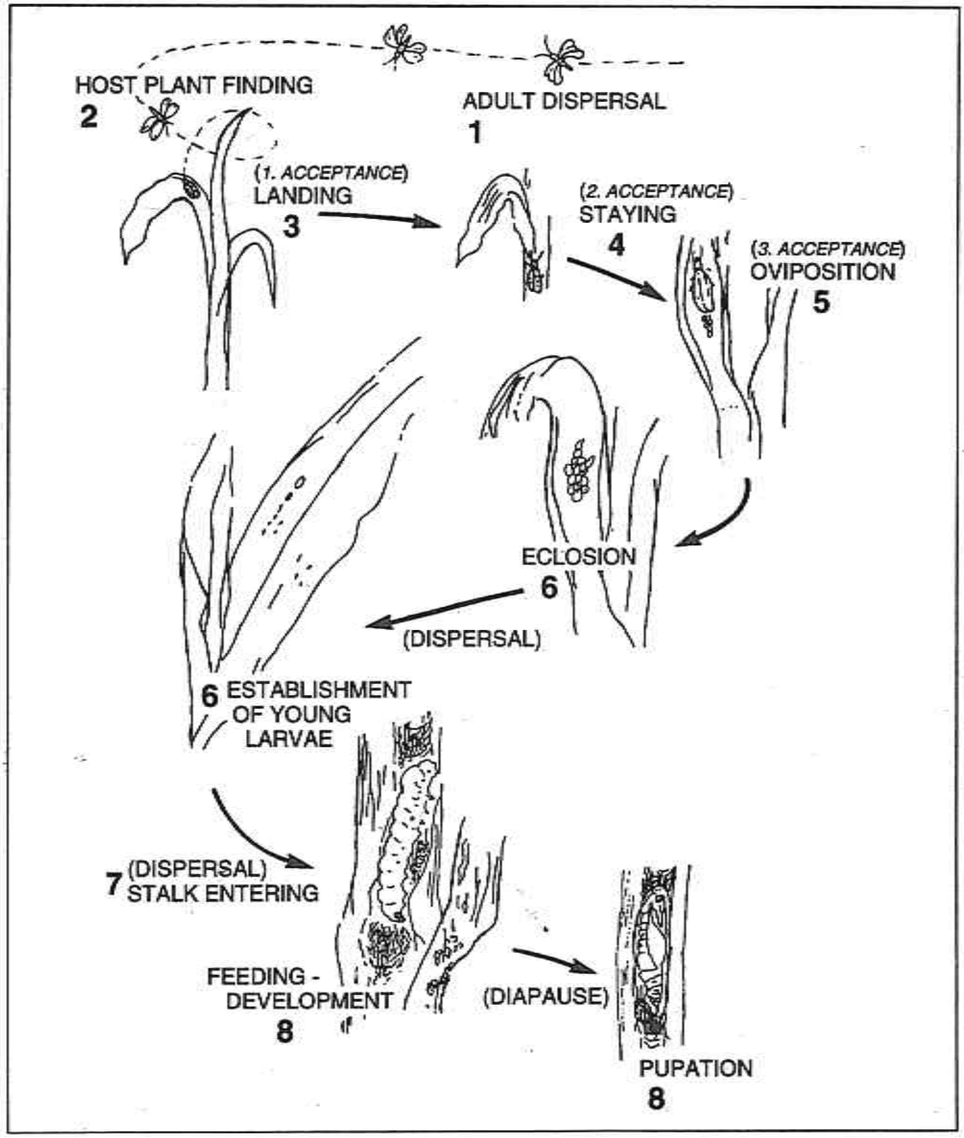

Fig. 1. Life cycle of grass borers, *Chilo partellus* and *Busseola fusca,* with emphasis on phases involving insect–plant interactions of importance for the borer strategy.

Adult Dispersal

In the case of *C. partellus,* it is known that mating takes place soon after emergence at the site of occurrence of pupae (Pats, 1992). It has also been found that females are strong fliers and may disperse over a considerable distance after mating. This means that the potential of dispersal and subsequent colonisation of new host plant resources is linked to the females which need to devote some of their own resources for host identification. Less information is available on *B. fusca,* but according to observations by Harris (1962) a similar pattern may be assumed.

The general outcome of this part of the life strategy of these borers is the capacity to avoid exhausting a limited grass resource and to escape a resource which has become depleted, for example, due to an ongoing drought.

Host Plant Finding and Landing

How *B.fusca, C. partellus* and other relatively specialised borers on grasses find their host plants at some distance (> 1 metre) is not known. However, the practical experience of borers concentrating on some plants rather than on others might indicate some host finding mechanism at a distance, volatile chemicals being an obvious possibility. As regards landing behaviour, details are lacking but studies by Saxena (1986) have demonstrated that *C. partellus* does react to different plants at short distance. This reaction may also underlie some of the demonstrated effect of intercropping (Amoako-Atta et al., 1983). Again, volatile chemicals are most likely involved as attractants or repellents for the approaching moths, but details have yet to be elucidated.

Colonisation: Staying and Ovipositing

In principle, a new behavioural step starts as soon as the moth has landed due to the possible influence not only of volatile chemicals but also of contact chemicals (stimulants and deterrents). Also, physical properties such as smoothness due to wax or roughness due to hairs might be of importance, but so far no studies have been published. Interestingly Chadha and Roome (1980) have reported "contact movements" of antennae, tarsi and ovipositor which clearly indicate a selection process by the females for oviposition. Some details are known at this step. Thus in field experiments Taneja and Woodhead (1989) have demonstrated ovipositional non-preference in *C. partellus* to some cultivars of sorghum, although Saxena (1990) found marked differences in oviposition responses to other sorghum cultivars under controlled conditions. Similarly, Van Rensburg et al. (1989) have found selective oviposition by *B. fusca* which laid more and larger egg masses on hybrids of maize with thicker stalks. In contrast to this behaviour being clearly regulated by host plant characteristics, Pats (1992) found no effect of previous ovipositions on successive ovipositing females of *C. partellus* indicating that no oviposition deterrent is produced by the female itself. No similar studies have been undertaken on *B. fusca,* but for comparison two other species may be of interest. In *Pieris rapae* (L.), both deterrents and attractants are of importance but when present together deterrents seem to outweigh attractants (Renwick and Radke, 1987). For the codling moth, *C. pomonella,* α-farnesene acts as an oviposition attractant as well as an attractant for the neonates (Wearing and Hutchkins, 1973).

Eclosion of Eggs—Establishment and Success of Young Larvae

While the host plant has, apparently, no influence on the eclosion as such, the period immediatly after represents a part of life most sensitive to the host plant environment. Specific knowledge on this phase of *B. fusca* is lacking. However, *C. partellus* has been well studied in this respect. The neonates are very active and may disperse by crawling both within plants and between plants. In addition, considerable ballooning activity between plants may take place aided by silken threads spun by the small larvae (Berger, 1989, 1992, 1993). This dispersal is influenced not only by larval density and subsequent encounters (Litsinger et al., 1991) but also by the surrounding host plants. From a more resistant host plant the dispersal rate to surrounding susceptible host plants is relatively high, while most larvae stay on a susceptible mid-plant that is surrounded by resistant plants (Ampofo, 1986). The mediating factors for this behaviour have not been investigated but volatiles are likely to be of importance.

The dispersal and establishment phase of tiny borer larvae is also subject to high mortality: A whorl must be reached expediently if the larva *(C. partellus)* is to survive (Taneja and Woodhead, 1989). In populations of young larvae of the European corn borer *(O. nubilalis),* mortalities of 76–83% have been reported (Ross and Ostlie, 1990). For comparison it may be mentioned that in this phase of dispersal and establishment the guiding value of α-farnesene to *C. pomonella* neonates (Wearing and Hutchkins, 1973) is vital for the avoidance of otherwise high mortality (Esbjerg, unpubl. observ.). For neonates of *R. buoliana,* which disperse eagerly within pine trees, their establishment in the soft bases of pine needles is a crucial step, and the phase may involve potentially high mortalities depending on the water status of the trees (Esbjerg, 1970). Saxena (1990) studied the settling behaviour of first- instar larvae of *C. partellus* and found less arrest of movement on resistant than on susceptible cultivars. The plant characteristics responsible for these differences were not studied, but both physical (structure, surface smoothness and hardiness) and chemical (attractants, repellents, phagostimulants and deterrents) host plant characteristics may be involved. Indeed, Bernays et al. (1983) have shown the influence of the wax layer on the movement of the larvae while Woodhead and Taneja (1987) demonstrated that leaf angles may also determine their settlement. Susceptible genotypes have floppy leaves with an angle greater than 45° between the leaves and the culm whereas resistant cultivars have more erect leaves. The erect leaves guide/mislead the larvae to the leaf tips where they disperse and, consequently, less larvae colonise in the leaf whorls (Taneja and Woodhead, 1989).

As regards the feeding behaviour during establishment nothing has been published on the very young larvae. However, Torto et al. (1990, 1991) have shown that the feeding behaviour of third-instar larvae of *C. partellus* is mediated by a complex of phagostimulating chemicals from the whorls of sorghum which include sugars and plant phenolic compounds.

Stalk Entering

The stalk entering phase which in the case of *C. partellus* takes place in the third or fourth larval instars is a phase of principal interest. The insect needs to pass from a more superficial life on the plant to the real boring phase which involves the penetration of the stalk surface. Often, this phase may involve dispersal from one plant to another as some of the larvae may walk way down the stalk to the ground and move up and enter another plant. Berger (1992), who has included this sort of behaviour in her experimental investigations of *C. partellus* dispersal, has suggested that this behaviour demonstrated by third and fourth larval instars is density-dependent and triggered by decreasing availability and/or quality of food.

The stalk-entering as such has not been studied in detail either for *B. fusca* or for *C. partellus*. It is, however, obvious that both physical and chemical plant properties, as f.i. surface hardiness and presence of phagostimulants/deterrents, may play a role in the success of the insect. The effect of stalk-entering on the plant has been discussed by Leuschner (1989) and, generally speaking, it may be concluded that the older the plants are when their stalks are entered the less is the potential damage. This has been related to the plant reaction, f.i. resulting from the destruction of the apical meristem (Leuschner, 1989), but it may also be assumed that fewer larvae are successful in entering older and harder plants.

Stalk Feeding

The ultimate success of larval development is dependent on successful feeding in the stalk. From the insect viewpoint, failure in this phase means losing the preceding 'investments', and from the plant's viewpoint it is its last chance of warding off the attacker or, at least, reducing its damage potential as expressed in its vitality and fecundity. Accordingly, the borer larva's success is likely to depend on two sets of food quality factors: nutritional, both physical (e.g. mechanical hardiness and levels of indigestible fibres) and chemical (nutrient levels and relative amounts of phagostimulants, phagodeterrents, growth inhibitors, etc.)

Saxena (1990) has shown that the feeding response of fourth-instar larvae of *C. partellus* vary considerably depending on the cultivar of sorghum offered. This has been shown to be in part due to quantitative differences in feeding kairomones in some cultivars (Torto et al., 1991).

To date, only one investigation on the dependence of the growth of *B. fusca* and *C. partellus* on food quality and contents has been reported (Agarwal et al., 1990). These authors have demonstrated that too high concentration of sterols, though essential, inhibit the growth of *C. partellus* but how these concentrations relate to concentrations present in the various host plant grasses including f.i. sorghum cultivars needs clarification.

For comparison some results on less specialised and more polyphagous insects are worth mentioning. Reese and Field (1986) have demonstrated experimentally that maize seedlings, which are a favoured food of *Agrotis ipsilon* larvae in US, contain an efficient but not destructive growth inhibitor. Larvae of the closely related *A. segetum* avoid onions as well as artificial diet containing freeze-dried onion in choice experiments. However, the growth of larvae fed solely on the latter material is undisturbed while the first and second instar larvae do not survive on onion plants (Esbjerg, unpublished).

Diapause and Pupation

Diapause may occur both in *B. fusca* and *C. partellus* at irregular intervals over generations. For a long time unspecific dry and cold conditions have been regarded as triggers of diapause but recently feeding experiments have revealed that diapause in *B. fusca* is induced by chemical changes in the host plant material (Onyango et al., 1992), normally associated with dry conditions. In *C. partellus* no similar trigger mechanism has been demonstrated. How diapause is terminated in *C. partellus* has not been adequately studied. In *B. fusca* it has been demonstrated that diapausing individuals rehydrate by water uptake (Harris, 1962; Adesiyun, 1983) and after some time diapause is terminated and pupation takes place. Interestingly, it has been found that horizontal placing of stalks with diapausing *B. fusca* larvae leads to the death of these larvae while more natural upright stalk positions is the basis for significant carryover populations (Gebre-Amlak, 1988). Clearly, this is a reflection of adaptation of these borers to grasses not only as a food resource but also as protection during periods of unfavourable conditions.

Discussion

The overall picture of the borers on grasses with particular reference to *B. fusca* and *C. partellus* as examples is that of insects with a fairly efficient strategy which falls between specialists and generalists insects. Specialists elements are their confinement to grasses as host plants and their obvious preference to some grasses and even cultivars as well as their adaptation to grasses for physical protection. Generalist elements are their utilisation of a wide range of grasses which on one hand ensures a widespread stable food resource but on the other hand acts as a barrier towards further specialisation and more efficient host selection and food utilisation. Their fairly efficient dispersal and presumably true migration (Johnson, 1969) may also be regarded as a generalist trait.

The practical implications of the borer strategy in grass living species are relatively clear. These borers are widespread and well-established pests and cause significant economic losses. Due to variations in local occurrence and to their 'protected life' traditional chemical control is difficult. The possible use of applying frequent schematic treatments is neither economically viable nor environmentally acceptable. Use of pheromone-based mass trapping or mating disruption is unrealistic as the rather strong flight tendency of gravid females (Pats, 1992) is prohibitive to this methodology.

Plant–insect interactions, however, offer a great potential for manipulation primarily based on effects of semiochemicals mediating these behaviours. The potential of such manipulations is partly being used already via intercropping (Amoako-Atta et al., 1983) and via resistance breeding (Taneja and Woodhead, 1989) but several major questions of practical as well as theoretical importance still need to be addressed before these behaviours can be fully manipulated. These include a better understanding of borer strategy on grasses and further investigations on the coherence of the responses of the insects to the host plants. The work of Saxena (1990) on the sorghum cultivars provides some indicatory answers to the above questions. According to this author, responses of *C. partellus* in terms of oviposition, larval orientation of instars 1 and 4 (arrest L1, arrest L4, attraction L1), larval feeding of L1 on leaves and of L4 on stem and development were in some cases coherent step by step but in others the picture was a little mixed. The cultivar with highest resistance elicited low responses at all the tested steps, whereas one cultivar with moderate resistance elicited high oviposition but medium or low responses to the following steps. In the latter case the ovipositional response may be regarded as an inappropriate reaction of the insect which may reflect its 'low' degree of specialisation and/or the exposure to a man-made new set of host plant characteristics.

Reactions as low responses to all the tested steps may be explained by the following hypothesis: "The most efficient reaction in terms of energy cost-benefit will be by responding to growth inhibitors and feeding deterrents as oviposition deterrents".

In principle a chemical component with detrimental effects such as a strong growth inhibitor may affect any phase in the life cycle. Some reactions may, however, be released by different derivatives as a chemical with regulating effect on ovipositing females may have been oxidised later due to the biting of a larva. While such reactions have not been systematically investigated it is obvious that a species could be at a selective advantage if it could recognise as early as possible an element as a growth inhibitor. Thus it will be advantageous for a species to react to a growth inhibitor of older larvae (or its precursor) as a feeding deterrent to small larvae leading to dispersal to other plants. If females react to these negative stimuli by ovipositional non-preference it will even be more advantageous. For the grass stemborers this would mean avoiding plants which have already been oviposited upon and which might in the end lead to suboptimal individuals with limited fecundity or even to increased mortality. Careful systematic investigations of the phases of the borer life cycle as described in Fig. 1 in the light of the above hypothesis would be most desirable and challenging. Such investigations will, however, have to take into account some potential complications as:

- How are responses to various host plant semiochemicals integrated at individual level? (Do deterrents or inhibitors outweigh attractants and stimulants?)
- What is the intraspecific variation in responses to host plants? (Are subpopulations present?)
- How fast do possible subpopulations adapt to certain plant characteristics? In *Heliothis virescens,* offspring of parents with different relative host plant preferences of males and females become intermediates as regards preference (Schneider and Roush, 1986). *Chilo partellus* reared on resistant maize caused more damage to the same maize than individuals reared on artificial diet with the former having metabolic efficiency (Kumar, 1993). (We must consider whether on one hand borers from cultivated plants are the worst potential pests and on the other whether borers from cultivated plants have difficulties in returning to wild grasses?)
- Are populations on wild hosts always the most flexible? (What role does the natural vegetation play as borer reservoir?)

Answers to the questions above will not only be a scientific challenge but may also lead to a wider understanding and a better strategic background for borer management in general.

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References

Adesiyun A. O. (1983) Studies on some effects of relative humidity, food and light in termination of larval diapause in *Busseola fusca* (Lepidoptera: Noctuidae). *Nigerian J. Entomol.* 4, 88–93.

Agarwal H. C., Gupta R., Rath R. and Goel V. (1990) Sterol inhibition in

Chilo partellus. Insect Sci. Applic. 11, 583–591.

Amoako-Atta B., Omolo E. O. and Kidega E. K. (1983) Influence of maize, cowpea and sorghum intercropping on stem-/pod-borer infestations. *Insect Sci. Applic.* 4, 47–57.

Ampofo J. K. O. (1986) Effect of resistant maize cultivars on larval dispersal and establishment of *Chilo partellus* (Lepidoptera: Pyralidae). *Insect Sci. Applic.* 7, 103–106.

Berger A. (1989) Ballooning activity of *Chilo partellus* larvae in relation to size of mother, egg batches, eggs and larvae and age of mother. *Entomol. Exp. Appl.* 50, 125–132.

Berger A. (1992) Larval movements of *Chilo partellus* (Lepidoptera: Pyralidae) within and between plants: Timing, density responses and survival. *Bull. Ent. Res.* 82, 441–448.

Berger A. (1993) Larval migration in the stem borer *Chilo partellus* (Lep., Pyralidae). Dissertation, Swedish Univ. of Agric. Sciences, Dept. of Plant and Forest Protection. P O Box 7044, S-750 07 Uppsala, Sweden.

Bernays E. A., Chapman R. F. and Woodhead S. (1983) Behaviour of newly hatched larvae of *Chilo partellus* (Swinhoe) (Lepidoptera: Pyralidae) associated with their establishment in the host plant, sorghum. *Bull. Ent. Res.* 73, 75–83.

Blair B. W. (1969) Recent research on the maize stalk borer (*Busseola fusca* Fuller): Influence on control methods. *Rhodesian Agric. J.* 68, 111–112.

Chadha G. K. and Roome R. E. (1980) Oviposition behaviour and the sensilla of the ovipositor of *Chilo partellus* and *Spodoptera littoralis* (Lepidoptera: Noctuidae). *J. Zool.* 192, 169–178.

Esbjerg P. (1970) Mortality of first instar larvae of the european pine shoot moth (*Rhyacionai buoliana* Schiff.) on waterlacking needles of lodgepole pine (*Pinus contorta* Loud.). *Ent. Scand.* 1, 215–218.

Gebre-Amlak A. (1988) Survival of maize stalk borer, *Busseola fusca* (Fuller) in crop residues in Ethiopia. *Crop Protection* 7, 183–185.

Gebre-Amlak A. (1989) Phenology and fecundity of maize stalk borer *Busseola fusca* (Fuller) in Awassa, Southern Ethiopia. *Insect Sci. Applic.* 10, 131–137.

Harris K. M. (1962) Lepidopterous stem borers of cereals in Nigeria. *Bull. Ent. Res.* 53, 139–171.

Johnson C. G. (1969) *Migration and Dispersal of Insects by Flight.* London, Methuen & Co. Ltd. 763 pp.

Kumar H. (1993) Resistance in maize to *Chilo partellus* (Lepidoptera: Pyralidae) in relation to crop phenology, larval rearing medium, and larval development stages. *J. Econ. Entomol.* 86, 886–890.

Leuschner K. (1989) A review of sorghum stem borer screening procedures, pp. 129–135. In *ICRISAT International Workshop on Sorghum Stem Borers,* 17–20 Nov. 1987, ICRISAT Centre, India. ICRISAT, Patancheru, A. P. 502 324, India.

Litsinger J. A., Hasse V., Barrion A. T. and Schmutterer H. (1991) Responses of *Ostrinia furnacalis* (Guenee) (Lepidoptera: Pyralidae) to intercropping. *Environ. Entomol.* 20, 988–1004.

Onyango F. O., Nyangwara A. G., Owiyo B. O., Okode D. J. and Ochieng'-Odero J. P. R. (1992) Procedure for sustained rearing of *Busseola fusca* on a semisynthetic diet. *1992 Anuual Report,* The International Centre of Insect Physiology and Ecology, pp. 110–111.

Pats P. (1992) Reproductive biology of the cereal stemborer *Chilo partellus.* Dissertation, Swedish Univ. of Agric.

Sciences, Dept. of Plant and Forest Protection. PO Box 7044, S-750 07 Uppsala, Sweden.

Reese J. C. and Field M. D. (1986) Defense against insect attack in susceptible plants: Black cutworm (Lepidoptera: Noctuidae) growth on corn seedings and artificial diet. *Ann. Entomol. Soc. Am.* 79, 372–376.

Rensburg J. B. J. van, Walters M. C. and Giliomee J. H. (1989) Selective oviposition by the maize stalk borer, *Busseola fusca* (Fuller) (Lepidoptera: Noctuidae). *J. Entomol. Soc. Southern Africa* 52, 105–108.

Renwick J. A. A. and Radke C. D. (1987) Chemical stimulants and deterrents regulating acceptance or rejection of crucifers by cabbage butterflies. *J. Chem. Ecol.* 13, 1771–1775.

Ross S. E. and Ostlie K. R. (1990) Dispersal and survival of early instars of European corn borer (Lepidoptera: Pyralidae) in field corn. *J. Econ. Entomol.* 83, 831–836.

Saxena K. N. (1986) Colonizing responses of *Chilo partellus* to certain sorghum cultivars in relation to their reistance or susceptibility to the stem borer. Presentation (S73), International Conference on Tropical Entomology 31 Aug.–5 Sep., 1986, Nairobi, Kenya.

Saxena K. N. (1990) Mechnisms of resistance/susceptibility of certain sorghum cultivars to the stem borer *Chilo partellus:* Role of behaviour and development. *Entomol. Exp. Appl.* 55, 91–99.

Schneider J. C. and Roush R. T. (1986) Genetic differences in ovipostion preference between two populations of *Heliothis virescens,* pp. 163–171. In *Evolutionary Genetics of Invertebrate Behaviour* (Edited by M. D. Huettel). Plenum, New York.

Sithole S. Z. (1989) Sorghum stem borers in southern Africa, pp. 41–47. In *ICRISAT International Workshop on Sorghum Stem Borers,* 17–20 Nov. 1987, ICRISAT Centre, India. ICRISAT, Patancheru, A.P. 502 324, India.

Taneja S. L. and Woodhead S. (1989) Mechanisms of stem borer resistance in sorghum, pp. 137–143. In *ICRISAT International Workshop on Sorghum Stem Borers,* 17–20 Nov. 1987, ICRISAT Centre, India. ICRISAT, Patancheru, A.P. 502 324, India.

Torto B., Hassanali A. and Saxena K. N. (1990) Chemical aspects of *Chilo partellus* feeding on certain sorghum cultivars. *Insect Sci. Applic.* 11, 649–655.

Torto B., Hassanali A., Saxena K. N. and Nokoe S. (1991) Feeding responses of *Chilo partellus* (Swinhoe) (Lepidoptera; Pyralidae) larvae to sorghum plant phenolics and their analogues. *J. Chem. Ecol.* 19, 67–78.

Wearing C. H. and Hutchkins R. F. N. (1973) Alpha-farnesene, a naturally occurring oviposition stimulant for the codling moth, *Laspeyresia pomonella. J. Insect Physiol.* 19, 1251–1256.

Woodhead S. and Taneja S.L. (1987) The importance of the behaviour of young larvae in sorghum resistance to *Chilo partellus. Entomol. Exp. Appl.* 45, 47–54.

Integrated Management of Stemborers of Sorghum and Pearl Millet

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Abstract—Several species of stemborers attack sorghum and pearl millet in Africa and Asia. The most common species on sorghum are *Chilo partellus* and *Busseola fusca* and on pearl millet, *Coniesta ignefusalis*. This paper discusses control options and the extent to which farmer perceptions of stemborers and associated crop losses have been considered. Examples of research aimed at developing IPM strategies are presented in the context of their impact or lack of it, on the farming community. Research efforts have traditionally focused on the development of resistant cultivars and only recently are they being targeted towards a combination with cultural and biological tactics. Conventional breeding procedures have not produced adequate levels of resistance to stemborers and natural enemies are not effective in regulating borer populations. The prospects of applied biological control and improved intercropping configurations are discussed. Reference is also made to progress in the use of sex pheromones in the control of *C. ignefusalis*. Unless resistance levels to stemborers are increased through biotechnological approaches, optimisation of the yield potential in existing cultivars requires that IPM research should focus on the improvement of cultural and biological components and should incorporate farmers' perceptions and an assessment of traditional pest management practices.

Key Words: IPM, stemborers, sorghum, pearl millet, *Chilo partellus, Busseola fusca, Coniesta ignefusalis*

Introduction

Several species of crop borers attack sorghum and pearl millet in Africa, Asia, and the Americas. Detailed reviews of the main stem boring species have been provided by Harris (1985, 1989a, b, 1990). These reviews contain information on species distribution, bioecologies and their control. The major species are lepidopterans which belong to the Pyralidae and Noctuidae whose larvae can develop on a range of cereal crops, including sorghum and pearl millet, and several wild graminaceous host plants. Among the noctuids, the African maize stemborer, *Busseola fusca* (Fuller) is the most important in Africa. Several species of *Sesamia* attack sorghum and pearl millet, although they are mainly pests of maize, rice and sugarcane in Africa, the Mediterranean and southern Europe, Asia and the Pacific. *Sesamia cretica* (Lederer), *S. calamistis* (Hampson), and *S. inferens* (Walker) are the most frequently reported species. Among the pyralids, three closely related genera *(Chilo, Diatraea* and *Coniesta)* contain several species which also attack other cereals. *Chilo partellus* (Swinhoe) is the most notorious sorghum stemborer species in India, Pakistan, and in a number of countries in eastern and southern Africa. *Diatraea saccharalis* (Fabricius) and several other *Diatraea*

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species occur in the Americas. *Coniesta ignefusalis* (Hampson) is the main stemborer of pearl millet although it also attacks sorghum in the drier areas of the West African Sahel. Apart from Africa, this species has not been reported elsewhere. Another pyralid, *Eldana saccharina* (Walker), a major pest of sugarcane in Africa, is of minor importance on sorghum and pearl millet. Some species of Lepidoptera feed on sorghum and pearl millet panicles e.g., *Helicoverpa* spp. and *Heliocheilus albipunctella* (de Joannis) but are not considered as crop borers in the context of this paper.

In this paper, we are restricting consideration to three major stemborer species (*C. partellus* and *B. fusca* on sorghum and *C. ignefusalis* on pearl millet) for which considerable integrated pest management (IPM)-related research information is available. Furthermore, we would like to approach the topic of this paper from a different perspective. The attempt is therefore not to add to the already existing long list of publications on the IPM of sorghum and pearl millet stemborers, but to examine outputs of IPM research during the last 20 years, their contribution to the reduction in borer damage and on-farm crop losses and the consequent effect, if any, on farm productivity. In the process, we hope to highlight the impact or lack of it, of the products of IPM-related research on stemborers, and revisit the basis for current strategies in IPM research and development (R&D).

What Is IPM?

Brader (1979) defined integrated pest control as a pest management system that in the context of the associated environment and the population dynamics of the pest species, utilises all suitable techniques and methods, cultural practices, host plant resistance, chemical insecticides, biological control and legislation, in as compatible a manner as possible and maintains the pest population at levels below those causing economic injury. This definition is the concept of the early years of IPM. Basically, it was only a concept, not a product or a technology. The emphasis was not on the target group or end-user! A recent definition by Wightman (1993) describes IPM as "management activities that are carried out by farmers..." Both definitions merit consideration in that they describe both ends of a continuum in R&D. In essence, the former emphasises the process of developing IPM strategies and the latter, that of its implementation. However, Brader's definition, like the early years of IPM, was only a concept in which all possible control options were implied and single option-based IPM strategies were not accommodated within the IPM framework. Today, IPM is synonymous with environmental safety and sustainability and therefore, any nonchemical control option can readily find a place in this framework.

The IPM R&D continuum can be sub-divided into four main phases: (a) research into individual IPM components or options; (b) on-station evaluation of a combination of options; (c) on-farm evaluation and validation studies; and (d) farmer implementation. Existing publications on IPM of sorghum and pearl millet stemborers suggest that in the past 20 years, our efforts have mostly been directed at the first two phases and only recently has attention been given to the implementation phase. This is perhaps understandable given the time lag between technology development, evaluation, implementation and adoption.

What Is Available?

A rapid, and by no means exhaustive, on-line search of CAB ABSTRACTS, AGRIS and AGRICOLA databases between 1975 and 1994, revealed more than 45 journal citations specifically on IPM of *C. partellus, B. fusca* and *C. ignefusalis* on sorghum and pearl millet in sub-Saharan Africa and India. This list does not include IPM-related research which addresses such areas as pest bioecologies and research into individual components nor non-conventional literature from published primary and secondary sources. Much of this information is available in reports and research papers on work in National Agricultural Research Centres (NARS) especially in India, Ethiopia, Nigeria and South Africa; International Agricultural Research Centres (IARCs), particularly ICIPE and ICRISAT; in Proceedings of various International Workshops (International Study Workshop on Crop Borers and Emerging Strategies for their Control, Mbita Point Field Station, Kenya, 14–18 June 1982; International Study Workshop on Host Plant Resistance and Its Significance in Pest Management, ICIPE, Nairobi, 10–15 June 1984; International Sorghum Entomology Workshop, 15–21 July 1984, Texas A & M, College Station, Texas, USA; International Workshop on Sorghum Stem Borers, 17–20 November 1987, ICRISAT, India; and the First International Symposium on the Cereal Stem Borer *Chilo*, 25–29 July 1989, ICIPE, Nairobi, Kenya); and in information bulletins such as '*Busseola fusca:* A Handbook of Information' by Harris and Nwanze (1992).

The evidence provided from the above-mentioned on-line search indicates that varietal resistance, intercropping and biological control are the three major elements in IPM of stemborers in sorghum and pearl millet and that recently, pheromone technology has shown good potential in pearl millet. Apart from work by ICIPE in its study villages in western Kenya (Saxena et al., 1989, 1990), this does not imply that there has been a concerted effort at developing well-focused IPM strategies for farmers but rather of experimentation of individual components, the results of which have been put together in publications as parts of an IPM strategy. Examples include Ajayi, 1990; Nwanze, 1985, 1991; Reddy, 1984; Ndoye and Gahukar, 1987; Sharma, 1985,1993; Gebre-Amlak, 1988; Gahukar, 1988,1989; Omolo et al., 1993; Minja, 1990; Sukhani, 1986; Saxena et al., 1989, 1990 and Sagnia, 1983. A major gap in these attempts is the absence of diagnostic research on the characterisation of the physical and biological environment, assessment of on-farm losses, socio-economic analysis of farmers' perceptions of stemborers as pests and their attitudes towards human and capital investment in borer management. These are pivotal elements in any research agenda that is targeted at the development of viable management options. As early as 1959, K. M. Harris at the inaugural meeting of the Science Association of Nigeria, concluded that "the first consideration, over and above technical considerations, is whether the farmer is interested in reducing attacks on his crops...There is a lack of interest and since without interest no progress can be made, it seems that any approach towards stem borer control must be based on the education of farmers. (a 'stem borers of cereals in northern Nigeria', unpublished report). Thirty years later, Nwanze and Mueller (1989) again concluded that "most recommendations are impractical as they do not take sufficient account of the situations, resources, and needs of farmers". How far have we progressed in the last five years?

It is generally accepted that the prospects for chemical insecticides in sorghum and pearl millet production in

Africa and Asia will remain low as long as these crops continue to fetch low market values compared with maize and rice. Several cultural methods have also been cited and include crop residue destruction, tillage, soil, water and fertiliser management. There exist good scientific data to support their potential contributions to IPM but for the present, these methods are usually classified as impractical because they conflict with traditional uses of crop residues, involve labour requirements and the simple lack of financial resources. We will therefore confine our discussion to the four major elements referred above.

Varietal Resistance

It is generally accepted that host plant resistance (HPR) is the most farmer-friendly pest control option. When combined with timely sowing, an HPR-based IPM strategy can readily capitalise on high yielding, moderately resistant/tolerant crop varieties. In a recent review, Sharma (1993) has provided detailed up-to-date information on the use of resistant sorghum cultivars in IPM in different ecosystems worldwide. Over 190 genotypes with varying degrees of resistance to *Chilo* and *Busseola* were reported between 1974 and 1989. Resistance mechanisms, factors and inheritance are also summarised. Question: What area is cultivated with these genotypes by farmers in stemborer endemic areas? Apart from selections such as Serena and Maldandi which are widely cultivated in eastern Africa and India respectively, no information is provided except for remarks indicating that these genotypes are "highly promising", have "good potential" and/or are "superior to the susceptible checks".

In the ICIPE village studies in western Kenya, although farmers were reported to be aware of insect resistant crop varieties, the local sorghum varieties 'Ochuti' and 'Andiwo' were grown by 48% of the farmers compared to 26% for the improved cultivars, Seredo and Serena. Fewer farmers also considered the improved cultivars less resistant to borer attack than the locals. Saxena et al. (1989) concluded that "most of the cultivars in use have little resistance to borers" and that farmers needed to be "aware of the existence of resistant cultivars". A landrace sorghum, IS 1044 of Indian origin was selected by ICIPE for resistance to *C. partellus* (Dabrowski and Kidiavi, 1983) and has been used in the development of agronomically improved HYD-8, a hybrid also reported to be as resistant as IS 1044 to deadheart and stem tunnelling (ICIPE, 1993). However, in preliminary on-station trials in coastal Kenya, farmers rejected four resistant test genotypes on the basis of long maturity, panicle compactness, crop height and poor vigour.

The situation with the millet stemborer is simpler. No resistant genotypes have been developed and research in this area is yet to deliver a uniform, repeatable and reliable screening technique for enhancing the potential for resistance source identification and utilisation in breeding programmes.

Biological Control

Several lists have been published on the natural enemies of *C. partellus, B. fusca* and *C. ignefusalis* and these provide an excellent reference on species composition, distribution and, where available, information on their efficiencies as natural control agents. The most recent of these are by Sharma and Davies (1988), Mohyuddin (1990), Harris and Nwanze (1992) and Nwanze and Harris (1992). These lists are not exhaustive but they are impressive and include parasitoids, predators, and insect pathogens. However, it is known that existing natural enemies do not appear to be effective in regulating populations of stemborers (Youm, 1990; Nwanze and Harris, 1992) and because of the range of natural enemies, it was suggested that applied biological control should be explored. This should be taken with caution since we really need to know more about indigenous natural enemy complexes before planning wider implementation of classical biological control by introduction of exotics.

Based on the large number of hymenopterous parasitoids in Asia, Mohyuddin and Greathead (1970) recommended the introduction of five species into eastern Africa. Gilstrap (1985) also indicated that the prospects were excellent for biological control of seven sorghum stemborers including *C. partellus* and *B. fusca* and that both importation and conservation tactics are most likely to be useful. Reports of various attempts are given in Appert et al. (1969), Alam et al. (1972), Ingram (1983), Skoroszewski and van Hamburg (1987). Records show that the only effective case so far was against stemborers on sugarcane in the Carribbean and no lasting success has been reported on sorghum. However, much effort continues and the prospects appear encouraging from work at ICIPE. Studies of an exotic parasitoid, *Cotesia flavipes* indicated higher searching ability and acceptability than the indigenous species. Similarly, research on insect pathogens have shown compatibility between resistant sorghum genotypes and *Bacillus thuringiensis, Nosema marucae* and *Beauveria 'bassiana* which alone are reported to effectively reduce *C. partellus* damage (ICIPE, 1993). On-farm implementation is yet to be reported.

Intercropping

The effects of intercropping on pest populations and crop damage are well documented in several publications and no attempt will be made to list them in this paper. Crop combinations range from sorghum/legume to sorghum/cereal and a range of several food and non-food crops. It also involves cropping patterns and crop density combinations. The effects of intercropping are believed to be due to increased diversity in the agroecosystem, increased fertilisation and crop growth, non-host effects from the associated crop etc. Intercropping is an age-old farming practice. It was not invented by scientists! The positive contribution from intercropping in IPM research is that scientists must first examine what farmers are doing, why they are doing it and hopefully, then ask how such practices can be improved. But do we know why farmers intercrop? Is it done primarily to reduce pest damage, or is it an insurance factor against crop failure and a strategy for food security? Have farmers adopted recommendations from our research? Are they now planting two rows of cowpea or pigeonpea after every four rows of sorghum or pearl millet? We believe that further research at the farm level is necessary. On-station experiments are often too small, too well managed and too often unrealistic to adequately represent on-farm conditions and therefore, on-station research in this area should be limited to the initial testing of intercropping configurations. Thereafter, we should move into farmers' fields.

Pheromone Technology

The use of pheromone traps in population monitoring and forecasting of lepidopterous pests is an important component in IPM. This is true for other crops and for other insect species. For example, the pheromone trap network for *Helicoverpa armigera* (Hubner) is well developed and constitutes an integral part in the management of this pest at many locations across India (Srivastava et al., 1992). There are few cases where this element has been successfully used in the direct reduction of pest populations and crop damage.

In a review by Campion and Nesbitt (1983), on the use of pheromones for stemborer management, it was concluded among other things, that mass trapping was unlikely to provide satisfactory control and that success with mating disruption was most likely on maize and other plantation crops. In initial field trials in Zimbabwe, Hall et al. (1981) showed that there were possibilities for *B. fusca* control with a synthetic pheromone mixture.

Bako (1977) reported evidence of female pheromone activity in *C. ignefusalis* in Niger. Ten years later, this work was reactivated at the ICRISAT Sahelian Centre in Niger in collaboration with the Natural Resources Institute (NRI), UK. A method of rearing *C. ignefusalis* has now been developed, pheromone components have been isolated and identified, optimum ratios and an attractive blend have also been determined and long-lasting pheromone dispensers have been developed (Youm et al., 1993). With the view that this product should be farmer-oriented, a relatively inexpensive water-based trap has been designed from local material (Youm and Beevor, 1995).

Two control tactics have been evaluated namely, mass trapping and mating disruption. On-farm experiments with considerable farmer participation have produced overwhelming results. With some minor refinements, and within a few years, this technology should be in the hands of NARS for implementation at the farm level. A regional monitoring of *C. ignefusalis,* using pheromone-baited traps, is in progress with participation of several countries through the West and Central African Millet Research Network (WCAMRN).

Revisiting Our Research Agenda

After more than 20 years of research, we still do not have products which have been time-proven and tested by farmers to reduce stemborer damage. Among the dozens of 'promising' stemborer resistant sorghum cultivars, not one single entry has been adopted by farmers of the semi-arid tropics. Yet, our knowledge of resistance mechanisms and factors, and the bases of gene action and inheritance is not lacking. How much must we understand resistance mechanisms and factors in order to produce sorghums that are better than the farmers' local material? What level of resistance is required in an HPR-based IPM strategy? How much resistance is required when HPR is integrated with biocontrol or other control options? To what extent will resistant millets contribute to reducing *C. ignefusalis* damage in an environment as extreme as the Sahelian semi-arid tropics?

In many countries, the farmers use sorghum and millet stalks for roofing, fencing, shade, small kiosks, bedding, fuel and animal feed. These practices serve to ensure carry-over of diapausing borer populations. There is sufficient evidence to convince farmers of the benefits from simple farm hygiene and crop residue management. Could there be other reasons why farmers have not adopted simple farm residue management?

What are the prospects for applied biological control? Why are the large and diverse natural enemy populations unable to contain borer populations? Why are parasitoid populations slow to build up and only become effective at the end of the crop season when borer damage is far advanced? Are there ecological barriers that slow down their innate rate of increase? Does this explain the failure of sustained recoveries from attempts at applied biological control of stemborers?

It is often argued that IPM is not a product but a management system. But oftentimes we are confronted with statements that a particular IPM technology has 'potential'. Farmers cannot use a potential technology unless it can be translated into actual productivity. Of what use is a variety that is promising and has potential to a farmer who year after year must battle with borer damage? Or are we overestimating the problem?

Unquestionably, borer incidence, crop damage and yield losses on research stations are high. Are our figures comparable with on-farm situations? How realistic are our estimates of borer-induced on-farm losses? Do farmers want to reduce borer-induced crop losses? Is the cost-benefit ratio attractive enough for the investment?

Conclusions

What, how and why do farmers do what they do? These questions imply that first we must understand the problem we are dealing with. That IPM involves options, components, which either alone or in combination with others can form the basis for successful reductions in pest damage. That the simple development of a technology does not mean successful IPM. That the success of IPM is determined by the farmer, not the scientist. That IPM is not just a system but an activity; an activity carried out by the practitioner—the farmer, and not the scientist! That the scientist is an adviser, not the one who executes. And as an adviser, he should give options and show that they can work. But also, like a good adviser, he must then stand back to watch; allow his client to experiment, to learn from experience, to modify and to adopt and adapt the technology that is offered. And in return, we also learn from the farmer!

References

Ajayi O. (1990) Possibilities for integrated control of the millet stem borer, *Acigona ignefusalis* Hampson (Lepidoptera: Pyralidae) in Nigeria. *Insect Sci. Applic.* 11,109–117.

Alam M. M., Beg M. N. and Ghani M. A. (1972) Introduction of *Apanteles* spp. against graminaceous borers into Pakistan. *Tech. Bull. Commonw. Inst. Biol. Control* 15, 1–10.

Appert J., Betbeder-Matibet M. and Ranaivosoa H. (1969) Vingt années de lutte biologique a Madagascar. *Agronomie Tropicale* 24, 555–572.

Bako O. (1977) Etude biologique de *Haimbachia ignefusalis* (Hamps.) (Lepidoptera: Pyralidae, Crambinae) en vue d'une lutte biologique. These de Maitrise. Université Laval, Quebec, Canada.

Brader L. (1979) Integrated pest control in the developing world. *Annu. Rev. Entomol.* 24, 225–254.

Campion D. G. and Nesbitt B. F. (1983) The utilisation of sex pheromones for the control of stem borers. *Insect Sci. Applic.* 4, 191–197.

Dabrowski Z. T. and Kidiavai E. L. (1983) Resistance of some sorghum lines to spotted stalk-borer *Chilo partellus* under Western Kenya conditions. *Insect Sci. Applic.* 4, 119–126.

Gahukar R. T. (1988) Problems and perspectives of pest management in the Sahel: A case study of pearl millet. *Trop. Pest Manage.* 34, 35–38.

Gahukar R. T. (1989) Insect pests of millets and their management: A review. *Trop. Pest Manage.* 35, 382–391.

Gebre-Amlak A. (1988) Ecology and management of maize stalk borer, *Busseola fusca* (Fuller) (Lepidoptera: Noctuidae) in southern Ethiopia including integrated management. Fil. Dr. Thesis, Sveriges Lantbruksuniv, Uppsala, Sweden, 23 pp.

Gilstrap F. E. (1985) Concepts for biological control of arthropods attacking sorghum, pp. 403–412. In *Proc. Int. Sorghum Entomology Workshop,* 15–21 July 1984. College Station, Texas, USA. International Crops Research Institute for the Semi-Arid Tropics, Patancheru, AP India.

Hall D. R., Beevor P. S., Cork A., Lester R., Nesbitt B. F., Nyirenda G. K. C., Nota Phiri D. D., Blair B. W. and Tannock J. (1981) The female sex pheromone of the maize stalk borer, *Busseola fusca* (Fuller) (Lepidoptera: Noctuidae): Identification and initial field trials. *Zimbabwe J. Agric. Res.* 19, 111–122.

Harris K. M. (1985) Lepidopterous stem borers of sorghum, pp. 161–167. In *Proc. Int. Sorghum Ent. Workshop,* 15–21 July 1984, College Station, Texas, USA. ICRISAT, Patancheru, AP, India.

Harris K. M. (1989a) Recent advances in sorghum and pearl millet stem borer research, pp. 9–16. In *Int. Workshop on Sorghum Stem Borers,* 17–20 November 1987, ICRISAT Centre. ICRISAT, Patancheru, AP, India.

Harris K. M. (1989b) Bioecology of sorghum stem borers, pp. 63–71. In *Int. Workshop on Sorghum Stem Borers,* 17–20 November 1987, ICRISAT Centre. ICRISAT, Patancheru, AP, India.

Harris K. M. (1990) Bioecology of *Chilo* species. *Insect Sci. Applic.* 11, 467–477.

Harris K. M. and Nwanze K. F. (1992) *Busseola fusca* (Fuller), the African maize stalk borer: A handbook of information. *Information Bulletin* No. 33. ICRISAT, Patancheru, AP, India and CAB International, Wallingford, UK, 92 pp.

ICIPE (1993) (The International Centre of Insect Physiology and Ecology) *1992 ICIPE Annual Report.* ICIPE Science Press, Nairobi, Kenya.

Ingram W. R. (1983) Biological control of graminaceous stemborers and legume pod-borers. *Insect Sci. Applic.* 4, 206–209.

Minja E. M. (1990) Management of *Chilo* spp. infesting cereals in eastern Africa. *Insect Sci. Applic.* 11, 489–499.

Mohyuddin A. I. (1990) Biological control of *Chilo* spp. in maize, sorghum and millet. *Insect Sci. Applic.* 11, 721–732.

Mohyuddin A. I. and Greathead D. J. (1970) An annotated list of the parasites of graminaceous stem borers in East Africa, with a discussion of their potential in biological control. *Entomophaga* 15, 241–274.

Ndoye M. and Gahukar R. T. (1987) Insect pests of pearl millet in West Africa and their control, pp. 195–205. In *Proc. Int. Pearl Millet Workshop,* 7–11 April, ICRISAT Centre. ICRISAT, Patancheru, Andhra Pradesh, India.

Nwanze K. F. (1985) Sorghum insect pests in West Africa, pp. 37–43. In *Proc. Int. Sorghum Entomology Workshop,* 15–21 July 1984, College Station, Texas, USA. ICRISAT, Patancheru, AP, India.

Nwanze K. F. (1991) Components for the management of two insect pests of pearl millet in Sahelian West

Africa. *Insect Sci. Applic.* 12, 673–678.

Nwanze K. F. and Harris K. M. (1992) Insect pests of pearl millet in West Africa. *Rev. Agric. Entomol.* 80, 1134–1155.

Nwanze K. F. and Mueller R. A. E. (1989) Management options for sorghum stem borers for farmers in the semi-arid tropics, pp. 105–113. In *Int. Workshop on Sorghum Stem Borers,* 17–20 November 1987, ICRISAT Centre, India. ICRISAT, Patancheru, AP, India.

Omolo E. O., Nyambo B., Simbi C. O. J. and Ollimo P. (1993) The role of host plant resistance and intercropping in integrated pest management (IPM) with specific reference to the Oyugis project. *Int. J. Pest Manage.* 39, 265–272.

Reddy K. V. S. (1984) Integrated approach to the control of sorghum stem borers, pp. 205–215. In *Proc. of the Int. Sorghum Entomology Workshop,* 15–21 July 1984, ICRISAT Centre. ICRISAT, Patancheru, AP, India.

Sagnia S. B. (1983) Possible integrated pest management tools for the effective control of cereal stemborers in the Gambia. *Insect Sci. Applic.* 4, 217–219.

Saxena K. N., Pala Okeyo A., Seshu Reddy K. V., Omolo E. O. and Ngode L. (1989) Insect management and socio-economic circumstances of small-scale farmers for food crop production in western Kenya: A case study. *Insect Sci. Applic.* 10, 443–462. ·

Saxena K. N., Reddy K. V. S., Omolo E. O. and Ngode L. (1990) Non-pesticidal approach to integrated management of sorghum stem borers for resource-limited small-scale farmers in Africa. In *Proc. Integrated Pest Management in Tropical and Subtropical Cropping Systems* (Volume 1). Deutsche, Landwirtschafts-Gesellschaft Frankfurt, Germany.

Sharma H. C. (1985) Strategies of pest control in sorghum in India. *Trop. Pest Manage.* 31, 167–185.

Sharma H. C. (1993) Host-plant resistance to insects in sorghum and its role in integrated pest management. *Crop Protection* 12,11–34.

Sharma H. C. and Davies J. C. (1988) *Insects and other Animal Pests of Millets.* ICRISAT, Patancheru, AP, India. 151 pp.

Skoroszewski R. W. and Hamburg H. van (1987) The release of *Apanteles flavipes* (Cameron) (Hymenpotera: Braconidae) against stalk borers of maize and grain sorghum in South Africa. *J. Entomol. Soc. S. Afr.* 50, 249–255.

Srivastava C. P., Pimbert M. P. and Reed W. (1992) Monitoring of *Helicoverpa* (=*Heliothis*) *armigera* (Hubner) moths with light and pheromone traps in India. *Insect Sci. Applic.* 13, 205–210.

Sukhani T. R. (1986) Insect pest management in sorghum. *Plant Prot. Bull.,* India 38, 57–61.

Wightman J. A. (1993) Towards the rational management of the insect pests of tropical legume crops in Asia: Review and remedy. *Crop Protection and Sustainable Agriculture, Ciba Foundation Symposium 177,* pp. 233–256.

Youm O. (1990) Evaluation of natural enemies associated with the millet stalk borer, *Haimbachia ignefusalis* (Hampson) (Lepidoptera: Pyralidae) in Niger. PhD dissertation. Texas A&M University, College Station, Texas USA. 145 pp.

Youm O. and Beevor P. S. (1995) Field evaluation of pheromone-baited traps for *Coniesta ignefusalis* (Lepidoptera: Pyralidae) in Niger. *J. Econ. Entomol.* 88, 65–69.

Youm O., Beevor P. S. and Hall D. R. (1993) Trap design studies with the pheromone of *C. ignefusalis* (Hampson) (Lepidoptera: Pyralidae) in sub-Saharan Africa. International Organisation for Biological Control of Noxious Animals and Plants, Western Palaeartic Regional Section *(IOBC/WPRS) Bull.* 16(10) 58–63.

Integrated Pest Management of Potato Tuber Moth *(Phthorimaea operculella)* and Sweetpotato Weevils *(Cylas* spp.)

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Abstract—The management of insect pests of potato *(Solanum tuberosum)* and sweetpotato *(Ipomoea batatas)* is a key research objective of the International Potato Centre (CIP). An interdisciplinary research team is supporting the development of integrated pest management (IPM) for CIP's mandate crops through flexible, farmer oriented crop protection technology components that minimise the need for pesticide application. The potato tuber moth *(Phthorimaea operculella)* is one of the most damaging pests of potatoes. The larvae infest the tubers in both field and store, rendering them unusable. The control components being studied for this species are host plant resistance, sex pheromones, repellent plants, cultural control practices and biological control with parasites, bacteria and a granulosis virus. CIP is supporting successful IPM programmes in Peru and Tunisia. Weevils (*Cylas* spp.) are the most destructive and widely distributed pests of sweetpotato in the world. The larvae tunnel through the storage roots, resulting in major yield and quality losses. CIP's current research on cultural control practices, sex pheromones, biological control with entomopathogens and predators, host plant resistance and treatment of planting material focuses on three key sweetpotato-producing countries: Uganda, Vietnam and Indonesia.

Key Words: CIP, *Cylas* spp., IPM, *Phthorimaea operculella*, potato tuber moth, sweetpotato weevil

General Introduction

The management of insect pests of potato *(Solanum tuberosum)* and sweetpotato *(Ipomoea batatas)* is a key research objective of the International Potato Centre (CIP). CIP's interdisciplinary research team places particular emphasis on farmers' perspectives when assessing pest problems. Our experience has shown that farmers are not willing to risk adopting new approaches unless the practical advantages are clear. Consequently, the following strategy was devised (Cisneros and Gregory, 1994). Technology development for integrated pest management (IPM) is participatory and is loosely divided into five phases: pest problem assessment, development of management components, integration of key components, testing in pilot areas, and large-scale implementation. The relative importance of each management component within an IPM programme is problem-specific, since social and economic factors strongly influence their practical value.

Both the potato and sweetpotato crops are inhabited by a great diversity of insect pests. We will limit our coverage to the two 'crop borers', which cause devastating losses under various environmental conditions throughout the developing world: the potato tuber moth (PTM) *(Phthorimaea operculella)* and the sweetpotato weevil (SPW) (*Cylas* spp.).

CIP has been working on IPM for PTM for more than 15 years. In CIP's areas of influence, especially Peru and Tunisia, PTM management is in the phase of large-scale implementation involving collaboration between farmers, national agricultural research systems (NARS), nongovernmental organisations (NGOs) and international donor agencies.

CIP has been working on IPM for sweetpotato since 1988. In Uganda SPW management is in the phases of development and integration of management components. Pilot IPM projects are being established in Vietnam and Indonesia. Additional collaborative efforts are taking place in Cuba and the Dominican Republic.

Part I. Potato Tuber Moth (PTM)

Introduction

Four PTM species occur in developing countries: *Phthorimaea operculella* (Zeller), *Scrobipalpula absoluta* (Meyrick), *Symmetrischema plaeseosema* (Turner) and *Scrobipalpopsis solanivora* (Povolny). The first is the most important and has been targeted by CIP for development of an effective and low cost management programme (Raman, 1988).

Phthorimaea operculella is widely distributed and is considered as one of the most devastating pests of potato in both fields and stores. PTM is a major pest mainly in warmer climates, but severe infestations have been reported in cooler areas as well, such as the highlands of Peru, Colombia, Kenya and Nepal. In the Middle East and North Africa, *P. operculella* is by far the most important pest for stored ware potatoes (Von Arx et al., 1987). Total loss is common in the absence of control measures in countries such as Algeria, Tunisia, Egypt, Morocco and Yemen. In San Ramon, Peru, more than 90% tuber infestation has been recorded following four months of storage (Raman et al., 1987). The adult moth lays eggs on the leaves, on the soil surface or directly on exposed tubers. The larva mines leaves and stems resulting in weakening and breaking of terminal leaflets and stems, but significant yield losses seldom occur. Larvae infesting tubers burrow galleries under the skin surface, also providing an entry point for various plant pathogens. Infestation in the field and subsequently in traditional non refrigerated stores renders tubers unusable. The pest also attacks other cultivated solanaceous crops, such as tomato, tobacco, eggplant and pepper, and other wild species of the same family.

Control of Potato Tuber Moth

Management practices in traditional potato-growing areas formerly depended on local knowledge and readily available materials. As potato production intensified, growers adopted an array of expensive and toxic chemical insecticides to achieve satisfactory control. All major classes of insecticides have been used against this pest, resulting in development, and later increase of pest resistance, destruction of natural enemies and emergence of secondary pests. Furthermore, pesticide costs have been increasing steadily, while achieving only partial control. The need for alternative control methods has led CIP's Integrated Pest Management Programme to study traditional control technologies and develop new ones. Presently PTM programmes in certain areas of the Andean Region in South America, North Africa and the Middle

East are in their implementation phase, as CIP is teaming up with various organisations (NARS and NGOs) to develop IPM programmes with farmers. The global PTM management strategy encompasses an array of control components.

Host Plant Resistance

For the past 20 years, host plant resistance was CIP's first and foremost line of defence in the control of arthropod pests. The development of resistant varieties is a major research effort at CIP, emphasising both conventional and non conventional breeding methods. Efforts have been made to improve resistance in existing and new potato clones. No fewer than 400 primitive, native cultivars and 452 wild species accessions have been evaluated (Raman and Palacios, 1982). Of these 22 primitive cultivars and 21 wild potato species were selected as highly promising. *Solanum berthaultii* was identified as a highly resistant species because of the density of its glandular trichomes (Tingey, 1991; Raman, 1994). Raman (1994) recommended this species as a progenitor in breeding PTM resistance in high-yielding cultivars by NARS. Although genotypes have been identified (Raman, 1988) farmers are sometimes reluctant to adopt these new clones, because the plants do not have the characteristics demanded by the local markets. An alternative approach is to add resistance to preferred cultivars. Recently, CIP engaged in collaborative projects with several advanced institutions, such as Plant Genetic Systems in Belgium, to develop transgenic potatoes with resistance to PTM (van Rie et al., 1994). Potato plants, able to produce delta endotoxins from the bacterium, *Bacillus thuringiensis* (*Bt*), have been developed and are currently being tested at CIP-Lima. Release of such plants for testing in the regions is pending for lack of rigorous risk assessment studies and biosafety regulations in developing countries.

Sex Pheromones

PTM pheromone lures consist of a blend of PTM 1 (*trans*-4, *cis*-7 tridecadien-1-ol acetate) and PTM 2 (*trans*-4, *cis*-7, *cis*-10-tridecatrien-1-ol acetate) (Voerman and Rothschild, 1978). This pheromone has been a useful tool for monitoring PTM populations in all of CIP's regional programmes. In California, pheromone traps are commonly used to trigger insecticide applications (Flint, 1986). Sex pheromones have also been tested as a mass trapping and a mating disruption tool (Raman, 1988). Farmers are advised to use 10 to 16 traps per hectare, as a control component in the field. In rustic stores two traps proved to be sufficient (Palacios et al., 1994).

CIP has distributed thousands of samples of PTM pheromone to more than 25 national programmes in developing countries. In North Africa and the Middle East, Egyptian technicians have been trained to produce their own capsules as they plan to use the lures for a large-scale monitoring and mass-trapping programme.

Repellent Plants

Farmers have traditionally used plant foliage with repellent compounds to control PTM in stores (Ewell et al., 1990). Dried and shredded leaves of the weeds *Lantana camara* and *Minthostachys* sp. as well as leaves from *Eucalyptus* trees, proved effective and significantly reduced damage when spread evenly to cover stored potatoes (Raman et al., 1987; Raman, 1988; Palacios et al., 1994). In collaboration with CIP, several national programmes, e.g. those of India, Bangladesh, Nepal and Kenya, have studied using this approach for PTM control. In Peru the use of repellent plants is a common component in IPM programmes.

Biological Control

The greatest diversity of natural enemies associated with *P. operculella* occurs in South America, where the potato and its major pests originated. The most important natural enemies are parasitic wasps (Hymenoptera) that attack eggs and young larvae. CIP designed simple mass rearing techniques for three promising species: *Copidosoma koehleri,* an egg parasite, *Chelonus phthorimaea,* an egg-larval parasite, and *Diadegma molliplum,* a larval parasite (Raman et al., 1993). As part of an IPM package, parasites can be very effective in reducing PTM populations. A CIP/NGO project in Peru uses regular releases of *C. koehleri* in potato fields (Palacios et al., 1994). In Tunisia and Yemen, several thousand individuals of both *Co. koehleri* and *Ch. phthorimaea* have been released. Their establishment and effectiveness has been hindered by excessive insecticide applications on alternate PTM hosts such as tomato, eggplant, pepper and tobacco. The establishment of *Copidosoma* may also be affected by high summer temperatures.

The bacterium *Bacillus thuringiensis (Bt)* proved effective in PTM control in Tunisia, Egypt and Peru (Von Arx et al, 1987; Raman et al., 1987; Lagnaoui et al., 1994). Despite its effectiveness, *Bt* did not find a niche in the local market as it had to compete with the cheaper and more effective pyrethroids.

A baculovirus of the type granulosis (GV) showed great success in controlling PTM in rustic storage. A simple technique has been developed to mass-rear PTM to produce large quantities of this virus (International Potato Centre, 1992a, b). In collaboration with CIP, several national programmes experimented with this promising PTM control technique. In Tunisia and Egypt, use of granulosis virus in field and storage significantly reduced PTM infestation (Fig. 1) (Ben Salah and Aalbu, 1992; Ben Salah et al., 1994). In Egypt, excellent control has been achieved using a liquid formulation in the field and a dust formulation in storage (Fig. 2) (Lagnaoui and El Bedewy, 1994). Initial results of large-scale testing of this biological insecticide have triggered a surge of interest in both Egypt and Tunisia to fund their own GV mass production units. In Peru and Bolivia the granulosis virus is produced commercially and is an important component of IPM for PTM in stores (Palacios et al., 1994).

Cultural Control

Cultural practices that help to control PTM in the field include selection of clean seed tubers, deep planting, high hilling, timely and adequate irrigation to minimise soil cracking, field sanitation, early planting and harvesting, and rotation. In Tunisia tuber infestation at harvest was related to farmers practices. On-farm research results showed that delayed harvesting after final irrigation was correlated with tuber infestation (Von Arx et al., 1990). Subsequent surveys of Tunisian farmers helped identify the most appropriate and widely used cultural measures under local conditions (Fuglie et al., 1993). Timely harvest was recognised as the most effective. Unfortunately farmers have no control over the arrival time of imported seed, so timely planting and harvest are not always an option. Hilling and timely irrigation up to the harvest date were also very important. Careful sorting of

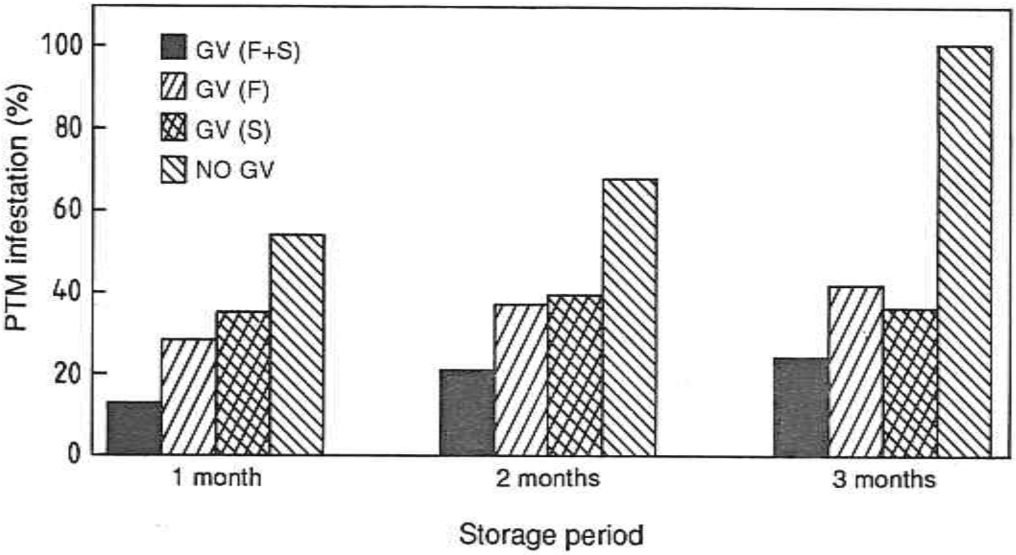

Fig. 1. GV use in field (F) and storage (S) (Egypt, 1993).

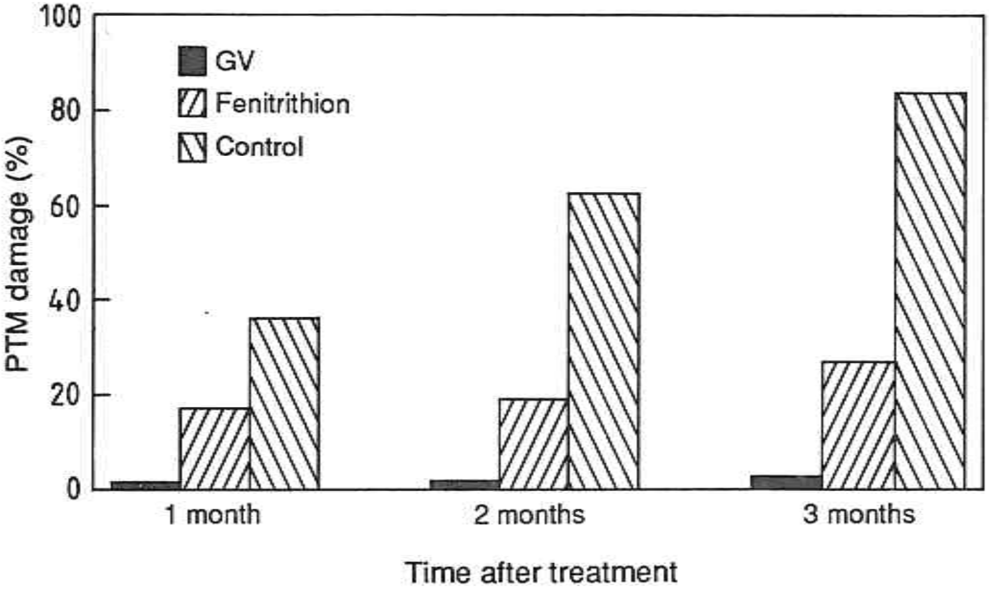

Fig. 2. GV use in on-farm trials (Kom hamada, Egypt, 1993).

infested tubers with thorough cleaning and disinfection of the storage facility before and during storage will minimise post-harvest losses (Palacios et al., 1994).

Chemical Control

In Tunisia a highly toxic insecticide, parathion, was commonly dusted on consumer potatoes until 1986. Research by CIP and the Tunisian national programme showed that the far less toxic synthetic pyrethroids were as effective as parathion (Von Arx et al., 1987). Pyrethroids have since replaced parathion as the insecticide of choice of farmers (Von Arx et al., 1988). The effectiveness and the price of this class of insecticides makes it very popular, which encourages its over-use. Surveys show that the majority of potato growers in Tunisia use, on average, 2.5 to 3 times the recommended rate. Insecticide residues are high in ware potatoes (Lagnaoui, unpubl. data). In Kenya, natural pyrethroid products are cheap and effective in controlling PTM in storage (N. Smit, unpubl. data).

Integrated Control

When PTM populations are low, single control measures may be effective when used efficiently. In areas where adult PTM populations are high, control components have to be integrated. Reliance on a single technique almost never works.

In the highlands of Peru, a very successful IPM programme for PTM is based on many components (Fig. 3). At planting: selection of clean seed tubers. During the growing season: mass trapping with sex pheromones, of *Copidosoma* parasitoids, hilling up. At harvest: timely harvest as soon as

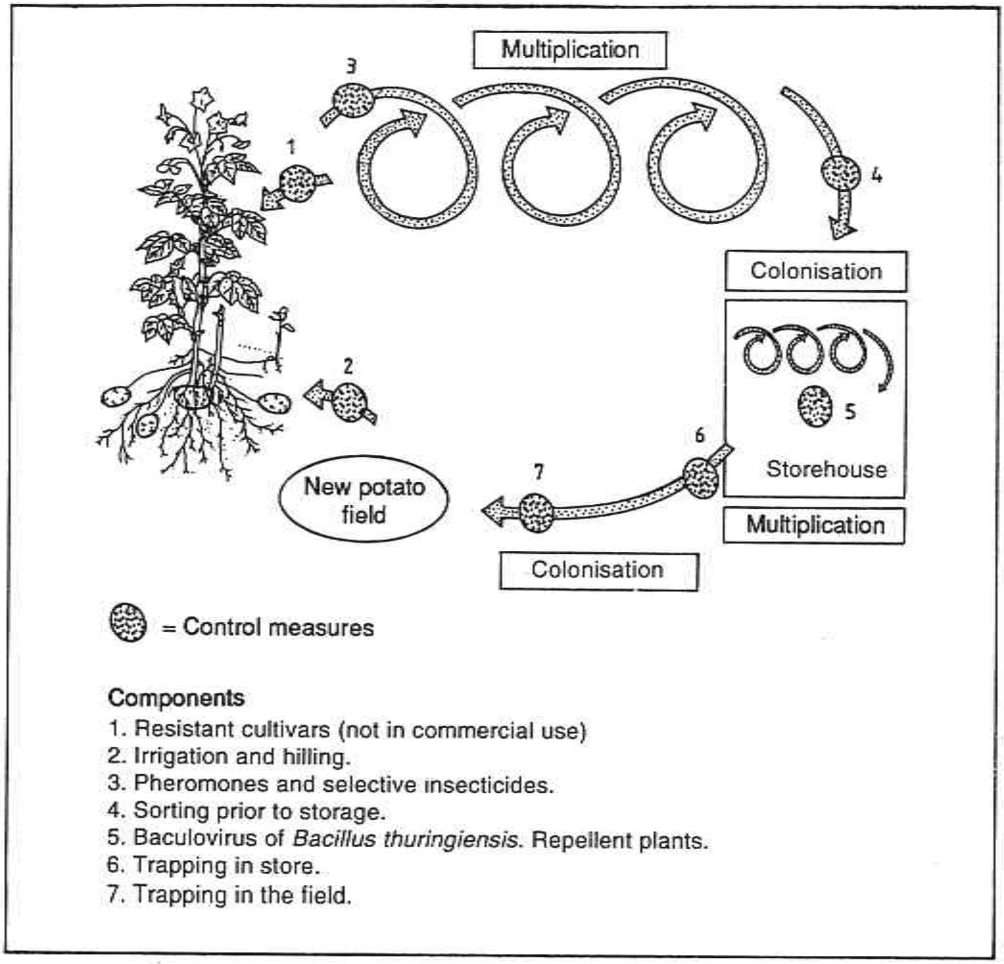

Fig. 3. Potato tuber moth: Population dynamics and management.

tubers are mature, sorting out of infested tubers. During storage: cleaning and disinfection of storage facility, use of granulosis virus, use of dried leaves of repellent plants, mass trapping with sex pheromones (Palacios et al., 1994).

In Tunisia, timely irrigation and early harvest are being implemented by more and more farmers (Fig. 4). A smaller proportion of farmers surveyed spray insecticides to control potato pests in the field (Fig. 5). PTM is perceived more as a storage pest than a field pest. Farmers, however, are aware that satisfactory PTM management starts in the field. A good crop management in the field results in lower PTM infestation at harvest, and in minimum losses under adequate storage conditions. The drastic decline in pesticide use gives the opportunity to explore the use of parasites to maintain PTM populaticns under damaging levels.

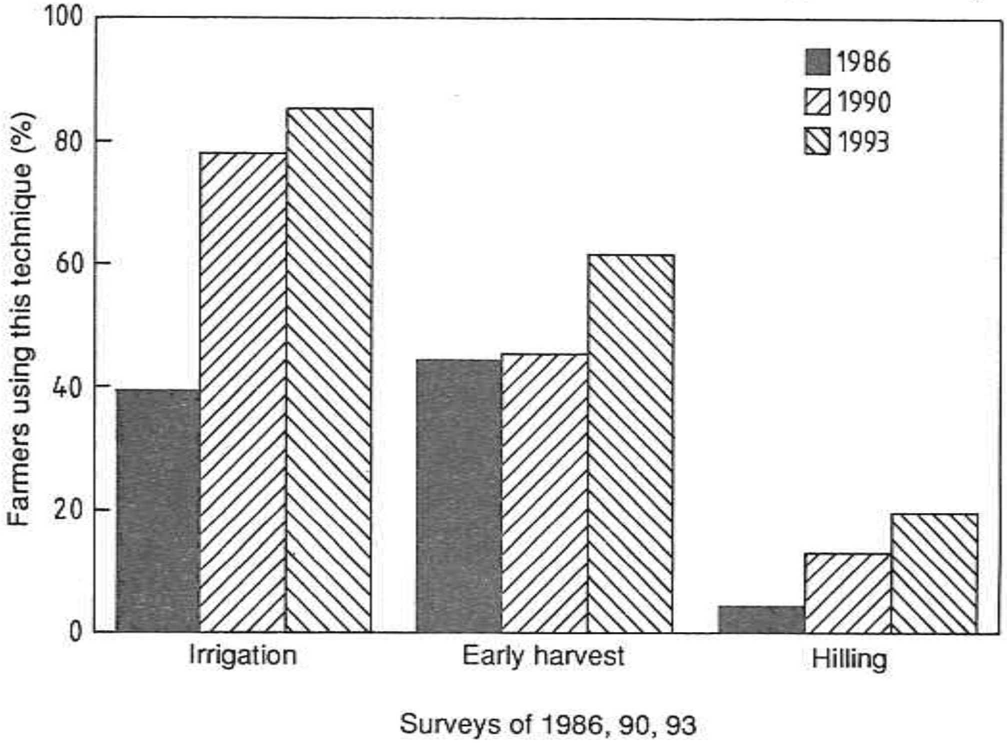

Fig. 4. Cultural practices for PTM control in Tunisia: Adoption of IPM technologies.

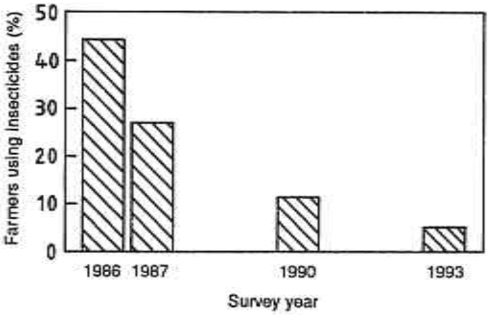

Fig. 5. Insecticide use for PTM control in potato fields in Tunisia: Impact of IPM technologies.

In Egypt, PTM damage on foliage is more pronounced. The IPM strategy is based on the use of sex pheromones to monitor pest populations and trigger insecticide applications. The use of the biological insecticide, *Bacillus thuringiensis,* is promoted.

In storage, emphasis is put on sanitation, and sorting before storing potato for the summer. Under local conditions, it is necessary to further treat the potatoes with GV, *Bt* or a combination of the two biological insecticides.

Impact of Integrated Control

IPM is already paying off. In Egypt, the highly toxic insecticide fenitrothion (Sumithion) was recently banned by plant protection authorities. They are promoting the use of *Bacillus thuringiensis* dust. The collaborative work between the NARS and CIP was credited for providing the necessary data (Lagnaoui and El Bedewy, 1994). In Tunisia, DDT and parathion were commonly used on ware potatoes. Efforts have been made to replace these toxic compounds with less harmful pesticides (pyrethroids) as a short term solution. IPM practices generated benefits estimated at US$ 1.6 million, representing about 8% of the wholesale value of Tunisia's main potato crop (Fuglie, 1995).

Part II. Sweetpotato Weevil (SPW)

Introduction

Four weevil species (Coleoptera: Curculionidae) are important pests of sweetpotato: *Cylas formicarius* (Fabricius), *C. puncticollis* (Boheman), *C. brunneus* (Fabricius) and *Euscepes postfasciatus* (Fairmaire).

Cylas spp. are the most important insect pests attacking sweetpotatoes worldwide (Chalfant et al., 1990). *Cylas formicarius* has the widest distribution, occurring in most sweetpotato-growing areas, although it is rare or absent in many parts of continental Africa (Parker et al., 1992). The ant-like adults have a red thorax and black abdomen. *Cylas puncticollis* and *C. brunneus* are restricted to Africa and both are important in Kenya and Uganda (Magenya and Smit, 1991). *Cylas puncticollis* is completely black, while coloration of *C. brunneus* varies from completely black to bicolored. The bicolored specimens were often confused with specimens of *C. formicarius* (Wolfe, 1991). The biology of the African SPWs was first studied by CIP (Table 1) (Smit and van Huis, in press).

Damage symptoms for the three species are similar. Although adult weevils feed on foliage, stem tissue and storage roots, most damage is caused by the larvae. Larval feeding inside the vines can cause vine malformation, thickening and cracking. The effect of weevil densities in vines on root yield has produced variable and often

Table 1. Mean total eggs per female (±SEM), range in egg production, mean daily oviposition between day 15 and 84 after adult eclosion, peak daily oviposition, survival (proportion of eggs surviving to adulthood) and sex ratio for *C. puncticollis* and *C. brunneus* on variety 'Kalamb Nyerere'

	Total no. eggs/female		Daily oviposition (eggs/female/d)		Survival	Sex ratio
	Average	Range	Average	Peak	(% of eggs)	% females
C. puncticollis	103 ± 16a	44–230	1.1 ± 0.1b	1.7	91 ± 4a	49.7
C. brunneus	100 ± 18a	7–177	1.5 ± 0.1a	2.2	87 ± 3a	51.5

Means within a column followed by different letters are significantly different by *t*-test ($P < 0.05$).

Source: Smit and van Huis, in press.

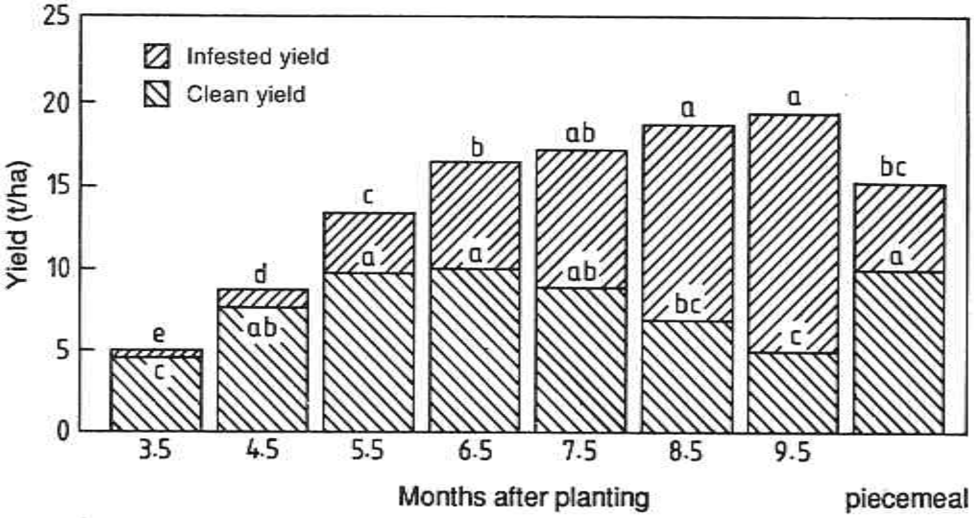

Fig. 6. Yield and quality loss due to sweetpotato weevils in Uganda at different harvest treatments averaged over 5 varieties.

contradictory results. Larval tunnelling imparts a characteristic terpene odour to the roots, rendering them unusable (Chalfant et al., 1990). Quality losses of more than 70% were reported in Uganda (Fig. 6) (Smit, in press). Several other species of *Ipomoea,* in addition to sweetpotato, and a few related convolvulaneous plants are alternate hosts of *Cylas* spp.

Euscepes postfasciatus, the West Indian sweetpotato weevil, is a major sweetpotato pest in the South Pacific, Caribbean basin and some countries of Central and southern America. Adult weevils are inconspicuous and easily overlooked because they resemble soil particles. The compact weevils have a reddish-brown body, which is covered with bristles and scales. The life cycle and damage resemble those of *Cylas* spp. The West Indian SPW occurs in Peru. CIP carried out research on the biology, dispersal and survival of the pest and found that *E. postfasciatus* does not fly, a characteristic that strongly influences control strategies for this pest. Standardised screening methods were developed at CIP to evaluate germplasm for resistance to this weevil. Although little information is available on biological control, CIP identified two larval ectoparasitoids in Peru. Their potential for controlling the weevils is being tested. The entomophagous fungus *Beauveria* sp. has also been isolated from infected adult weevils and is undergoing field testing. Results from field experiments showed that considerable control of this pest can be achieved if certain cultural practices are followed. These practices, such as sanitation and rotation, are similar to the ones that will be discussed for *Cylas* spp. (Raman and Alleyne, 1991).

Control of Sweetpotato Weevils

CIP's current research effort concentrates on *Cylas* spp. A CIP regional IPM specialist based in Indonesia works with *C. formicarius,* while control of *C. puncticollis* and *C. brunneus* is studied from Uganda. The control components being studied are presented in the following paragraphs.

Host Plant Resistance

The use of weevil-resistant cultivars would provide a practical and economical approach for managing sweetpotato weevils. Several studies have been conducted during the past 50 years to identify resistance to *Cylas* spp. Major efforts were made in the USA, at AVRDC, Taiwan and at IITA, Nigeria (Talekar, 1987; Collins et al., 1991). CIP collaborated with national programmes to screen cultivars in Kenya, Uganda, the Philippines and Indonesia (Magenya and Smit, 1994; Chuhoy et al., 1989; Waluyo and Mok, 1993). While no germplasm immune to SPW has been identified, research suggests that sweetpotato clones differ in their level of resistance. These levels are low and do not stand up under high weevil population pressure (Collins and Mendoza, 1991). Breeding for weevil resistance is presently considered low priority research at CIP, as its potential appears limited and other, more promising, control strategies are present.

Biological Control

Although 15 wasp parasitoids have been reported to attack *Cylas* weevils, none has been found effective enough to start a biological control programme (Jansson, 1991). At least five predators have been reported of which the ants *Pheidole megacephala* and *Tetramorium guineense,* are used as a biological control agent of *C. formicarius* in Cuba (Castineiras et al., 1982; Morales, 1994). In Indonesia the importance of generalist predators such as spiders, ants, staphylids and earwigs is under investigations. Laboratory studies of the predator *Orthotylinea* sp. (Miridae) have also been initiated (Iqbal et al., 1994). CIP supports national research on biological control.

Because several life stages of sweetpotato weevils are completed underground, within the roots, it is difficult for parasites to locate them. Entomopathogenic fungi, bacteria, nematodes and ground-dwelling insect predators may be better suited to the underground conditions, and may have greater potential as biological control agents of *Cylas* spp.

In Kenya CIP conducted preliminary experiments to test the toxicity of commercially available formulations of the bacterium *Bacillus thuringiensis* (*Bt*) on adults and larvae of *C. brunneus* and *C. puncticollis.* Results showed that FOILT™ and Novodor did not have an effect on adult and larval mortality (N. Smit, unpubl. data). Jansson (1991) reported similar results with *C. formicarius. Bt* was isolated from infected *C. formicarius* larvae in the Philippines (Amalin and Vasquez, 1993). Further surveys should be conducted worldwide to isolate bacteria-infected *Cylas* spp. Identification of bacterial isolates that are toxic to these weevils will also be useful for developing transgenic sweetpotato plants that are resistant to these insects.

Of all known fungal pathogens reported to attack *Cylas* spp., *Beauveria bassiana* is the predominant species (Jansson, 1991). In East Africa scientists from the International Institute for Biological Control (IIBC) isolated several strains from field-infested *C. puncticollis* and *C. brunneus* specimens (Allard et al., 1991). In collaboration with CIP and national programmes of Burundi, Uganda and Kenya, strains that proved the most pathogenic in the laboratory are used in field experiments to test the effectiveness of the fungus for control of weevils in the field. Preliminary results are inconclusive (Allard et al., 1994; Allard, pers. commun.). Amalin and Vasquez (1993) report *B. bassiana* on field-infested *C. formicarius* specimen in the Philippines. In Cuba *B. bassiana* is used as a component of the IPM programme (Castellon et al., 1993).

Research on entomopathogenic nematodes of *C. formicarius* was carried out in Florida, USA. Although the potential of nematodes for killing weevils in the laboratory was demonstrated, field results were inconsistent (Jansson, 1991).

Control approaches based on microbial agents can be highly labour intensive because they involve the production, formulation and application of the biological insecticide. In developing countries, cottage industries could have a role in production.

Sex Pheromones

In 1985, the sex pheromone of *C. formicarius* was identified. The active female-produced pheromone is (Z)-3-dodecen-1-ol (E)-2-butenoate (Heath et al., 1986). The pheromone has potential as a monitoring and training tool and as a component of an IPM programme. In East Africa, CIP and the national programmes tested the pheromone widely and helped confirm the finding that *C. formicarius* was absent from all but one location in coastal Kenya (Parker et al., 1992).

Male *C. formicarius* are extremely sensitive to the female-produced sex pheromone. Traps baited with high dosages of pheromone (1 mg) collect large numbers (>10,000) of males in a short time (Jansson et al., 1991). Present information suggests that mass trapping of male populations with the pheromone has potential to suppress *C. formicarius* populations. CIP is collaborating with national programmes of Cuba, the Dominican Republic, Vietnam, Indonesia, India, Bangladesh and the Philippines to explore this potential. In Cuba *B. bassiana* or a chemical pesticide is spread around pheromone traps, to guarantee a higher mortality among attracted males and avoid feeding damage caused by the large number of insects (Castellon et al., 1993).

Smit et al. (1994) proved that *C. puncticollis* and *C. brunneus* have their own species-specific female-produced pheromones (Table 2). In Uganda CIP, the national programme and the Chemical Ecology Group of the Natural Resources Institute (NRI), UK have begun a project, funded by ODA, to isolate, identify and synthesise the sex pheromones of the African *Cylas* species.

Table 2. Average number of *Cylas puncticollis* or *C. brunneus* males caught per trap per week (Mbita Point, Kenya, Feb–April 1991)

C. puncticollis		*C. brunneus*	
Bait	Female/week	Bait	Female/week
C. punc virgin male	42.6a	C. brun virgin male	16.4a
C. punc mated male	30.6a	C. brun mated male	5.6b
C. punc virgin female	0.4b	C. brun virgin female	0.0c
C. form pheromone	0.3b	C. form pheromone	0.0c
Control	1.7b	Control	0.0c

C. form—C. formicarius.

Chemical Control

Pre-planting insecticide applications are used to manage weevils in planting material (vine cuttings). Systemic insecticides kill weevil life stages within the vine and can protect it for at least one month after planting in the field. In developing countries, dipping planting material in insecticide can play a role in larger planting material multiplication projects. Individual farmers in many cases cannot afford the insecticide and do not have the facilities to handle these highly toxic chemicals safely. Weevil control is difficult with conventional spraying. Frequent applications are required to kill adults that migrate from other fields. Frequent spraying of insecticides, however, is not cost effective for subsistence farmers and smallscale commercial farmers in many developing countries (Talekar, 1991). However, in some areas in Southeast Asia insecticide use in sweetpotato is relatively commonplace.

Cultural Control

Cultural control covers management practices that make the environment less favourable to pest reproduction, dispersal and/or survival (Flint and van den Bosch, 1981). According to Talekar (1991) integration of different cultural practices has specific potential for managing SPW, as *Cylas* spp. have a limited flight activity, a limited host range and a characteristic mode of entry into the plant. Cultural practices such as crop rotation, sanitation, use of clean planting material, and others were the earliest control measures advocated for reducing damage by SPW. Cultural practices that are often advocated include crop rotation, sanitation, use of clean planting material, planting away from weevil-infested fields, hilling-up to reduce soil cracking, and prompt harvesting. Some of these practices, such as hilling up and rotation, have become so common among farmers that they are often not even recognised as control techniques. 'Key' cultural practices are location-specific and depend on the existing cultural practices, the environment and socio-economic conditions. A study conducted by CIP in South Nyanza District of western Kenya, identified key cultural practices for this region. Crop protection workers should concentrate their research and extension efforts on crop sanitation and the avoidance of adjacent, staggered planting (Fig. 7). Hands-on training on the biology and behaviour of the SPW should be provided so that farmers will understand the effects of their cultural practices on the infestation process (Smit and Matengo, 1995; Widodo et al., 1994). In East Africa the traditional practice of in-ground storage combined with piecemeal harvesting is contrary to the recommendation of prompt harvesting. Collaborative on-station research, however, demonstrated that accumulated yield and yield loss under piecemeal harvesting compared favourably with once-over harvesting at the optimum harvesting time (Fig. 6) (Smit, in press).

Weevils in Storage

Storage of harvested sweetpotato storage roots is not practised in most sweetpotato growing countries. But in Vietnam, household storage of sweetpotato is commonly practised so that farmers can take advantage of better market prices. Losses from weevils are high even though farmers cull damaged tubers before storing. The use of sand as barrier and plant materials such as dried neem leaves as a repellent is under study.

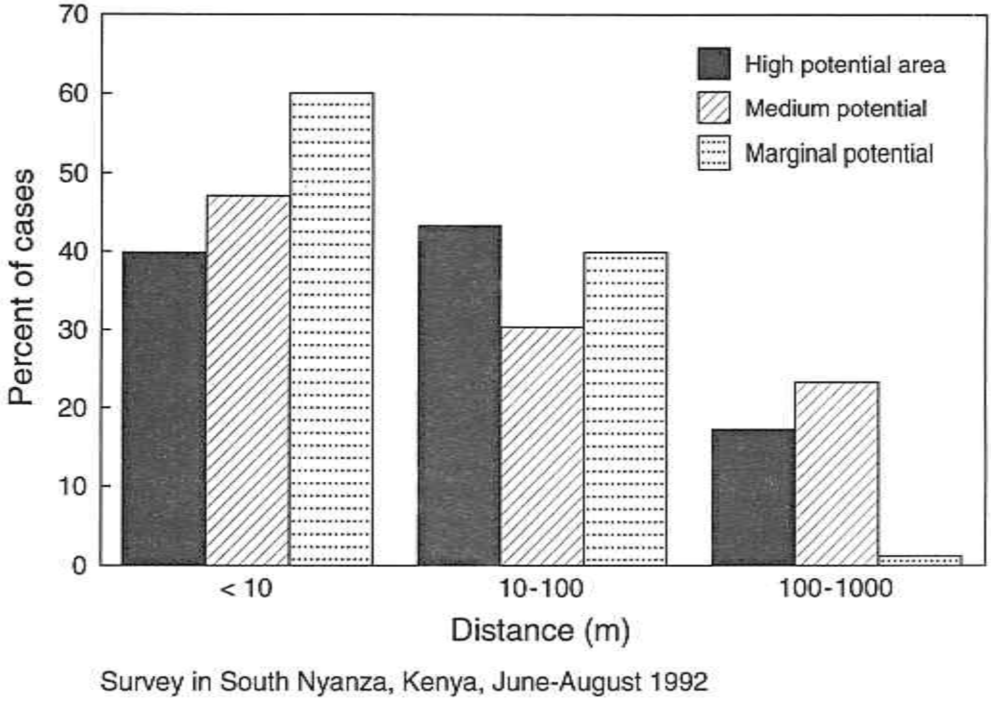

Fig. 7. Staggered and adjacent planting: Distance between sample plots and next sweetpotato plot for a total of 85 farms in 3 different sample areas.

The Integration of Control Components (IPM)

In most cases, none of the control measures described, used singly, will provide adequate control of *Cylas* weevils where sweetpotato is grown throughout the year and the weevil is endemic. However, a combination of tactics can provide satisfactory control of this pest. In East Africa, we presently have to rely on cultural control, as no resistant varieties or sex pheromones are available, and chemical insecticides are not economical for the subsistence farmers. Biological control with *B. bassiana* could play a role in future, specifically in areas where planting material is maintained in nurseries in swampy areas during part of the year. Cuba's national programme has developed the use of sex-pheromone traps in combination with a biological insecticide or chemical insecticide, the use of less-susceptible varieties (probably deep-rooted) and the transfer of colonies of predatory ants into sweetpotato fields (CIP, 1995).

In Indonesia and Vietnam, participatory technology development for sweetpotato IPM is occurring within the framework of Farmer's Field Schools, an IPM model originally developed for rice. Through hands-on experience, farmers learn to analyse pest problems within the context of overall crop health. Concepts such as insect life cycles, the role of natural enemies, and the action of sex pheromones are introduced in the field schools, and farmers learn to recognise and distinguish the different roles that insects play in the crop ecosystem. The logic underlying pest/crop management options is discovered by the participants themselves through a non formal education process. Learning occurs through observation and analysis of field conditions and through experimentation.

References

Allard G. B., Cock M. J. W. and Rangi D. K. (1991) Integrated control of arthropod pests of root crops, Final Report November 1988–October 1990. CAB International Institute of Biological Control, Nairobi, Kenya. 130 pp.

Allard G. B., Vincke H., Njenga D. N., Nkubaye E., Ndayiragije P. and Ntimpirangeze M. (1994) Field application of a biological insecticide, *Beauveria bassiana* for the control of the sweet potato weevils, *Cylas puncticollis* and *Blosyrus* spp., in Burundi, pp. 69–82. In *Root and Tuber Pest Management in East and Southern Africa.* Proceedings of a regional workshop, Mombasa, Kenya, 10–14 Aug 1992 (Edited by Allard, Skoglund, Neuenschwander and Murphy). IIBC, Nairobi, Kenya.

Amalin D. M. and Vasquez E. A. (1993) *A Handbook on Philippine Sweet Potato Arthropod Pests and their Natural Enemies.* International Potato Centre, Los Banos, Laguna, Philippines. 82 pp.

Ben Salah H. and Aalbu R. (1992) Field use of granulosis virus to reduce initial storage infestation of the potato tuber moth, *Phthorimaea operculella* (Zeller), in North Africa. *Agric., Ecosyst. Environ.* 38, 119–126.

Ben Salah H., Lagnaoui A. and Ben Temime A. (1994) Granulosis virus testing in on-farm trials for control of potato tuber moth, *Phthorimaea operculella* (Zeller) in Tunisia (in review).

Castellon M. C., Morales L. and Morales A. (1993) Efectividad de la aplicacion de *Beauveria bassiana* y de productos quimocos localizados alrededor de la trampa. INIVIT internal report, Cuba, 9 pp.

Castineiras A., Caballero S., Rego G. and Gonzalez M. (1982) Efectividad tecnico economica del empleo de la hormiga leona, *Pheidole megacephala,* en el control del tetuan del boniato, *Cylas formicarius elegantulus. Cienc. Tec. Agric., Prot. Plantas,* Supl. 5, 103–109.

Chalfant R. B., Jansson R. K., Seal D. R. and Schalk J. M. (1990) Ecology and management of sweet potato insects. *Annu. Rev. Entomol.* 35, 157–180.

Chuhoy E., Ona I. and Ona C. (1989) Sweet potato germplasm evaluation in the Philippines in 1989. CIP Working papers, GIP, Los Baños. pp. 196-204.

CIP (1995) Program report: 1993–1994. Lima, Peru. 192 pp.

Cisneros F. and Gregory P. (1994) Potato pest management. *Aspects Appl. Biol.* 39, 113–124.

Collins W. W., Jones A., Mullen M. A., Talekar N. S. and Martin F. W. (1991) Breeding sweet potato for insect resistance: A global overview, pp. 379–398. In *Sweet Potato Pest Management. A Global Perspective* (Edited by R. K. Jansson and K. V. Raman). Mohan Primlani, New Delhi, India.

Collins W. W. and Mendoza H. A. (1991) Breeding sweet potato for weevil resistance: Future outlook, pp. 399–406. In *Sweet Potato Pest Management. A Global Perspective* (Edited by R. K. Jansson and K. V. Raman). Mohan Primlani, New Delhi, India.

Ewell P. T., Fano H., Raman K. V., Alcazar J., Palacios M. and Carhuamca J. (1990) Farmer management of potato insect pests in Peru. International Potato Centre, Lima. 87 pp.

Flint M. L. (Ed.) (1986) Integrated Pest Management for Potatoes in

Western United States, Univ. Calif. *Div. of Agr. Publ. 3316*, 1986.

Flint M. L. and Bosch R. I. van den (1981) *Introduction to Integrated Pest Management.* Plenum Press, New York. 240 pp.

Fuglie K. O., Ben Salah H., Essamet M., Ben Temime A. and Rahmouni A. (1993) The development and adoption of integrated pest management of the potato tuber moth, *Phthorimaea operculella* (Zeller) in Tunisia. *Insect Sci. Applic.* 14, 501–509.

Fuglie K. O. (1995) Measuring welfare benefits from improvements in technology with an application to Tunisian potatoes. *American J. Agric. Econ.* 77, 162–173.

Heath R. R., Coffelt J. A., Proshold F. I., Dueben B. and Tumlinson J. H. (1986) Identification of a sex pheromone produced by female sweet potato weevil, *Cylas formicarius elegantulus* (Summers). *J. Chem. Ecol.* 12, 1489–1503.

International Potato Centre (CIP) (1992a) Potato tuber moth baculovirus (BCP), a powdered biological insecticide. Biological Control of Potato Tuber Moth in Seed Tubers. *CIP Training Bulletin* 1. CIP, Lima, Peru 7 pp.

International Potato Centre (CIP) (1992b) Biological control of potato tuber moth using *Phthorimaea* baculovirus. *CIP Training Bulletin 2.* CIP, Lima, Peru 27 pp.

Iqbal A., Waluyo I. T., Herpan S. and Mok I.-G. (1994) Orthotylinea (Hem: Miridae) sebagai serangga predator hama lanas, *Cylas formicarius* F. (Col: Curculionidae) pada ubi jalar. In *Penerapan Teknologi Produksi Dan Pasca Panen Ubijalar untuk Mendukung Agro-industri.* Seminar 30 Nov.–1 Dec. 1993. Balai Penelitian Tanaman pangan Malang. Fakultas Pertanian Univ. Brawijaya Malang. International Development Research Centre, Canada. 23 pp.

Jansson R. K. (1991) Biological control of *Cylas* spp., pp. 169–202. In *Sweet Potato Pest Management. A Global Perspective* (Edited by R. K. Jansson and K. V. Raman). Mohan Primlani, New Delhi, India.

Jansson R. K., Mason L. J. and Heath R. R. (1991) Use of sex pheromone for monitoring and managing *Cylas formicarius,* pp. 79–96. In *Sweet Potato Pest Management. A Global Perspective* (Edited by R. K. Jansson and K. V. Raman). Mohan Primlani, New Delhi, India.

Lagnaoui A., Ben Salah H. and Ben Temime A. (1994) Potato tuber moth granulosis virus (PTMgv), a prime candidate for integrated pest management. In *Proceedings of the Third International Conference of the African Potato Association. Sousse, Tunisia, 9–13 May 1994.* (In press).

Lagnaoui A. and El Bedewy R. (1994) An integrated management approach to reduce pesticide use for potato tuber moth control in Egypt. In *Proceedings of the Third International Conference of the African Potato Association. Sousse, Tunisia, 9–13 May 1994.* (In press).

Magenya O. and Smit N. E. J. M. (1991) Preliminary note on sweet potato pests and local control practices in South Western Kenya, pp. 130–138. In *The Role of Root Crops in Regional Food Security and Sustainable Agriculture.* Proceedings of the Fourth Eastern and Southern Africa Regional Workshop on Root and Tuber Crops, Mansa, Zambia, 29 Oct. –2 Nov. 1990 (Edited by M. N. Alvarez and R. Asiedu). IITA, Ibadan, Nigeria.

Magenya O. E. V. and Smit N. E. J. M. (1994) On-farm screening test for weevil (*Cylas* spp.) resistance among various sweet potato cultivars in

Kenya, pp. 89–98. In *Root and Tuber Pest Management in East and Southern Africa.* Proceedings of a regional workshop, Mombasa, Kenya, 10–14 Aug 1992 (Edited by Allard, Skoglund, Neuenschwander and Murphy). IIBC, Nairobi, Kenya.

Morales L. (1994) Uso de predatores en el control de *Cylas formicarius.* INIVIT working paper, Cuba, 14 pp.

Palacios M., Raman K. V., Alcazar J. and Cisneros F. (1994) Control integrado de la polilla de la papa. Centro International de la Papa, Lima, Peru. *Boletin de Capacitacion CIP 4.* 18 pp.

Parker B. L., Wolfe G. W. and Abubaker A. (1992) Occurrence of *Cylas formicarius* (F.) (Col., Apionidae) in Central and Southern Africa. *J. Appl. Ent.* 114, 400–402.

Raman K. V. (1988) Integrated insect pest management for potatoes in developing countries. *CIP Circular* 16, 1–8.

Raman K. V. (1994) Potato pest management in developing countries, pp. 583–596. In *Advances in Potato Pest Biology and Management* (Edited by C. Zehnder, R. K. Jansson, M. Powelson and K. V. Raman). American Phytopathological Society, New York.

Raman K. V. and Alleyne E. H. (1991) Biology and management of the West Indian sweet potato weevil, *Euscepes postfasciatus,* pp. 263–281. In *Sweet Potato Pest Management. A Global Perspective* (Edited by R. K. Jansson and K. V. Raman). Mohan Primlani, New Delhi, India.

Raman K. V. and Palacios M. (1982) Screening potato for resistance to potato tuberworm. *J. Econ. Entomol.* 75, 47–49.

Raman K. V., Booth R. H. and Palacios M. (1987) Control of potato tuber moth *Phthorimaea operculella* (Zeller) in rustic potato stores. *Trop. Sci.* 27, 175–194.

Raman K. V., Palacios M. and Mujica N. (1993) Control biologico de la polilla de la papa *Phthorimaea operculella* por el parasitoide *Copidosoma koehleri.* International Potato Centre, Lima, Peru. *Boletin de Capacitation CIP 3.* 28 pp.

Rie J. van, Janssens S. and Reynaerts A. (1994) Engineered resistance against potato tuber moth, pp. 499–508. In *Advances in Potato Pest Biology and Management* (Edited by G. Zehnder, R. K. Jansson, M. Powelson and K. V. Raman). American Phytopathological Society, New York.

Smit N. E. J. M. (in press) The effect of the indigenous practices of in-ground storage and piecemeal harvesting of sweet potato on yield and quality loss due to sweet potato weevil in Uganda. *Agric., Ecosyst. Environ.*

Smit N. E. J. M., Magenya O. and Parker B. L. (1994) Biology and pheromone studies with the sweet potato weevils *Cylas puncticollis* and *C. brunneus,* pp. 399–405. In *Tropical Root Crops in a Developing Economy.* Proceedings of the Ninth Conference of the International Society for Tropical Root Crops, 20–26 Oct. 1991, Accra, Ghana (Edited by F. Ofori and S. K. Hahn). IITA, Ibadan, Nigeria.

Smit N. E. J. M. and Matengo L. O. (1995) Farmers' cultural practices and their effects on pest control in sweet potato in South Nyanza, Kenya. *Int. J. Pest Manage.* 41, 2–7.

Talekar N. S. (1987) Resistance in sweet potato to sweet potato weevil. *Insect Sci. Applic.* 8, 819–823.

Talekar N. S. (1991) Integrated control of *Cylas formicarius,* pp. 139–156. In *Sweet Potato Pest Management. A Global Perspective* (Edited by R. K. Jansson and K. V. Raman). Mohan Primlani, New Delhi, India.

Tingey W. (1991) Potato glandular trichomes: Defensive activity against insect attack. In *Naturally Occurring Pest Bioregulators* (Edited by P. A. Hedin). *ACS Symposium Series 449.* American Chemical Society, Washington, DC. 456 pp.

Voerman S. and Rothschild G. H. L. (1978) Synthesis of the two components of the sex pheromone system of the potato tuberworm moth, *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelichiidae) and field experience with them. *J. Chem. Ecol.* 4, 531–542.

Von Arx R., Goueder J., Cheikh M. and Ben Temine A. (1987) Integrated control of potato tuber moth *Phthorimaea operculella* (Zeller) in Tunisia. *Insect Sci. Applic.* 8, 989–994.

Von Arx R., Ewell P. T., Goueder J., Essamet M., Cheikh M. and Ben Temine A. (1988) Management of the potato tuber moth by Tunisian farmers: A report of on-farm monitoring and a socioeconomic survey. CIP, Lima and INRAT, Tunisia, 30 pp.

Von Arx R., Roux O. and Baumgaertner J. (1990) Tuber infestation by potato tuber moth, *Phthorimaea operculella* (Zeller), at potato harvest in relation to farmers' practices. *Agric., Ecosyst. Environ.* 31, 277–292.

Waluyo I. T. and Mok I.-G. (1993) Uji ketahanan varietas atau klon ubijalar terhadap hama *Cylas formicarius* (hama lanas) di lapangan. In *Penerapan Teknologi Produksi Dan Pasca Panen Ubijalar untuk Mendukung Agro-industri.* Seminar 30 Nov.–1 Dec. 1993. Balai Penelitian Tanaman pangan Malang. Fakultas Pertanian Univ. Brawiiaya Malang. International Development Research Centre, Canada. 23 pp.

Widodo Y., Supriatin and Braun A. R. (1994) Rapid assessment of Integrated Pest Management needs for sweetpotato in some commercial production areas of Indonesia. Working Document. International Potato Center. East, Southeast Asia and the Pacific Region. Bogor, Indonesia and Malang Research Institute for Food Crops, Malang, Indonesia, 19 pp.

Wolfe G. W. (1991) The origin and dispersal of the pest species of *Cylas* with a key to the pest species groups of the world, pp. 13–44. In *Sweet Potato Pest Management. A Global Perspective* (Edited by R. K. Jansson and K. V. Raman). Mohan Primlani, New Delhi, India.

Management of Rice Stemborers in Asia

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Abstract—Stemborers are major pests in all rice ecosystems. The insects infest rice crops throughout their growth, from the seedling stage to maturity. Fifty species in three families—Pyralidae, Noctuidae (Lepidoptera) and Diopsidae (Diptera)—have been found to attack rice crops. In Asia, stemborers are responsible for a steady annual damage of 10% of the rice crop, with occasional localised outbreaks of up to 50 to 60%. No one insect control method will maintain stemborer numbers below economic injury levels. The combination of control tactics that are effective is highly dependent on site characteristics. Stemborer management practices should be as harmonious among themselves as is practical. In addition, they should be compatible with economic pest control and crop production practices.

Key Words: rice stemborers, Asia, rice crop, management

Introduction

Rice is a primary staple diet of over half of the world's population. It is grown in 145 million ha in 11 countries with 90% of the area in Asia (IRRI, 1988). Average rice yields vary from less than 1 t/ha in some African countries to more than 6 tonnes in Japan, South Korea, and the USA. The two major factors responsible for poor yields are adverse weather conditions and pest endemic.

The stemborers, generally considered the most serious pests of rice worldwide, occur and infest rice plants from seedling to maturity. All common rice stemborers belong to the order Lepidoptera and the families Pyralidae or Noctuidae. The pyralid borers are more common and destructive and usually have high host specificity; noctuids are polyphagous and only occasionally cause economic losses to the rice crop. Twenty-three pyralid species belonging to 11 genera and 4 noctuid species, all in the genus *Sesamia,* have been recorded from rice (Table 1) (Banerjee and Pramanik, 1967; Pathak and Khan, 1994). Five of these stemborers—yellow stemborer *Scirpophaga incertulas* (Walker), striped stemborer *Chilo suppressalis* (Walker), white stemborer *Scirpophaga innotata* (Walker), dark-headed stemborer *Chilo polychrysus* (Meyrick), and pink stemborer *Sesamia inferens* (Walker)—are the most widely distributed. Damage by *S. incertulas* and *C. suppressalis* in Asia is reported at 5 to 10% with local catastrophic outbreaks of up to 60% damage (Kapur, 1967; Litsinger et al., 1987). *Chilo suppressalis* (Walker) is perhaps the most widespread species, extending from Asia and Oceania into the Middle East and Europe. The most prevalent species in Asia are *Scirpophaga incertulas* (Walker), *Chilo suppressalis, Scirpophaga innotata* (Walker), and *Sesamia inferens* (Walker). *Chilo agamemnon* Bleszynski occurs in the Middle East and North Africa. *Maliarpha separatella* Ragonot is the most prevalent species in Africa. In North and South America, *Diatraea saccharalis* (Fabricius) is the most widespread species, followed by *Elasmopalpus lignosellus* (Zeller) and

Table 1. Stemborers of rice worldwide

Order	Family	Species	Distribution
Lepidoptera	Pyralidae	*Acigona ignefusalis* (Hampson)	Africa
		Adelpherupa flavescens Hampson	Africa
		Ancylolomia chrysographella (Kollar)	Asia
		Catagela adjurella Walker	China
		Chilo agamemnon Bleszynski[+]	Middle East/North-East Africa
		Chilo aleniellus (Strand)	Africa
		Chilo auffcilius Dudgeon[+]	Asia
		Chilo diffusilineus (J. de Joannis)[+]	Africa
		Chilo luniferalis Hampson	Africa
		Chilo mesoplagalis (Hampson)	Africa
		Chilo partellus (Swinhoe)	West Asia/Africa
		Chilo plejadellus Zincken[+]	North America
		Chilo polychrysus (Meyrick)[+]	Asia
		Chilo psammathis (Hampson)	Africa
		Chilo sacchariphagus indicus (Kapur)	Asia
		Chilo suppressalis (Walker)[+]	Europe/Middle East/Asia/Oceania
		Chilo zacconius Bleszynski[+]	Africa
		Diatraea lineolata (Walker)	Central/South America
		Diatraea saccharalis (Fabricius)[+]	North/South America
		Elasmopalpus lignosellus (Zeller)[+]	North/South America
		Eldana saccharina Walker	Africa
		Maliarpha separatella Ragonot[+]	Africa/West Asia
		Niphadoses palleucus Common	Australia
		Rupela albinella (Cramer)[+]	North/South America
		Scirpophaga aurivena (Hampson)	Asia
		Scirpophaga fusciflua Hampson	Asia
		Scirpophaga gilviberbis Zeller	Asia
		Scirpophaga incertulas (Walker)[+] =*Schoenobius incertulas* (Walker) =*Tryporyza incertulas* (Walker)	Asia/Australia
		Scirpophaga innotata (Walker)[+] =*Tryporyza innotata* (Walker)	East Asia/Australia
		Scirpophaga lineata (Butler)	Asia
		Scirpophaga nivella (Fabricius)	Asia/Australia/Oceania
		Scirpophaga occidentella (Walker)[+]	Africa
		Scirpophaga subumbrosa Meyrick[+]	Africa
		Scirpophaga virginia Schultze	Asia
	Noctuidae	*Bathytricha truncata* (Walker)	Australia
		Busseola fusca (Fuller)	Africa
		Sesamia botanephaga Tams & Bowden[+]	Africa
		Sesamia calamistis Hampson[+]	Africa
		Sesamia cretica Lederer	Africa/Europe/Middle East
		Sesamia epunctifera Hampson	Africa
		Sesamia inferens (Walker)[+]	Asia/Australia/Oceania
		Sesamia nonagrioides (Lefebvre)[+]	Africa
		Sesamia penniseti Tams & Bowden	Africa
		Sesamia uniformis Dudgeon	Asia

[+] Species commonly occurring on rice.

Rupela albinella (Cramer). North America is also home to *Chilo plejadellus* Zincken, which attacks wild rice *Zizania aquatica* Linnaeus as well as *Oryza*. *Scirpophaga innotata* is most prevalent in Australia; *C. suppressalis* and *S. inferens* are most prevalent in Oceania. Four stemborer species are generally monophagous to *Oryza: S. incertulas, S. innotata, M. separatella,* and *R. albinella*. Among the stemborers, *Elasmopalpus lignosellus* is the most polyphagous; it is a pest not only of rice and other cereals, but also of legumes.

The yellow stemborer is the predominant species in Bangladesh, India, Malaysia, Pakistan, Philippines, Sri Lanka, Thailand, Vietnam, and parts of Indonesia followed by *C. suppressalis* and *S. innotata* (Pagden, 1930; Jepson, 1954; Catling and Islam, 1982). In Bangladesh, *S. incertulas* is followed by *S. inferens* in importance (Alam and Catling, 1977). *Chilo suppressalis* is a serious problem in Korea but *S. incertulas* does not occur there (Paik, 1967). In Japan, C. *suppressalis* and *S. incertulas* are the two economically important rice borers. The distribution of *S. incertulas* is restricted to southern Japan, thus the maximum area infested by this species is one tenth that of *C. suppressalis* (Kiritani, 1988). *Scirpophaga incertulas* is a major pest of deepwater rice in eastern India, Bangladesh, and Thailand and may cause more than 20% yield loss in many fields (Catling et al., 1987).

Rice stemborers often show preferences for different climates and ecosystems. *Scirpophaga incertulas* is adapted to the aquatic rice-growing environments of the tropics, where it causes the highest annual yield loss of all insect pests. *Scirpophaga innotata* is adapted to tropical climates that have a distinct dry season. *Scirpophaga incertulas* also can aestivate over a dry season, but is less adapted to this condition. *Scirpophaga incertulas* is an aquatic species, the only stemborer able to survive submergence. Larvae hatch and enter the stem, sealing off the entrance hole to develop inside the stem under water. Submerged larvae and pupae of other species would drown, because their entrance holes remain open. Periodic flooding of irrigated ricefields ensures the supremacy of *S. incertulas* in tropical Asia. It is also an important pest of deepwater rice. *Chilo suppressalis,* although it occurs in the tropics, is more adapted to temperate regions, where it hibernates over winter. *Elasmopalpus lignosellus* is a purely upland-adapted stemborer. All stemborers, however, can survive well in the uplands, and that ecosystem typically harbours many species. Stemborers with broad host ranges also are likely to be found in the uplands, because they prefer maize, sorghum, or sugarcane to rice.

Damage

The initial boring and feeding by neonate lepidopteran larvae in the leaf sheath causes broad longitudinal, whitish discolored areas at feeding sites, but only rarely results in wilting and drying of the leaf blades. About a week after hatching, larvae from the leaf sheaths bore into the stem and, staying in the pith, feed on the inner surface of the stem walls. Such feeding frequently results in severing the apical parts of the plant from the base. When this kind of damage occurs during stem elongation, the central leaf whorl does not unfold, turns brownish, and dries up, although the lower leaves remain green and healthy. This condition is known as 'deadheart'. Affected tillers dry without bearing panicles. Sometimes deadhearts are caused by larval feeding above the primordia. If no further damage occurs, the severed portions get pushed out by new growth.

During panicle exertion, severing of growing plant parts from the base results in the drying of panicles. Panicles may not emerge at all, and those that have already emerged do not produce grain. The empty panicles become very conspicuous in a field because they remain straight and are whitish. They are called 'whiteheads'. Shrivelled grains can be found when the panicles are cut off at the base after grain formation is partially completed. Although stemborer damage becomes evident only as deadhearts and whiteheads, significant losses also can be inflicted by larvae that feed within the stem without severing the growing plant parts. Such damage, more common in deepwater rice, results in reduced plant vigour, fewer tillers, and many unfilled grains (Alam and Catling, 1977; Catling et al., 1983).

The damage potential is related to the inner diameter of the stem in relation to the diameter of the larvae. If the tiller is relatively wider than the larva, then damage is less. There may be differences among species in this regard: although high levels of infestation can occur with *R. albinella* and *M. separatella*, recorded yield loss is minimal (Arregoces et al., 1981; Akinsola, 1984).

Little definitive work has been done to determine the relationship between stemborer damage and yield loss, particularly in modern high-tillering varieties. It has been shown that these varieties are able to compensate for extensive damage during the vegetative stage of growth, and damage incurred during the reproductive stage of the plant must reach nearly 10% tiller (stem) loss before yield reduction can be detected.

Control Methods

Cultural Control

Crop cultural practices have a profound bearing on the stemborer population. Some methods are effective only if carried out through community-wide cooperation; others are effective in a single field. Community-wide practices act to prevent colonisation and have the greatest potential to minimise infestation. China and prewar Indonesia developed effective cultural practices, often in combinations that isolate the rice crop through time and space. Practices that can be carried out in a single field include using optimal rates of N fertiliser in split applications. Applying slag increases the silica content of the crop, making it more resistant.

Since the eggs of *S. incertulas* are laid near the tip of the leaf blade, the widespread practice of clipping the seedlings before transplanting greatly reduces the carryover of eggs from the seedbed to the transplanted fields (Khan, 1967). However, this control method has merit only if older seedlings are transplanted. Similarly, the height at which a crop is harvested is an important factor in determining the percentage of larvae that are left in the stubble. At harvest, *Chilo suppressalis* larvae are usually about 10 to 15 cm above ground. Although *Scirpophaga incertulas* larvae are located somewhat lower, most of them are above ground as well. Therefore, harvesting at ground level can remove a majority of the larvae of all species (Li, 1972; Islam, 1976). To destroy those remaining in the stubble, burning or removing the stubble, decomposing the stubble with low rates of calcium cyanide, plowing, and flooding have been suggested (Lee, 1954). Burning is only partially effective because after harvest the larvae generally move below ground level. It is also difficult to uniformly burn stubble in a field. Plowing and flooding are apparently most effective. Since stubble is the major source of the overwintering stemborer population, proper stubble management cannot be overemphasised. However, stubble burning not only destroys overwintering borers but also their natural enemies. Therefore, such practice should be discouraged.

In several countries, delayed seeding and transplanting have been effective in evading first-generation moths (Saha and Saharia, 1970). This practice has not been highly effective against *Chilo suppressalis* in Japan since emergence is delayed if planting is delayed. It has been effective, however, against *S. incertulas,* the appearance of which is not affected by planting dates. The number of generations of this species is determined by the growth duration of the crop. Thus, where continuous rice cropping is practised, a change in planting time has little effect unless practised over large areas. In such areas, crop rotation to include some short-duration nongraminaceous crops should significantly reduce the borer population.

Changing planting time may not always be feasible because of other agronomic considerations. In Pakistan, the planting date has been regulated by releasing canal water only after the first brood *S. incertulas* moths have emerged. This late-planted crop is far less infested than fields planted early with private irrigation systems. The early planted fields, however, minimise the full impact of late planting on the stemborer population. In Japan, where highly effective insecticides are available, early planting has been reintroduced at several sites, resulting in high survival of first-generation *S. incertulas* larvae. Also, the first and second broods of *C. suppressalis* moths appeared earlier, possibly introducing a distinct third generation in the warmer sections of the country. Light-trap catches of moths reveal a change from a unimodal to a bimodal pattern in both the first and second broods.

Biological Control

Most biological control of stemborers in tropical Asia and Africa comes from indigenous predators, parasites, and entomopathogens. The conservation of these valuable organisms is the key to development of stable and successful integrated pest management. Over 100 species of stemborer parasitoids have been identified (Nickel, 1964; Yasumatsu, 1967). The three most important genera are the egg parasitoids *Telenomus, Tetrastichus* and *Trichogramma* (Delfinado, 1959; Nickel, 1964; Catling et al., 1983, Shepard and Arida, 1986). *Tetrastichus* wasps have elongated ovipositors and can lay their eggs in stemborer eggs, even if the latter are covered with a mat of hair. *Telenomus* wasps, however, parasitise stemborer eggs while the moth is in the act of oviposition—before the eggs are covered with hair. The wasp locates the female moth, possibly by the sex pheromone, attaches itself to the tuft of anal hair near the ovipositor, and waits for the moth to lay eggs.

Egg masses are also the food of several predators. The longhorned grasshopper *Conocephalus longipennis* (Haan) preys voraciously on eggs of the yellow stemborer (Shepard and Arida, 1986; Pantua and Litsinger, 1984). Other orthopteran predators such as the crickets *Metioche vittaticollis* (Stål) and *Anaxipha longipennis* (Serville) feed on eggs of *Chilo suppressalis* (Pantua and Litsinger, 1984; Canapi et al., 1986).

A wide range of predatory species attacks the small larvae of stemborers before they enter the stem of the rice plant. Some important predators are coccinellid beetles *Micraspis crocea* (Mulsant), *Harmonia octomaculata* (Fabricius), and carabid beetles such as *Ophionea* spp. When young larvae fall in the water, they are preyed upon by *Microvelia douglasi atrolineata* Bergroth and *Mesovelia vittigera* (Horvàth). Ants and a dozen other predators prey upon stemborer larvae.

The larval and pupal stages are attacked by a large number of parasites, but parasitisation rates are often low. The adult moths are attacked by several spiders while resting on foliage or are caught in webs while flying. Dragonflies and birds are also effective daytime predators, bats are active at dusk.

Several species of fungi can infect a stemborer larva at the base of the stem when it is about to pupate. The fungus *Cordyceps* sp. grows long, noodle-like arms on the body of stemborer larvae. Pathogen activity is greatest against larvae resting over winter or summer, particularly when the stubble has decayed and moisture has entered. Epizootics during the crop are rare because the larvae are protected and, for the most part, solitary.

The widely used insect pathogen of rice insects is *Bacillus thuringiensis* and several commercial formulations are available for lepidopteran pests. Stemborers can be infested by *B. thuringiensis* (Nayak et al., 1978). M. C. Rombach demonstrated reduced feeding by stemborer larvae when fed on *B. thuringiensis* (pers. commun.), but the bacterium is not likely to be effective against this pest in the field because feeding and development of the larvae take place inside the stem.

Varietal Resistance

During the last 25 years, local and introduced germplasm have been extensively screened for resistance to stemborers in several countries. At IRRI, more than 17,000 rice varieties have been screened for resistance to *C. suppressalis* and more than 39,000 varieties to *S. incertulas* (Pathak and Khan, 1994). Common resistance sources such as TKM6, Chianan 2, Taichung 16, Ptb 10, Su-Yai 20, and WC 1263 have been identified. However, varieties resistant to one stemborer species are not necessarily resistant to others. The differences in varietal resistance are only quantitative in nature. Very high levels of resistance have not been found in rice, and resistance scores vary from highly susceptible to moderately resistant. Even varieties classified as resistant suffer some damage under high insect populations. However, several wild rices have high levels of resistance to stemborers. Genetic analysis has shown such resistance to be polygenic in nature (Pathak, 1970; Chaudhary et al., 1984).

The nature of resistance to *Chilo suppressalis* has been studied in detail. Several morphological and anatomical characteristics of the rice plant show a general association with resistance to stemborers (Pathak et al., 1971). Generally, tall varieties with long, wide leaves and large stems are more susceptible. Varieties containing more layers of lignified tissue, a greater area under sclerenchymatous tissue, and a large number of silica cells are more resistant. Although each of these characteristics appears to contribute to borer resistance, none by itself appears to be the main cause of such resistance (Pathak and Saxena, 1980). A rice plant biochemical oryzanone (*p*-methylacetophenone) was identified as an attractant to ovipositing moths and to larvae (Munakata and Okamoto, 1967). The resistance of TKM6 and other resistant rice varieties was mostly due to allomones, which inhibit oviposition and disturb the insect's growth and development. IRRI in collaboration with the Tropical

Development Research Institute, London, recently identified this biochemical resistance factor, coded as Compound A, as a pentadecanal. Compound A in resistant plants inhibits oviposition and adversely affects eggs and larval and pupal stages (M. D. Pathak, unpublished report).

On the other hand, differences in nonpreference for oviposition of *S. incertulas* are not distinct in screenhouse tests. In such tests, moths often laid more eggs on the frames of the cages than on the rice plants. Such ovipositional behaviour is very peculiar for a species considered to be monophagous. But larvae feeding on resistant varieties were smaller, had low survival, and caused lower percentages of deadhearts than those feeding on susceptible varieties (IRRI, 1976).

At IRRI, breeding for resistance to *C. suppressalis* started in 1965. Selected resistant varieties have been used in a hybridisation programme to improve their resistance to *C. suppressalis* and to incorporate their resistance into plants with desirable agronomic characters. TKM6 has been used extensively in breeding for borer resistance in several countries. IR20, the first borer-resistant, improved-plant-type variety, was developed by crossing TKM6 with Peta/TNI (Pathak et al., 1973). It has moderate resistance to *C. suppressalis* and *S. incertulas;* resistance to green leafhopper, tungro virus, and bacterial leaf blight; and tolerance for several adverse soil conditions. Subsequent studies on breeding for resistance to *C. suppressalis* involved the diallel selective mating (DSM) system using seven rice varieties moderately resistant to *C. suppressalis.* DSM for three generations has produced progenies distinctly more resistant than any parent (Chaudhary et al., 1984).

The breeding programme for *S. incertulas* resistance was initiated at IRRI after 1972. Three improved plant types—IR1721-11, IR1917-3, and IR1820-52-2—were found resistant. A series of multiple crosses was also made to accumulate resistance from several breeding lines. Breeding lines such as IR4791-80 and IR4791-89, which emanated from this system, had a higher level of resistance than IR1820-52-2. A new approach to upgrade the level of *S. incertulas* resistance was adapted in 1980, using the male-sterile-facilitated current selection scheme. Genetic male sterile IR36 used as female parent was crossed with 26 donor parents (Chaudhary et al., 1984).

The rice breeding programmes of many countries aim at incorporating into their improved germplasm genes for resistance to *C. suppressalis* and *S. incertulas* from many donors. However, none of the rice varieties developed so far have more than a moderate level of resistance. There is also little cross resistance; varieties resistant to *C. suppressalis* are not necessarily resistant to *S. incertulas.* Some wild rices such as *Oryza officinalis* and *O. ridleyi* have very high levels of resistance to stemborers. Their resistance needs to be transferred to cultivated rice, using appropriate distant hybridisation techniques.

Breeding for plant type has probably had a greater impact on reducing stemborer incidence than breeding for other characters associated with resistance. Endemic areas of high stemborer damage occur where long-duration, tall cultivars are planted. Photoperiod-insensitive cultivars mature early, and that reduces population buildup. A new stemborer generation occurs every 30–40 days and theoretically each generation brings about an exponential increase in abundance. When the crop is harvested before a generation is completed, mortality in a stemborer population is heavy. Breeding for photoperiod-insensitive cultivars has reduced the time that allowed population buildup. Stemborer populations are often lower when two short-duration crops replace a single long-duration crop. Breeding for short stature has reduced the time of stem elongation and the period of plant susceptibility.

Chemical Control

Stemborers are difficult to control with insecticides. After hatching, the larvae are exposed only for a few hours before they penetrate a tiller or enter the plant. Successful control involves repeated foliar applications with spray volumes more than 400 litres/ha. In temperate climates, stemborer populations are more synchronised and well-timed applications have a greater degree of control than in the tropics where generations overlap. The decline in stemborer abundance in Japan and the Republic of Korea is attributed to the frequent use of insecticides over many years, even though the stemborers have developed insecticide resistance.

Foliar sprays, which act on the larvae and on the adult moths and eggs, also come into greater contact with natural enemies of the stemborer. Cases of stemborer resurgence are not evident, although secondary pest outbreaks have been reported in areas of heavy insecticide usage against stemborers (Kobayashi, 1961).

Granular formulations, particularly gamma BHC and diazinon, give higher control than foliar sprays or dusts, particularly in high rainfall environments. Granules broadcast into irrigation water are particularly effective in preventing deadhearts in a young crop. Gamma BHC has a fumigant action that kills resting moths. The insecticide is partly dissolved in the water and moves by capillary action between the leaf sheath and stem to come into contact with young larvae: the nonsystemic insecticide granules act as though they were systemic. The limitation to using granules is cost—they are more expensive to transport. Stable water supply and deep water levels are also necessary for high levels of control. As the water level falls, the capillary activity progressively declines. If the field dries out, insecticide efficacy ceases. Flooding from heavy rains also washes the insecticide out of the field. Dosage levels have declined, consistent with the relatively higher costs of insecticides.

Systemic granules have an advantage in that the chemical can enter the plant even with low water levels. The chemical percolates into the soil and is taken up by the roots. From the roots, the chemical is transmitted through the xylem tissues to the stems and eventually to the tips of the leaves. Carbofuran exudes in droplets of water from leaf hydathodes and evaporates into the air. If systemic granules are broadcast into the irrigation water, high dosages are necessary because much of the chemical is absorbed in the soil. The dosage needed increases with plant biomass. If granules are broadcast during the last harrowing of levelling operation before planting, dosages can be cut in half. Effectivity lasts more than a month because the granule is protected from rapid degradation. Heavy use of granules, however, can lead to microbial degradation. Several species of soil bacteria respond to and rapidly consume the insecticide, rendering it ineffective. The process can be slowed by using lower dosages in rotation with foliar sprays. The problem with soil incorporation of insecticides before planting is that the stemborer population cannot be assessed—it might not be large enough to warrant control.

A combination of sex attractant (pheromones) and chemosterilant could also be a promising control tactic. High moth populations in overlapping generations, however, and the difficulties involved in mass rearing some stemborer species are major limitations to the mass release of artificially irradiated sterile male moths as a control measure. Exploratory experiments on mass rearing have shown that, when provided with 1% tepa, apholate, or tretamine, or 20% hempa as food, the moths mated normally but deposited 50% fewer eggs. Of the eggs deposited, 20% of those laid by moths exposed to tepa and apholate were sterile.

Economic Threshold

Economic injury levels are useful in setting economic or action thresholds on which to base decisions on borer control usually through applying insecticides, but possibly through release of natural enemies.

Usually, insect pest assessment cannot predict a stemborer population more than a week in advance. A rice crop is vulnerable during tiller elongation, 3–4 weeks after transplanting. Different characters have been used in establishing economic thresholds for rice stemborer moths, egg masses, damaged tillers, larvae-infested tillers, deadhearts and whiteheads. Whiteheads are obviously not a timely character. Deadhearts have been used widely. With deadhearts, however, it should be remembered that only late-instar larvae that had entered a tiller several weeks earlier can sever the tiller. Damaged and infested tillers present the same problem: assessment is too late unless systemic insecticides are used, but normally the active rates are not economical. Thresholds based on moth counts would be timely, but there is a danger of overreaction: often natural enemies can prevent population buildup, with no need for chemical application.

A more logical economic threshold would be based on egg masses. Egg masses are even more timely than moths, but are more difficult to detect. The presence of moths could be an early warning signal to look for eggs. Pheromone traps could also forecast the time for egg counting. Egg masses per square metre or per hill can be counted. The masses could be held in containers to assess the presence of egg parasites. If a large proportion of the egg masses are parasitised, chemical application would not be needed. If egg parasite activity is low, then the time of egg hatch would dictate the time to apply insecticides to kill young larvae.

Pest Management

No one insect control method will maintain stemborer numbers below economic injury levels. The combination of control tactics that are effective is highly dependent on site characteristics. If a farm community is organised, a number of powerful cultural control methods can be used to decrease egg laying in the field thereby preventing stemborer build up. The larger the area where cultural control methods are used, the greater is the chance of isolating stemborers in time and space.

Early- to medium-duration varieties are chosen and crop planting is timed to avoid mass flights of moths emerging from the stubble, particularly after dormancy is broken. Fields are planted in synchrony within a period less than the length of one stemborer generation. After harvest, the rice straw is managed to kill resident stemborer larvae and the stubble is plowed up. If the stemborer population in the stubble is high, then the fields can be flooded before land preparation for the next crop and kept submerged up to a week to kill resident larvae.

Varieties planted should have some level of resistance to the prevalent species of stemborers, if possible. Varieties should be bred with combinations of various components of resistance—nonpreference, antibiosis, and tolerance. Nonpreference for oviposition is a better choice for protecting a crop from infestation.

Varieties and management practices should be selected to shorten the tiller elongation period. This can be achieved by choosing short-statured varieties. Nitrogen fertiliser should be applied at optimal rather than maximum levels, in split applications.

Varieties and management practices also should enhance the rice plant's ability to compensate for damage. If possible, select high-tillering varieties. The crop should be planted at the higher range of crop density recommendations.

Parasites and predators should be conserved by judiciously applying petroleum-based pesticides. Microbial insecticides are not highly effective against stemborers, for the simple reason that contact between the pathogen and the larvae is minimal: the larvae quickly enter the rice plant stem. New developments in genetic engineering could overcome that problem by transferring the genes of an insect pathogen such as *Bacillus thuringiensis* into the genome of the rice plant. Then the cells of the rice plant would produce toxic crystals, and stemborer larvae would be exposed when they consume any tissue.

Economic injury levels should be developed for each rice-growing region within a country. The injury levels should consider the crop growth stage, and monitoring should focus on two periods of susceptibility: during tiller elongation and during panicle exertion. Forewarning of egg density could be achieved by flushing moths from the field or field borders, or by using counts from pheromone traps. Stemborer management practices should be as harmonious as is practical. In addition, they should be compatible with economical pest control practices and crop production practices.

References

Akinsola E. A. (1984) Effects of rice stem borer infestation on grain yield and yield components. *Insect Sci. Applic.* 5, 91–94.

Alam S. and Catling H. D. (1977) Preliminary observations of deepwater rice pests in Bangladesh. In *Proceedings Deepwater Rice Workshop,* Bangkok, 205 pp.

Arregoces O., Castro E., Cardona C., Gonzales J., Reyes J. A., Garcia J. and Raigosa J. (1981) Rice stem borers and their control in Latin America. *Cent. Int. Agric. Trop. CIAT. Ser.* 04SR-04.02.

Banerjee S. N. and Pramanik L. M. (1967) The lepidopterous stalk borers of rice and their life cycles in the tropics, pp. 103–124. In *The Major Insect Pests of the Rice Plant.* Proceedings of a symposium at the International Rice Research Institute, Sep. 1964. The Johns Hopkins Press, Baltimore, Maryland, USA.

Canapi B. L., Rubia E. G., Litsinger J. A., Shepard B. M. and Rueda L. M. (1986) Predation by sword-tailed cricket, *Anaxipha longipennis* (Serville) (Gryllidae) on eggs of three lepidopterous pests of rice. *Int. Rice Res. Newsl.* 13 (4),40.

Catling H. D. and Islam Z. (1982) The problem of yellow rice borer in Asian deepwater rice, pp. 451–458. In *Proceedings of the 1981 International Deepwater Rice Workshop.* International Rice Research

Institute, Los Banõs, Laguna, Philippines.

Catling H. D., Islam Z. and Alam B. (1983) Egg parasitism of the yellow rice borer, *Tryporyza incertulas* (Walker), in Bangladesh deepwater rice. *Entomophaga* 28, 227–239.

Catling H. D., Islam Z. and Pattrasudhi R. (1987) Assessing yield losses in deepwater rice due to yellow stem borer, *Scirpophaga incertulas* (Walker), in Bangladesh and Thailand. *Crop Prot.* 6, 20–27.

Catling H. D., Leamsaeng P. and Pattrasudhi R. (1983) Assessing yield losses from yellow rice borer. Paper presented during the deepwater rice planning meeting, 28–29 Mar 1983. Thai/IRRI deepwater rice collaborative project, Rice Research Institute, Department of Agriculture, Bangkok, Thailand. 3 pp.

Chaudhary R. C., Khush G. S. and Heinrichs E. A. (1984) Varietal resistance to rice stem borers in Asia. *Insect Sci. Applic.* 5, 447–463.

Delfinado M. D. (1959) A survey of rice stem borer parasites in Rizal, Laguna and Pangasinan. *Philipp. Agric.* 42, 345–357.

IRRI (International Rice Research Institute) (1976) *Annual Report for 1975.* International Rice Research Institute, Los Banõs, Laguna, Philippines. 479 pp.

IRRI (International Rice Research Institute) (1988) *IRRI Rice Facts,* International Rice Research Institute, Los Banõs, Laguna, Philippines, 10 pp.

Islam M. A. (1976) Heights of the leftover rice-stubbles and its relation with the stem borer population. *Bangladesh J. Agric. Res.* 2, 1–33.

Jepson W. F. (1954) A critical review of the world literature on the lepidopterous stalk borers of tropical graminaceous crop. *Commonw. Inst. Entomol.,* London. 127 pp.

Kapur A. P. (1967) Taxonomy of the rice stem borers, pp. 3–43. In *The Major Insect Pests of the Rice Plant.* Proceedings of a symposium at the International Rice Research Institute, Sep. 1964. The Johns Hopkins Press, Baltimore, Maryland, USA.

Khan M. Q. (1967) Control of the paddy stem borers by cultural practices, pp. 369–389. In *The Major Insect Pests of the Rice Plant.* Proceedings of a symposium at the International Rice Research Institute, Sep. 1964. The Johns Hopkins Press, Baltimore, Maryland, USA.

Kiritani K. (1988) What has happened to the rice borers during the past 40 years in Japan? *Jap. Agric. Res. Q.* 21, 264–268.

Kobayashi H. (1961) Control method for rice stem borer [in Japanese] . *Nogyo Oyobi Engei* 36, 855–858.

Lee S. Y. (1954) Effect of calcium cyanamide on the rice borer. *J. Econ. Entomol.* 47, 186–187.

Li C. S. (1972) Integrated control of the white rice borer, *Tryporyza innotata* (Walker) (Lepidoptera: Pyralidae), in Northern Australia. *Mushi* 45 (Suppl.), 51–59.

Litsinger J. A., Barrion A. T. and Soekarna D. (1987) Upland rice insect pests: Their ecology, importance and control. International Rice Research Institute Research Paper Series No. 123, 41 pp.

Munakata K. and Okamoto D. (1967) Varietal resistance of rice stem borers in Japan, pp. 419–430. In *The Major Insect Pests of the Rice Plant.* Proceedings of a symposium at the International Rice Research Institute, Sep. 1964. The Johns Hopkins Press, Baltimore, Maryland, USA.

Nayak P., Rao P. S. and Padmanabhan S. Y. (1978) Effect of thuricide on rice stem borers. *Proc. Indian Acad. Sci. (B)* 87, 59–62.

Nickel J. L. (1964) Biological control of rice stem borers: A feasibility study. *Tech. Bull. No. 2,* International Rice Research Institute, Los Banõs, Philippines. 111 pp.

Pagden H. T. (1930) A preliminary account of three rice stem borers. Straits Settlement Federated Malay States. *Dept. Agric. Sci. Ser. Bull.* 1, 30 pp.

Paik W. H. (1967) Insect pests of rice in Korea, pp. 657–674. In *The Major Insect Pests of the Rice Plant.* Proceedings of a symposium at the International Rice Research Institute, Sep. 1964. The Johns Hopkins Press, Baltimore, Maryland, USA.

Pantua P. C. and Litsinger J. A. (1984) A meadow grasshopper *Conocephalus longipennis* (Orthoptera: Tettigoniidae) predator of rice yellow stem borer (YSB) egg masses. *Int. Rice Res. Newsl.* 9(4), 13.

Pathak M. D. (1970) Genetics of plants in pest management. In *Concepts of Pest Management.* North Carolina State University, Raleigh, USA.

Pathak M. D., Andres F., Galacgac N. and Raros R. (1971) Resistance of rice varieties to striped rice borers. *Int. Rice Res. Inst. Tech. Bull.* 11, 35–69.

Pathak M. D., Beachell H. M. and Andres F. (1973) IR20, a pest and disease resistant high yielding rice variety. *Int. Rice Comm. Newsl.* 22(3), 1–8.

Pathak M. D. and Khan Z. R. (1994) *Insect Pests of Rice.* International Rice Research Institute and International Centre of Insect Physiology and Ecology. 89 pp.

Pathak M. D. and Saxena R. C. (1980) Breeding approaches in rice, pp. 421–455. In *Breeding Plants Resistant to Insects* (Edited by F. G. Maxwell and P. R. Jennings). John Wiley and Sons, Inc., New York, USA.

Saha N. N. and Saharia D. (1970) Effects of dates of transplanting and levels of nitrogen on the incidence of stem borer, *Tryporyza incertulas* (Walker) in paddy in Assam. *Indian J. Entomol.* 32, 225–229.

Shepard M. and Arida G. S. (1986) Parasitism and predation of yellow stem borer, *Scirpophaga incertulas* (Walker) (Lepidoptera: Pyralidae) eggs in transplanted and direct-seeded rice. *J. Entomol. Sci.* 21, 26–32.

Yasumatsu K. (1967) The possible control of rice stem borers by the use of natural enemies, pp. 431–442. In *The Major Insect Pests of the Rice Plant.* Proceedings of a symposium at the International Rice Research Institute, September 1964. The Johns Hopkins Press, Baltimore, Maryland, USA.

Development of Effective and Environmentally Sound Strategies to Control *Helicoverpa armigera* in Pigeonpea and Chickpea Production Systems

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Abstract—Pigeonpea and chickpea are two of the most important pulse crops worldwide. They are especially important in the traditionally vegetarian societies of south Asia, providing both high quality dietary protein and an integral component to sustainable cropping systems. In India, a major producer of both crops, *Helicoverpa armigera* is the most important biotic constraint to increasing production and yields. Worldwide this pest causes yield losses worth more than $600 million annually in these two crops. Indian farmers increasingly rely on chemical pesticides to manage *H. armigera*, contributing to the dramatic increase in pesticide use in this country over the past two decades. There are two primary concerns with a pest control technology based predominantly on the use of pesticides: the adverse effect of these compounds on humans and the environment; and the increasing amount of pesticides required to produce adequate control levels due to the development of resistance and the creation of secondary pests. In this paper we summarise *H. armigera* pest management strategies in pigeonpea and chickpea. Many of these technologies, developed at national and international research centres, have yet to be tested rigorously in farmers' fields. In addition, we highlight gaps in the knowledge base which may limit the development of appropriate control measures. A framework for conducting on-farm pest management research is also presented. This framework draws on farming systems research methods and utilises the accumulated knowledge of agricultural scientists, extension agents, NGOs and farmers in developing effective, economical and environmentally sound strategies for managing *H. armigera*. The framework developed out of ICRISAT's on-farm pest management research in the pigeonpea-based cropping systems of Marepally, a village in the core pigeonpea production zone of South India. Part of the proposed framework envisages a comparison of a range of pest management strategies under realistic farmer conditions. These strategies can be characterised along a three-dimensional continuum of: (a) individual vs group focus; (b) chemical vs non chemical use; and (c) information intensive vs simple rules of thumb. Strategies are evaluated for their economic performance, social acceptability, and environmental impact. Preliminary results from this study are presented and application of the framework to chickpea production systems discussed.

Key Words: pigeonpea, chickpea, pest management, participatory research

Introduction

Pigeonpea and chickpea are the fifth and third most important pulse crops in terms of worldwide production respectively (Table 1). These crops are especially important in the traditionally vegetarian societies of South Asia, where the bulk of world production is centred (Table 1). In addition to the historical preference for these two crops, they are important in the region because they provide high quality dietary protein, have high nitrogen fixing ability and are drought tolerant. For these reasons, pigeonpea and chickpea are integral components of traditional and sustainable cropping systems of the region.

Table 1. World pulse production (metric tonnes)

Crop	World	South Asia[1]
Dry bean	17,525	4308
Dry pea	16,317	703
Chickpea	7700	5863
Broad bean	5422	nil
Pigeonpea	2888	2666
Lentil	2384	1098
Total pulses[2]	62,002	15,917

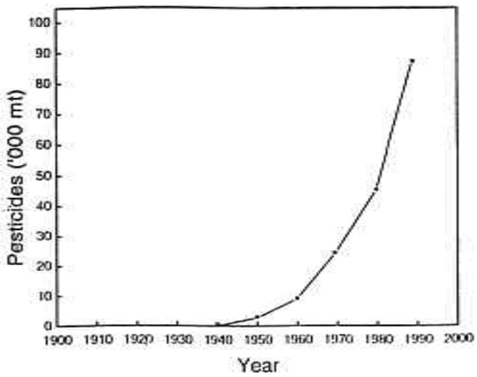
Source: FAO, 1992 and unpublished data.
[1]Bangladesh, India, Nepal, Pakistan, Sri Lanka.
[2]Includes all pulse crops.

Pigeonpea, cultivated on > 3.9 million ha worldwide (Government of India, 1990; FAO, 1992), is attacked by more than 200 species of insect, though relatively few cause serious yield losses (Lateef and Reed, 1992). The key pests belong to two guilds: pod boring insects (primarily *Helicoverpa armigera, Maruca testulalis* and *Melanagromyza obtusa),* and pod sucking insects *(Clavigralla* spp., *Riptortus* spp., *Anoplocnemis* spp. and *Nezara viridula* among others). In recent years, *H. armigera* has emerged as the dominant pest of pigeonpea, particularly in peninsular India. At ICRISAT's Asia Centre (IAC) near Hyderabad, pod damage by *H. armigera* to cultivar BDN-1 grown under unsprayed conditions ranged from 14 to 100% from 1981–92 (Crop Protection Division, unpublished data). Crop losses in pigeonpea due to *H. armigera* alone were recently estimated to be worth more than US$ 310 million annually (ICRISAT, 1992).

In contrast, chickpea is cultivated on a larger area, 10.7 million ha (FAO, 1992), but is attacked by relatively few insect pests (Reed et al., 1987). In West Asia the leaf miner, *Liriomyza cicerina* and pod borers, *Helicoverpa* spp., are the most important insect pests of chickpea while in south Asia, *H. armigera* is the dominant field pest. In India, pod damage caused by *H. armigera* ranges from 0 to 84% depending on location. Worldwide losses due to *Helicoverpa* spp. in chickpea have been estimated at nearly US$ 330 million annually (ICRISAT, 1992).

India is the largest producer of both pigeonpea and chickpea, though yields have remained low (Kelley and Parthasarathy Rao, 1993). The most important biotic constraint to increasing production of these two crops is *Helicoverpa armigera. Helicoverpa armigera* is also an important pest of cotton, tomatoes, chillies and several other crops. Its wide host range, migratory ability, high fecundity and multi-voltinism make it one of the most difficult insect pests in the world (Fitt, 1989; Pimbert et al., 1989).

One of the changing dimensions in pigeonpea and chickpea pest management in India is the shift from subsistence to commercial production. The substantial rise in the price of both crops (Kelley and Parthasarathy Rao, 1993) has provided farmers with the opportunity to consider pest management options which formerly would have been uneconomic. One option which farmers are increasingly choosing is the use of synthetic organic insecticides. As recently as 15 years ago, India-wide surveys revealed that <5% of pigeonpea farmers applied insecticides (Reed et al., 1981). The situation has changed significantly since then. Our results indicate a rapid and complete adoption of the use of insecticides to control pigeonpea pests, mainly *H. armigera,* in the village of Marepally, Andhra Pradesh (AP) (Fig. 1). This village is located in the core pigeonpea growing area of peninsular India and there is no reason to believe that the situation is unique to this village. Prior to 1975 less than 20% of farmers used insecticides on pigeonpea;



(From: Verma, 1990; Mathews, 1993)

Fig. 1. Adoption curve for pesticide use on pigeonpea by farmers in Marepally, Andhra Pradesh, India.

by 1993 there was complete adoption of this technology so that now, all farmers routinely use insecticides to control *H. armigera* on pigeonpea (Fig. 1).

The shift from subsistence to commercial production, and the concomitant adoption of chemical pest control technology in pigeonpea production systems, is reflective of the widespread and increasing use of insecticides in India. The amount of chemical pesticides used in India has risen exponentially in the last two decades (Fig. 2). Consumption of technical grade pesticide increased from approximately 2000 tons in 1950–51 to 86,000 tons in 1989–90. Approximately half of all pesticides used in India are applied to cotton (Verma, 1990; Reynolds and Armes, 1994), with *H. armigera* being the most important pest. There are two primary concerns with a pest control technology based predominantly on the use of chemical pesticides: the effect of these compounds on human health (e.g. Loevinsohn, 1987) and the degradation of ecosystems (e.g. loss of biodiversity); and second, the increasing amount of pesticides required to produce adequate levels of control due to the development of resistance in the pest insects (Armes et al., 1992).

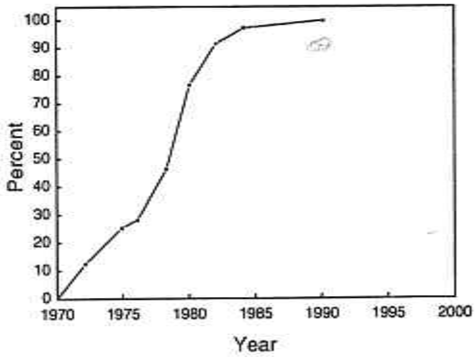


Fig. 2. Demand for pesticides in India.

Integrated Pest Management

Smith (1969) classified pest management practices into five phases based on the level of insecticide use. The phases, subsistence, exploitation, crisis, disaster and integrated control, describe a pattern of increasing reliance on insecticides, culminating in resistance, resurgence and the creation of secondary pests. This is the disaster phase in which pest control collapses. The development and implementation of integrated pest management procedures represents the fifth phase, and is viewed as the only workable solution to the pesticide induced problems. Pest control in developed countries has often followed this pattern (Metcalf, 1980; Perkins, 1982). Management of *H. armigera* in India appears to be entering the crisis stage, due in large part to mismanagement in cotton agroecosystems. The spillover effect will be to make management of *H. armigera* on pigeonpea and chickpea more difficult.

Many definitions of integrated pest management (IPM) are used but the basic concept is containment of a pest below economic thresholds, using a suitable combination of control strategies. Two fundamental premises are that individual pest control methods are often not successful and that pests need only be controlled when present at populations which cause economic damage (Teng, 1994). As first articulated by Stern et al. (1959), IPM relies on the use of natural enemies and a selective use of insecticides in a supervised programme. In this context, 'supervised' refers to an active programme of monitoring pest and natural enemy population dynamics. In the remainder of this paper we summarise control methods for *H. armigera* on pigeonpea and chickpea, highlight gaps in the knowledge base, present a model for integrating on-farm and on-station pest management research, and discuss preliminary results from a case study village. In the final section we briefly discuss how this model can be applied to IPM of *H. armigera* on chickpea.

Summary of *Helicoverpa armigera* Control Technologies

The search for effective methods to control *H. armigera* on pigeonpea and chickpea has been under way in national and international research centres for many years. Reed and Lateef (1990) and Pimbert (1990) have recently reviewed the pest management tools available to pigeonpea and chickpea farmers. Below we summarise the current status of host plant resistance, cultural or agronomic methods, biological control and chemical control, including the use of biorational insecticides for controlling *H. armigera* on pigeonpea and chickpea.

Host Plant Resistance

More than 13,000 pigeonpea germplasm accessions have been evaluated under pesticide-free conditions at ICRISAT. Because of the highly variable nature of *H.armigera* infestations, both within and across seasons, the development of a technique to compare the performance of germplasm under field conditions was a precondition to progress in this area. An open-field screening methodology was developed by Lateef and Reed (1981) and has now been adopted by the All India Co-ordinated Pulse Improvement Project for multilocation testing. Material is evaluated in groups with similar flowering and duration times, and rather than advance promising material, any entry more susceptible than standard checks, is rejected. In this way, an entry which escapes pest attack will not be inadvertently promoted. Over a period of several years only material showing consistently superior performance, relative to the checks, is advanced (Reed and Lateef, 1990).

A recent summary of 12 years data highlighted a number of pigeonpea genotypes with resistance to *H. armigera* (Table 2). In each of the three maturity groups presented, several genotypes have been identified which suffer less pod damage than standard checks. Seven medium duration lines which have consistently shown less pod damage compared to checks over a number of years are shown in Table 3. As this table indicates, in at least 7 of 9 years (>75%) pod damage was lower on the resistant lines than in either of the two standard checks. The resistant lines had 8–50% less pod damage, relative to the susceptible lines, though yields were not always higher. One resistant line,

Table 2. Mean resistance rating and percentage of pod borer damage of *Helicoverpa* resistant lines at Hisar and ICRISAT Centre, 1979–90 (ICRISAT, 1991)

Genotype	Mean resistance rating[1]	Range of borer damage (%)
Extra-short duration (IC and Hisar)		
ICPX 80324-E31	3.3 (3)[2]	13–28
ICPL 84052	3.8 (5)	4–36
ICPX 74146-E1-E2	4.0 (4)	17–38
ICPL 86015	4.0 (3)	6–38
ICP 12932-E3	4.0 (2)	25–40
ICPL 8318	4.3 (4)	10–38
ICPL 87112	4.3 (3)	9–40
ICPL 8315	4.4 (5)	9–47
Control		
Prabhat	6.0 (5)	14–50
UPAS 120	6.0 (3)	25–49
Short-duration (Hisar)		
ICPL 1	3.7 (7)	5–32
ICPL 2	3.9 (8)	6–45
ICPL 269	4.7 (6)	11–29
ICPL 187-1	3.7 (7)	8–29
Control		
Pant A1	6.0 (9)	14–58
Medium and medium-long duration (IC)		
ICP 909-E3	4.5 (11)	6–50
PPE 45-2	4.4 (11)	4–37
ICP 1811-E3	4.1 (11)	9–50
ICP 1903-E1	3.8 (11)	13–67
ICP 10466-E3	3.7 (11)	3–67
ICP 3615	3.6 (11)	14–50
ICP 5036	3.5 (11)	7–61
PPE 37-3	4.4 (9)	10–29
ICP 8094-2-S2	3.5 (11)	7–30
ICP 8102-5-S1	4.7 (11)	11–49
Control		
ICP 1691 (Susceptible)	7.5 (11)	11–100
BDN 1	6.0 (11)	16–90
C 11	6.0 (11)	18–76

[1] Relative resistance rating in comparison with controls scored on a scale of 1–9, where 1 = resistant, 9 = susceptible.

[2] Figures in parentheses indicate number of years tested.

Table 3. Pod damage caused by *Helicoverpa armigera* to medium duration pigeonpea genotypes under unsprayed conditions (1981–92) at ICRISAT Asia Centre

					Pod damage relative to			
					BDN-1		C-11	
Genotype	DF 50% (Mean)	Years	Yield (kg/ha) (Mean ± SE)	Pod damage % (Range)	Years[1]	Mean (%)[2]	Years	Mean (%)
ICP 10466-E3	117.0	8	576.2 ± 206.36	18.5–66.7	7/6	17.19	7/6	8.48
ICP 1811-E3	119.8	8	930.5 ± 290.29	8.7–58.7	8/8	36.22	6/6	34.44
ICP 1903-E1	120.6	11	833.4 ± 165.74	13.1–61.7	10/10	31.53	9/8	20.03
ICP 3615	141.7	10	799.4 ± 165.25	9.6–49.9	9/7	22.26	9/7	25.58
ICP 4070	122.0	5	641.2 ± 192.96	7.8–33.6	4/4	46.24	5/5	40.72
ICP 5036	131.6	7	477.1 ± 150.80	7.3–60.6	6/6	41.62	7/7	35.25
ICPL 84060	121.0	6	709.5 ± 266.44	5.8–56.7	6/6	51.25	4/4	44.38
Controls								
BDN-1	112.6	10	828.6 ± 237.21	13.5–100.0	NA	NA	8/4	-12.05
C-11	121.1	9	1143.9 ± 268.36	11.7–76.2	8/4	6.33	NA	NA

[1] Number of years tested/Number of years superior (i.e. less pod damage) to control.

[2] Mean superiority (%) relative to control.

ICP 1903-El (= ICP 332), outperformed the widely cultivated BDN-l every year for a decade in addition to recording higher, more stable yields. Two other medium duration lines (ICPL 87088 and ICPL 87089) have demonstrated *H. armigera* resistance and superior yield under both on-farm and on-station conditions (ICRISAT, unpublished data).

The development of consistent, albeit low, levels of resistance to *H. armigera* is a welcome achievement but there are other characteristics which must be considered as well. The resistant lines may be less preferred in terms of taste, seed colour or size, and may also be susceptible to *Fusarium* wilt and sterility mosaic diseases. This was demonstrated in a recent on-farm evaluation of four *H. armigera* resistant lines in Maharashtra. Each farmer grew two *H. armigera* resistant cultivars adjacent to their local cultivar and under similar management. At the end of the season they were asked to rank the cultivars for a number of characteristics in comparison with the local cultivar. The ICRISAT cultivars ranked superior to the local cultivar for yield, duration and pod damage, but the local cultivars ranked better for seed size, seed colour and market price (Table 4). Overall farmers preferred ICRISAT cultivars to the local cultivars in both sets.

Since 1976 ICRISAT has also screened more than 14,000 chickpea accessions and breeding lines. Several genotypes with exploitable levels of resistance to *H. armigera* have been identified (Table 5). The resistant genotypes have consistently suffered lower pod damage compared to the check cultivars, though the checks often produced higher yields. This was partly due to the relatively small seed size of several of the resistant lines. In addition, most of the *H. armigera* resistant lines were susceptible to diseases, particularly, to *Fusarium* wilt and *Ascochyta* blight. The incidence of disease in chickpea growing areas appears to have increased in recent years (Lateef and Sachan, 1990) and efforts have been made to incorporate multiple disease resistance into high yielding, *H. armigera* resistant material, thus ensuring yield stability.

Table 4. Matrix ranking of ICRISAT and local pigeonpea lines by farmers in Umari, Maharashtra

	Set I			Set II		
Characteristic	ICPL 332	ICPL 84060	Local	ICPL 87088	ICPL 87089	Local
Yield	2	1	3	1	2	3
Duration	2	1	3	1	1	2
Pod damage	1	1	2	1	1	2
Wilt	0	0	1	2	1	1
Seed colour	2	2	1	2	2	1
Seed size	2	2	1	2	2	1
Market price	2	2	1	2	2	1
Plant height	1	3	2	2	2	1
Pod bearing	1	1	2	1	2	3
Branching	2	2	1	-	-	-
Overall rank	2	1	3	1	2	3

Table 5. Mean relative resistance rating and percentage pod borer damage of chickpea genotypes resistant to *Helicoverpa armigera* (Hübner) under pesticide-free conditions at ICRISAT Asia Centre, 1979–89 (Pimbert, 1990)

Genotype	Mean resistance rating[1]	Range of borer damage (%)
Desi short-duration group		
ICC 506	3.0 (9)[2]	1.1–12.8
ICC 100667	3.1 (9)	1.7–14.2
ICC 10619	3.4 (9)	2.7–21.0
ICC 6663	3.5 (10)	1.1–31.8
ICC 10817	3.6 (10)	2.4–30.0
ICCV 7 (ICCX 730008-8)	3.8 (8)	3.8–11.8
Controls		
Annigeri	6.0 (10)	3.8–11.8
ICCX 730266 (susceptible)	7.1 (9)	14.9–33.0
Desi medium-duration group		
ICC 4935-E2793	2.8 (10)	2.3–11.9
ICCX 730041-8-1-B-BP-EB	3.8 (10)	1.7–38.2
ICCX 730094-18-2-IP-BP-EB	4.6 (10)	3.8–20.0
Controls		
K 850	6.0 (10)	11.4–40.9
ICC 3137 (susceptible)	8.5 (10)	13.5–65.5
Desi long-duration		
ICCX 730020-11-1-1H-B-EB	4.3 (10)	2.8–26.9
Control		
H 208	6.0 (10)	3.8–44.3
Kabuli medium-/long-duration		
ICC 10870	4.3 (9)	4.4–39.3
ICC 5264-E10	3.8 (10)	2.5–28.3
ICC 8835	5.4 (8)	11.6–26.7
Control		
L 550	6.0 (10)	2.8–39.4

[1] Relative resistance rating in comparison with controls scored on a scale of 1–9, where 1 = resistant, 9 = susceptible.

[2] Figures in parentheses indicate number of years tested.

Several lines which combine wilt and *H. armigera* resistance are currently being screened at IAC. One line (ICCV 93122) which combines the *H. armigera* resistance of ICC 506 and the wilt resistance and larger seed of Annigeri (a popular local cultivar) is also being screened in multi-locational trials in south India.

Cultural/Agronomic Control

Pigeonpea is often grown as part of an intercropping system, with cereals, cotton or other legumes, and is ideally suited to these cropping systems as it is slow growing and doesn't compete with the companion crop (Ali, 1990). The companion crop is usually harvested before the reproductive phase of pigeonpea. Thus, during the flowering/podding stage, when it is most attractive to *H. armigera*, pigeonpea is functionally a monocrop. This may be one reason why there is seldom any reduction in pest incidence or damage in intercropped pigeonpea relative to sole cropped pigeonpea (Bhatnagar and Davies, 1981; King, 1988).

The only other agronomic manipulation which has been systematically studied for its effect on *H. armigera* population dynamics in pigeonpea, is sowing time. Avoiding periods of high pest attack by manipulating sowing dates and/or selecting cultivars with appropriate flowering/maturity times has often been suggested as a potential control strategy. In northern India, *H. armigera* populations are lower in the winter and crops which mature early will avoid heavy damage (Yadava et al., 1983; 1988). In South India, host evasion is less effective as *H. armigera* remains active throughout the year.

Chickpea is grown as a monocrop or in mixed cropping systems where it is intercropped or mixed with wheat, linseed, mustard or safflower. Both *H. armigera* populations and pod damage are lower in intercropped chickpea compared to sole crops (Yadav, 1987; Mehto et al., 1988). The mechanisms responsible for these differences have not been extensively studied. There is some evidence that intercropping chickpea and coriander may result in increased rates of *H. armigera* larval parasitism (Pimbert and Srivastava, 1989). This has not been observed for other chickpea intercrop combinations, and in these systems larval mortality during dispersal from intercrop plants may be important.

Other cultural control methods which have been studied for chickpea include manipulation of sowing date, plant density and sowing genetic mixtures. Studies of the effect of sowing date on *H. armigera* population dynamics and pod damage have shown that early sowing of chickpea in North India can be an effective method for minimising *H. armigera* attack (Chhabra et al., 1978). Consequently, the second fortnight of October is the recommended sowing time for chickpea in the North East Plains Zone and Central Zone of India (DPR, 1990). In southern India the typically higher and more prolonged *H. armigera* population pressure limits the usefulness of manipulation of sowing date as a management option.

Results of studies on the effect of manipulation of chickpea density on *H. armigera* population dynamics and yield are equivocal. In general, *H. armigera* populations are higher in plots of closely planted chickpea than in plots of more widely spaced plants (Bhatnagar et al., 1982). Yield is frequently reduced because of inter-plant competition in the plots with more closely spaced plants and overall there appears to be little yield advantage when plant densities are greater than 8 plants/m^2 (ICRISAT, unpubl.).

Studies of mixtures of *H. armigera* resistant and susceptible chickpea genotypes have shown intermediate levels of damage between pure stands of the susceptible genotype (Annigeri) and resistant genotypes, when resistant and susceptible genotypes were sown in the ratio 3:1 and 1:1. However, there was no significant increase in the yield of mixed plots (ICRISAT, unpubl.) because of the small seed size of the resistant genotypes.

Biological Control

A large number of natural enemies have been recorded from *H. armigera* on pigeonpea. More than 70 parasitoids and 30 predators have been recorded as natural enemies of *H. armigera* (Manjunath et al., 1989). *Helicoverpa armigera* populations on pigeonpea suffer less natural enemy induced mortality than populations on alternative crops such as sorghum (Bhatnagar et al., 1983). The reasons for this are unknown and this knowledge gap makes it difficult to devise strategies to enhance natural control in pigeonpea cropping systems.

With short-duration pigeonpea it may be possible to alter the cropping system to make it more attractive to *H. armigera*'s natural enemies. An intensive study of the effect of intercropped sorghum and short duration pigeonpea on the impact of natural enemies of *H. armigera* indicated that there may be scope to improve natural control in this system by careful selection of crop cultivars (Duffield, 1994). Of particular importance is the sequence of flowering times for the two crops (Duffield, 1994).

Chickpea is similar to pigeonpea in supporting lower *H. armigera* natural enemy loads than alternative crops. In South India the major natural enemies of *H. armigera* larvae include predatory birds and several dipteran and hymenopteran parasites. Of these, the ichneumonid, *Campoletis chloridae* has been recorded as the dominant species (Pawar et al., 1986). There are very limited data on the impact of the various natural enemies on *H. armigera* populations on chickpea. Several studies have attempted to enhance the natural control processes on chickpea by diversifying the cropping system through the inclusion of flowering intercrops and by the provision of bird perches or alteration of sowing patterns to enhance bird predation. There is no consensus as to the effectiveness of these methods.

Chemical Control

Current recommendations for chemical control of *H. armigera* on pigeonpea and chickpea have recently been summarised by Sachan (1992). A number of synthetic organic pesticides, including synthetic pyrethroids, are recommended. Recently, high levels of resistance to organophosphate and synthetic pyrethroid insecticides have been reported in *H. armigera* (Armes et al., 1992). This has resulted in control failures and an impression among farmers that insecticides are not working (Reynolds and Armes, 1994).

Economic thresholds have not been developed for *H. armigera* on pigeonpea and calendar sprays, beginning at 50% flowering, are recommended and practised. This is a critical gap which limits the development of IPM in pigeonpea. An understanding of the relationships between pest density and damage or yield loss would be a useful first step. Thresholds for *H. armigera* are available for chickpea. Studies have identified densities of more than two larvae per plant during the flowering and early podding stage as the economic injury level (Reed et al., 1987). This threshold may not be appropriate in farmers' fields where plant spacings are often not uniform. Surveys of chickpea plant densities have shown that plant stand in most farmers' fields is less than half of the recommended density (Reed, pers. commun.). In this situation thresholds based on the number of larvae per square meter may be more accurate. Results of on-station experiments designed to examine the economics of insecticide application to chickpea have shown that if insecticides are applied when the threshold of two larvae per plant is exceeded, yields can be increased from 0.7 to 2.4 t/ha (Wightman et al., 1994).

Another area of research which is receiving increasing attention is the use of 'biorational' insecticides to control *H. armigera*. Biorational insecticides include plant-derived products such as neem and insect pathogens such as the *Helicoverpa* nuclear polyhedrosis virus (NPV) and *Bacillus thuringiensis (Bt)* based products. These are generally considered to be softer on the environment, have less impact on beneficial organisms and are safer for humans. Neem products have traditionally been used by Indian farmers to protect grain from storage and field pests (Ahmed and Koppel, 1987). Commercially formulated products are currently available, though studies of their efficacy on pigeonpea and chickpea have not produced consistent results (Srivastava et al., 1984; Singh et al., 1985; Sinha and Mahrotra, 1988; Sehgal and Ujagir, 1990; Sachan and Lal, 1993). Further work is required to establish appropriate application rates and procedures. Future research should also include the potential use of other botanical insecticides such as those derived from *Ipomea fistulosa* (Gupta and Patel, 1992), *Jatropha curcas* (Solsoloy and Morallo-Rejesus, 1992) and custard apple seed, *Annona squamosa* (Anon, 1948; and references in Grainge and Ahmed, 1988). Farmers' 'home remedies' often include one or more plant-derived compounds and could be the starting point for this potentially profitable area of research.

The use of NPV to control *H. armigera* has received much attention, and appears to be a viable control option for chickpea; results for pigeonpea are more equivocal (Santharam et al., 1981; Sanap and Deshmukh, 1988; Venugopal Rao et al., 1992). On chickpea, the control provided by the virus can be as effective as or better than that provided by conventional synthetic insecticides (Rabindra and Jayaraj, 1988; Cowgill, unpubl.). The commercially available formulations of NPV in India are of variable quality; stated concentrations are often inaccurate and the products are frequently contaminated with protozoan parasites (Grzywacz, pers. commun.). Stricter quality control standards are needed to prevent the loss of farmers' confidence in NPV.

Currently there is little published data referring to the effectiveness of *Bt* products against *H. armigera* on pigeonpea and chickpea in the field. A combination of further on-farm testing of available formulations, and research station development and evaluation of new adjuvants and product formulations is required before the potential contribution of these biorational products can be assessed.

A Framework for Pest Management Research

An approach for implementing an integrated pest management research programme is presented in Fig. 3. A key feature of this framework is the simultaneous use of on-station and on-farm research to test and verify management components and strategies. The framework evolved as a result of field research activities at a specific location (described in more detail below) for *H. armigera* on pigeonpea but has more general applicability. Collaboration between researchers, extension agents, farmers and nongovernmental organisations (NGOs) in developing and testing IPM components and strategies is considered essential. Without the full cooperation of all four groups, development, implementation and adoption of an effective and environmentally sound programme is unlikely.

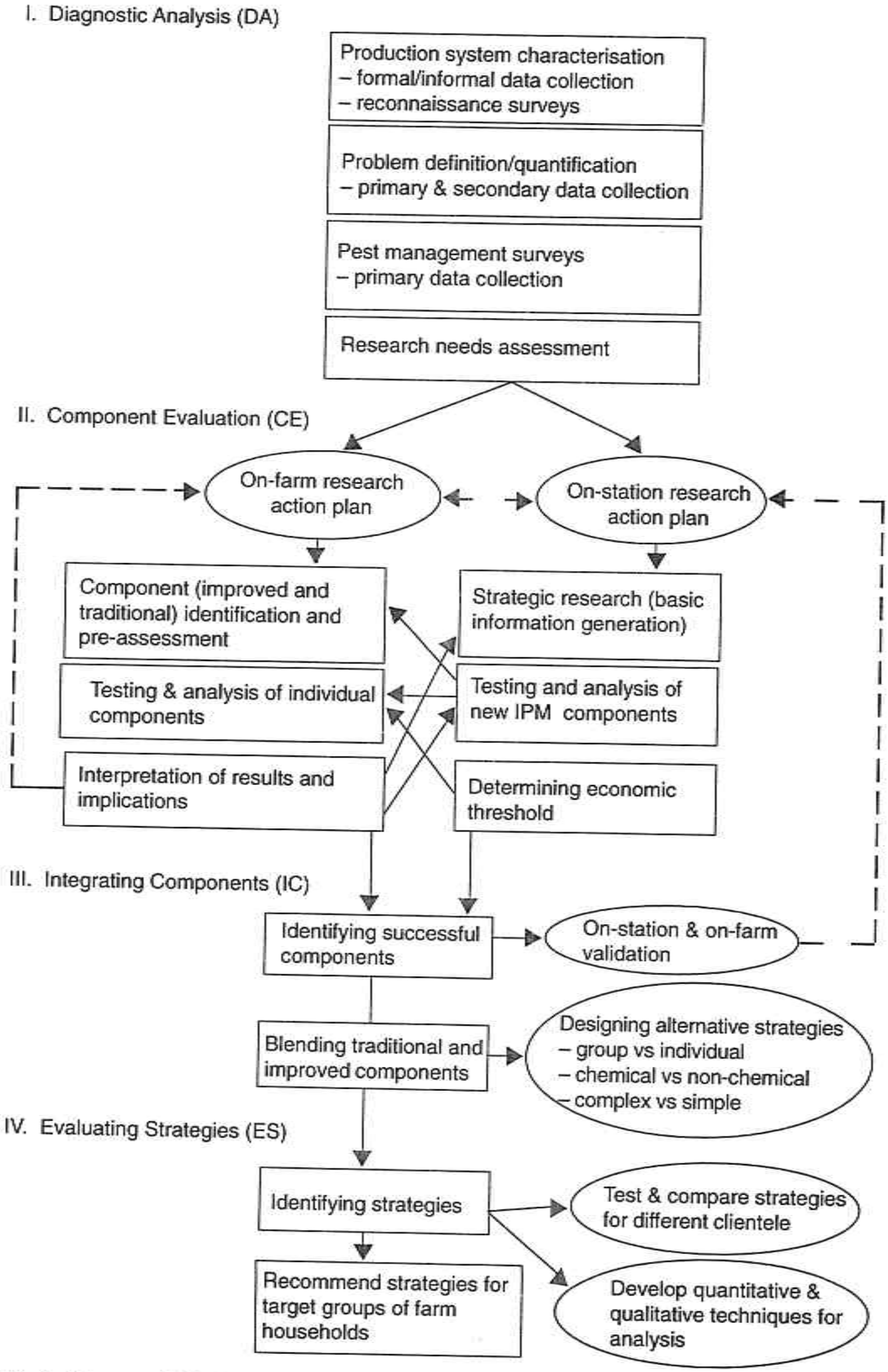


Fig. 3. A framework for incorporating on-farm and on-station pest management research.

The framework consists of four main steps, which appear chronologically separate, but which in practice may overlap considerably. In the first step, diagnostic analysis, the production system is characterised, production constraints identified and quantified, and the research needs prioritised. Both formal and informal data collection techniques may be used. This includes group interviews using participatory rural appraisal (PRA) techniques and reconnaissance surveys. Production system data are collected from secondary sources such as Department of Agriculture/Revenue offices. Pest management surveys to quantify pest occurrence, pest damage and associated yield losses are also needed. These data are then used to prioritise constraints to production and the research needs to overcome these constraints.

Information gathered in the first step is used to frame the activities in the second step: developing action plans for on-station and on-farm research. A large body of information covering basic and applied aspects of *H. armigera* management has already been generated. In the first part of this paper we briefly summarised work relevant to pigeonpea and chickpea. Unfortunately, little research or even testing/evaluation of control strategies has been carried out on-farm. Therefore, it is most useful if on-station and on-farm research are undertaken in tandem, with the same researchers/collaborators involved in both. Lessons learned in on-farm activities will lead to subsequent modification of the on-station action plans and the converse will also occur. Another important feature of this framework is the recognition of the bi-directional flow of information between both on-station and on-farm researchers, and also between farmers, extension agents, NGOs and research scientists. On-station research focuses on generating basic information and new pest management components, while the emphasis in on-farm research is to evaluate traditional and improved management components under realistic conditions.

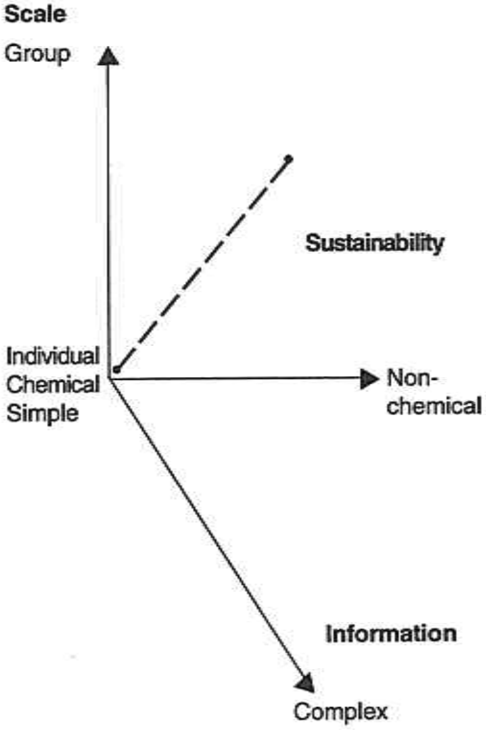


Fig. 4. Three important attributes of a pest management programme.

In the third phase of the framework, components which were identified as effective and environmentally sound are integrated and evaluated for compatibility. This involves both on-station and on-farm validation trials, results of which may modify activities in the component evaluation stage. Both traditional and improved components are utilised to produce a more comprehensive and hopefully more effective, management strategy. We are particularly interested in comparing combinations of strategies which form a three dimensional continuum (Fig. 4). The three dimensions are scale, sustainability and information. The 'scale' axis refers to the unit-area on which a *H. armigera* pest management programme must operate to be successful: individual fields, farms, farm clusters, villages or some larger political unit. The 'sustainability' axis reflects the degree to which farmers rely on synthetic organic pesticides to control *H. armigera*. Currently, pigeonpea farmers depend almost entirely on synthetic pesticides for managing *H. armigera*. The third axis, 'information', concerns the level of farmers' knowledge, and includes pest and natural enemy identification and ecology, pest incidence/damage/yield loss relationships, alternative control technologies, proper pesticide application techniques, etc. At present, *H. armigera* pest management practices in pigeonpea are carried out by individual farmers, relying primarily on synthetic organic pesticides, with a low level of pest management relevant information. Our hypothesis is that a more sustainable approach to *H. armigera* management will involve community-wide participation, will replace sole reliance on synthetic pesticides with a more effective yet environmentally friendly blend of components, and will require that farmers have and use more complex sets of information.

The fourth stage involves large-scale testing and implementation of a pest management strategy in the target area. This is essentially an on-farm, pilot project-type activity and includes the development and use of analytical techniques to quantitatively and qualitatively assess the overall effectiveness of the strategy. The pest management strategy must be evaluated for its economic performance, social acceptability and environmental impact. We have not yet reached the stage of evaluating strategies, the fifth step, for *H. armigera* management on pigeonpea.

Marepally: Case Study

As noted above, this pest management research framework developed out of ICRISAT's on-farm pigeonpea pest management activities in Marepally, Andhra Pradesh. Highlights of these activities are presented below as a case study of the proposed framework. The first step was the identification of major pigeonpea production systems in India and selection of one for more comprehensive analysis. The system selected is the core pigeonpea production zone of peninsular India, which includes portions of northern Karnataka, southern Maharashtra and western Andhra Pradesh. Medium duration pigeonpea is grown both as a sole crop and as an intercrop with cereals and short season legumes such as blackgram and greengram. Discussions with state and district agricultural extension officers and early reconnaissance surveys in the region revealed that *H. armigera* was a major yield reducer in this production zone. The village which was selected, Marepally, is located on the western edge of Andhra Pradesh, near to the Karnataka border. It is about 90 km west of IAC and is on the eastern edge of this major pigeonpea production system.

A stratified random sample of 35 farmers in Marepally village were selected to participate in on-farm, component trials in 1993–94. These trials were simple comparisons between *H. armigera* tolerant varieties, a high-yielding but susceptible variety and farmers' current variety (ICPL 8863) under farmers' present management practices. Plots were monitored twice weekly throughout the season for *H. armigera* eggs and larvae, and pest management practices.

Farm household pest management surveys were also conducted. This is an example of the chronologically overlapping of activities between the stages in the framework (a diagnostic activity during the component testing phase). The objectives of the survey were to gain a better understanding of the pest problems in pigeonpea and how farmers' manage them, and to assess deficiencies in farmers' awareness and perception of the pest problem and in their method of control.

Simultaneously, an experiment at the Tandur Agricultural Research Station, located 12 km from Marepally village, was conducted in collaboration with the Entomology Department of Andhra Pradesh Agricultural University to examine the effect of different pesticide treatments on three cultivars of pigeonpea. The purpose of the trial was to compare pest incidence, pest damage and yields under protected and unsprayed treatments using the same cultivars as used in Marepally. The timing of pesticide applications was based on recommendations from a simulation model (Holt et al., 1991) which predicted that 3 sprays at 7, 10 and 14 days after flowering would provide optimal control of *H. armigera*. Weekly pest counts were made and converted to cumulative egg- and larval-days. Yields and pod damage were regressed against cumulative pest loads.

Highlights of the Results From 1993/94

Results of the household surveys conducted in 1993 and 1994 are currently being summarised in preparation for publication. The surveys confirmed that farmers consider pigeonpea the most important crop in the area. It is grown almost entirely as an intercrop, primarily with blackgram *(Vigna radiata),* and in rotation with post-rainy season sorghum. The survey also confirmed that *H. armigera* is the most important constraint. Most farmers believe that *H. armigera* has increased in severity in the past 10 years and attribute this to excessive use of chemicals, climate changes and adulterated chemicals in the market. Of particular interest and concern was the finding that less than 20% of farmers get information on pesticide related topics from extension officers. Most households rely on information from friends and/or other household members. In fact, pesticide retailers are a more frequently cited source of information than extension or Department of Agriculture officials. Also, as earlier indicated, in a span of only 18 years, use of pesticides on pigeonpea has increased from 0 to 100% of farmers. One difficulty mentioned by almost all farmers, was obtaining water for mixing pesticide solutions. This may lead to incorrect application rates. No farmer has used LV or ULV type application equipment.

Egg and larval populations of *H. armigera* were monitored twice weekly in each of the 35 participating farmers' fields. *Helicoverpa armigera* prefers to lay its eggs on reproductive structures in pigeonpea, beginning with flower buds. Eggs are also laid on open flowers and pods, and larvae of all ages feed on flowers and pods. Ten terminal branches were sampled in each cultivar in each field. Analysis of these data is not yet complete. At harvest, all pods from five plants were collected and assessed for pod damage caused by *H. armigera* and podfly, an agromyzid and the second most important pest of pigeonpea. The pod damage assessment data from six farmers, two cultivating each improved genotype, are shown in Table 6. Pod damage and per plant yield were compared to the adjacent local cultivar. Pod damage was relatively low this year (< 30%) with *H. armigera* accounting for the major share in all of the cultivars. These farmers sprayed between 5 and

Table 6. Pod damage on pigeonpea cultivars grown in six farmers' fields in Marepally village, AP (1993/94)

Name	Genotype	Pods/ plant	Pod damage (%)			Yield (g)/plant
			Borer	Podfly	Total	
Ashok V. Reddy	ICPL 87119	189.4	6.8	0.0	6.8	57.0
	Local	119.4	14.0	1.8	15.8	35.0
Saianna	ICPL 87119	391.2	22.2	1.7	23.9	82.8
	Local	303.0	23.6	2.0	25.6	69.2
Ismail	ICPL 84060	324.4	22.6	0.7	23.3	64.2
	Local	197.4	30.4	0.1	30.5	51.0
Hanpa Naik	ICPL 84060	132.4	26.1	0.1	26.2	28.0
	Local	84.0	20.5	1.0	21.5	19.6
Ramanna/Muthyalu	ICPL 87089	235.2	21.5	0.5	22.0	50.0
	Local	260.8	22.6	0.2	22.8	71.6
Balwant Reddy	ICPL 87089	178.0	27.7	0.7	28.4	33.4
	Local	80.4	30.2	0.2	30.4	19.4
	Overall mean	207.9	22.3	0.8	23.1	48.4
	SE ±	44.52	4.64	0.45	4.66	10.69
	CV(%)	55.1	52.2	102.6	50.3	56.3

Table 7. Cumulative larval-days, pod damage and yield of four pigeonpea cultivars grown under sprayed and unsprayed conditions at the Tandur Agricultural Research Station, Tandur, Andhra Pradesh, 1993/94

Genotypes	Cumulative Larval-days	*H. armigera* Pod damage (%)	Yield kg/ha
Sprayed			
ICPL 84060	9.6	20.3	3595.6
ICPL 87119	14.4	35.7	4349.6
ICP 8863	13.5	45.0	3463.0
Local (White)	21.4	34.7	4571.9
Unsprayed			
ICPL 84060	13.7	36.2	3537.0
ICPL 87119	23.2	34.1	4017.8
ICP 8863	20.4	50.1	2986.7
Local (White)	29.1	53.0	4285.2
Trial mean	18.1	38.6	3850.8
SEM	2.43	4.02	413.1
CV(%)	20.3	14.0	17.6

7 times, and in general, the improved lines had lower damage and higher yields than local cultivars sprayed an equivalent number of times (Table 6).

Insecticide-treated plots at the Tandur Research Station trial had fewer *H. armigera* larvae than control plots of the same cultivar. All four cultivars had higher yields and equal or lower pod damage when protected with insecticides (Table 7). The regressions of cumulative egg- and larval-days on pod damage and yields were not significant for any of the cultivars but did indicate a trend of greater damage and lower yields at higher pest densities. The currently utilised cultivar in Marepally, ICP 8863, was the lowest yielding and suffered the greatest pod damage under both sprayed and unsprayed conditions (Table 7). This indicates potential for newly developed, higher yielding cultivars.

Activities in 1994/95

The on-farm and on-station action plans for 1994/95 include activities in both component evaluation and component integration stages of the framework. The on-farm activities include evaluation of three components: cultivars, improved pesticide application and biorational insecticides. The design of the on-farm experiments also includes combinations of cultivars and pesticides or biorationals. The trials will also provide preliminary information on the role of two factors, sustainability and information, in the previously discussed three dimensional continuum. The third factor, scale, was to have been investigated by organising an entire village to adopt a community-wide pest management approach. By comparing results in this village to farmers in Marepally, who manage *H. armigera* on individual fields, it was hoped that some insight into the question of scale would be gained. This 'group action' village was to have been organised by our NGO partner, but due to several reasons this was not possible.

The action plan for on-station research includes three investigations: evaluation of several bio-rational insecticides including neem and custard apple *(Annona squamosa)* seed extract formulations, *Bt*-based products and NPV; a study of *H. armigera* density/damage/yield relationships; and an investigation into the searching behaviour of a key *H. armigera* natural enemy. In addition to these activities at IAC, collaborators at the Tandur Research Station are testing advanced *H. armigera* and wilt/sterility mosaic resistant pigeonpea lines.

Application of the Framework to Chickpea Pest Management Research

This framework was developed in conjunction with pigeonpea pest management research, but to be of value the framework must be generally applicable. As an example, we discuss how current and planned chickpea pest management research could utilise this framework. Chickpea cropping systems are comparatively simple, minimising some of the diagnostic stage work. An analysis of the target chickpea cropping systems would assist in prioritising research needs.

Several promising pest management components for chickpea have been identified in earlier on-station trials (see above). This work is analogous to the component evaluation stage of the model and the next step is to verify these findings in on-farm trials. The action plan for on-farm research will focus on comparing a wilt and *Helicoverpa* resistant genotype with local chickpea cultivars under farmer management.

This work, in collaboration with a local NGO, has already begun. Two genotypes, one with combined wilt and *Helicoverpa* resistance (ICCV 93122) and one with disease and drought resistance (ICC 4958), have been supplied to a group of farmers in Pastapur village, 100 km northwest of IAC. The improved cultivars are being grown adjacent to the local cultivar and under similar management practices. Farmers will evaluate the material for pod damage and yield, as well as compare the relative acceptability of the improved genotypes.

Concurrently, on-station trials will be conducted to study the efficacy and compatibility of combinations of individual components, the third stage in the model. Several biorational insecticides will be evaluated in combination with resistant genotypes. *Helicoverpa* NPV has been shown to be effective in controlling *H. armigera* on chickpea. This season, four genotypes with various combinations of wilt and *Helicoverpa* resistance will be treated with NPV, on a calendar basis, beginning at flowering. The effectiveness of a commercially available *Bt* product will also be compared with that of *Helicoverpa* NPV.

Conclusion

Helicoverpa armigera is the most important biotic constraint to increasing production of pigeonpea and chickpea in India. Farmers recognise this and have attempted to manage the problem, largely through the use of synthetic organic insecticides. A pest management strategy which primarily relies on insecticides is not sustainable. Though substantial research has been devoted to the management of *H. armigera* on these two crops, little progress is evident in farmers' fields. The framework proposed here integrates on-farm and on-station pest management research and recognises the important contributions to be made by extension staff, nongovernmental organisations and farmers. This methodology helps to establish research priorities and ensures that components and strategies are not only effective in farmers' fields but are sustainable, environmentally sound and socially acceptable.

References

Ahmed S. and Koppel B. (1987) Use of neem and other botanical materials for pest control by farmers in India, pp. 623–626. In *Natural Pesticides from the Neem Tree and Other Botanical Plants* (Edited by H. Schmutterer and K. R. S. Ascher). Deutsche Gesellschaft fur Technische Zusammenarbeit.

Ali M. (1990) Pigeonpea: Cropping systems, pp. 279–302. In *The Pigeonpea* (Edited by Y. L. Nene, S. D. Hall and S. K. Sheila). CAB International, Wallingford, UK.

Anonymous (1948) Raw materials, pp. 80–81. In *The Wealth of India* (Volume 1). Council of Scientific and Industrial Research, Delhi, India.

Armes N. J., Jadhav D. R., Bond G. S. and King A. B. S. (1992) Insecticide resistance in *Helicoverpa armigera* in South India. *Pesticide Sci.* 34, 355–364.

Bhatnagar V. S. and Davies J. C. (1981) Pest management in intercrop subsistence farming, pp. 249–257. In *Proceedings of the International Workshop on Intercropping.* ICRISAT Patancheru, AP, India.

Bhatnagar V. S., Lateef S. S., Sithanantham S., Pawar C. S. and Reed W. (1982) Research on *Heliothis* at ICRISAT, pp. 385–396. In *Proceedings of International Workshop on* Heliothis *Management.* (Edited by W. Reed). ICRISAT, Patancheru, India.

Bhatnagar V. S., Pawar C. S., Jadhav D. R., Rao V. K. and Reed W. (1983) Conservation and augmentation of natural enemies with reference to IPM in chickpea and pigeonpea, pp. 157–180. In *Proceedings of the International Workshop on Integrated Pest Control in Grain Legumes* (Edited by P. C. Matteson). ICRISAT, Patancheru, AP 502324, India.

Chhabra K. S., Kooner B. S., Dhingra K. K. and Tripathi H. P. (1978) Preliminary studies on the influence of sowing dates on the incidence of gram pod borer, *Heliothis armigera.* In *Proceedings of All India Rabi Pulses Workshop,* 3–6 October 1978, Bhubaneswar, India.

DPR (Directorate of Pulses Research) (1990) *Helicoverpa Management: Current Status and Future Strategies, Proceedings of first national workshop* (Edited by J. N. Sachan). Directorate of Pulses Research, Kanpur, India.

Duffield S. (1994) The role of natural enemies in sorghum: Short-duration pigeonpea intercrops. Cereals Entomology Progress Report 93/1. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, AP, India (limited distribution).

FAO (Food and Agriculture Organisation) (1992) *Production Yearbook 1991.* 45, 98–106.

Fitt G. P. (1989) The ecology of *Heliothis* spp. in relation to agroecosystems. *Annu. Rev. Entomol.* 34, 17–52.

Government of India (1990) Area and production of principal crops. Directorate of Economics and Statistics, Ministry of Agriculture, New Delhi, India.

Grainge M. and Ahmed S. (1988) *Handbook of Plants with Pest Control Properties.* John Wiley & Sons, New York.

Gupta A. K. and Patel K. K. (1992) Survey of farmers' innovations in Gujarat: Part III. *Honey Bee* 3, 17. (Quarterly newsletter, available from A. K. Gupta, Indian Institute of Management, Ahmedabad, India).

Holt J., King A. B. S. and Armes N. J. (1991) Use of simulation analysis to assess *Helicoverpa armigera* control on pigeonpea in southern India. *Crop Protection* 9, 197–206.

ICRISAT (International Crops Research

Institute for the Semi-Arid Tropics) (1991) *Legumes Program Annual Report for 1990.* Patancheru, AP, India.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) (1992) *The Medium Term Plan.* Patancheru, AP, India.

Kelley T. G. and Parthasarathy Rao P. (1993) Chickpea: A preferred pulse? *International Chickpea Newsl.* 28, 6–7.

King A. B. S. (1988) An Overview of Cropping Systems Entomology Trials, 1975–1982. ICRISAT unpublished report (limited distribution).

Lateef S. S. and Reed W. (1981) Development of a methodology for open-field screening for insect pest resistance in pigeonpea, pp. 315–322. In *Proceedings of the International Workshop on Pigeonpeas,* Volume 2. ICRISAT, Patancheru, AP, India.

Lateef S. S. and Reed W. (1992) Insect pests of pigeonpea, pp. 193–242. In *Insect Pests of Tropical Food Legumes* (Edited by S. R. Singh). John Wiley and Sons, New York.

Lateef S. S. and Sachan J. N. (1990) Host-plant resistance to *Helicoverpa armigera* in different agroecological contexts. In *Chickpea in the Nineties: Proceedings of the Second International Workshop on Chickpea Improvement.* ICRISAT, Patancheru, India.

Loevinsohn M. E. (1987) Insecticide use and increased mortality in rural central Luzon, Philippines. *The Lancet.* 13 June, 1359–1362.

Manjunath T. M., Bhatnagar V. S., Pawar C. S. and Sithanantham S. (1989) Economic importance of *Heliothis* spp. in India and an assessment of their natural enemies and host plants, pp. 197–228. In *Proceedings of the Workshop on Biological Control of* Heliothis: *Increasing the Effectiveness of Natural Enemies* (Edited by E. G. King and R. D. Jackson). Far East Regional Office, OICD, USDA, Chanakya Puri, New Delhi, India.

Mehto D. N., Singh K. M. and Singh R. N. (1988) Influence of intercropping on succession and population build-up of insect pests in chickpea, *Cicer arietinum. Indian J. Entomol.* 50, 257–275.

Metcalf R. L. (1980) Changing role of insecticides in crop protection. *Annu. Rev. Entomol.* 25, 219–256.

Pawar C. S., Bhatnagar V. S. and Jadhav D. R. (1986) Host plants and natural enemies of *Heliothis* spp. in India: A compendium. Progress Report 13, Cropping Entomology, ICRISAT.

Perkins J. H. (1982) *Insects, Experts and the Insecticide Crisis.* Plenum Press, New York.

Pimbert M. P. (1990) Some future research directions for integrated pest management in chickpea: A viewpoint. In *Chickpea in the Nineties: Proceedings of the Second International Workshop on Chickpea Improvement.* ICRISAT, Patancheru, India.

Pimbert M. P., Lateef S. S., Sehgal V. K. and Wightman J. A. (1989) *Helicoverpa armigera:* "The worst pest problem in the semi-arid tropics?", pp. 219–233. In *Integrated Pest Management in Tropical and Subtropical Cropping Systems, Proceedings* (Volume 1). Deutsche Gesellschaft für Technische Zusammenarbeit.

Pimbert M. P. and Srivastava C. P. (1989) Vegetation management and the biological control of *Helicoverpa armigera* in chickpea. *International Chickpea Newsletter* 21, 16–19.

Rabindra R. J. and Jayaraj S. (1988) Efficacy of nuclear polyhedrosis virus with adjuvants as high volume and ultra low volume applications against *Heliothis armigera* Hbn. on chickpea. *Trop. Pest Manage.* 34, 441–444.

Reed W., Lateef S. S. and Sithanantham S. (1981) Constraints to effective pest management in pigeonpea, pp. 67–71. In *Conference on Future Trends of Integrated Pest Management.* International Organization for Biological Control, Special Issue.

Reed W., Cardona C., Sithanantham S. and Lateef S. S. (1987) The chickpea insect pests and their control, pp. 283–318. In *The Chickpea* (Edited by M. C. Saxena and K. B. Singh). CAB International, Wallingford, UK.

Reed W. and Lateef S. S. (1990) Pigeonpea: Pest management, pp. 349–374. In *The Pigeonpea* (Edited by Y. L. Nene, S. D. Hall and V. K. Sheila). CAB International, Wallingford, UK.

Reynolds D. and Armes N. J. (1994) When insecticides fail: The case of the cotton bollworm in India, pp. 39–42. *World Agriculture 1994* (Edited by A. Cartwright). Sterling Publications, London.

Sachan J. N. (1992) Present status of *Helicoverpa armigera* in pulses and strategies for its management, pp. 7–23. In Helicoverpa *Management: Current Status and Future Strategies, Proceedings of First National Workshop* (Edited by J. N. Sachan). Directorate of Pulses Research, Kanpur, India.

Sachan J. N. and Lal S. S. (1993) Role of botanical insecticides in *Helicoverpa armigera* management in pulses. In *Botanical Pesticides in Integrated Pest Management: Proceedings of National Symposium* (Edited by M. S. Chari and G. Ramaprasad). Central Tobacco Research Institute, Rajamundry, India.

Sanap M. M. and Deshmukh R. B. (1988) Efficacy of nuclear polyhedrosis virus against *Heliothis armigera* (Hubner) infesting pigeonpea. *Indian J. Pulses Res.* 1, 80–82.

Santharam G., Balasubramanian M. and Chelliah S. (1981) Control of *Heliothis armigera* (Hubner) on redgram *(Cajanus cajan* L.) with a nuclear polyhedrosis virus and insecticides. *Madras Agric. J.* 68, 417–420.

Sehgal V. K. and Ujagir R. (1990) Effect of synthetic pyrethroids, neem extracts and other insecticides for the control of pod damage by *Helicoverpa armigera* on chickpea and pod damage relationships at Pantnagar in northern India. *Crop Protection* 9, 29–32.

Sinha S. and Mahrotra K. N. (1988) Diflubenzuron and neem oil in control of *Heliothis armigera* infesting chickpea. *Indian J. Agric. Sci.* 58, 238–239.

Singh R. P., Singh Y. and Singh S. P. (1985) Field evaluation of neem *(Azadirachta indica* A. Juss.) seed kernel extracts against the pod borers of pigeonpea, *Cajanus cajan* (L.) Millsp. *Indian J. Entomol.* 47, 111–112.

Smith R. F. (1969) The old and the new in pest control. *Proc. Accad. Nazional Lincei, Rome (1968).* 366, 21–30.

Solsoloy A. D. and Morallo-Rejesus B. (1992) The juvenile hormone effect of the insecticidal principle from psychic nut *Jatropha curcas* Linn. on cotton bollworm, *Helicoverpa armigera* (Hubn.). *Phillipine Entomol.* 75, 17–27.

Stern V. M., Smith R. F., Bosch R. van den and Hagen K. S. (1959) The integrated control concept. *Hilgardia* 29, 81–101.

Srivastava K. P., Agnihotri N. P., Gajbhiye V. T. and Jain H. K. (1984) Relative efficacy of fenvalerate, quinalphos and neem kernel extracts for the control of pod fly, *Melanagromyza obtusa* (Malloch) and pod borer, *Heliothis armigera* Hubner infesting red gram, *Cajanus cajan* (L.) Millsp. together with their residues. *J. Entomol. Res.* 8, 1–4.

Teng P. S. (1994) Integrated pest management in rice. *Experimental Agric.* 30, 115–137.

Venugopal Rao N., Tirumala Rao K., Sathyanarayana Reddy A. and Meera G. (1992) Control of pigeonpea pod borer, *Helicoverpa armigera* (Hbn.) with nuclear polyhedrosis virus. *J. Biol. Contr.* 6, 106–108.

Verma J. S. (1990) India agrochemical industry comes of age. *Farm Chem. International* November: 20–21.

Wightman J. A., Anders M. M., Rameshwar Rao V. and Mohan Reddy L. (1994) The management of *Helicoverpa armigera* (Lepidoptera: Noctuidae) on chickpea in southern India: Thresholds and the economics of host plant resistance and insecticide application. *Crop Protection* (in press).

Yadav C. P. (1987) Ecological studies on gram pod borer, *Heliothis armigera,* in chickpea in relation to its biotic and abiotic factors. PhD Thesis, Kanpur University, India.

Yadava C. P., Lal S. S., Dias C. A. R. and Nigam R. (1983) Host evasion: A prospective approach for suppressing *Heliothis* damage. *International Pigeonpea Newsl.* 2, 62–64.

Yadava C. P., Lal S. S. and Sachan J. N. (1988) Assessment of incidence and crop loss due to pod-borers of pigeonpea *(Cajanus cajan)* of different maturity groups. *Indian J. Agric. Sci.* 58, 216–218.

Biointensive Management of Crop Borers of Banana

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Abstract—Banana is attacked by several species of borers. Among these *Cosmopolites sordidus* is the most serious and widely distributed. As a result of resistance development of weevil to insecticides, research workers are in pursuit of alternate methods of management. Host plant resistance plays a major role as a component of IPM of the borer. A few varieties like Lacatan, Lacknau, Figo Vermelho, Ouro, those of Prata group and Soth have been found to be tolerant. Damage by banana weevils is generally associated with neglected fields. The weevil populations could be kept under check by eliminating banana waste material from the base of the mat. Selection of healthy and clean planting material is a very important and essential component of IPM. Intercropping of groundnut or beans and trapping using split pseudostem traps can reduce the weevil populations and prolong the life of a banana plantation. Predators such as *Pheidole megacephala, Tetramorium guineense, Dactylosternum abdominale* and *Plaesius javanus* were as effective as insecticides in controlling the weevils. Entomopathogenic fungi, *Beauveria bassiana, Metarhizium anisopliae* and a few strains of entomopathogenic nematodes belonging to genera *Neoaplectana* and *Heterorhabditis* were found to be promising in controlling this pest. As negative correlation exists between *C. sordidus* and nematodes, it is very important to deal with these problems as a complex.

Key Words: banana, *Cosmopolites sordidus*, host plant resistance, IPM of banana weevil

Introduction

Bananas (*Musa* spp.) as a carbohydrate staple, stand eighth in the world and third in Africa (FAO, 1993) and in gross value of production, they rank fourth after rice, wheat and maize (CGIAR, 1992, 1993), feeding 400 million people throughout the world. Bananas also rank fourth as a major tropical export commodity. Bananas are a rich source of nutrition. They are high in carbohydrates (35%) and fibre (7%) and are also an important source of minerals (potassium, magnesium, phosphorus, calcium and iron) and vitamins A and C (Marriot and Lancaster, 1983) and therefore are especially important in the producing countries as food for expectant mothers and children.

Bananas have become a part of life in many countries, with their multivarious uses. Besides their use for food, bananas are used for brewing, thatching, cattle fodder, making ropes and various handicrafts. Because banana leaves contain 8.3 and 63.4% of digestible crude protein and total digestible nutrients respectively they are considered good fodder for cattle (Bhuyan et al., 1989). Banana is ideally suited for prevention of soil erosion, intensive agroforestry and mixed farming systems. Due to the wide range of its uses, the banana tree has become so ubiquitous that one cannot find a household without a banana tree in many parts of eastern Africa.

Banana production is in a state of severe decline mainly due to insect borers, nematodes, diseases as well as poor agronomic practices. In this article we will discuss the management of

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borers of the banana crop. Several borers have been reported to attack different vegetative parts of banana worldwide (Table 1). However, *Cosmopolites sordidus* and *Odoiporus longicollis,* both corm borers which are extremely important and widely distributed, cause economic losses. The life cycle of *C. sordidus* and damage symptoms are briefly discussed, as a typical example of a corm borer. Besides the fruit borers mentioned in Table 1, insects such as *Frankliniella parvula* (Harrison, 1963), *Thrips florum* (Swaine and Corcoran, 1970) and *Nacoleia octasema* (Paine, 1964) were found to enter the fruit in the bud stage.

Life Cycle of *C. sordidus*

The egg of the weevil is elongate, oval about 2 mm long and pure white. Hatching takes place after 5–8 days. The fully grown larva is 12 mm long, creamy white, stout, fleshy, legless and distinctly curved and swollen in the middle. It has a brown head with strong jaws. The larval period lasts 14–21 days. The pupa is white and about 12 mm long and lasts for 5–7 days. As it develops, the shape of the adult within becomes visible. The newly emerged beetle is brown in colour. It turns almost black after a few days and may live upto 2 years. Its normal food is dead or dying banana plants. It moves mainly by terrestrial means and may seldom resort to flying.

Damage

The larva or grub of the weevil feeds and tunnels in the corm of the banana plant. The tunnel is roughly circular and increases to about 8 mm diam. as the larva grows. The corm can be riddled with tunnels and fungal decay then reduces it to a blackened mass of rotten tissue. Occasionally the tunnels extend 30 cm or more up the stem (Treverrow, 1985). The authors have observed the tunnels extending up the stem to 1.5 m. The reasons for such unusual behaviour of the larva is not known. The tunnels in the corm and stem reduce the structural strength of the plant resulting in snapping of plants when exposed to high winds late in the season (Hord and Flippin, 1956).

Yield Losses

Though *C. sordidus* has been recognised as a serious pest of banana, information on extent of yield losses based on experiments is lacking. Yield losses upto 30% in Brazil (Anon, 1980), 20–40% in Equador (Liceras et al., 1973) and 25–85% in Honduras (Roberts, 1955) due to *C. sordidus* were reported.

Alternate Hosts of *C. sordidus*

Besides banana, *Musa textilis, Saccharum officinarum, Dioscorea* spp. (Anon, 1968), *Ricinodendron hendeloti, Panicum maximum, Ensete* spp., *Xanthosoma sagittifolium* and *Dioscoria batatas* (Anon, 1966; Beccari, 1967) were reported to be the hosts of *C. sordidus*. Under laboratory conditions, it was observed to attack *Xanthosoma sagittifolium* and *X. violaceum* but eggs were not laid (Martinez et al., 1990).

Farmers' Perception

Though *C. sordidus* is widespread in occurrence in the banana growing areas throughout the world, farmers knowledge on this pest is limited (Anon, 1992a). Most of the farmers do not know the reasons for the decline of their plantations and could not relate the tunnelling, decaying and snapping of plants to the presence of weevils. They were also not aware of how this pest could be controlled. Staver (1989) in a

Table 1. Insect borers of banana, plant part attacked and their distribution

Name of borer	Family attacked	Plant part	Distribution	Reference
Order: Coleoptera				
1. *Cosmopolites sordidus* (Germar)	Curculionidae	Rhizome, Pseudostem	All over the world	Stover (1977), Stover and Simmonds (1987)
2. *C. pruinosus* Heller	Curculionidae	Rhizome, Pseudostem	Philippines, Hawaii, Borneo, Caroline Islands	Zimmerman (1968) Stover (1977)
3. *Metamasius ensirostris*	Curculionidae	Pseudostem	South America	Reis and DeSouza (1986)
4. *M. hemipterus* Linnaeus	Curculionidae	Pseudostem	West Indies, West Africa	Wyniger (1962)
5. *M. inaequalis*	Curculionidae	Pseudostem	South America	Reis and DeSouza (1986)
6. *M. sericeus* Ol.	Curculionidae	Pseudostem	Africa	Lepesme and Paulian (1941)
7. *Odoiporus longicollis* Oliv	Curculionidae	Pseudostem	Pacific Islands, Asian Mainland	Stover (1977) Isahaque (1978)
8. *Polytus mellerborgii*	Curculionidae	Pseudostem	China	Zhou and Wu (1988)
9. *Temnoschoita basipennis* Duviv	Curculionidae	Pseudostem	Uganda	Cuille (1950)
10. *T. delumbrata*	Curculionidae	Pseudostem	Tanzania	Walker et al. (1983)
11. *T. erudita* Duviv	Curculionidae	Pseudostem	Uganda	Cuille (1950)
12. *T. nigroplagiata* Qued.	Curculionidae	Pseudostem	Uganda, Congo, Kenya	Whalley (1957), Wyniger (1962), Stover (1977), Seshu Reddy (1987)
13. *T. quadripustulata*	Curculionidae	Pseudostem	Sao Tome, Fiji, Dahomey, Congo, Ghana	Stover (1977), Asante and Kumar (1986)

Contd.

Table 1. Contd.

Name of borer	Family attacked	Plant part	Distribution	Reference
14. *Rhynchophorus palmarum* Linnaeus	Curculionidae	Rhizome	Colombia	Parra (1989)
15. *Philicoptus iliganus*	Curculionidae	Root	Philippines	Stephens (1984)
16. *Heteronychus cladius*	Scarabaeidae	Pseudostem	Papua Guinea	Annet (1940)
17. *Ligyrus ebenus*	Scarabaeidae	Root	West Indies	Anon (1913)
18. *Phyllophaga pleei* Bl.	Scarabaeidae	Pseudostem	Guadeloupe, Puerto Rico, Caribbean	Walcott (1921), Morez (1962), Gruner (1969)
Order: Diptera				
19. *Assurania* sp.	Chloropidae	Pseudostem	India	Abraham et al. (1978)
20. *Dacus musae* Tryon	Trypetidae	Fruit	Australia	Saunders and Elder (1966)
21. *D. curvipennis* Frogg	Trypetidae	Fruit	Fiji Islands	Wyniger (1962)
Order: Lepidoptera				
22. *Opogona sacchari* Bojer/*basipennis*	Tineidae	Fruit, Pseudostem	Tropics and Sub-tropics	Billen (1978)
23. *O. subcervinella*	Tineidae	Fruit	Canary Islands	Stover and Ostmark (1979)
24. *Castnia licus* Fabricius	Castiniidae	Pseudostem	Central and South America	Bodkin (1916), Stover (1977)
25. *Castniomera humboldti* Boisduval	Castiniidae	Rhizome, Pseudostem	Costa Rica to Venezuela, Trinidad	Chapman and Emsley (1963), Ostmark (1974), Stover (1977)
26. *Hieroxestis subcervinella* Meyr	Lyonetiidae	Fruit	Canary Islands, Seychelles, Mauritius, St Helena	Wyniger (1962)
27. *Plusia chalcytes* Esp.	Noctuidae	Fruit	Africa	Vilardebo and Guérout (1964)
28. *Tiracola plagiata*	Noctuidae	Fruit	Australia	Temperley (1930), Weddell (1932)

systematic study in the Peruvian Amazon on "why farmers rotate fields in maize-cassava-plantain-bush fallow agriculture", found during the 18–30 months of cropping fields a build-up of weeds and an increase in banana stemborer and nutrient deficiency symptoms. These farmers attributed the decline in plantain from the first to third harvests to attack of banana stemborer, weeds or soil infertility but were not unanimous as to the exact cause. He observed that any or all of these factors facilitated the decision to abandon a field.

A survey carried out in western Kenya by the ICIPE has revealed that banana is grown by almost all the farmers. It provides them food and income. Ninety percent of their knowledge on banana farming comes from relatives, neighbours, parents and friends and only 7% from government extension services. However, the impact of government extension services on other crops is about 50%. Banana is mainly grown as a mixed crop in 86% of the cases and farmers' knowledge on pest and disease problems and solutions were almost non-existent.

IPM Strategies

A number of efficient control measures can be used to develop integrated pest management strategies for the weevil. The most important will be discussed in detail below:

(a) Chemical control
(b) Host plant resistance
(c) Cultural approaches
(d) Trapping
(e) Biocontrol
(f) Botanicals
(g) Semiochemicals.

Chemical Control

Chemicals were initially found to be quite effective against *C. sordidus*. Whalley (1957) reported that 100% control of weevils *(C. sordidus)* was possible by dusting at the base of pseudostems with dieldrin (0.5%) at 35 lb to 112 lb/acre. Treatment of traps made from pieces of cut pseudostem also resulted in killing of attracted adults. He recommended two applications, 6 months apart in the first year and subsequently one dusting per year. Chlordane, diluted 3:2000, applied at the rate of 200 gallons/hectare at monthly intervals to the mats greatly reduced weevil populations (Hord and Flippin, 1956).

Dieldrin, aldrin and heptachlor given at 1.12 oz/mat or 2 lb active ingredient/acre were effective in that order in reducing the weevils, i.e. they were effective for 18, 16 and 15 consecutive months (Bullock and Evers, 1962). Liceras et al. (1973) found carbofuran to be effective in controlling the weevil. However, the well known action of carbofuran in accelerating plant growth in some agricultural crops does not seem to be of economic significance in banana production (Mitchell, 1978).

For the control of the weevil, application of pirimiphos-ethyl (Pullen, 1973), mephosfolan 5% granules at 50 g/stool (Sampaio et al., 1982), active ingredients of a prothiophos as dust at 3 g/stool or as a liquid at 2.5 ml/stool, chlorpyriphos at 4.5 g/stool (Peasley and Treverrow, 1984), aldicarb (10 g) thrice annually at 1.5 g (a.i.)/plant (Sarah, 1988) or at 2 g (a.i.)/plant (Vilardebo et al., 1988) and fenamiphos (Ingles and Rodriguez, 1989) were suggested. Six months after soil treatment with dieldrin (15% EC), carbofuran (10%) and fensulfothion (15%) at 5 ml, 20 g and 14 g/plant reduced *C. sordidus* infestation to 0, 0.52 and 3.12% respectively (Gaud et al., 1975). Braithwaite (1967) showed that dieldrin would give control of *C. sordidus* for over a year from a single application at the base surrounding the stool. However, Loebel (1975), after two years of continuous tests with several insecticides found that the infestation was controlled but no significant increase in plant growth and yield occurred.

Besides the application of chemicals directly to the mats, treatment of pseudostem traps, planting holes and sucker drenches have also been tried. Franzmann (1972) reported that paring the suckers, and dipping them in 0.1% solution of dieldrin or sprinkling 0.05% dieldrin in planting hole and subsequent spraying at the base of the plant 12 inches from the stem with one pint of 0.05% dieldrin/stool was helpful in the management of the weevil. Whalley (1957) obtained control of the pest by dusting banana stools and the undersides of the split rhizome traps with 0.5% dieldrin. Insertion of aluminium phosphide tablets (celphos) at the rate of 3 x 0.5 g tablets/plant which release phosphene gas into the thick basal region of the pseudostem of banana plants successfully controlled eggs, pupae and adults of the weevil, *O. longicollis* (Dutt and Maiti, 1974).

Application of one part of paris green with 6 parts of flour (Froggatt, 1925, 1928) or 1% propoxur (Sotomayor, 1972), isoamyl and butyl alcohols or butyl acetate (Noqueira et al., 1985) as baiting material attracted higher number of weevils. Good control was obtained with ekadrin at 0.3 g/bait (Noqueira et al., 1985), carbofuran at 0.25 g/trap or fenamiphos at 0.2 g/trap (Yaringano and Meer, 1975).

Braithwaite (1967) suggested that the use of an insecticide over a long period of time against a specific pest is likely to result in the development of a resistant strain. Therefore, he advised minimising the use of pesticides thereby delaying as long as possible the establishment of weevil strains resistant to a chemical or similar compounds.

As foreseen by Braithwaite (1967) though the chemicals were effective, the continued use of cyclodienes led initially to a general deterioration in crop hygiene and then to the development of resistance in weevils. Eventually, these two factors led to a resurgence of the banana borer, *C. sordidus* (Mitchell, 1980). Edge (1974), Shanahan and Goodyer (1974) and Edge et al. (1975) in New South Wales, Swaine and Corcoran (1973) and Swaine et al. (1980) in southern and northern Queensland, Australia respectively, Mello et al. (1980) and Sampaio et al. (1982) in Brazil; Sotomayor (1972) in Ecuador and in Kagera region of Tanzania (Anon, 1984) and in Uganda (Sebasigari and Stover, 1987), reported occurrence of such resistance in weevils following the continuous usage of dieldrin. Effective control of the weevils resistant to dieldrin was obtained by spraying the bases of plants and surrounding soil to a radius of 30 cm in spring and autumn with pirimiphos-ethyl and chlorpyriphos emulsions at 2.24 kg a.i./ha (1.12 g/plant)/application. Chlortecore dust, pirimiphos-ethyl granules and chlorpyriphos powder sprinkled by hand at 2.8 kg/ha a.i. (1.42 g/plant)/application also gave effective control and could be used where water is unavailable (Wright, 1977). The tendency towards the development of resistance following treatment with cyclodiens may well have been enhanced by poor formulation procedures in some areas and excessive application in others (Mitchell, 1978).

Application of chemicals demeton-methyl, phosphomidon, dimethoate, monocrotophos, carbofuran, carbosulfan applied at 0.05 g a.i./ha resulted in residues of 1.29 to 11.31 µg/g in different parts (sheath, petiole and leaf) of 8-

month-old banana (Suresh and Regupathy, 1988). Yuningih (1987) investigating on the suspected aldicarb poisoning cases of cattle in Indonesia reported that the samples of bananas and maize from rumen and faeces of cattle contained residue levels above the 0.2 ppm WHO/FAO recommended level. Overviewing the disadvantages of using these chemicals, Stover and Ostmark (1979) felt that the use of insecticides for *C. sordidus* control could be eliminated except in new plantings in old banana plantations where residual populations of the weevil are high. Similarly, Daniells et al. (1992) stated that in some situations, it should be possible to completely eliminate the use of pesticides.

More research and development are necessary to better understand the factors affecting pest incidence, so that pests can be controlled more efficiently with diminished use of pesticides. They also insisted that the economics of alternate crop management options require particular attention. Sery (1988) stressed the need to alter strategies dispensing on extended use of chemicals. He suggested that research should be directed towards improving and intensifying prophylaxis, improving cultural methods screening for resistance and tolerance as well as genetic improvement of existing cultivars. Supporting his views, Landono (1991) appealed that integrated pest control is indispensible and includes (1) cultural control involving all practices embracing plant growth (desuckering, fertilisation, weed control, etc.) which prevent or reduce pest attack and enhance the density of beneficial insects; (2) physico-chemical control including the use of traps for detecting, capturing and eliminating part of the pest population; (3) natural biological control with the use of parasitoids and entomopathogenic predators to reduce pest levels; (4) chemical control consisting of targeted applications of insecticides only when necessary, negligence in pest management or sudden changes in environmental conditions. The need of the day is a cheap environmentally safe chemical which could be applied with ease and effective against both the weevils and nematodes in banana.

In view of development of pest resistance to pesticides, health hazards and environmental pollution, it is important and essential to develop and promote environmentally safe and sustainable plant protection strategies.

Host Plant Resistance

It is not known whether borers are attracted to plants by chemical means or whether they simply move at random and accumulate at points which they find favourable, perhaps assisted by pheromones. It is certainly widely believed that some varieties of *Musa* spp. are preferred to others (Mitchell, 1978). Plantains are said to be particularly vulnerable (Simmonds, 1973) with older stools, especially those in an abandoned or neglected condition, showing the highest levels of infestation. Of the wild bananas, *Musa acuminata* is generally susceptible whereas *M. balbisiana* seems to be resistant (Simmonds, 1973). In Fiji, Jepson (1914) found that the insect attacked all the cultivars with equal intensity. Haddad et al. (1980) observed that compared with the AAA group, cultivars of the AAB and ABB groups showed higher coefficients of infestation and larger numbers of adult weevils captured in pseudostem traps. Interestingly, a high yielding plantain cultivar 'Lacknau' was reported to possess field resistance to weevils yielding 11 to 23 t/ha more than a susceptible entry 'Maricongo' without insecticide treatment (Irizarry et al., 1988).

The biology of *C. sordidus* is influenced by the host. Susceptibility varies both between and within genomic groups. The cultivars Figo Vermelho, Ouro and those of the 'Prata' sub-group were evidently resistant while Nancia and Leite were susceptible. The time needed for the development of *C. sordidus* increased by 7 days when fed on Figo Vermelho (AAB) in comparison to Nancia (AAA). The latter resulted in a higher larval death rate and lowest pupal cases (Mesquita et al., 1984). *Cosmopolites sordidus* showed a feeding preference for Gros Mitchel rhizomes, over those of the cultivar Bout Round which is also highly resistant to Panama and head rot diseases.

Viswanath (1977, 1981) in his work on the biology, varietal response and control of the banana rhizome weevil found that among the 15 cultivars studied, Lacatan (AAA) was least susceptible while Maduranga (ABB) was most susceptible to the weevil attack. The cultivar Peykunnan (ABB) was next to Maduranga in level of susceptibility, followed in increasing order of tolerance by Budubale (ABB), Nallabontha (ABB), Neypoovan (AB), Nendran (AAB), Sirumah (AAB), *M. acuminata* (AB), Rasabale (AAB), Virupakshi (AAB), Poovan (AAB), Cavendish (Robusta) (AAA), Cavendish (dwarf) (AAA) and *M. balbisiana* (AA). The cultivars Soth, Kainja, Muraru, Sukalindizi were found to be resistant to *C. sordidus* at the ICIPE (Anon, 1990–92).

Masefield (1944) observed that Baganda (Uganda) tribe maintained that some of the cultivars they cultivated were more resistant to weevil than others. He gave examples of cultivars like Namwezi and Nakabululu as being resistant, while Nsowe being particularly susceptible.

Corms upto 15 months of age are equally attractive as food material for adult borers. Borers did not discriminate between the corms of different cultivars. The tetraploid cultivars were more attractive to adult borers than other cultivars (Ittyeipe, 1986). Corms belonging to hybrid groups: plantains (AAB) and bluggoes (ABB) showed the highest infestation index (Haddad et al., 1980). However, the attraction of adults to the corm of a cultivar need not necessarily indicate its susceptibility. The fact that a significantly smaller number of adult borers were attracted to the tissues of the cultivars, Valery and Robusta, did not necessarily indicate that these cultivars were less susceptible to borer attack in the fields as most of the damage is caused by the tunnelling and feeding activity of the larvae. It is possible that more eggs are laid on the corms to which more adults are attracted and that the extent of larval feeding and tunnelling on a corm is proportionate to the number of eggs laid on it (Ittyeipe, 1986). Wolcott (1933) finds that no cultivar of banana or plantain is immune to attack by the weevil though some are more susceptible to injury by the weevil. Mesquita and Caldas (1986) reported that young plants were the most favourable for development, and resulted in a shorter life-cycle time, reduction in duration of larval stage and less mortality among young larvae as well as increased larval weight. However, in the field, the largest number of larvae and pupae were found at flowering and harvesting, indicating that the ovipositing females are influenced more by secondary stimuli than by the presence of plant tissues optimum for the development of their progeny.

It was observed that rhizome hardness apparently plays a major role in larval development and is therefore an important factor in observed resistance reactions (Pavis and Minsot, 1992; Sarah and Jones, 1992).

Olfactometer tests showed that fresh pseudostems were more attractive than fermented pseudostems. Attractivity was very strong for all the tested cultivars, hence the low infestation rate recorded in this study cannot be due to failure to locate host plant by the pest (Pavis and Minsot, 1992). Although cooking and beer type bananas were found to be more susceptible to the weevil than the dessert types, there was no direct correlation between the genome grouping of the cultivar with the number of insects surviving or developing (Seshu Reddy and Lubega, 1992; Speijer et al., 1993).

Cultural Approaches

Several workers observed that severe levels of damage by banana weevils is generally associated with poorly managed fields (Wallace, 1938; Lara, 1966; Acland, 1980). McNutt (1974) and Pinese (1989) have suggested the following precautions for growing a healthy plantation: (i) The planting material should be free of weevils and nematodes; and, should be procured from a weevil-free nursery or from tissue cultured material. (ii) If the planting material is infested with weevils, paring and hot water treatment should be given. (iii) If old plantations are to be replanted, the soil should first be prepared by repeated plowing to cut old corms and stems and to destroy the volunteer plants. These operations will speed up the destruction of crop residues and expose adults and larvae of weevils to desiccation. (iv) A period of six months fallow to allow the banana debris to decompose should be allowed to ensure that all the weevils have died. (v) Weevils thrive in trashy and weedy plantations. The weevils are protected from sunlight and desiccation under such conditions. Hence, the plantations should be kept free from weeds and the place around the mat should be kept clean. This also provides accessibility for agricultural operations like application of chemicals and fertilisers.

Wallace (1938) also reported that favourable growing conditions followed by moderately good cultivation induce a high degree of tolerance or help bananas escape attack by *C. sordidus*. Essentially, the planting hole for bananas is 90 cm in diameter and 60 cm deep. Deeper and wider holes of 120 cm are preferable in dry areas. Deep planting helps in discouraging the egg laying by weevils by preventing high matting.

The importance of clean planting material has been emphasised by several workers. Utilising tissue-culture generated material wherever economically feasible is advised for a clean plantation. Recently Rao et al. (1993) developed a method to encapsulate the shoot tips of banana to give "artificial or synthetic seeds". When compared to suckers, these encapsulated shoot tips present an inexpensive, easy and safe material for germplasm exchange and transportation. However, tissue culture and shoot-tip encapsulation are not within the reach of the resource-poor farmers of the Third World.

Paring followed by hot water treatment at 55°C for 15 to 25 minutes has been found to be an effective and simple method for the elimination of weevils and nematodes from the planting material (Stover, 1972; Bridge, 1975; Getmann et al., 1992). Although this treatment is considered superior to chemical dips, the technique is quite difficult to manage because of the critical balance required between a temperature that is lethal to nematodes in the corm tissue and one that causes permanent damage to the plant (Gowen and Queneherve, 1990). This technique is not practised in many countries because of the costs for expensive tanks, thermostats and energy for resource-limited banana growers. Keeping this in mind, an easily adoptable and simple technique ("poor man's thermostat") for determining desired temperature for hot water treatment of banana suckers has been developed (Prasad and Seshu Reddy, 1994). In this method, a piece of metal was attached to a wooden block with molten wax having a melting point of 55°C. The wax-block-thermostat was dropped into the water in a simple oil-drum in which suckers were placed for hot water treatment. When the water temperature at the bottom of the treatment tank reached 55°C the wax melted and released the wood of the thermostat. The floating wooden block on the surface of the water acted as an indicator to resource-limited farmers. The suckers could be removed after 20 minutes which ensured weevil- and nematode-free suckers.

Lara (1966) reported that the borer, *Castniomera humboldti* in Costa Rica could be kept under check by eliminating the water and sword suckers, as soon as possible, and especially by keeping the banana area clean of debris. Earthing up of pseudostems and using coffee bark to cover the soil in the plantation were found useful in the management of *C. sordidus* (Kehe, 1988). Tests by Nanne and Klink (1975) in Costa Rica indicated that the numbers of *C. sordidus* in banana plantations can be considerably reduced if rhizomes that have become uprooted are cut longitudinally into four pieces to stimulate drying. They suggested not to leave rhizomes in the field for more than a week before being split for best results.

Beans *(Phaseolus vulgaris)* and cowpea (*Vigna unguiculata*) that had been interplanted with banana suffered less infestations of *Diabrotica balteata* and *Cerotoma ruficornis* than the monocultures of beans and cowpeas (Risch, 1980; 1982). Rao and Reid (1987) found the association of cowpeas with dwarf bananas as most profitable. Ternisien (1989) obtained 10 to 15% increase in yields and reduction in pest incidence in banana when *Brachiaria decumbens, Sorghum vulgare, Canavalia ensiformis* or *Crotalaria juncea* were cultivated for one year between two banana production cycles. Bananas also act as wind breaks to such crops (Stover and Simmonds, 1987). Mulching and intercropping food crops like maize *(Zea mays)*, beans *(Phaseolus vulgaris)* or sweet potato (*Ipomaea batatas*) with banana resulted in significant reductions in weevil populations (Uronu, 1992). Yao (1988) reported decline in plantations intercropped with coffee and cocoa in Ivory Coast due to the susceptible plantains to pests (weevils and nematodes), unfavourable soil conditions (compaction) and low soil acidity.

Trapping

Rhizome traps were more effective than those cut from pseudostems. The fresh surfaces cut on the rhizome traps every 2 days increased efficacy of catch appreciably (Hord and Flippin, 1956; Mesquita, 1991). Using such traps Yaringano and Meer (1975) achieved 50% reductions in weevil populations in 4 months. They also observed that *C. sordidus* prefers traps of rhizome or of the lower part of the pseudostem, whilst *Metamasius* sp. showed no particular preference but tend to prefer pseudostem traps.

Climatology has a strong influence on trapping efficiency. Few insects come to the traps in the dry season or during periods of heavy rainfall. Variations in the populations of weevils with time were not significant because the rate of multiplication was very slow (Vilardebo, 1973). The idea of trapping borers and then destroying them by mechanical or chemical means has been a recommended control technique since the beginning of modern commercial production of bananas (Wallace, 1938; Yaringano and Meer, 1975).

A trap made up of a commonly called 'tile' 40-cm long pieces of pseudostem longitudinally divided, and another made up of diagonal cut slices of pseudostem called 'sandwich' both renewed in periods of 20 to 30 days is commonly used. Both traps showed the same attractivity to *C. sordidus* and both were active for 3 or 4 weeks after installation. However, the 'tile' trap was found to be more advantageous because it was more economical (Filho, 1990). In an experiment conducted during 1992–94 by the authors, trapping with 15 cm pseudostem 'tile' traps resulted in 31% increase in banana yields and 50% decrease in weevil numbers when compared to no trapping treatment (Seshu Reddy et al., 1995).

Biological Control

Predators

Mitchell (1978) reported *Bufo marinus* (Giant toad), *Dactylosternum hydrophiloides*, *Plaesius javanus* as good biological control agents of *C. sordidus*. In 1912 *P. javanus* was introduced from Java to Fiji and became established within five years. By 1936, Fiji became a source for the supply of *Plaesius javanus* to other countries (Harris, 1947). It was also found to be an efficient predator in Australia (Frogatt, 1925). In 1938, *D. hydrophiloides*, native to Malaya was introduced in Queensland, Australia. Two years later, Veitch (1941) found it increasing rapidly. In both cases, good control of *C. sordidus* was reported. *Physoderes curculionis* was reported to be predating on the grubs of *C. sordidus* and *Odoiporus* sp. (Corbett, 1936), whereas *Phorticus pygmaes*, *Geotomus pygmaes* and *Fulvius nigricornis* were found to be preying on the eggs of both the borers (Corbett, 1936). A list of predators on different life stages of borers is presented in Table 2. In addition, Beccari (1967) has observed *Annisolabis annelipes*, *Psalis americana* (Dermaptera: Labiduridae), *Chrysopilus feruginosus* (Diptera: Rhagionidae),

Table 2. Natural enemies of borers of banana

Name of borer	Family	Stage attacked	Reference
Order : Coleoptera			
1. *Abacetus optimus* Periguey	Carabidae	Eggs	Koppenhoefer (1993b)
2. *Hister niloticus*	Histeridae	Larvae	Koppenhoefer (1993b)
3. *Hister tropicus*	Histeridae	Eggs, larvae, pupae	Koppenhoefer (1993b)
4. *Hololepta striatidera* Marsuel	Histeridae	Larvae, pupae	Koppenhoefer (1993b)
5. *Plaesius javanus* Erichson	Histeridae	Eggs, larvae	Froggott (1928), Beccari (1967) Harris (1947), Mitchell (1978)
6. *Dactylosternum abdominale* Fabricius	Hydrophilidae	Eggs, larvae	Beccari (1967) Koppenhoefer (1993b)

Contd.

Table 2. Contd.

Name of borer	Family	Stage attacked	Reference
7. *D. hydrophiloides*	Hydrophilidae	Eggs	Veitch (1941), Beccari (1967)
8. *Charichirus* sp.	Staphylinidae	Eggs, larvae	Koppenhoefer (1993b)
9. *Hesperus sparior* Bernhauer	Staphylinidae	Eggs and larvae	Koppenhoefer (1993b)
10. *Thyreocephalus interocularis* Eppelsheim	Staphylinidae	Eggs, larvae, pupae	Koppenhoefer (1993b)
11. *Eulissus* sp. Erichson	Staphylinidae	Larvae	Seshu Reddy (1987)
12. *Eutochia pulla* Erichson	Tenebrionidae	Eggs	Koppenhoefer (1993b)
13. *Euborellia annulipes* Lucas	Carcinophoridae	Eggs, larvae	Koppenhoefer (1993b)
14. *Labia borellii* Burr	Labiidae	Eggs, larvae	Koppenhoefer (1993b)
15. *L. curvicauda* Motschulsky	Labiidae	Eggs, larvae	Koppenhoefer (1993b)
16. *Fulvius nigricornis* Popp	Capsidae	Eggs	Corbett (1936), Beccari (1967)
17. *Geotomus pygmaes* Dall	Cynidae	Eggs	Corbett (1936), Beccari (1967)
18. *Phorticus pygmaes* Popp	Nabidae	Eggs	Corbett (1936), Beccari (1967)
19. *Physoderes curculionis*	Curculionidae	Larvae	Corbett (1936), Beccari (1967)
Order : Hymenoptera			
20. *Anochaetus* sp.	Formicidae	Larvae	Seshu Reddy (1987)
21. *Pheidole megacephala* Fabricius	Formicidae	Eggs, larvae	Castineiras and Ponce (1991)
22. *Tetramorium bicarinatum* Nyl.	Formicidae	Eggs, larvae	Roche (1975)
23. *T. guineense* Act.	Formicidae	Eggs, larvae	Roche and Abreu (1982)
Phylum : Amphibia : Saliencia			
24. *Bufo marinus*	Bufonidae	Adults	Beccari (1967) Mitchell (1978)

Belonuchus quarates, *B. ferrugatus*, *Leptochirus unicolor* (Coleoptera: Staphylinidae), *Dactylosternum intermedium*, *D. profundum*, *D. subquadratum*, *Omicrogiton insularis* (Coleoptera: Hydrophilidae), *Lioderma quadridentatum*, *Platysoma abruptum* (Coleoptera: Cucujidae) and *Geoplama coevulea* (Platyhelminthes: Turbelaria) predating on *C. sordidus*. However, the life stage of the pest attacked is not mentioned.

Castineiras and Ponce (1991) compared the effectiveness of the ant, *Pheidole megacephala* in the biological control of *C. sordidus* at densities of 9 and 15 colonies per unit area with carbofuran application at 4 g (a.i.)/plant. Biological control at both densities were similar to those obtained with the chemical. The pest population decreased (54–69%), damage to rhizome (64–66%) and yield increased (15–22%) over the control at both densities respectively. In Cuba, *Tetramorium guineense* colonised all the stools in a plantation within 2 or 6 months when initially released on to 50% and 8% of the stools, respectively (Roche and Abreu, 1982). *Cosmopolites sordidus* infestations were reduced by 65 and 84% respectively, when *T. guineense* was released on 25–30% stools within one year in heavily and less heavily infested plantations (Roche and Abreu, 1983). They also observed that the ant could be easily reared on banana pseudostem pieces provided with additional carbohydrates, proteins and minerals (Roche and Abreu, 1984). Lopez and Ramos (1986) found that the interaction between *C. sordidus* was most intense during the dry season. The greatest increase in numbers of larvae and pupae of the curculionid occurred during the dry season, showing that the formicid was not as effective in controlling the pest under dry conditions as compared to wetter season of the year, even though the number of ants was higher during the dry season. The perception capacity or host-finding time period of the ant was acceptable. They located the larvae of the weevil, *C. sordidus* in less than 25 to 96 hrs, and controlled 68% of the pest (Lopez and Lopez, 1987).

In Cuba, Roche (1975) observed that *T. bicarinatum* when established either naturally or as a result of artificial introduction, kept *C. sordidus* populations under control by destroying the weevil larvae. The biological control afforded by the ant was more effective than that obtained by chemical treatments. Stover and Ostmark (1979) reported ants to be the major biological control agents destroying eggs and larvae of *C. humboldti* for which no practical chemical control exists. Epidemics of this pest in the 1950s in Central America were the result of killing the predator ants with insecticides such as dieldrin. There have been no significant epidemics in the past decade or ever since the use of chemicals was discouraged. Similarly, Stephen (1992) observed deleterious side-effects of pesticides on beneficial insects in Central America. He noticed that parasites and predators of important pest insects were easily collected in untreated areas but they were eliminated in plantations sprayed with insecticides. Insecticide spraying was stopped in the 1970s and epidemics soon decreased. A balanced ecosystem was attained in two years in banana areas and numerous epidemics caused by *C. sordidus* have practically disappeared.

Koppenhoefer et al. (1992) identified 12 predators of the banana weevil. Of the 12 tested in cages in screen houses, *Dactylosternum abdominale* and *Thyreocephalus interocularis* reduced weevil multiplication by 40–90% and 42% respectively (Koppenhoefer and Schmutterer, 1993). Koppenhoefer (1993) further observed that *Eutochia pulla*, *Euborellia annulipes* and *D.*

abdominale reduced weevil multiplication in banana suckers through egg predation by 21, 28 and 40% respectively under high pest and predator densities. *Dactylosternum abdominale* was also effective at lower weevil and predator densities.

Eulissus sp. and *Anochaetus* sp. were found to be effective predators on larvae of *C. sordidus* (Seshu Reddy, 1987). Luo et al. (1985) reported mites and earwigs as the natural enemies of both *C. sordidus* and *O. longicollis*. Neuenschwander (1988) suggested the need for research on life table studies on natural enemies of *C. sordidus* in Africa and Southeast Asia. In fact, such studies led to the successful use of *T. guineense* in Cuba (Roche and Abreu, 1982).

Pathogens

Entomopathogenic fungi, *Beauveria bassiana* (Luo et al., 1985) and *Metarhizium anisopliae* were found to be effective against *C. sordidus* (Delattre and Bart, 1978). When adult weevils were allowed to walk on split media cultures of these fungi, 85% and 95% mortality was recorded, respectively (Filho et al., 1987). *Beauveria bassiana* isolated from species of the scarabaeid genus *Ligyrus* caused mortality of *C. sordidus* adults 10 days after application (Busoli et al., 1989). Four isolates of *B. bassiana* and one of *Metarhizium anisopliae* were pathogenic to third instar larvae of *C. sordidus* causing mortalities of 98–100% after 9 days of exposure to fungal spores. *Metarhizium anisopliae* was least pathogenic to larvae with LT_{50} attained after 4.2 days. *Beauveria bassiana* was also pathogenic to adult *C. sordidus*, causing mortality rates varying from 63–97% by 35 days after exposure depending on isolate. The LT_{50} for the bacterium, *Serratia marcescens* against larvae was 2.8 days. However, the bacterium did not kill adult *C. sordidus* even at 10 times the concentration applied on larvae (Kaaya et al., 1993).

A study on pathogen compatibility with chemical for use in combined applications against *C. sordidus* revealed that the fungus *B. bassiana* was compatible with paraquat (1200 ppm) and pirimiphos-ethyl (32 ppm) (Calderon et al., 1991).

Entomopathogenic Nematodes

Infection with *Neoaplectana carpocapsae* was reported to have a synergistic effect in increasing the mortality of *C. sordidus* when combined with insecticide kepone under laboratory conditions (Kermarrec and Mauleon, 1989). Figuera (1990) obtained 100% larval mortality of *C. sordidus* using three species, *Steinernema felitae, S. glaseri* and *S. bibionis* at populations of 4000 to 40,000/plant. The micro-environment within the corm supported survival and movement necessary for attraction and infection of larvae within the tunnels. The studies showed that 6th to 7th instar larvae of the weevil were vulnerable to all three nematode species. Parnitski et al. (1994) working with 31 strains of *Heterorhabditis* spp. and *Steinernema* spp. have demonstrated the variation in *C. sordidus* susceptibility to these nematodes between countries of nematode origin. Adults of *C. sordidus* were highly resistant to infection by *S. carpocapsae* and many other strains (Parnitski et al., 1994). The juveniles of entomopathogenic nematodes enter an insect's haemocoel via natural orifices (Poinar, 1990) and through interskeletal membranes (Bedding and Molyneux, 1983). In case of *C. sordidus* adults, the first abdominal spiracles provided an excellent site for entry, but the spiracles are well protected by the closely fitting elytra, unless they were partially removed (Treverrow, 1994). When various formulations of petroleum oil were added to preparations of *Steinernema carpocapsae*, 100% mortality of adult *C. sordidus* was consistently achieved in laboratory tests (Treverrow, 1994). Kermarec and Mauleon (1989) observed that though *S. carpocapsae* is effective in controlling *C. sordidus*, it is not economical under field conditions when the quantities of the nematode required are taken into consideration. The system may have been uneconomical because of application to soil and the use of an unspecified strain (Parnitski et al., 1994). However, Treverrow et al. (1991) reported promising results with densities considered economically acceptable in field trials when applied directly to the rhizome. Parnitski et al. (1994) expect considerable improvement in control with the use of superior strains of entomopathogenic nematodes. The use of semiochemicals to attract weevils to nematode-treated baits would also improve the economics of this control system.

Schmitt et al. (1992) reported that *S. carpocapsae* could be used to control *C. sordidus* through baiting. Spraying *S. carpocapsae* ALL and UK strains at a dosage of 5 x 10^6 nematodes/m^2 in 0.4 L water onto split pseudostems and pseudostem stumps as a baiting technique gave up to 70% mortality of adult *C. sordidus* recovered from traps 7 days after treatment and up to 40% mortality 14 and 21 days after treatment. Overall, the application of nematodes to pseudostem traps gave significantly greater control of weevils than the application of nematodes to soil around banana plants. Treverrow (1994) sees four advantages in using the entomopathogenic nematodes for the control of *C. sordidus:*

(i) Safety for the applicator and for the environment;
(ii) Avoidance of resistance inherent with conventional insecticides use;
(iii) Lack of disruption of the general terrestrial insect fauna including certain predators;
(iv) Elimination of the need to remove trash from the base of the mat prior to treatment which reduces labour costs and potential soil degradation due to increased erosion of bare soil and of depletion of soil organic matter.

Botanicals

Walangululu et al. (1993) applied a leaf powder mixture of *Tephrosia candida* and *T. vogelii* to pseudostem traps. The traps with the powders attracted only one weevil against 57 in the untreated traps. Lwande et al. (1985) isolated a new 60-hydroxylated pterocarpan, named hildecarpin from *Tephrosia hilderbrandtii*, which showed antifeedant behaviour against *Maruca testulalis*. This principle could be taken advantage of to prevent weevils feeding in the plantations by applying these plant powders or extracts at the junction of pseudostem and rhizome—the zone preferred by the weevil for egg laying. Although this pterocarpan is quite unstable (Prof. Hassanali, pers. commun.), other botanical-based plant repellents could exist in nature, and require more study.

Semiochemicals

Semiochemicals were found to play a role in the attraction and orientation of the weevils to the host plant. Attempts to understand the chemical basis of attraction revealed that pseudostem of Githumo, a susceptible cultivar, emanates volatile chemicals which include α-pinene (23.4%), β-pinene (14.2%), limonene (7.7%), α-cubebene (7.1%), α-copaene (17.8%), α-cedrene (2.8%), β-caryophyllene (15%) and α-humulene (65.6%) (Ndiege et al., 1991). Although the weevil can locate the source of the attraction, comparative studies of Githumo (susceptible) and Wangae (resistant) show no preference for one set of volatiles over the other. This suggests that preference of a cultivar may be controlled at the oviposition or feeding stage. Behavioural assays and electroantennograms have now confirmed the presence of male-produced aggregation pheromone system that is attractive to both males and females (Ndiege et al., 1991).

A blend of the major components of semiochemicals of cultivar Githumo failed to elicit any increase in behavioural or electrophysiological activity, over the natural component. Electrophysiological examination of the host plant volatiles showed the presence of several active minor components, which are very attractive. Budenberg et al. (1993b) suggested that these components should be identified to provide a chemical which can be used in traps. They identified a minor component monoterpene cineole as attractant.

Budenberg et al. (1993a) also demonstrated the release of an aggregation pheromone via the hindgut of the male banana weevil. It was observed that the male weevils produced the aggregation pheromone only when they have had access to banana tissue. Thus, males kept away from food source, elicited lower electro-antennogram signals and lost their attraction. Interestingly, trapped volatiles from large groups of male weevils that had been kept together without females in the laboratory for many months contained less pheromone per weevil than those similarly kept in the presence of females. This may have been due to the fact that the females were already present and available.

Mating behaviour of *C. sordidus* also strongly suggests the mediation of a female-produced sex pheromone as evidenced from male responses to body washings and volatile trappings of adult and virgin females.

Interrelationship between Banana Weevil and the Nematodes

Weevils and nematodes are often found attacking the same plant but their individual importance in causing yield loss is often debated (Ostmark, 1974; Jones, 1986; Waterhouse and Norris, 1987; Sikora et al., 1989). Walker et al. (1983) hypothesised that though nematodes and weevils occurred together on the same plants, there was no direct relationship between the two pests; both the pests caused different types of damage independent of each other. However, Herrera et al. (1976) observed that it is virtually impossible to deduce the role of borers in isolation, since banana growing without nematode control results in such large numbers of toppled plants. In the Kagera district of Tanzania, the damage caused by the weevil, the nematode and the combination of the two were estimated as rhizome breakage 57%, uprooting 85% and combined damage 40% respectively (Bujulu et al., 1983). Loebel (1975) found that control of the weevil infestation alone produced no significant improvements in plant growth or yield which indicated the presence of other limiting factors. Where borers do play a decisive role is at the planting stage. When planting takes place in fields with high residual borer populations or adjacent to old fields with high populations, losses of 100% are not uncommon. Nsemwa (1991) observed the combined damage by banana weevil and nematodes significantly affected banana production in Tanzania. He suggested that in order to improve production of the crop both of these pests had to be controlled. Bridge (1987) envisaged that understanding the role plant parasitic nematodes play in highland banana cultivation in relation to other pest and disease organisms, environmental constraints, and cropping systems is essential if we are to produce the required solutions. Sikora et al. (1989) considered weevil damage by *C. sordidus* and nematode infestations by *P. goodeyi* together with poor agronomic practices as maladies of banana plantations in Tanzania. Herrera et al. (1976) treated a mixed infestation of *C. sordidus* and the nematode, *Radopholus similis* with doses of 12.5, 24.0, 37.5 and 75.0 g per mat of aldicarb, and found net yield increases in the average numbers of commercial fingers per bunch of 7.7, 9.6, 12.8 and 15.7 t/ha. Speijer et al. (1993) observed a strong association between nematode and weevil infestation. They reported that the suckers infested with nematodes were more than four times more likely to be infested by weevil than suckers without nematodes. In addition, Mitchell (1978) observed increases in nematode population when *C. sordidus* was eliminated.

Field experiment with continuous trapping of weevils over 2 years resulted in a 50% reduction in the weevil population and a 31.2% increase in yield over no trapping (Seshu Reddy et al., 1994). However, the yield increase recorded in the trapping treatments was low, i.e. 5.01 t/ha which is far below the potential yield of the cultivar Nakyetengu, used in the experiment. The yield reduction was explained when the nematode population was taken into consideration. Infestations of *Pratylenchus goodeyi* (97,975/100 g root) in the plots with weevil trapping increased 13 times in comparison to plots without trapping. This indicated the plants infested with weevils are not as suitable for *P. goodeyi* reproduction as weevil-free plants. This may be because the roots of plants where the rhizomes are debilitated by larval tunnelling may be poor sources of nutrients and hence not preferred by the nematode. Furthermore, *C. sordidus*-infested plants showed brittle roots, that were less in number and usually in a state of rotting. The problem of poor or nil yield responses in Tanzania, Uganda and Australia even after control of weevils using insecticides (Loebel, 1975; Anon, 1984; Sebasigari and Stover, 1987) might be due to nematode population buildup in the absence of weevils resulting in poor yields.

Interaction of Environmentally Sustainable Plant Protection (ESPP) for Low Input Banana Production

A critical review of the information available on different components for the management of borers in banana reveals that no single component by itself is adequate in controlling the pest especially in low input agriculture. As Peasley and Treverrow (1986) put it "Intensively worked plantations often prove more profitable than simply expanding acreage and compromising plantation hygiene". Selection of compatible and combination of available components will go a long way in the management of weevils.

Chemicals are uneconomical and are hazardous for use in low input agriculture associated with resource-limited farming practices. However, chemicals could form a good component in ESPP if used with discretion. Chemicals such as aldicarb, could be used against the banana weevil in commercial plantations, under expert supervision, where quality of the produce plays a major role and the returns are assured. Host plant resistance constitutes a major component of most IPM programmes, however, few cultivars tolerant to the weevils are presently available. Genetic improvement of these cultivars with incorporation of resistance to other major pests like nematodes and black sigatoka and Panama diseases is essential. As bananas are parthenocarpic, and conventional breeding is not practical, non-conventional methods should be adopted for the incorporation of resistant characters and improved traits. The working group on nonconventional strategies for producing banana and plantain resistant to pathogens and pests in the workshop on biotechnology application for banana and plantain improvement held in San Jose, Costa Rica (1992) suggested that "resistance to banana borer weevil, mediated by genes from *Bacillus thuringiensis* for toxin production should be investigated" (Anon, 1992b).

Selection of healthy and clean planting material, deep planting and field sanitation are important. Trapping of weevils using split pseudostem traps from the start helps to keep the weevil populations under control. However, studies show that trapping alone was not effective. Weeding every four weeks along with trapping was more efficient in the management of weevils than chemical treatments (Murillo and Bernal, 1987). Application of entomopathogenic fungi or nematodes to the traps could help to do away with manual collection and killing of the weevils. However, it is essential to select highly virulent strains of nematodes or pathogens for the control of the weevils. Utilisation of semiochemicals for the improvement of catch efficiency in combination with pathogens and nematodes on the traps is a viable proposition. The botanicals with antifeedant properties need more consideration and study. Though the predators, *D. abdominale* and *Tetramorium* spp. are reported to be effective in controlling the weevil, field scale studies are required to determine their efficiency. The interplay of environmental conditions and biocontrol requires special attention in finding suitable predators, parasitoids or pathogens which are equally effective in the dry season when higher number of developing stages of the weevil prevail. Field studies are required to confirm the effectiveness and the compatibility of the predators and pathogens.

The importance of selection of suitable intercrops and maintenance of nutrient balance in the fields also needs intensive study.

References

Abraham C. C., Remamony K. S. and Joy P. J. (1978) On the occurrence of *Assurania* spp. (Chloropidae : Diptera) as a pest of banana. *Entomon* 3, 311.

Ackland J. D. (1980) *Bananas* Musa *spp. in East African Crops.* FAO, Longman Ltd.

Annet E. (1940) Note sur les dégats causés aux bananiers par l'*Heteronychus claudius. Rev. Bot. Appl.* 20, 119–121.

Anonymous (1913) Root borers and other grubs in West Indian soils. *Agric. News,* Barbados, 12, 154–155.

Anonymous (1966) Instituto Agronomico per L'oltre Mare. Scheda entomologia di *Cosmopolites (Calandra) sordidus* (Germar, 1824). *Rivista di Agricultural Subtropicale e Tropicale, Firenze* 60, 1–4.

Anonymous (1968) Commonwealth Institute of Entomology. Distribution maps of pests, Series A. (Agricultural) Map 4 (revised). Queensgate, London.

Anonymous (1980) Empresa Brasileira de Pesquisa Agropecuaria. Centro Nacional de Pesquisa de Mandioca e Fruticultura, Cruz das Almas—BA. Relatório técnico anual do Centro National de Pesquisa de Mandioca e Fruticultura, Brasela, D. F. DID, 183 pp.

Anonymous (1984) Banana Pest Control in Tanzania. Report, Centre for Overseas Pest Research, UK, 37 pp.

Anonymous (1990) *Annual Report*, ICIPE, Nairobi.

Anonymous (1992a) Annual Research Progress Report on the Development of banana-based integrated pest management (IPM) strategies for the Lake Victoria Basin Countries in Eastern Africa. Submitted to the Ministry of Economic Cooperation, Germany.

Anonymous (1992b) Proceedings of International Symp. on Biotechnology Applications for Banana and Plantain Improvement. 27–31 Jan 1992. San Jose, Costa Rica.

Asante S. K. and Kumar R. (1986) Biology of *Temnoschoita quadrimaculata* (Coleoptera: Curculionidae) on oil palm in Ghana. *Insect Sci. Applic.* 7, 129–134.

Beccari F. (1967) Contributo alla Conoscenza del *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae). *Rivista di Agriculture Subtropicale e Tropicale, Firenze* 61, 131–150.

Bedding R. A. and Molyneux A. S. (1983) Penetration of insect cuticle by infective juveniles of *Heterorhabditis* spp. (Heterorhabditidae: Nematoda). *Nematologica* 28, 354–359.

Bhuyan R., Buragohain S. C. and Baruah K. K. (1989) Evaluation of banana (*Musa* spp.) leaves in the diet of kids. *Indian J. Anim. Nutrition* 6, 62–64.

Billen W. (1978) Informationen zum Bananentnebbohrer (*Opogona sacchari* Bojer 1956) (Lepidoptera: Tineidae). *Gebunde-Polanzen* 39(11), 458–465.

Bodkin G. E. (1916) Report of the economic biologist. Report of the Dept. Sci. and Agric. British Guiana for the period 31st September 1915 to 12 July 1916. 10 pp.

Braithwaite B. M. (1967) Banana beetle borer control investigations on the north coast of New South Wales. *Agricultural Gazette of New South Wales* 78, 359.

Bridge J. (1975) Hot water treatment to control plant parasitic nematodes of tropical crops. *Meded. Facult. Landbouww., Gent.* 40, 249–259.

Bridge J. (1987) Plant nematode pests of banana in East Africa with particular reference to Tanzania, pp. 35–39. In *Nematodes and the Borer Weevil in Bananas.* Proceedings of a Workshop held in Bujumbura, Burundi, 7–11 December 1987.

Budenberg W. J., Ndiege I. O. and Karago F. W. (1993a) Evidence for volatile male-produced pheromone in banana weevil *Cosmopolites sordidus. J. Chem. Ecol.* 19, 1905–1916.

Budenberg W. J., Ndiege I. O., Karago F. W. and Hansson B. S. (1993b) Behavioural and electrophysical responses of the banana weevil *Cosmopolites sordidus* to host plant volatiles. *J. Chem. Ecol.* 19, 267–277.

Bujulu J., Uronu B. and Cumming C. N. E. (1983) The control of banana weevil and plant parasitic nematodes in Tanzania. *E. Afr. Agric. For. J.* 49, 1–13.

Bullock R. C. and Evers C. (1962) Control of banana root borer (*Cosmopolites sordidus* Germar) with granular insecticides. *Trop. Agric. Trin.* 39, 109–113.

Busoli A. C., Fernandes O. A. and Tayra O. (1989) Controle de broca da bananneira *Cosmopolites sordidus* Germar 1824 (Coleoptera: Curculionidae) atraves dos fungos entomopatogenicos *Beauveria bassiana* (Bals.) Vuill. e *Metarhizium anisopliae* (Metschn.) Sorok. (Hyphomycetes). *Anais da Sociedade Entomologica do Brasil,* 18, (Suppl) 33–41.

Calderon A., Castineires A. and Lopez M. (1991) Efecto de los biocidas y fertilizantes empleados el cultivo del plátano en cuba sobre los hongos entomopatógenos. I. *Beauveria bassiana. Protecion de Plantas* 1(1), 21–31.

Castineiras A. and Ponce E. (1991) Effectiveness of the use of *Pheidole megacephala* (Hymenoptera: Formicidae) in the biological control of *Cosmopolites sordidus* (Coleoptera: Curculionidae). *Proteccion de Plantas* 1(2), 15–21.

CGIAR (1992) Future Priorities and Strategies. CGIAR Technical Advisory Committee. TAC Secretariat FAO, Rome, Italy.

CGIAR (1993) Progress Report by the CGIAR Task Force on Banana and Plantain Research, CGIAR Secretariat, World Bank, Washington, DC, USA.

Chapman T. and Emsley M. (1963) The banana moth borer *(Castniomera humboldti)* in Trinidad. *J. Agric. Soc., Trinidad and Tobago* 63, 269.

Corbett G. H. (1936) Division of Entomology —Annual Report for the year.

Cuille J. (1950) Recherches sur le charancon du bananier *Cosmopolites sordidus* (Germar). *I.F.A.C. Ser. Tech. No. 4,* 225 pp.

Daniells J. W., Pinese B., Peterson R. A. and Piper R. G. (1992) Strategies for reducing pesticide use in bananas in Australia. In *Breeding Banana and Plantain for Resistance to Diseases and Pests.* Proceedings of the International Symp. on Genetic Improvement of Bananas for Resistance to Diseases and Pests 7–9 Sep. 1992. CIRAD-FLHOR, Montpellier, France.

Delattre P. and Bart A. J. (1978) The effect of entomopathogenic fungi (Fungi imperfecti) on adults of *Cosmopolites sordidus* Germ. (Coleoptera: Curculionidae). *Turrialba* 28, 287–293.

Dutt N. and Maiti B. B. (1974) Studies on the control of banana pseudostem weevils *Odoiporus longicollis* (Oliv). *Indian J. Entomol.* 34, 272–289.

Edge V. E. (1974) Cyclodiene-BHC resistance in *Cosmopolites sordidus* (Germ.) (Coleoptera: Curculionidae) in New South Wales, Australia. *Bull. Entomol. Res.* 64, 1–7.

Edge V. E., Wright W. E. and Gondyer G. J. (1975) The development and distribution of dieldrin resistance in banana weevil borer, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) in New South Wales. *J. Australian Entomological Soc.* 14, 165–169.

FAO (1993) *Food and Agriculture Organization Production Year Book,* 1992.

Figuera W. (1990) Biocontrol of the banana root borer weevil, *Cosmopolites sordidus* (Germar), with *Steinernematid* nematodes. *J. Agric. P. R.* 74, 17–19.

Filho B. (1990) Attracao de *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) por iscas do tipo “Sanduiche” e “telha”. *Arquivos do Instituto Biologico* 57, 9–13.

Filho A. B., Camargo L. M. P. C. A., Myazaki I., Cruz B. P. B., Oliveira D. A., Camargo L. M. C. D. A. and Cruz B. P. B. (1987) Biological control of the banana root borer (*Cosmopolites sordidus* Germar, 1824) by entomogenous fungi in the laboratory. *Biologico* 53, 1–6.

Franzmann F. A. (1972) Banana weevil borer in North Queensland.

Queensland Agric. J. 98, 319–321.

Froggatt J. L. (1925) The banana weevil borer *Cosmopolites sordidus* (Germ.). *Queensland Agric. J.* 24, 558–593.

Froggatt J. L. (1928) Notes on banana insect pests. *Queensland Agric. J.* 29, 15–35.

Gaud S. M., Tuduri G. J. and Martorell L. F. (1975) Preliminary screening of pesticides for control of banana root borer *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae). *J. Agric. Univ. Puerto Rico* 59, 79–81.

Getmann A. D., Mitchel W. C., Loui P. R. and Mau R. F. L. (1992) A hot water treatment for the banana root borer, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) in banana planting stock. *Proceedings of the Hawaiian Entomological Society* (USA) 31 Dec, 1992.

Gruner L. (1969) Le hanneton autillais *Phyllophaga pleei* Bl et ses dégats en zone bananière de la Guadaloupe, pp. 148–155. In *Proc. Ann. Meet. Assoc. Inter. Caribb. Plantes Alimen. Caribb. Food Crops Soc.*

Gowen S. R. and Queneherve P. (1990) Nematode parasites of bananas, plantains and abaca, pp. 431–460. In *Plant Parasitic Nematodes in Sub-Tropical and Tropical Agriculture* (Edited by M. Luc, R. A. Sikora and J. Bridge). CABI, Wallingford, UK.

Haddad G. O., Surga R. J. R. and Manuel W. O. y (1980) Relacion de la complosicion genomica de las musaceas con el grado de atraccion de adultos y de larvas de *Cosmopolites sordidus* G. (Coleoptera: Curculionidae). *Agronomia Tropical.* XXIX(5), 429–438.

Harris W. V. (1947) The banana borer. *The East African Agric. J.* July 1947, pp. 15–18.

Harrison J. O. (1963) Notes on the biology of the banana flower thrips, *Frankliniella parvula* in the Dominican Republic. *Ann. Ent. Soc. Am.* 56, 664–666.

Herrera T. A., Viera H. M. T. and Zarate L. L. (1976) Chemical control of *Radopholus similis* (Cobb) and *Cosmopolites sordidus* (Germ.) with aldicarb and aldrin in a banana plantation, variety Isla, in Tingo Maria, Peru. *Acta Hort.* 57, 223–231.

Hord H. H. V. and Flippin R. S. (1956) Studies on banana weevils in Honduras. *J. Econ. Entomol.* 49, 296–300.

Ingles R. and Rodriguez J. (1989) Evaluacion de plaguicidas y metodos para combatir el picudo negrodel plantano (*Cosmopolites sordidus* Germar). *J. Agric. Univ. Puerto Rico* 73, 97–107.

Irizarry H., Rivera E., Rodriguez J. A., Caloni I. B. De, Orarnas D. and Caloni I. B. de (1988) The Lacknow plantain: A high yielding cultivar with field resistance to the corm weevil, *Cosmopolites sordidus* (Germar). *J. Agric. Univ. Puerto Rico* 72, 353–363.

Isahaque N. M. M. (1978) A note on the incidence of *Odoiporus longicollis* (Oliv.) on banana in Assam. *Pesticides* 12(6), 22–24.

Ittyeipe K. (1986) Studies on host preference of banana weevil borer, *Cosmopolites sordidus* Germ. (Coleoptera: Curculionidae). *Fruits* 41(6), 375–379.

Jepson J. F. (1914) A mission to Java in quest of natural enemies for a Coleopterous pest of bananas. *Fiji Department of Agriculture, Suva. Bulletin.* No. 7, 18 pp.

Jones M. T. (1986) Pests and diseases of bananas and plantains of Trinidad and Tobago. *J. Agric. Soc. Trinidad and Tobago* 86, 18–33.

Kaaya G. P., Seshu Reddy K. V., Kokwaro E. D. and Munyinyi D. M. (1993) Pathogenicity of *Beauveria bassiana, Metarhizium anisopliae* and *Serratia marcescens* to the banana weevil *Cosmopolites sordidus. Biocontr. Sci. Technol.* 3, 177–187.

Kehe M. (1988) Banana weevil *(Cosmopolites sordidus)* experiences and perspectives of research: Contribution of IRFA-CIRAD/Ivory Coast. In *Nematodes and Borer Weevil in Bananas: Present Status of Research and Outlook.* Proceedings of the Workshop held in Bujumbura, Burundi, 7–11 December 1987. INIBAP, Montpellier, France.

Kermarrec A. and Mauleon H. (1989) Synegie entre le chlodecone et *Neoaplactana carpocapsae* Weiser (Nematoda: Steinernematidae) pour le controle de *Cosmopolites sordidus,* (Coleoptera: Curculionidae). *Revue Nematol.* 12, 324–334.

Koppenhoefer A. (1992) Zum spektrum der natürlichen feinde des bananenrüblers *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) in West Kenia und seiner integrierten bekämfung. Dissertation zur Eralangung des Doktorgrades im Fachbereich Agvar wissenschaften der Justus-Léebig-Universitat, Germany.

Koppenhoefer A.M. (1993) Egg predators of the banana weevil, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) in western Kenya. *J. Appl. Ent.* 116, 352–357.

Koppenhoefer A.M. and Schmutterer H. (1993) *Dactylosternum abdominale* (F.) (Coleoptera : Hydrophilidae): A predator of the banana weevil. *Biocontrol Science and Technology* 3, 141–147.

Koppenhoefer A.M., Seshu Reddy K. V., Madel G. and Lubega M. C. (1992) Predators of the banana weevil *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) in western Kenya. *J. Appl. Entomol.* 114, 530–533.

Landono Z. M. E. (1991) Manejo integrado de plagas. In *El cultivo del platano* (Musa *ABB Simmonds) en el tropico-Belalcazar* 5, 299–326.

Lara E. F. (1966) The banana stalk borer *Castniomera humboldti* (Boisduval) in da Estrella Valley, Costa Rica. V. Cultural control. *Turrialba* 16, 136–138.

Lepesme P. and Paulian R. (1941) Sur la présence de *Metamarius sericeus* Ol. dans l'Ouest Africain (Coleoptera: Curculionidae). *Bull. Soc. Entomol.* 31–37.

Liceras L., Urrelo G. R. and Beltran F. S. (1973) Test for the control of banana weevil, *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae) at the time of planting. *Revista Peruana de Entomologia* 16, 50–54.

Loebel R. (1975) Weevil borer not main cause of plantation decline. *Banana Bulletin* 39(7), 10.

Lopez A. B. and Lopez M. (1987) Poder de percepcion de la hormiga *Tetramorium guineense* para el control del picudo negro del plantano. *Ciencias de la Agricultura* 30, 13–15.

Lopez A. B. and Ramos N. G. (1986) Comportamiento de poblaciones de *Cosmopolites sordidus* y *Tetramorium guineense* on condiciones naturales. *Ciencias de la Agricultura* 28, 9–12.

Luo L. Y., Luo Q. C., Yao X. and Liu Z. L. (1985) Weevils injurious to banana in Guizhou and their biological features. *Insect Knowledge Kunchang Zhishi* 22(6), 265–267.

Lwande W., Hassanali A., Njoroge P. W., Bentley M. D., Monache F. D. and Jondiko J. I. (1985) A new 6-hydroxypterocarpan with insect antifeedant and antifungal properties from the roots of *Tephrosia hildebrandti* Vatke. *Insect Sci. Applic.* 6, 537–541.

Marriot H. and Lancaster P.A. (1983) Bananas and plantains, pp. 85–143.

In *Handbook of Tropical Foods* (Edited by H. T. Cham). Marcel Dekker, New York, USA.

Martinez M. D. L., Gonzalez A. and Longoria G. (1990) Oviposición y dessarollo de *Cosmopolites sordidus* (Coleoptera: Curculionidae) en plátano y malanga. *Ciencias de la Agricultura* 40, 169–171.

Masefield G. B. (1944) Some recent observations on the plantain crop in Buganda. *The East African Agric. J.* July, 1944, 12–17.

McNutt D. N. (1974) A review of banana weevil control in Uganda, with further tests on dieldrin formulations. *East African Agric. For. J.* 39, 205–209.

Mello E. J. R., Mello R. H. de and Filho N.S. (1980) Laboratory tests to verify the action of phosphorus and carbamate granular insecticides on banana borers, resistant to aldrin. *Biologico* 46(7), 141–143.

Mesquita A. L. M. (1991) Iscas controlam to moleque. *Lavoura* 27–28.

Mesquita A. L. M., Alves E. J. and Caldas R. C. (1984) Resistance of banana cultivars to *Cosmopolites sordidus* (Germar, 1928). *Fruits* 39(4), 254–257.

Mesquita A. L. M. and Caldas R. C. (1986) Efeito da idade e da cultivar de bananeira sobre a biologia a preferência do *Cosmopolites sordidus* (Germar, 1920) (Coleoptera, Curculionidae). *Fruits* 41(4), 245–249.

Mitchell G. A. (1978) The estimation of banana borer population and resistance levels. *WINBAN Research and Technical Bulletin* No. 2. Windward Islands.

Mitchell G. A. (1980) Banana Entomology in the Windward Islands. Final Report, 1974–1978. Centre for Overseas Pest Research, London.

Morez H. (1962) Note sur un coleopteres *Phyllophaga* dans les bananeraies in Guadeloupe. *Fruits* 17, 7.

Murillo C. R. and Bernal L. G. R. (1987) Control del picuda negro *Cosmopolites sordidus* (Germar 1924) del plantano *Musa* AAB Simmonds. *Mediante practicas culturales Cenicafé,* 38(1–4), 50–61.

Nanne H. W. and Klink J. W. (1975) Reducing banana root weevil adults from an established banana plantation. *Turrialba* 25, 177–178.

Neuenschwander P. (1988) Prospects and proposals for biological control of *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) in Africa, pp. 54–57. In *Nematodes and the Borer Weevil in Bananas. Present Status of Research and Outlook.* Proceedings of a Workshop held in Bujumbura, Burundi, 7–11 December 1987. INIBAP, Montpellier, France.

Ndiege I. O., Budenberg W. J., Lwande W. and Hassanali A. (1991) Volatile components of banana pseudostem of a cultivar susceptible to the banana weevil. *Phytochemistry* 30, 3929–3930.

Noqueira S. B., Lima J. O. G. de and Manica I. (1985) Effect of some insecticides, alcohols, and esters applied in baits against the banana borer *Cosmopolites sordidus. Agronomia Subriograndense* 19, 15–34.

Nsemwa L. T. H. (1991) Problems of banana weevils and nematodes in southern highlands of Tanzania. Paper presented at the Banana Sigatoka Disease Workshop in Zanzibar, 23–25 January 1991.

Ostmark H. E. (1974) Economic insect pests of bananas. *Annu. Rev. Entomol.* 19, 161–174.

Paine R. W. (1964) The banana scab moth *Nicoleia octasema* (Meyrick): Its distribution, ecology, and control.

Tech. Pap. S. Pac. Comm. 145, 70 pp.

Parnitski P., Treverrow N. L., Bedding R. A. and Sikora R. A. (1994) Screening of 31 *Heterorhabditis* spp. and *Steinernema* spp. for the control of adults of *Cosmopolites sordidus* in laboratory trials in Tonga and Australia. *Fundam. Appl. Nematol.* (in press).

Parra O. C. (1989) Manejo de problemas entomologicas en los cultivos de plátano y banano, pp. 100–126. In *Manual sobre el cultivo del plántano.* Federacion Nacional de Cafeteros de Colombia.

Pavis C. and Minsot C. (1992) Banana resistance to the banana weevil borer *Cosmopolites sordidus*: Role of pseudostem attractivity and physical properties of the rhizome. In *Breeding Banana and Plantain for Resistance to Diseases and Pests.* Proceedings of the International Symposium on Genetic Improvement of Banana for Resistance to Diseases and Pests. CIRAD-FLHOR, 7–9 Sep. 1992, Montpellier, France.

Peasley D. L. and Treverrow N. (1984) Control of high populations of banana weevil borer from a single application of insecticide. *Banana Bulletin* 48(8), 9–11.

Peasley D. L. and Treverrow N. (1986) *Count, Cut and Dry: Management of Banana Weevil Borer in Bananas.* Australia, New South Wales, Dept. of Agriculture. 4 pp.

Pinese B. (1989) Controlling banana weevil borer. *Banana Bulletin* 53(1), 6–8.

Poinar G. O. (1990) Biology and taxonomy of Steinernematidae and Heterorhabditae, pp. 23–61. In *Entomopathogenic Nematodes in Biological Control* (Edited by R. Gaugler and H. K. Kaya). CRC Press, Boca Raton, Boston, USA.

Prasad J. S. and Seshu Reddy K. V. (1994) Hot water treatment for banana planting material made easier! *InfoMusa* 3(2), 16.

Pullen J. (1973) The control of the banana weevil (*Cosmopolites sordidus*) in Latin America and the Caribbean with pirimiphos ethyl. *PANS* 19(2), 178–181.

Rao M. M. and Reid E. D. (1987) Studies on plantain based cropping system in the Windward Islands. *4th Ann. Rep.* Winban Research and Dev. Div.

Rao P. S., Ganapathi T. R., Suprasanna, P. and Bapat V. A. (1993) Encapsulated shoot tips of banana: A new propagation and delivery system. *InfoMusa* 2(2), 4–5.

Reis P. R. and DeSouza J. C. (1986) Principais Pragas da bananeira. *Informe Agropecuario* 12(133), 45–55.

Risch S. J. (1980) Fewer beetle pests on beans and cowpeas interplanted with banana in Costa Rica. *Turrialba* 30, 228–229.

Risch S. J. (1982) Fewer beetle pests on beans and cowpeas interplanted with banana in Costa Rica. *Turrialba* 32, 210–212.

Roberts F. S. (1955) The banana root borer (*Cosmopolites sordidus* Germar), La Lima. United Fruit Company (*Circular,* 29), 11 pp.

Roche R. (1975) Preliminary note on the ant *Tetramorium guineense*, for biological control of the banana weevil. *Revista de Agricultura,* Cuba 8, 35–37.

Roche R. and Abreu S. (1982) Dispersal of the ant *Tetramorium guineense* (Meyr) (Hymenoptera : Formicidae). *Cliencias de Agricultura* No. 13, 12.

Roche R. and Abreu S. (1983) Control of the banana weevil (*Cosmopolites sordidus*) by the ant *Tetramorium guineense. Cliencias de la Agricultura* 17, 41–49.

Roche R. and Abreu S. (1984) Artificial rearing of the ant *Tetramorium guineense* under laboratory conditions. *Cliencias de la Agricultura* No. 18, 47–52.

Sampaio A. S., Myazaki I., Filho N. S. and Oliveira D. A. (1982) Banana borer—*Cosmopolites sordidus* (Germar, 1924) (Coleoptera: Curculionidae) resistant to aldrin and its control with systemic insecticides applied to the soil. *Biologico* 48(4), 91–98.

Sarah J. L. (1988) Future prospects for the control of parasitic nematodes of bananas and plantains, pp. 75–79.In *Nematodes and the Borer Weevil in Bananas. Present Status of Research and Outlook.* Proceedings of a Workshop held in Bujumbura, Burundi, 7–11 December 1987. INIBAP, Montpellier, France.

Sarah J. L. and Jones D. (1992) Constraints related to pests and diseases. In *Breeding Banana and Plantain for Resistance to Diseases and Pests.* Proceedings of the International Symposium on Genetic Improvement of Bananas for Resistance to Diseases and Pests, 7–9 Sept. 1992, CIRAD-FLHOR, Montpellier, France.

Saunders G. W. and Elder R. J. (1966) Sterilization of banana fruit infested with banana fruitfly. *Queensland J. Agric. Anim. Sci.* 23, 81–85.

Schmitt A. T., Gowen S. R. and Hague N. G. M. (1992) Baiting techniques for the control of *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae) by *Steinernema carpocapsae* (Nematoda: Steinernematidae). *Nematropica* 22, 159–163.

Sebasigari K. and Stover R. H. (1987) Banana diseases and pests in East Africa. Report of a Survey, 1987.

Seshu Reddy K. V. (1987) Some biological observations on the banana weevil in western Kenya. *Proceedings of the International Symposium on Nematodes and the Borer Weevil in Bananas. Present Status and Outlook.* 7–11 December 1987, Bujumbura, Burundi. INIBAP Montpellier, France.

Seshu Reddy K. V. and Lubega M. C. (1992) Evaluation of banana cultivars for resistance/tolerance of the weevil *Cosmopolites sordidus* Germar. In *Breeding Banana and Plantain for Resistance to Diseases and Pests.* Proceedings of the International Symposium on Genetic Improvement of Bananas for Resistance to Diseases and Pests, 7–9 Sept. 1992, CIRAD-FLHOR, Montpellier, France.

Seshu Reddy K. V., Prasad J. S., Ngode L. and Sikora R. A. (1995) Influence of trapping of weevil, *Cosmopolites sordidus* (Germar 1824) on root lesion nematode, *Pratylenchus goodeyi* Sher and Allen (1953). Population densities and subsequent banana yield. *Acta Oecologica* 16, 593–598.

Sery G. D. (1988) Orientation of research for formulating new methods for the control of nematodes and borer weevil on bananas and plantain. In *Nematodes and the Borer Weevil in Bananas. Present Status of Research and Outlook.* Proceedings of a Workshop held in Bujumbura, Burundi, 7–9 December, 1987. INIBAP, Montpellier, France.

Shanahan G. J. and Goodyer G. J. (1974) Dieldrin resistance in *Cosmopolites sordidus* in New South Wales, Australia. *J. Econ. Entomol.* 67, 446–447.

Sikora R. A., Bafokuzara N. D., Mbwana A. S. S., Oloo G. W., Uronu B. and Seshu Reddy K. V. (1989) Interrelationship between the banana weevil, root lesion nematode and agronomic practices, and their importance in banana decline in the United Republic of Tanzania. *FAO Plant Prot. Bull.* 37(4), 151–157.

Simmonds N. W. (1973) Plagas, pp. 315–

382. In *Los Platanos.* Editorial Blume, Barcelona.

Sotomayor B. B. (1972) Resistance of *Cosmopolites sordidus* Germar to organochlorine compounds in Ecuador. *Revista Peruana de Entomologia* 15, 169–175.

Speijer P. R., Budenberg J. W. and Sikora R. A. (1993) Relationships between nematodes, weevils, banana and plantain cultivars and damage. *Ann. Appl. Biol.* 123, 517–525.

Staver C. (1989) Why farmers rotate fields in maize – cassava – plantain bush fallow agriculture in the wet Peruvian Amazon. *Human Ecology,* New York. 17, 401–426.

Stephen C. (1992) Control natural de las plagas del banano en algunas plantaceones de Centro America. In *International Congress on Integrated Pest Management.* Tegucigalpa, Spain.

Stephens C. S. (1984) Bionomics of three *Philicoptus* banana pests (Coleoptera: Curculionidae) and notes on other weevils in Mindanao, Philippines. *Philippine Agriculturist* 67(2), 243–253.

Stover R. H. (1972) *Banana, Plantain and Abaca Diseases,* pp.179–181. Commonwealth Mycological Institute, Kew, UK.

Stover R. H. (1977) Banana (*Musa* spp.). In *Plant Health and Quarantine in International Transfer of Genetic Resources* (Edited by W. B. Hewitt and L. Chiarappa). CRC Press Inc., Cleveland, Ohio.

Stover R. H. and Ostmark H. E. (1979) *Integrated Plant Protection in Bananas and Plantains,* pp. 564–567.

Stover R. H. and Simmonds N. W. (1987) Bananas. Ed–3. Tropical Agriculture Series, Harlow, Essex, U.K. Longman Scientific and Technical. 467 pp.

Suresh S. and Regupathy A. (1988) Residues of systemic insecticides in banana. *South Indian Horticulture* 36(5), 232–236.

Swaine G. and Corcoran R. J. (1970) Corky scab of bananas. *Queensland Agric. J.* 96, 474–475.

Swaine G. and Corcoran R. J. (1973) Laboratory tests against banana weevil borer showing indications of being resistant to dieldrin. *Queensland J. Agric. Anim. Sci.* 30, 73–77.

Swaine G., Pinese B. and Corcoran R. J. (1980) Dieldrin resistance in the banana weevil borer, *Cosmopolites sordidus* Germ. in Queensland. *Queensland J. Agric. Anim. Sci.* 37, 35–37.

Temperley M. E. (1930) Life history notes on the banana fruit-eating caterpillar (*Tiracola plagiata* Walk.). *Queensl. Agric. J.* 33, 251–261.

Ternisien E. (1989) Crop rotation is profitable for banana producers in the French West Indies. *Nematropica* 19(1), 19.

Treverrow N. (1985) Banana weevil borer. Agdex 231/622, Dept. of Agric., New South Wales, Australia.

Treverrow N. (1994) Control of banana weevil borer, *Cosmopolites sordidus* with entomopathogenic nematodes. Paper presented at the International Symposium on Bananas. 18–22 April 1994, Kuala Lumpur, Malaysia.

Treverrow N., Bedding R. A., Dettman E. B. and Maddox C. (1991) Evaluation of entomopathogenic nematodes for control of *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae), a major pest of bananas in Australia. *Ann. Appl. Biol.* 119, 139–145.

Uronu B. E. M. A. (1992) The effect of plant resistance and cultural practices on the population densities of banana weevil, *Cosmopolites sordidus* (Germar) and on banana yield. PhD thesis submitted to Kenyatta University, Nairobi.

Veitch R. (1941) Report of the Director

of Plant Industry. Rep. Dept. Agr. Queensland 1940–41.

Vilardebo A. (1973) Le efficient d'infestation critere d'evaluation du degre et attaques des bananerais par *Cosmopolites sordidus* Germ. le charancon noir du bananier. *Fruits* 28(6), 416–417.

Vilardebo A. and Guérout R. (1964) *Phesia chalcytes* Esp. nuisible au bananier dans ces régions côtieres de l'Ouest Africain. *Fruits* 19, 195–208.

Vilardebo A., Boisseau M., Lassoudiere A., Melin P. and Ternisien E. (1988) Experimentation avec l'aldicorbe pour lutter contre *Radopholus similis* Cobb (Nematoda: Pratylenchidae) et *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) en bananeraie. I. Experimentation réalisée en Martinique et au Caméroun. *Fruits* 43, 417–431.

Viswanath B. N. (1977) Studies on the biology, varietal response and control of banana rhizome weevil, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae). *Mysore J. Agric. Sci.* 4, 597–598.

Viswanath B. N. (1981) Development of *Cosmopolites sordidus* (Coleoptera: Curculionidae) on banana varieties in South India. *Colemania* 1(1), 57–58.

Walangululu M., Litucha B. M. and Musasa M. (1993) Potential for the control of the banana weevil *Cosmopolites sordidus* Germar with plants reputed to have an insecticidal effect. *InfoMusa* 2, 9.

Walker P. T., Hebblethwaite M. J. and Bridge J. (1983) Project for banana pest control and improvement in Tanzania. A report to the Government of Tanzania. Tropical Development and Research Institute with Commonwealth Institute of Parasitology, 141 pp.

Wallace C. R. (1938) Measurement of beetle migration in banana plantations. *Journal of the Australian Institute of Agricultural Science* 4, 215–219.

Waterhouse D. F. and Norris K. R. (Eds) (1987) *Biological Control: Pacific Prospects.* Melbourne, Inkata Press.

Whalley P. E. S. (1957) The banana weevil and its control. *The East African Agric. J.* 110–112.

Wolcott G. N. (1921) Annual Report of the Division of Entomology. *Ann. Rep. Insul. Exp. Stn Rio Piedras, P. Rico,* 1920–21.

Wolcott G. N. (1933) *An Economic Entomology of West Indies.* The Entomol. Soc. Puerto Rico, San Juan, 688 pp.

Wright W. E. (1977) Insecticides for the control of dieldrin resistant banana borer, *Cosmopolites sordidus* Germar. *Australian J. Exp. Agric. Anim. Husbandry* 17, 500–504.

Wyniger R. (1962) Pests of crops in warm and humid climates and their control. *Verlog für Recht und Gesellschaft Ag.* 555 pp.

Yao N. (1988) Enquête sur les systêms de culture intégrant le bananier plantain en ani lieu paysan de Côte d'Ivoire. *Fruits* 43(3), 149–159.

Yaringano C. V. M. and Meer F. van der (1975) Control of the banana weevil, *Cosmopolites sordidus,* by means of various traps and granulated pesticides. *Revista peruana de Entomologia Agricola* 18(1), 112–116.

Yuningih (1987) Kasus Keracunan insektisida "Temik" pada sapi di Sumatra. *Penyakit Hewan* 19(33), 38–39.

Zhou S. and Wu X. (1988) A species of Curculionidae first recorded in China. *J. Zhong Kai. Agrotech. Coll.,* China 1(1), 33–34.

Zimmerman E. C. (1968) *Cosmopolites pruinosus,* a new pest of banana. *J. Econ. Entomol.* 61, 870–871.

Tropical Myiasis

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Attracting Agents of Wound Myiasis with Artificial Baits for Monitoring and Control

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Abstract—The host location behaviour of agents of wound myiasis has not been studied in the same detail as has host location by biting flies. However, a similar requirement to respond to a combination of host associated stimuli is involved, to visual and olfactory stimuli in particular. Past work on attracting myiasis flies by artificial baits, traps and targets is reviewed. The interaction of visual and olfactory stimuli in the responses of wound myiasis species to artificial baits is considered and compared to responses of these flies to stimuli associated with natural sites for feeding and for oviposition or larviposition.

Key Words: wound myiasis, artificial baits, traps, targets, host location

Introduction to Host Associated Stimuli

The attraction of biting flies to artificial baits has been intensively studied, in particular with respect to tsetse flies, *Glossina* species. The development of baited traps and targets for tsetse flies has been the subject of a number of recent reviews (Holmes and Torr, 1988; Wall and Langley, 1991; Vale, 1993; Green, 1994). Many of the ideas for traps and targets were developed as a result of observations on the flies' orientation towards host animals (Sutcliffe, 1987; Colvin and Gibson, 1992; Willemse and Takken, 1994), hence olfactory baits are based on components of host animal breath and excretions. Cattle urine was found to be attractive entirely due to phenolic components (Bursell et al., 1988) and two of these, 3-*n*-propylphenol and 4-methylphenol (Vale et al., 1988) are now regularly combined with breath derivatives, acetone and 1-octen-3-ol, to form a standard tsetse lure. Alternatives to such a totally synthetic lure combine acetone with natural cattle urine (e.g. see Dransfield et al., 1991).

Comparable work on attracting agents of myiasis is not new but it has been given a fresh excitement and impetus because of interest in developing alternative control techniques and in improving the monitoring of control or eradication programmes. The major agents of myiasis are found in three families, the Oestridae, the Calliphoridae and the Sarcophagidae (Hall and Wall, 1994). From what little is known about them, the orientation of oestrid myiasis species towards host animals appears to be mediated by the same stimuli that attract biting flies. Thus females of *Cephenemyia*, the nose bot flies of cervids, were captured in CO_2 -baited traps whereas none were captured in non-baited control traps (Anderson and Olkowski, 1968). Continuing this study, Anderson (1989) used deer models baited with CO_2, 1-octen-3-ol and Deer Trail Scent to attract females of *Cephenemyia* and to induce them to larviposit. There is great potential for further studies of the host-oriented behaviour of adult oestrids using artificial odours. However, this paper will concentrate on the calliphorids and sarcophagids, in particular the

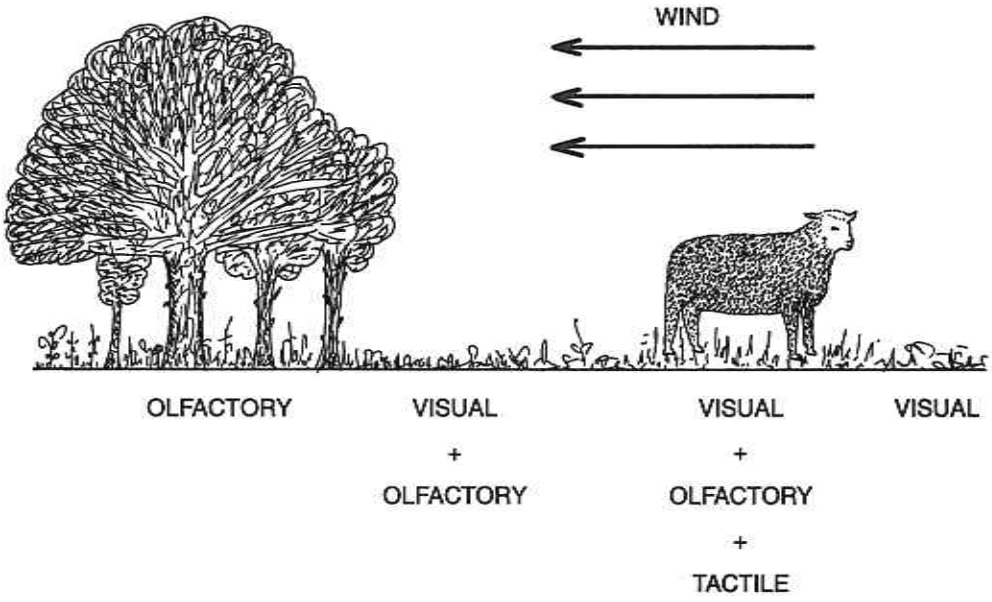

Fig. 1. Potential exogenous stimuli used in host and oviposition site location. Upwind of the host, flies will only receive visual stimuli, but downwind they will also receive olfactory stimuli. Olfactory stimuli will be the only stimuli detectable at locations beyond the visual range of the fly or in situations where the host is hidden. Visual, olfactory and tactile stimuli can all contribute to oviposition site location on the host.

screwworm and sheep strike flies that are responsible for causing wound myiasis.

The major potential stimuli involved in orientation of myiasis flies to their hosts are visual and olfactory (Fig. 1). A sequence of activation, followed by orientation followed by landing is followed in host location (Sutcliffe, 1987; Ashworth and Wall, 1994) and these responses are modulated by the physiological state and sex of the fly. Following landing on the host, it is probable that tactile and thermal (Holt et al., 1979) stimuli are also involved in the selection of oviposition or larviposition sites, but they will not be considered here since this paper will concentrate on pre-landing and landing stimuli only. A fundamental difference between the orientation of most biting flies to hosts and agents of wound myiasis to hosts is that the biting flies are mainly responding to odours naturally produced by healthy hosts whereas the agents of wound myiasis are mainly responding to odours associated with host wounding and necrosis. This is in keeping with the likely origins of wound myiasis species, i.e., with saprophagous species attracted to carrion for feeding and oviposition (Zumpt, 1965).

In developing artificial baits for wound myiasis species, stimuli must be selected to which they will actively orient. Wound myiasis flies such as screwworms spend most of their time (>75%) in passive behaviours, resting and grooming. Just under 10% of time is spent in feeding and <1% on courtship, mating and oviposition (Thomas, 1991). Unfortunately, it is not possible to use sex pheromones of these flies to attract adults to a trapping device, because they have essentially non-volatile, contact pheromones (Hammack, 1992). It is possible that stimuli associated with orientation to "mating stations" (Guillot et al., 1978; Krafsur, 1978; Mackley and Long, 1983; Hall et al., 1995) might be used to attract flies, but generally the options are to use stimuli associated with feeding and oviposition, i.e. stimuli associated with hosts and with other feeding and oviposition sites such as carrion.

Why Study Food and Host Associated Stimuli and Artificial Baits?

The objective of studying natural and artificial baits is to improve means of attracting adult flies for three purposes: (i) research, (ii) monitoring, and (iii) control. Examples of these are given below.

Research

Traps are essential for any field based research on the ecology and behaviour of insects, for studies of such topics as dispersal and population dynamics (Muirhead-Thompson, 1991).

Monitoring

The main technique for eradication of the New World screwworm (NWS), *Cochliomyia hominivorax* (Coquerel) (Diptera: Calliphoridae), is the sterile insect technique (SIT), used with success in the USA, Mexico, Libya and now being used in Central America. An important component of the campaign is the intensive surveillance service, necessary to monitor the movement of *C. hominivorax* populations and the effectiveness of the SIT programme. In the screwworm eradication programme in Libya, some 280,000 screwworm flies were trapped and inspected in the laboratory (Cunningham et al., 1992). In addition to improving traps for monitoring, there is a need to develop alternatives to the use of artificially wounded live sheep as sentinel animals (e.g. Krafsur and Hightower, 1979) to collect screwworm egg masses in monitoring programmes.

Control

Many current, preventive operations against myiasis species are based on topical applications of insecticide to the host, by sprays, dipping and pour-ons (Hall and Wall, 1994). However, there are examples of resistance to such practices (e.g. Levot, 1993). Curative measures demand regular inspection of livestock (2–3 times per week), removal of larvae from infested animals and individual treatment. The expenses of such measures are high when account is taken of the direct costs of the insecticide and the animal handlers' time and the indirect costs of lost grazing time, with potential reductions in milk and meat yields. An estimate of the losses due to surveillance and medication for treatment of *Cochliomyia hominivorax* ranged from US$4.82–US$10.71 per animal (Rawlins, 1985). The need for frequent treatment of livestock was most frequently cited by veterinarians in Hungary as a negative economic consequence of wound myiasis (R. Farkas and M. J. R. Hall, unpublished).

Early trials of traps for reducing the incidence of fly strike due to *Lucilia cuprina* indicated that carrion baited traps might be useful (Mackerras et al., 1936), but at that time traps were not considered economic due to high construction costs, poor efficiency, large numbers needed and the high frequency of bait replacement and trap maintenance. Subsequent advances in trap construction and bait delivery have reduced the costs of deployment and servicing traps and made them a more attractive proposition for control.

Traps and Targets for Wound Myiasis Species

It is interesting to note that the development of traps for tsetse flies began by concentrating on visual elements and only later was there an emphasis on olfactory components. The development of traps for blowflies involved in wound myiasis followed the reverse trend, with an emphasis on olfactory components and little input from visual elements.

Early traps of the sort described by Bishopp (1916) were of the conical type, in which flies were attracted to a bait (usually food) underneath a mesh cone. When leaving the bait, the tendency was for the adult to fly upwards and so into the cone and eventually via a small opening into a cage. Such traps were used to study screwworm flies until quite recently, using artificial baits in place of carrion (e.g. swormlure-2, Ahrens et al., 1977) and traps on the same general theme are still being described (e.g. Jiron, 1984).

In the early conical traps, flies could become lodged in the bait. Vogt and Havenstein (1974) developed an improved 'West Australian' blowfly trap in which the bait was kept out of reach of flies entering the entry chamber by a grill. To minimise the catch of non-target calliphorids, another grill was placed over the entrance to the cone, with a mesh size that was just large enough to allow passage of *Lucilia cuprina*, but too small to permit entry of larger flies. The traps were painted yellow to increase attractiveness to *Lucilia*, an early use of visual cues. The standard bait was two minced sheep's livers, 20 g crystalline sodium sulphide and 1 litre of water. Liver-baited West Australian and Bishopp traps have been used to sample for the Old World screwworm, *Chrysomya bezziana*, but with limited success (Spradbery, 1979).

Williams (1984) described a simplified version of the West Australian blowfly trap based on plastic components, which reduced the price from about A$130 to A$5. Again, bait pan and entry chamber were painted yellow. In a single trial the modified traps caught 30% of the *Lucilia cuprina* caught by the original West Australian design, but they used only 4% of the bait mass of the original and so were more effective per unit of bait.

Cone traps were considered inefficient for New World screwworm because many of the flies attracted did not move up the funnel and so were not trapped. A new trap design was developed by Broce et al. (1977) to overcome this problem and for use in conjunction with artificial odour baits being developed at the same time. The wind-oriented trap resembles a cone trap suspended on its side so that it can swing freely and, as its name implies, orient with the cone pointing into the wind, by large vanes at the downwind end. However, instead of the bait being placed below the mesh cone, it is now placed upwind of the cone so that as attracted flies land on the cone they continue to move upwind in response to odours blowing through the mesh, and so move through the apical hole and into the trap body where they are retained. This design caught more *Cochliomyia hominivorax* than the standard collapsible Bishopp type of trap and, just as important, caught a higher ratio of primary screwworms to secondary screwworms, thereby increasing the efficiency of sampling. A wind-oriented trap was designed on similar principles by Vogt et al. (1985) for sampling *Musca vetustissima* and has been used to sample for *Chrysomya rufifacies* (Vogt, 1988).

All the traps discussed so far require a trap entry response by the flies and there is the possibility of failure to enter or of escape after entry. Sticky traps reduce such problems because they only require flies to land on an adhesive surface to which they become stuck. A simple sticky trap embodying a horizontal trapping surface was developed for *Chrysomya bezziana* by Spradbery (1981), using the artificial attractant swormlure as bait. It has been used to study screwworm biology in the field (Spradbery and Vogt, 1993). Spradbery's trap was suspended and had a roof to protect the sticky surface from rain. Wardhaugh et al.'s (1984) sticky trap for sampling *Lucilia cuprina* was much more simple, consisting of a simple white sheet (15 cm square) placed at ground level and baited with liver and sodium sulphide. Wall et al. (1992) developed a similar target for monitoring *Lucilia sericata* in the UK (Wall et al., 1993), but their target was larger (41 cm square), was yellow and was positioned vertically with the base about 20 cm above ground level.

The development of targets for suppressing populations of New World screwworm fly was studied by Torr and Hall (1992) and Green et al. (1993). The objective was to produce a system similar to the target system used to control tsetse flies, *Glossina* species, that included a long lived artificial lure combined with an insecticide-treated surface. Over 60% of flies that contacted the surface of an insecticide-treated target did so for more than 5 seconds, but only 36% for more than 10 seconds (Green et al., 1993) a contact time which would have resulted in 100% of males and 87% of females acquiring a fatal dose of insecticide (3.2% solution of deltamethrin suspension concentrate) (Harris et al., 1991). Multiple visits by individuals would increase the possibility of acquiring a fatal dose of insecticide, but the target system has not yet been tested in a control trial. The target technique bears similarities to the screwworm adult suppression system (SWASS: Coppedge et al., 1980) and to the bait station system (Coppedge et al., 1981), both devised for suppression of screwworm populations, by attracting adult flies (using swormlure) to an insecticide-treated food source.

Problems associated with the behavioural complexity of entering traps were mentioned above, with the use of simple sticky screens being an alternative. Another option for use in research are electrocuting traps (Goodenough and Snow, 1977; Goodenough, 1979), which have been fitted with interval timers for sequential sampling (Goodenough and Snow, 1979), and electrocuting targets (Torr and Hall, 1992; Green et al., 1993; Hall et al., 1995) of the type developed for tsetse research (Vale, 1974). Both devices catch more screwworm flies than the wind-oriented trap.

Trap and target location and placement is an important aspect of trapping that has not been considered so far. Taking *C. hominivorax* as an example, in Chiapas State, Mexico, more screwworm flies were caught in traps located in open pasture than in those in woods and, in the pasture, more were caught in traps suspended below isolated trees than in those suspended under tripods (Welch, 1988). Some of the difference between woods and pasture might be due to difference in performance of the wind-oriented trap in the two localities rather than to differences in the abundance of screwworm flies. Thus, catching flies from sentinel sheep rather than traps demonstrated a greater abundance of screwworms in forest than in pastures in tropical habitats in Mexico and Belize (Mangan and Thomas, 1989). Having selected a trapping site, then subsequent trap placement can also affect captures, e.g. Peterson (1982) found that twice as many female *C. hominivorax* were captured in wind-oriented traps hung 0.4 m above the ground compared to those hung 1.5 m above ground. An area for future research in the field is the effect of vertical or horizontal placement of sticky targets on catches.

The trapping systems described above share some common stimuli, e.g. common odour baits are carrion or liver, enhanced by the addition of sodium sulphide solution, and artificial swormlure baits. The role of visual and olfactory stimuli in attracting wound myiasis flies are discussed in more detail below.

Visual Stimuli

The primary objectives of studies of visual stimuli, and those to be discussed on olfactory stimuli, are to improve our understanding of fly responses to these stimuli and thereby improve the performance of artificial baits for use in control or monitoring systems.

Visual components of artificial baits which are important include colour, shape, size, movement and micro-visual stimuli.

Colour

There are contrasting reports of the effects of colour on catch at targets, some suggesting black is most effective, others yellow. These are summarised in Table 1. A surprising observation is the impact of Lee's 1937 note on the attraction of *L. cuprina* to colours which, without obvious follow-up, has been the basis for using yellow in many subsequently produced trapping devices in Australia. Clearly there are important differences in the experimental techniques listed which go some way to explaining the differences in observed results, e.g., (i) the difference between trap and target results, (ii) differences in single or paired colour presentations, (iii) differences in odour baits used and, of course, (iv) differences between species and, possibly, strains.

Recent work in Mexico has suggested that colour had no effect on the attraction of *Cochliomyia hominivorax* to single targets, but that screwworm flies showed a preference for landing on black compared to white or yellow surfaces, when given a choice (M. J. R. Hall and A. Cork, unpublished).

Shape, Size and Movement

There has been little work done on the effect of target shape on attraction of flies to targets, but in laboratory wind tunnel experiments, Green and Warnes (1992) could detect no significant effect of shape (diamond, square, vertical or horizontal rectangle and circle) on landings of *C. hominivorax*.

Wall et al. (1992) recorded a significant effect of target size on the catch of *L. sericata* at liver and sodium sulphide baited sticky targets: larger targets caught more flies than smaller targets. Conversely, Green et al. (1993) using electrified cloth targets baited with swormlure-4 could detect no significant effect of size on catches of *C. hominivorax*. However, even if size had no affect on attraction to and landing on a target, it certainly has an effect on the potential number of flies that can be retained on sticky targets and so could be an important consideration in monitoring using sticky surfaces.

Movement of artificial baits has not been studied with respect to wound myiasis species and so is an area open to investigation. It is possible that moving sheep are not struck by *L. cuprina* to the extent that are sheep which 'go down' or are slow and lagging behind at the tail end of a flock (A. Heath, pers. commun.).

Table 1. Effects of colour of traps and targets on capture of wound myiasis species

Species	Trap type	Colour preference	Reference	Odour baits and comments
L. cuprina	Tropometer (single, cellophane)	yellow>blue>pink>green	Lee (1937)	No odour, flies attracted to transmitted light in laboratory apparatus
L. sericata	Cloth target (single, sticky)	white>yellow>aluminium> black>red>blue	Wall et al. (1992)	Liver plus sodium sulphide
L. sericata	Cloth target (single,electrified)	black>blue>white>yellow	Hall et al. (1995)	Swormlure-4
L.sericata	Cloth target (pairs, electrified)	black>blue>white>yellow	Hall et al. (1995)	Swormlure-4
C. hominivorax	Wind-oriented trap	yellow=white>green= black=red	Peterson (1982)	Swormlure-2
C. hominivorax	Cloth target	black=red>blue=yellow= white	Green and Warnes (1992)	Swormlure-4, in laboratory wind tunnel
C. hominivorax	Cloth target (single)	black=blue=yellow	Torr and Hall (1992)	Swormlure-4, flies trapped approaching targets
C. hominivorax	Cloth target (pairs)	black>blue=yellow>white	Torr and Hall (1992)	Swormlure-4
C. hominivorax	Cloth target (single, electrified)	black>red	Green et al. (1993)	Swormlure-4
C. hominivorax	Cloth target (pairs, electrified)	black>white, black>yellow	Hall and Cork (unpub.)	Swormlure-4
C. hominivorax	Cloth target (pairs, sticky)	black>white, black>yellow	Hall and Cork (unpub.)	Swormlure-4
C. hominivorax	Cloth target (single, sticky)	black=white=yellow	Hall and Cork (unpub.)	Swormlure-4
W. magnifica	Cloth target (Single, electrified)	black>blue>white>yellow	Hall et al. (1995)	Swormlure-4

Micro Visual Stimuli

The site of landings of *C. hominivorax* on targets could be important with regard to capture efficiency. In order to maximise the catch of *C. hominivorax* all the available target surface should be equally available to the flies. Torr and Hall (1992) made the observation that flies tended to concentrate around dead flies on electrified targets and suggested that this be studied as a potential means of improving fly:target contact. The same behaviour has been observed on sticky targets, towards dead, 'decoy' flies, in addition to a concentration of flies around the edge of targets (M.J.R. Hall and A. Cork, unpublished), similar to the edge response shown by walking adults of *Lucilia cuprina* (Osorio et al., 1990).

Olfactory Stimuli

Olfactory components of traps and targets appear to play a more important role than visual components for wound myiasis species. For example, in Libya, Green et al. (1993) demonstrated that swormlure-4-baited targets caught significantly more adult *C. hominivorax* than did unbaited targets. The same has been shown for *L. sericata* in Hungary (Hall et al., 1995). In Australia, Eisemann (1988) found that gravid female *L. cuprina* were attracted preferentially to the upwind wall of a cage when sheep were placed upwind of the cage. No downwind movement of flies was observed when sheep were placed downwind of the cage, again suggesting that odour cues were more important than visual cues in attracting flies.

Potential olfactory stimuli attractive to wound myiasis flies are mainly associated with three behaviours: (i) sexual, (ii) feeding, and (iii) oviposition. The latter two have been studied most with regard to trap development. Published studies on olfactory cues for wound myiasis species will not be discussed in great detail here because these have been reviewed very recently and thoroughly by Spradbery (1994) for screwworms (see also Mackley and Brown, 1985) and by Ashworth and Wall (1994) for *Lucilia*. However, important contributions are shown in Table 2.

The important point is that the major olfactory stimuli which have previously been identified and used to attract wound myiasis species are sulphur rich volatiles associated with the breakdown products of host tissues. Many baits for wound myiasis species are composed of whole carrion (e.g. Baumgartner, 1988; Avancini and Linhares, 1988) or discrete organs (especially liver), either used alone (e.g. Coppedge et al., 1977; Parker and Welch, 1992) or enhanced with chemicals such as sodium sulphide (e.g. Wall et al., 1992). Swormlure-4 (Mackley and Brown, 1984) is the only wholly artificial attractant for wound myiasis species that is routinely used in trapping studies. It is composed of ten chemicals and is the end product of testing a variety of mixtures of compounds chosen on the basis of their occurrence in decomposing animal wounds or as products of the bacterial decay of meat (Jones et al., 1976; Snow et al., 1982). In the presence of Swormlure-4, the flight behaviour of screwworm flies is affected in a manner that would enhance their chances of location of an odour source (Warnes and Green, 1992). Lucilure^{R} has recently been produced in Australia to attract *L. cuprina* to traps for population suppression (see page 301).

There is presently little information on host location by screwworm flies and the roles of non-wound host odours, visual or other sensory information in that location (Thomas, 1993). Thomas (1993) reported only one instance of a

Table 2. Olfactory stimuli for attracting wound myiasis species (With selected references. For general discussion see: Mackley and Brown, 1985; Spradbery, 1994; Ashworth and Wall, 1994)

Lucilia sericata/cuprina		
Attraction	Putrefactive sulphur rich volatiles, (e.g. hydrogen sulphide, ethanethiol, dimethyldisulphide) from:	Cragg and Ramage (1945) Cragg (1950) Gherardi et al. (1983)
	(i) bacterial decomposition products of cystine component of wool (flystruck sheep > sound wet sheep > sound dry sheep)	Eisemann (1988)
	(ii) sulphurous decomposition products of carrion (especially when enhanced by sodium sulphide)	
Oviposition	Ammonia-rich compounds (e.g. ammonia, ammonium carbonate used as baits); indole	Cragg and Thurston (1950)
Cochliomyia hominivorax and *Chrysomya bezziana*		
Attraction	Decomposing liver; bacterially inoculated blood	Parker and Welch (1992) DeVaney et al. (1973) Eddy et al. (1975)
	'Swormlure' (*sec*-butyl alcohol, *iso* butyl alcohol, *n*-butyric acid, *n*-valeric acid, acetic acid, dimethyl disulphide, phenol, *p*-cresol, indole, benzoic acid [+ acetone in early formulations])	Jones et al. (1976) Snow et al. (1982) Mackley and Brown (1984)
Attraction & oviposition	Wounded host (natural wound fluid), especially if wounds are infested; blood	Hammack (1991)
Wohlfahrtia magnifica		
Attraction	Carrion for feeding	Hall and Farkas (unpublished)
Attraction & oviposition	Wounded hosts for feeding and oviposition (wounded host > sound host)	Hall et al. (1995)

screwworm approaching an unwounded animal. Hall et al. (1995) have shown in Hungary that the obligate wound myiasis fly *Wohlfahrtia magnifica* is attracted more to healthy sheep than are the facultative species *L. sericata* and the saprophage *Phormia regina*. Thus, of the total fly catch at a healthy, uninfested sheep and at a *Wohlfahrtia* infested sheep, 26.8% of the *W. magnifica* were caught at the healthy sheep compared to only 3.8% of the *L. sericata* (Hall et al., 1995).

Returning to synthetic baits, it has been demonstrated that adult *C. hominivorax* landing at wounds infested with *C. hominivorax* larvae are predominately mature females, males are either not seen (Thomas and Mangan, 1989) or are very rare (Parker and Welch, 1991). Females caught at wounded hosts are more mature than those caught at swormlure baits (Guillot et al., 1977) or at liver baits (Parker and Welch, 1991). By identifying the natural attractant(s) present in the fluid associated with infested wounds it should be possible to produce an essentially female specific lure. Using a technique linking gas chromatography to electroantennography (GC-EAG) (Cork et al., 1990), twenty-five electrophysiologically active compounds were identified in the fluid associated with wounds infested with *C. hominivorax* larvae (Cork, 1994). Of significance is the fact that no sulphur rich compounds were included. These compounds were divided into groups composed of structurally related compounds, in the ratio they were observed in the wound fluid, and blends were tested on electrified nets and sticky targets. The most effective formulation caught a comparable number of *C. hominivorax* to the standard synthetic attractant, swormlure-4, and trapped a much higher proportion of female flies (A. Cork and M.J.R. Hall, unpublished). In other words, it more closely replicated the stimulus of natural wounds than did swormlure-4.

Further work is necessary to optimise and simplify the blend of chemicals needed to produce a viable synthetic replacement for natural wound fluids. A female specific lure could be used in a trapping system that would complement SIT, because sterile male *C. hominivorax* would not be so affected by the attractant. It would also complement the use of swormlure-4 baited traps for either surveillance or control because it is attractive to a different portion of the *C. hominivorax* population. It could also be used to replace sentinel animals in conjunction with a medium provided to stimulate oviposition.

The Future

At the end of their General Discussion on the effect of trapping on the incidence of sheep strike, Mackerras et al. (1936) concluded that, "... the methods of trapping at present available are far from perfect, and what may not be economical today may very well become a sound proceeding in the future....". I believe that the future they predicted is with us now.

The combination of a killing or sterilising device with a powerful synthetic attractant could provide a means for effective population suppression, but there is still considerable potential to enhance the visual and olfactory attractiveness of such devices. It is to be hoped that much more work will be done to realise that potential. First in the laboratory, using techniques such as electroantennography (Cork, 1994) linked with behavioural bioassays such as wind tunnel observations (Green and Warnes, 1992); second in the field, to realistically test the results of the laboratory work. Hall et al. (1995) have shown that sheep infested with *W. magnifica* are more attractive to that fly species than unwounded sheep. If the attractant stimuli of infested sheep could be identified and synthesised, then traps baited with these stimuli would be more attractive to flies than healthy sheep. Therefore, if such traps were placed in pastures at the beginning of the fly season, before infested sheep were available as competing stimuli, they would preferentially attract and catch or otherwise treat (kill/sterilise) the newly emerging adult flies.

Commercial fly traps using a variety of odour baits are already available in Australia, with such names as "Aussie flybuster" (e.g. see Dadour and Cook, 1992), mainly for domestic use. On a larger scale, bait bins for the attraction or killing of blowflies, including those responsible for wound myiasis, are being developed (Anderson et al., 1990; but see Cook, 1990). These basically consist of a yellow dustbin with lid and entry holes, to which flies are attracted by a sodium sulphide-treated carrion bait, dosed with an insecticide to kill flies that enter.

Another example, on which I will conclude, is the Lucitrap^R available from 1994 in Australia for the suppression of *L. cuprina* on sheep farms. This is a very simple device which avoids the need for insecticides since the trapped flies, entering through holes of a carefully calculated size, desiccate in the body of the trap. The attractant stimuli used include a yellow coloured lid, as a visual element, and Lucilure^R, a blend of four compounds frequently associated with tissue putrefaction. Preliminary data have shown that the lure is a more potent attractant of *L. cuprina* than the standard liver plus sodium sulphide (Urech et al., 1993). Field trials have indicated that a significant reduction in the observed numbers of adult *L. cuprina* can be obtained by deployment of the Lucitrap at densities of approximately 1 trap per 100 sheep (R. Urech, P. E. Green and M. J. Rice, unpublished).

It will be fascinating to follow the progress of this system and the development of other surveillance and suppression techniques that involve the use of artificial baits for monitoring and/or for control. Ideally, they would be combined with other management practices to enable targeting of both adult and larval stages. In addition to their use in ongoing control operations, they could also be valuable as an emergency tool: for instance, where there are new introductions of screwworm flies (e.g. Cunningham et al., 1992), they could offer a means of fly suppression before the infrastructure for SIT comes into place.

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References

Ahrens E. H., Coppedge J. R., Guillot F. S. and Goodenough J. L. (1977) Comparison of the distribution and daily activity periods of released and native screwworm flies. *Environmental Entomology* 6, 138–142.

Anderson J. M. E., McLeod L. J., Shipp E., Swan A. and Kennedy J. P. (1990) Trapping sheep blowflies using bait-bins. *Australian Veterinary Journal* 67, 93–97.

Anderson J. R. (1989) Use of deer models to study larviposition by wild nasopharyngeal bot flies (Diptera: Oestridae). *Journal of Medical Entomology* 26, 234–236.

Anderson J. R. and Olkowski W. (1968) Carbon dioxide as an attractant for host-seeking *Cephenemyia* females (Diptera: Oestridae). *Nature* 220, 190–191.

Ashworth J. R. and Wall R. (1994) Responses of the sheep blowflies *Lucilia sericata* and *L. cuprina* to odour and the development of semiochemical baits. *Medical and Veterinary Entomology* 8, 303–309.

Avancini R. M. P. and Linhares A. X. (1988) Selective attractiveness of rodent-baited traps for female blowflies. *Medical and Veterinary Entomology* 2, 73–76.

Baumgartner D. L. (1988) Spring season survey of the urban blowflies (Diptera: Calliphoridae) of Chicago, Illinois. *The Great Lakes Entomologist* 21, 119–121.

Bishopp F. C. (1916) Flytraps and their operation. *US Department of Agriculture Farmers' Bulletin* 734, 1–14.

Broce A. B., Goodenough J. L. and Coppedge J. R. (1977) A wind oriented trap for screwworm flies. *J. Econ. Entomol.* 70, 413–416.

Bursell E., Gough A. J. E., Beevor P. S., Cork A., Hall D. R. and Vale G. A. (1988) Identification of components of cattle urine attractive to tsetse flies, *Glossina* spp. (Diptera: Glossinidae). *Bull. Entomol. Res.* 78, 281–291.

Colvin J. and Gibson G. (1992) Host seeking behaviour and management of tsetse. *Annu. Rev. Entomol.* 37, 21–40.

Cork A. (1994) Identification of electrophysiologically-active compounds for New World screwworm, *Cochliomyia hominivorax*, in larval wound fluid. *Med. Vet. Entomol.* 8, 151–159.

Cork A., Beevor P. S., Gough A. J. E., and Hall D. R. (1990) Gas chromatography linked to electroantennography: A versatile technique for identifying insect semiochemicals, pp. 271–279. In *Chromatography and Isolation of Insect Hormones and Pheromones* (Edited by A. R. McCaffery and I. D. Wilson). Plenum Press, London.

Cook D. F. (1990) Trapping sheep blowflies using bait bins. *Aust. Vet. J.* 67, 310–311.

Coppedge J. R., Ahrens E., Goodenough J. L., Guillot F. S. and Snow J. W. (1977) Field comparisons of liver and a new chemical mixture as attractants for the screwworm fly. *Environmental Entomology* 6, 66–68.

Coppedge J. R., Brown H. E., Goodenough J. L., Tannahill F. H., Snow J. W., Petersen H. D. and Hofmann H. C. (1980) Field performance of a new formulation of the screwworm adult suppression system. *J. Econ. Entomol.* 73, 411–414.

Coppedge J. R., Brown H. E., Snow J. W. and Tannahill F. (1981) Bait stations for the suppression of screwworm populations. *J. Econ. Entomol.* 74, 168–172.

Cragg J. B. (1950) The reactions of *Lucilia sericata* (Mg.) to various substances placed on sheep. *Parasitology* 40, 179–186.

Cragg J. B. and Ramage G. R. (1945) Chemotropic studies on the blow-flies *Lucilia sericata* (Mg.) and *Lucilia caesar* (L.). *Parasitology* 36, 168–175.

Cragg J. B. and Thurston B. A. (1950) The reactions of blowflies to organic sulphur compounds and other materials used in traps. *Parasitology* 40, 187–194.

Cunningham E. P., Abusowa M., Lindquist D. A., Sidahmed A. E. and Vargas-Terán M. (1992) Le programme d'éradication de la lucilie bouchère d'Afrique du Nord. *Rev. Méd. Vét. Trop.* 45, 115–118.

Dadour I. R. and Cook D. F. (1992) The effectiveness of four commercial fly traps at catching insects. *J. Aust. Entomol. Soc.* 31, 205–208.

DeVaney J. A., Eddy G. W., Ellis E. M. and Harrington R. Jr (1973) Attractancy of inoculated and incubated bovine blood fractions to screwworm flies (Diptera: Calliphoridae): Role of bacteria. *J. Med. Entomol.* 10, 591–595.

Dransfield R. D., Williams B. G. and Brightwell R. (1991) Control of tsetse flies and trypanosomiasis: Myth or reality? *Parasitology Today* 7, 287–291.

Eddy G. W., DeVaney J. A. and Handke B. D. (1975) Response of the adult screwworm (Diptera: Calliphoridae) to bacteria-inoculated and incubated bovine blood in olfactometer and oviposition tests. *J. Med. Entomol.* 12, 379–381.

Eisemann C. H. (1988) Upwind flight by gravid Australian sheep blowflies, *Lucilia cuprina* (Wiedemann) (Diptera: Calliphoridae), in response to stimuli from sheep. *Bull. Entomol. Res.* 78, 273–279.

Gherardi S. G., Sutherland S. S., Monzu N. and Johnson K. G. (1983) Field observations on body strike in sheep affected with dermatophilosis and fleece-rot. *Austr. Vet. J.* 60, 27–28.

Goodenough J. L. (1979) Adult screwworms: Comparison of captures in wind oriented and electrocuter grid traps. *J. Econ. Entomol.* 72, 419–422.

Goodenough J. L. and Snow J. W. (1977) Increased captures of adult screwworms and secondary screwworms in electrocuter grid traps. *J. Econ. Entomol.* 70, 70–71.

Goodenough J. L. and Snow J. W. (1979) Capture of screwworm and secondary screwworm flies (Diptera: Calliphoridae) in a time-interval grid trap and correlation with temperature and humidity. *J. Med. Entomol.* 16, 95–103.

Green C. H. (1994) Bait methods for tsetse fly control. *Advances in Parasitology* 34, 229–291.

Green C. H. and Warnes M. L. (1992) Responses of female New World screwworm flies, *Cochliomyia hominivorax*, to coloured targets in the laboratory. *Med. Vet. Entomol.* 6, 103–109.

Green C. H., Hall M. J. R., Fergiani M., Chirico J. and Husni M. (1993) Attracting adult New World screwworm, *Cochliomyia hominivorax*, to odour-baited targets in the field. *Med. Vet. Entomol.* 7, 59–65.

Guillot F. S., Brown H. E. and Broce A. B. (1978) Behaviour of sexually active male screwworm flies. *Ann. Entomol. Soc. Am.* 71, 199–201.

Guillot F. S., Coppedge J. R., Goodenough J. L., Ahrens E. and Adams T. S. (1977) Reproductive status of female screwworms captured from hosts or in traps. *The Southwestern Entomologist* 2, 49–52.

Hall M. J. R. and Wall R. (1994) Myiasis of humans and domestic animals. *Advances in Parasitology* 35, 257–334.

Hall M. J. R., Farkas R., Kelemen F., Hosier M. J. and El-Khoga J. M. (1995) Orientation of agents of wound myiasis to hosts and artificial stimuli in Hungary. *Med. Vet. Entomol.* 9, 77–84.

Hammack L. (1991) Oviposition by screwworm flies (Diptera: Calliphoridae) on contact with host fluids. *J. Econ. Entomol.* 84, 185–190.

Hammack L. (1992) Intra- and interspecific sex pheromone responses of screwworm and secondary screwworm flies. *J. Chem. Ecol.* 18, 1327–1336.

Harris E.G., Brown M. and Smith S. (1991) Laboratory investigations of insecticide impregnated materials for the control of New World screwworm flies. *In* Development of an Odour-Baited Insecticidal Target System for the Suppression of Adults of the New World Screwworm Fly. Final Report to Joint FAO/IAEA Division. NRI, Chatham, 77 pp.

Holmes P. H. and Torr S. J. (1988) The control of animal trypanosomiasis in Africa: Current methods and future trends. *Outlook on Agriculture* 17, 54–60.

Holt G. G., Adams T. S. and Sundet W. D. (1979) Attraction and ovipositional response of screwworms, *Cochliomyia hominivorax* (Diptera: Calliphoridae), to simulated bovine wounds. *J. Med. Entomol.* 16, 248–253.

Jiron L. F. (1984) A blowfly trap for standardized field sampling. *Entomological News* 95, 202–206.

Jones C. M., Oehler D. D., Snow J. W. and Grabbe R. R. (1976) A chemical attractant for screwworm flies. *J. Econ. Entomol.* 69, 389–391.

Krafsur E. S. (1978) Aggregations of male screwworm flies, *Cochliomyia hominivorax* (Coquerel), in South Texas (Diptera: Calliphoridae). *Proceedings of the Entomological Society of Washington* 80, 164–170.

Krafsur E. S. and Hightower B. G. (1979) Field tests of sterile screwworm flies, *Cochliomyia hominivorax* (Diptera: Calliphoridae), against natural populations in three coastal areas of Mexico. *J. Med. Entomol.* 16, 33–42.

Lee D. J. (1937) A note on the colour responses of *Lucilia cuprina*. *Journal of the Council for Scientific and Industrial Research* 10, 275–276.

Levot G. W. (1993) Insecticide resistance, new developments and future options for fly and lice control on sheep. *Wool Technology and Sheep Breeding* 41, 30–41.

Mackerras I. M., Fuller M. E., Austin K. M. and Lefroy E. H. B. (1936) Sheep blowfly investigations. The effect of trapping on the incidence of strike in sheep. *J. Council for Scientific and Industrial Research* 9, 153–162.

Mackley J. W. and Brown H. E. (1984) Swormlure-4: A new formulation of the swormlure-2 mixture as an attractant for adult screwworms, *Cochliomyia hominivorax* (Diptera: Calliphoridae). *J. Econ. Entomol.* 77, 1264–1268.

Mackley J. W. and Brown H. E. (1985) Screwworm research 1976–84: Attractants, behaviour, ecology, and development of survey and control technologies. *Miscellaneous Publications of the Entomological Society of America* Number 62, 49–55.

Mackley J. W. and Long G. L. (1983) Behaviour of sterile adult screwworms (Diptera: Calliphoridae) on flowering trees and shrubs. *Ann. Entomol. Soc. Am.* 76, 839–843.

Mangan R. L. and Thomas D. B. (1989) Habitat preferences and dispersal patterns in native female screwworm flies (Diptera: Calliphoridae). *Ann. Entomol. Soc. Am.* 82, 332–339.

Muirhead-Thompson R. C. (1991) *Trap Response of Flying Insects: The Influence of Trap Design on Capture Efficiency*. Academic Press, London, New York, xii + 287 pp.

Osorio D., Srinivasan M. V. and Pinter R. B. (1990) What causes edge fixation in walking flies? *J. Exp. Biol.* 149, 281–292.

Parker F. D. and Welch J. B. (1991) Influence of attractants on behaviour of screwworms (Diptera: Calliphoridae) in a tropical wet forest in Costa Rica. *J. Econ. Entomol.* 84, 1468–1475.

Parker F. D. and Welch J. B. (1992) Monitoring adult populations of the screwworm (Diptera: Calliphoridae) with feeding stations baited with liver. *J. Econ. Entomol.* 85, 1740–1753.

Peterson R. D. (1982) Influence of trap colour and height above ground on capture of screwworms. *The Southwestern Entomologist* 7, 240–243.

Rawlins S. C. (1985) Current trends in screwworm myiasis in the Caribbean region. *Veterinary Parasitology* 18, 241–250.

Snow J. W., Coppedge J. R., Broce A. B., Goodenough J. L. and Brown H. E. (1982) Swormlure: Development and use in detection and suppression systems for adult screwworm (Diptera: Calliphoridae). *Bull. Entomol. Soc. Am.* 28, 277–284.

Spradbery J. P. (1979) The reproductive status of *Chrysomya* species (Diptera: Calliphoridae) attracted to liver-baited blowfly traps in Papua New Guinea. *J. Aust. Entomol. Soc.* 18, 57–61.

Spradbery J. P. (1981) A new trap design for screw-worm fly studies. *J. Aust. Entomol. Soc.* 20, 151–153.

Spradbery J. P. (1994) Screw-worm fly: A tale of two species. *Agric. Zool. Rev.* 6, 1–62.

Spradbery J. P. and Vogt W. G. (1993) Mean life expectancy of Old World screwworm fly, *Chrysomya bezziana*, inferred from the reproductive age-structure of native females caught on swormlure-baited sticky traps. *Med. Vet. Entomol.* 7, 147–154.

Sutcliffe J. F. (1987) Distance orientation of biting flies to their hosts. *Insect Sci. Applic.* 8, 611–616.

Thomas D. B. (1991) Time-activity budget of adult screwworm behaviour (Diptera: Calliphoridae). *J. Med. Entomol.* 28, 372–377.

Thomas D. B. (1993) Behavioural aspects of screwworm ecology. *J. Kansas Entomol. Soc.* 66, 13–30.

Thomas D. B. and Mangan R. L. (1989) Oviposition and wound-visiting behaviour of the screwworm fly, *Cochliomyia hominivorax* (Diptera: Calliphoridae). *Ann. Entomol. Soc. Am.* 82, 526–534.

Torr S. J. and Hall M. J. R. (1992) Odour-baited targets to control New World screwworm, *Cochliomyia hominivorax* (Diptera: Calliphoridae): A preliminary study. *Bull. Entomol. Res.* 82, 417–423.

Urech R., Green P. E., Rice M. J., Brown G. W., Duncalfe F., Webb P. D. and Pritchard D. A. (1993) Field performance of synthetic lures for the Australian sheep blowfly *Lucilia cuprina* (Diptera: Calliphoridae), pp. 277–279. In *Pest Control and Sustainable Agriculture* (Edited by S. A. Corey, D. J. Dall and W. M. Milne). CSIRO, Australia.

Vale G. A. (1974) New field methods for studying the responses of tsetse flies (Diptera: Glossinidae) to hosts. *Bull. Entomol. Res.* 64, 199–208.

Vale G. A. (1993) Development of odour baits for tsetse flies (Diptera: Glossinidae) in Zimbabwe. *J. Med. Entomol.* 30, 831–842.

Vale G. A., Hall D. R. and Gough A. J. E. (1988) The olfactory responses of tsetse flies, *Glossina* spp. (Diptera: Glossinidae), to phenols and urine in the field. *Bull. Entomol. Res.* 78, 293–300.

Vogt W. G. (1988) Influence of weather on trap catches of *Chrysomya rufifacies* (Macquart) (Diptera: Calliphoridae). *J. Aust. Entomol. Soc.* 27, 99–103.

Vogt W. G. and Havenstein D. E. (1974) A standardized trap for blowfly studies. *J. Aust. Entomol. Soc.* 13, 249–253.

Vogt W. G., Runko S. and Starick N. T. (1985) A wind-oriented trap for quantitative sampling of adult *Musca vetustissima* Walker. *J. Aust. Entomol. Soc.* 24, 223–227.

Wall R. and Langley P. (1991) From behaviour to control: The development of trap and target techniques for tsetse fly population management. *Agric. Zool. Rev.* 4, 137–159.

Wall R., Green C. H., French N. and Morgan K. L. (1992) Development of an attractive target for the sheep blowfly, *Lucilia sericata. Med. Vet. Entomol.* 6, 67–74.

Wall R., French N. P. and Morgan K. L. (1993) Predicting the abundance of the blowfly *Lucilia sericata* (Diptera: Calliphoridae). *Bull. Entomol. Res.* 83,431–436.

Wardhaugh K. G., Read P. and Neave M. (1984) A sticky-trap for studying the spatial distribution of the Australian sheep blowfly *Lucilia cuprina. Aust. Vet. J.* 61, 132.

Warnes M. L. and Green C. H. (1992) Responses of female New World screwworm flies, *Cochliomyia hominivorax*, to swormlure-4 in the laboratory. *Med. Vet. Entomol.* 6, 98–102.

Welch J. B. (1988) Effect of trap placement on detection of *Cochliomyia hominivorax* (Diptera: Calliphoridae). *J. Econ. Entomol.* 81, 241–245.

Willemse L. P. M. and Takken W. (1994) Odor-induced host location in tsetse flies (Diptera: Glossinidae). *J. Med. Entomol.* 31, 775–794.

Williams H. (1984) Modification of the West Australian blowfly (Diptera: Calliphoridae) trap for population studies. *J. Econ. Entomol.* 77, 806–809.

Zumpt F. (1965) *Myiasis in Man and Animals in the Old World.* Butterworths, London.

Insights into the Management of Migratory Insect Pests

Convenor: *Prof. S. El-Bashir*
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Monitoring the Movement of Migratory Insect Pests

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Abstract—It is generally recognised that monitoring the movement of migratory insect pests is a prerequisite for their optimal management. In some species (e.g. locusts and migratory grasshoppers), the adult stage may invade an area at risk in numbers high enough to produce immediate serious or even devastating losses. In others (e.g. armyworm), damage may be caused by the progeny which result from earlier adult immigration. In both cases, monitoring changes in the geographical distribution of the pest forms an essential part of a preventive management strategy, which may include forecasting. More commonly, monitoring is undertaken only within the area at risk (e.g. to detect immigration into farmers' fields) as part of a defensive management scheme. This paper gives an overview of how ground and air surveys, and trapping techniques (by pheromones, light, suction and netting) have been used to assess insect migration for both preventive and defensive management in subtropical and tropical areas. Reference is also made to ways in which remote sensing (including insect monitoring radar) can be used to complement these techniques.

Key Words: insect pests, pest management, migration monitoring, remote sensing

Introduction

In order to carry out effective management of migratory insect pest species, it is usually considered necessary to have some knowledge of their movements so that potentially harmful infestations can be detected, and consequent damage prevented or reduced. It is this requirement which has provided the principal motivation for the development and application of the techniques for monitoring insect migration which are outlined in this paper. Migration can be defined as "a syndrome of interacting behavioural responses especially evolved for the displacement of an individual in space beyond its normal station-keeping or foraging movements" (Dingle, 1989). Many, perhaps most, insect species have a period (or periods) during their life-cycle when they engage in specialised migratory behaviour (Kennedy, 1985; Hardie, 1993), although the distances moved may often be small (<1 km) when judged on a human scale. For practical purposes, however, an insect species has to move over distances of at least several kilometres before it would be considered to be 'migratory', and the term is most commonly reserved for those species which regularly undertake aerial migrations of several hundred kilometres in one or more prolonged windborne flights (Johnson, 1969; Rabb and Kennedy, 1979; Pedgley, 1982; Drake and Farrow, 1988; Drake and Gatehouse, 1995). Long distance movement may also result from the cumulative effect of 'foraging' flights, especially where the sought-after resource (food, a mate, oviposition sites, etc.) is not encountered quickly (Kennedy, 1985). Although 'extended foraging' movements (e.g. in *Helicoverpa armigera* moths) (Joyce, 1981; Riley et al., 1992) are not migration in the behavioural sense, from a control point of view the result is much the same.

Occasionally, the migration of insect pests can be observed whilst it is actually in progress. For example, swarms of day-flying locusts are visually conspicuous, and high-flying insect migrants can be detected by entomological radars by day or night (Riley, 1989). More usually, migration is deduced from a variety of direct and circumstantial evidence (Johnson, 1969; Pedgley, 1982; Drake, 1990). Apart from the unequivocal proof of movement obtained from the capture of artificially or naturally marked specimens, inferences that migration has taken place are drawn from the temporal changes in pest distribution as revealed by survey data or trap catches. Catches of insects high in the air, e.g. in aerial nets or in traps on high towers (e.g. Gregg et al., 1993) are also indicative of migration. In some cases it is possible to deduce that migration has occurred even when the migrants themselves are not detected, because of the effects which they cause (for example, outbreaks of animal diseases spread by the windborne movement of mosquito and midge *(Culicoides)* vectors (Sellers, 1980; Sellers and Pedgley, 1985)). Lastly, there may be evidence from behavioural or physiological studies that particular species have the capacity to migrate. Examples include assessments of flight potential using flight mills or balances (Cooter, 1993), and from fuel reserves (Padgham, 1983).

Details of a large number of methods for sampling insect populations, including those of migratory species, can be found in standard texts (e.g. Southwood, 1978; Muirhead-Thomson, 1991; Service, 1993; Ruesink and Kogan, 1994), but in this paper we have focused on examples of operational, wide-area monitoring of migratory insects for pest management objectives, rather than on sampling for research purposes. We have also concentrated on examples from the tropics and subtropics rather than from the temperate zone.

Pest Management Monitoring Requirements

Types of Management

Pest management programmes can be categorised as preventive or defensive (Pedgley, 1993), and an ideal strategy would probably include both types. In preventive management, pests are controlled before they reach the areas most threatened by their attacks, and this strategy is typified by the programmes against locusts, grasshoppers, armyworm moths and blackflies as discussed in Gunn and Rainey (1979), Joyce (1981) and Rainey et al. (1990). The classic example is that of the desert locust, *Schistocerca gregaria,* where concentrations of the pest occurring virtually anywhere in its distribution area are viewed as a threat, and consequently as targets for strategic control. Preventive management may involve forecasting (e.g. Magor, 1995; Day and Knight, 1995), undertaken to gain more time in which to plan and initiate strategic control measures.

In defensive management, monitoring and control actions are taken against pests, even highly mobile ones, only when they actually invade the area at risk (e.g. when they are in the crop or, in the case of biting flies, are attacking livestock or people). There are, however, a few examples of forecasting or warning schemes which are used to activate a defensive response when invasion seems likely, and these involve monitoring either source populations (e.g. overwintering eggs of *Aphis fabae* in UK (Cammell and Way, 1987)) or populations in transit (e.g. suction trap sampling of cereal, hop and potato aphids in Europe (Tatchell, 1991)). Another example of forecasting for defensive management is that of rice planthoppers in East Asia, where source populations are monitored in order to assess the risk of damage occurring elsewhere, later in the season. This forecasting is supplemented by schemes to confirm the actual arrival of adult planthopper immigrants in susceptible crops (Hirao, 1979; Tang et al., 1994; Zhou et al., 1995). Generally, defensive management schemes have been more commonly adopted than have preventive ones, mainly because it is often impractical, uneconomic or environmentally damaging to control pests in distant source areas (Joyce, 1981).

Monitoring Requirements

The monitoring objectives for defensive and preventive management strategies differ in that the former tends to focus mainly on the detection of pest immigration into an area at risk, or on tracking the subsequent build-up of immigrants' progeny, whereas the latter is concerned with the magnitude and redistribution of pest populations on a geographical scale. Nevertheless, in both cases the same basic techniques of survey and trapping are used as the principal means of monitoring insect movement. The main difference is that in the case of preventive management, the techniques are applied over areas very much larger than those at risk, and they are increasingly being supplemented by data obtained from satellite imagery.

Surveys

The term survey is used to describe the process of systematically searching a habitat in order to form a quantitative estimate of the population of the target species. In the case of preventive management, surveys are usually on a large geographical scale, require substantial logistic support and may even use remote sensing data recorded by satellites. Examples of large-scale surveys used in the preventive management of locusts and of blackflies are outlined below. Surveys for defensive management might simply take the form of regular inspections of a crop considered to be at risk, and would often be conducted by farmers themselves: some examples are also described below.

Locust Surveys

Historically, much of our knowledge of desert locust *(S. gregaria)* migration patterns has been deduced from data on the redistribution of locust populations over the whole of the species' range, and this still forms the basis of current forecasting and control operations (Pedgley, 1981; Steedman, 1990; FAO, 1992, 1994; Magor, 1995).

The accepted method of assessing locust populations is the synoptic survey, where a picture of the distribution of the whole population is obtained for one point in time and is compared to those at other times (Joyce, 1981). Ideally, the survey scheme should provide a high degree of confidence that all significant pest populations will be discovered, and that areas recorded as uninfested actually are substantially free from locusts. Some aerial surveys of the desert locust carried out in the early 1960s apparently achieved these objectives (Joyce, 1981), but survey information has generally been much less complete.

Information about the state of locust habitats over very wide areas is inferred from satellite observations (see below) and this is used to direct ground or aerial survey teams into regions judged to be favourable to locusts. On a smaller scale, a similar process is carried out using fixed-wing aircraft and helicopters to search for areas of green vegetation which might harbour significant locust populations, and which should then be surveyed from the ground. Practical details of carrying out desert locust surveys are described in Meinzingen (1993) and FAO (1994), including methods for estimating locust densities such as 'flushing' adults by foot, vehicle or helicopter transects.

If the locusts have gregarised, aerial surveys may be used to locate bands of hoppers or adult swarms. The subject of aircraft reconnaissance for the desert locust swarms has been reviewed by Rainey (1963), and he has graphically described (Rainey, 1958) the great variation in appearance of these swarms. Special training and experience are required for locust survey pilots and observers, and this expertise is becoming increasingly scarce; it is not usually found in pilots trained solely in agricultural crop spraying (Kitenda, 1990).

In contrast to the desert locust, plagues of some other locust species (e.g. the red locust, *Nomadacris septemfasciata*) are initiated from relatively restricted outbreak areas. However, these areas can be difficult of access because of marshy ground and seasonal flooding. Specialised survey methods for monitoring the red locust are outlined in Meinzingen (1993).

Surveying for Blackflies in West Africa

Surveys for blackflies of the *Simulium damnosum* complex, the vector of human onchocerciasis, are of vital importance to the Onchocerciasis Control Programme (OCP) in West Africa, both to evaluate the efficacy of control measures against the aquatic larvae, and to detect reinvasion of treated areas by migration of the adult flies. Walsh et al. (1981) describe the methods used in this vast monitoring effort which relies on a large database of potential riverine habitats, and which requires teams to visit the many possible breeding sites to search for larvae and pupae. Many of the sites are remote, so very substantial logistic support, including the regular use of helicopters, is required to deploy survey teams. Estimates of adult fly populations are made by counting the number of flies caught per man per day by human 'vector-collectors'.

Field Monitoring by Farmers and Pest Control Operatives

If migrant pests arrive in vulnerable crops, defensive management may be necessary. In these cases, simple monitoring techniques such as in-field visual inspection (scouting) or trapping are required to detect the presence of the pest and to assess whether numbers are likely to exceed a threshold at which control measures are judged to be prudent. Monitoring thus has the important function of preventing the unnecessary application of insecticides, and so yields consequential economic and environmental benefits.

Sometimes the presence of damaging numbers of pest insects in a crop will be painfully obvious (e.g. with locusts and pest grasshoppers such as *Oedaleus senegalensis*), but with other species, this may not be the case. For example, the early instars of the African armyworm are not at all conspicuous, but if numerous, they should be controlled before they reach the fourth instar (DLCO-EA, 1992). Thus one week after high trap catches of moths, or after a storm in the vicinity (see below), when an infestation is likely, farmers are advised to examine the leaves of their crops for the characteristic 'windowing' damage or shake the plants and look for young larvae hanging by threads or dropping onto the ground (DLCO-EA, 1992).

Reissig et al. (1985) present simple methods of scouting for tropical Asian rice pests, some of which are migratory (e.g. Oriental armyworm *(Mythimna separata)*, rice cutworm *(Spodoptera* *litura)*, rice leaf-roller *(Cnaphalocrocis medinalis)*, brown planthopper *(Nilaparvata lugens)* and whitebacked planthopper (*Sogatella furcifera*)). Surveillance systems for the brown planthopper have been established in several Asian countries (e.g. Ooi, 1982; Ooi and Heong, 1988; Zhou et al., 1995) and these usually include field scouting. Chiang (1977) describes routine field monitoring procedures employed in the People's Republic of China for insects of rice, wheat, maize and cotton. Field monitoring of this type may sometimes be limited by the inability of farmers to make the critical distinction between pests and beneficial arthropods.

Satellite Imagery

Data from earth observation and meteorological satellites have been used to make inferences about the probable long-range movement of two insect pests: locusts and armyworm moths. Both cases have been outlined by Riley (1989) and by Meinzingen (1993), and are reviewed in more detail by Robinson (1995). Robinson also illustrates the uses of GIS (geographic information systems) for the integration of satellite-derived data, and information from other sources, on the habitats of migratory insect pests.

Rainfall Monitoring

Desert locusts need moist soil in which to lay their eggs, and to support the growth of vegetation which their hoppers need for food. The species has consequently evolved flight behaviour which tends to move both night-flying solitarious-phase individuals and day-flying swarms downwind, and so into areas where rain has fallen or is likely to fall in their otherwise arid environment. Monitoring the occurrence of rainfall and green vegetation may thus be used to indicate the areas in which significant populations of desert locusts are likely to be found: the probable movements to and from these areas can then be deduced from historical analogues (Pedgley, 1981). Rainfall monitoring has the advantage that it gives more advanced warning of the occurrence of areas suitable for breeding. Conventional rain-gauge recordings are unfortunately too sparse and reporting is too infrequent to give an adequate measure of precipitation in much of the desert locust habitat, so forecasters try to estimate rainfall distribution from satellite imagery of deep convective clouds. The current FAO system derives estimates of cloud temperature from infra-red emission imagery available from Meteosat. These data are used to monitor the extent and duration of cloud tops with temperatures below the thresholds normally associated with clouds deep enough to give convective rainfall. The 'cold cloud duration' or CCD is then used as an indicator of integrated rainfall over the area covered by the cloud tops; the calibration and validation of this method is discussed by Milford and Dugdale (1990). A geostationary satellite (such as Meteosat) is preferable to a polar orbiting one as frequent images (in practice, every 30 minutes) are required.

Limitations of the current CCD methodology include the difficulty of estimating the amount of rain (if any) falling from cold, middle-level stratiform cloud and the occurrence of extensive areas of cold, high cirrus cloud which is not associated with heavy rain (convective systems below the cirrus may be weak, or have weakened over time) (Milford and Dugdale, 1990 and following discussion; Robinson, 1995). Even if the estimation of precipitation is correct, it may not reflect the subsequent distribution of moisture in the soil because in some cases rain may evaporate before reaching the ground and in others, enough water for locust breeding may accumulate in areas such as wadis as a result of run-off from otherwise inadequate light rain, or from rain falling considerable distances away (Milford and Dugdale, 1990; Robinson, 1995). Nevertheless, it appears that the method has worked reasonably well in some desert locust areas (e.g. the western Sahel).

A dedicated computer system (ARTEMIS) for processing of satellite data to produce standardised outputs for routine use by FAO desert locust forecasters, has been described by Hielkema (1990). These outputs consist of 10-day or monthly maps of wide-area precipitation (estimated from cold cloud duration) and various vegetation indices (see below).

In an analogous development, cold cloud imagery from a geostationary satellite (in this case the Japanese GMS) is currently used by the Australian Plague Locust Commission for the detection of rainfall in the interior of eastern Australia (Bryceson et al., 1993). The objective here is to locate areas into which the plague locust *(Chortoicetes terminifera)* is likely to have migrated, and to which ground survey teams should be directed (Hamilton and Bryceson, 1993).

CCD estimates from satellite imagery are also used in African armyworm forecasting in East Africa (Rose et al., 1997; Robinson, 1995). Outbreaks of gregarious larvae are believed to result from mass oviposition which follows the aerial concentration of the nocturnally-migrating moths by the wind outflows generated by rainstorms. Significant associations between outbreaks and rainstorms have been found for some periods during the armyworm season (viz: October–March, but not April–May) (Tucker and Pedgley, 1983; M.R. Tucker, unpublished). Location of the convective rainstorms which may have caused moth concentration may thus indicate the likely position of new larval infestations. Operationally, data from Meteosat is received at the Regional Armyworm Forecasting Service in Nairobi, via a low-cost Primary Data User System (PDUS) utilising a desk-top computer. Because the locations of rainstorms on particular nights are required, the CCD maps are composited for each 18.00–06.00 h (local time) period, rather than over 10-day periods as required for estimation of rainfall amounts. Further work is required to properly assess the value of the technique, but a limited study (M.R. Tucker, unpublished) found that outbreaks were associated with the edges of cold cloud clusters, and it was concluded that the use of Meteosat images greatly reduced the areas needing to be surveyed for armyworm infestations.

Vegetation Monitoring

The amount and condition of the vegetation within the desert locust distribution area may be estimated by using images from the NOAA AVHRR (advanced very high resolution radiometer) satellite. This is because the satellite provides measurements of scene luminance in a series of wavelength bands in the near infra-red, and the luminance ratio formed by (channel 2 - channel 1)/(channel 2 + channel 1), has been found to give a reasonable indication of the density of green leaf biomass in the scene (Hielkema, 1990). This ratio is called the normalized difference vegetation index (NDVI). In practice, however, there are several problems with the NDVI. It is affected by scan geometry; there may be obscuration from clouds, water vapour or dust; some soils give an NDVI similar to that for green vegetation; and the degree of vegetation cover may be too low to generate an NDVI, but nevertheless still provide adequate food for desert locusts (FAO, 1992). Research is currently being undertaken to improve the reliability and usefulness of vegetation indices in the desert locust area (Cherlet et al., 1991; Cherlet and DiGregorio, 1991).

Bryceson et al. (1993) describe how infra-red data available from NOAA APT (automatic picture transmissions) in the thermal (emitted) and reflected bands, can be used to produce an empirical factor which they call a *moisture index*. Data from field observations in eastern Australia showed that this index could be related to vegetation condition, if the habitat type was previously known. The accuracy of the maps produced was variable (40 to 80%), but the technique was considered a useful supplement to rainfall estimation in operational monitoring of the habitat of the Australian plague locust.

Traps

In contrast to the scouting and flushing techniques mentioned above, trapping methods depend on the activity of insects rather than on searches by an observer (Southwood, 1978). Trapping has traditionally been the most widely used method of detecting insect movement (Johnson, 1969), and a great variety of 'attractive' and 'non-attractive' techniques is available. The most commonly used are outlined below.

Light Trapping

Light trapping is effective for monitoring the movement of a variety of species, particularly moths and mosquitoes, and many different designs of trap have emerged (Southwood, 1978; Muirhead-Thomson, 1991). Some of these automatically segregate the catches from different periods of the night so that the time of arrival of immigrants can be estimated (Taylor et al., 1982). The design and position of light traps both affect the catch, and even when these factors are taken into account, interpretation of the numbers caught is not always straightforward because the presence of moonlight and strong winds both dramatically affect trap efficiency (Bowden and Church, 1973; Morton et al., 1981; Muirhead-Thomson, 1991). The response of insects to light may also vary with their behavioural or physiological state—some species, for example, are not attracted to light during the ascent phase of aerial migration (Johnson, 1969). Moreover, it seems likely that high-flying migrants will often not be detected at all, unless the traps happen to be placed in an area where the migrants are descending (Farrow, 1979; Reynolds and Riley, 1988), or on structures high enough to intercept them at their flight altitude (Gregg et al., 1993). In spite of these limitations, the technique was successfully used in the initial investigations of the migration of the African armyworm moth, *Spodoptera exempta* (Brown et al., 1969; Tucker et al., 1982), although the advent of easier-to-use pheromone traps made it possible to set-up a much higher density of catching points for long-term monitoring (see below). Light trapping is also successfully used to monitor the annual immigration of the planthoppers *N. lugens* and *S. furcifera* into Japan. Information on the timing and intensity of these invasions is used to forecast outbreaks by subsequent generations of the planthoppers (Ministry of Agriculture and Forestry, 1971; Hirao, 1979, 1985). A light trap network has also been employed for the surveillance of *N. lugens* in other Asian countries, for example, China (Zhou et al., 1995), Taiwan (Wang and Yen, 1985) and Malaysia (Ooi, 1982; Ooi and Heong, 1988).

Light-traps of the New Jersey or CDC type (in which small insects approaching the light are drawn into the trap by the suction from a fan) are effective monitors of nocturnally-flying mosquitoes and biting midges. These traps have been used for many years in public health programmes, e.g. the surveillance of insect-borne viral diseases (Service, 1993). The attractiveness of the CDC trap is often increased by adding to it a source of carbon dioxide, usually dry ice.

Pan Traps

Open trays or pans containing water with a small amount of detergent or oil added to make insect escape less likely, have proved to be very convenient monitors of the presence of small species such as aphids (Robert, 1987) and rice planthoppers (Kisimoto, 1968). Yellow-coloured pan traps often catch more insects than do traps of other colours. As in the case of light traps, quantitative interpretation of the catch is made difficult because efficiency is a function of trap position and wind speed (Perfect, 1986), and because insect behavioural response is likely to be affected by ambient illumination.

Trapping by Pheromones or Other Chemical Attractants

Pheromone traps are a widely used and very powerful method of detecting specific pests, and the general principles of their application in monitoring have been outlined by Wall (1990). Pheromones of hundreds of insect species have now been characterised, and artificially synthesised versions of a number of these chemicals are used as lures in attractant traps for both monitoring and control. Most monitoring activities have been 'in-field', often designed to optimise the timing of insecticide applications, rather than to detect potentially harmful changes in abundance and distribution of highly mobile species.

The main advantages of pheromone traps are that they are robust and easy to maintain in the field; they require no electrical power; and their high degree of species specificity means that labour-intensive, entomological expertise is not required to sort the insects. However, there can be difficulties in interpreting the catch because the numbers caught are not always related to the numbers of eggs or larvae subsequently found in surrounding fields (Wall, 1990; Campion, 1994). Also, like light traps, pheromone traps fail to detect high-flying migrants unless the traps are in areas where the migrants descend.

A network of pheromone traps, supplemented with a few light traps, is routinely used in eastern Africa to monitor moths of the African armyworm, *S. exempta*. Data on the number of moths caught are used (in conjunction with information on previous armyworm outbreaks and on rainstorms —see above), to forecast new outbreaks of the high-density gregarious-phase larvae. The aim is twofold: strategic control of 'critical' outbreaks, i.e. those which might otherwise give rise to damaging infestations in the next generation, and direct protection of presently-infested crops and pastures (Rose et al., 1997). Practical details of the methodology, including duties of the trap operator, siting of traps, and storage of lures are given in Rose et al. (1995).

Pheromone traps have also been used to monitor other migratory noctuid pests, with a view to predicting damage levels in crops so that insecticide applications can be made in a more rational manner (see, for example, the monitoring of *Heliothis*/*Helicoverpa* spp. moths in the USA and other places (Lopez et al., 1990) and *Spodoptera litura* and *Helicoverpa armigera* in India (Wightman and Ranga Rao, 1993)).

Chemical attractants other than pheromones are also used to monitor migratory pests. An example is the odour-bait 'swormlure' used to trap the New World screwworm, *Cochliomyia hominivorax,* a fly whose larvae infest mammalian wounds, and which is a very serious pest of livestock in the Americas. A lure trap network was recently employed to monitor the successful eradication campaign in Libya (where the fly had been accidentally introduced) (Lindquist et al., 1992).

A variant of the bait trap is the stationary human blackfly collector (see above) where a man acts as both bait and trapping 'device'.

Suction Trapping

In Europe, networks of suction traps have been employed for many years to routinely monitor airborne populations of small insects, particularly in order to forecast outbreaks of pest aphids (Tatchell, 1991). Suction trap networks have also found application in other temperate areas, for example, in the western USA (Halbert et al., 1990), but the technique seems to have been taken up in the tropics only as a research tool (Johnson et al., 1982; Perfect et al., 1985), and we know of no programme where suction trapping is routinely used to monitor tropical migrants.

Aerial Netting

Nets or other traps mounted on aircraft, balloons and kites have proved to be very useful devices for investigating the atmospheric transport of insect pests, particularly small-sized species, in both temperate areas (see references in Greenstone et al., 1991) and in the tropics (Riley et al., 1995). Netting is especially effective when used with insect-detecting radar, because the net can then be placed at the altitude where the insects are seen to be most dense. The cost and logistic demands of lifting devices for airborne nets preclude their use for routine operational monitoring, but similar 'wind sock' nets fixed to poles and located, for example, on mountain tops, near coastlines or on-board ships, have been used to monitor the migration of the rice planthoppers, *N. lugens, S. furcifera* and *Laodelphax striatellus,* in East and Southeast Asia (e.g. National Co-ordinated Research Group, 1981; Ooi, 1982; Hirao, 1985; Liu, 1985; Kisimoto, 1991).

Insect Monitoring Radars

Research programmes using scanning entomological radars have provided unique insights into insect migration because the technique provides the only means of observing insects in undisturbed migratory flight at altitude (see references in Riley, 1989). These radars are not suitable for extended periods of monitoring because both their operation and the associated data analysis are very labour intensive (Drake, 1993), and because their capacity to identify the insects which they detect is limited. However, the recent development of an inexpensive vertical-looking radar (VLR) system means that routine monitoring of migration is now a practical possibility (Smith et al., 1993; Riley, 1993; Riley and Reynolds, 1993). This is because the radar is controlled by computer, so long-term automated operation is feasible, but more importantly, because the formidable, time-consuming tasks of signal analysis and data handling have now been fully automated.

In addition to measurements of the altitude, orientation, speed and direction of individual migrating insects, VLR provides estimates of their mass, shape and wingbeat frequency, so species of significantly different size and shape may be discriminated from one another. The possible application of the

VLR technique to monitoring desert locust and Australian plague locust migration have been outlined by Riley and Reynolds (1993) and by Drake (1993), and recent field trials in Mauritania have shown that VLR can identify desert locusts amongst other flying insects (J.R. Riley, unpublished data). The feasibility of operating VLR hardware for extended periods has been demonstrated by the experiments carried out over 2 years by Beerwinkle et al. (1994) in the USA, but the full potential of VLR, equipped with the powerful new analytical software, remains to be exploited.

Conclusions

Conventional entomological techniques for detecting the presence of insects, such as light- and pheromone-trapping, have been used successfully in the past to monitor the migration of tropical pest species. These methods, together with surveys supplemented by data from satellite imagery, seem certain to remain the basis for migration monitoring in the foreseeable future. However, ground trapping methods do not detect high-flying migrants while they are in transit, and trap results can be very difficult to interpret in a quantitative manner. Surveys are logistically expensive, and like light-trapping, are labour intensive, so monitoring over extended periods is often impracticable.

The recent advent of the VLR radar technique brings two potential advantages. First, it is now possible to routinely complement the traditional methods of monitoring migration, with direct, quantitative measurements of high altitude insect flight. This should allow trap catches and survey findings to be interpreted in terms of actual migratory flux, at least for numerically dominant species or those of distinctive size or shape which could be identified by VLR. Second, the automated nature of VLR observations and data reduction means that long-term migration monitoring has for the first time become an economic and practicable possibility. This capacity to make measurements of the abundance and diversity of migratory insects over the long term seems likely to find application in studies of the effects of climate and environmental changes on both pest and innocuous species (Porter et al., 1991; Harrington and Stork, 1994; Woiwod and Harrington, 1994).

References

Beerwinkle K. R., Lopez J. D., Schleider, P. G. and Lingren P. D. (1994) Annual patterns of aerial insect densities at altitudes from 500 to 2300 meters in east-central Texas indicated by continuously-operating vertical-looking radar, pp. 415–418. In *Proceedings of 21st Conference on Agricultural and Forest Meteorology—11th Conference on Biometeorology,* March 7–11 1994, San Diego, California. American Meteorological Society, Boston.

Bowden J. and Church B. M. (1973) The influence of moonlight on catches of insects in light traps in Africa. Part II. The effect of moon-phase on light-trap catches. *Bull. Ent. Res.* 63, 129–142.

Brown E. S., Betts E. and Rainey R. C. (1969) Seasonal changes in distribution of the African armyworm, *Spodoptera exempta* (Wlk.) (Lepidoptera: Noctuidae), with special reference to eastern Africa. *Bull. Ent. Res.* 58, 661–728.

Bryceson K. P., Hunter D. M. and Hamilton J. G. (1993) Use of remotely sensed data in the Australian Plague Locust Commission, pp. 435–439. In *Pest Control and Sustainable Agriculture* (Edited by S. A. Corey, D. J. Dall and

W. M. Milne). CSIRO Publications, Melbourne.

Cammell M. E. and Way M. J. (1987) Forecasting and monitoring, pp. 1–26. In *Integrated Pest Management* (Edited by A. J. Burn, T. H. Coaker and P. C. Jepson). Academic Press, London.

Campion D. G. (1994) Pheromones for the control of cotton pests, pp. 505–534. In *Insect Pests of Cotton* (Edited by G. A. Matthews and J. P. Tunstall). CAB International, Wallingford, UK.

Cherlet M. and Di Gregorio A. (1991) *Calibration and Integrated Modelling of Remote Sensing Data for Desert Locust Habitat Monitoring.* Report of FAO projects ECLO/INT/004/BEL and GCP/INT/439/BEL. FAO, Rome.

Cherlet M. R., DiGregorio A. and Hielkema J. U. (1991) Remote sensing applications for desert-locust monitoring and forecasting. *EPPO Bull.* 21, 633–642.

Chiang H. C. (1977) Pest management in the People's Republic of China – monitoring and forecasting insect populations in rice, wheat, cotton and maize. *FAO Plant Prot. Bull.* 25, 1–8.

Cooter R. J. (1993) The flight potential of insect pests and its estimation in the laboratory: Techniques limitations and insights. *The Gooding Memorial Lecture, given to The Central Association of Bee-Keepers, 13 September 1992.* The Central Association of Bee-Keepers, Hadleigh, Essex, UK.

Day R. K. and Knight J. D. (1995) Operational aspects of forecasting migratory pests, pp. 323–334. In *Insect Migration: Tracking Resources through Space and Time* (Edited by V. A. Drake and A. G. Gatehouse). Cambridge University Press, Cambridge, UK.

Dingle H. (1989) The evolution and significance of migratory flight, pp. 99–114. In *Insect Flight* (Edited by G. J. Goldsworthy and C. H. Wheeler). CRC Press, Boca Raton, Florida.

DLCO-EA (Desert Locust Control Organisation for Eastern Africa) (1992) *The African Armyworm: Regional Armyworm Programme of Desert Locust Control Organisation for Eastern Africa* (2nd Edition). DLCO-EA, Nairobi.

Drake V. A. (1990) Methods for studying adult movement in *Heliothis*, pp. 109–121. In *Heliothis: Research Methods and Prospects* (Edited by M. P. Zalucki). Springer-Verlag, New York.

Drake V. A. (1993) Insect-monitoring radar: A new source of information for migration research and operational pest forecasting, pp. 452–455. In *Pest Control and Sustainable Agriculture* (Edited by S. A. Corey, D. J. Dall and W. M. Milne). CSIRO Publications, Melbourne.

Drake V. A. and Farrow R. A. (1988) The influence of atmospheric structure and motions on insect migration. *Annu. Rev. Entomol.* 33, 183–210.

Drake V. A. and Gatehouse A. G. (1995) (Eds) *Insect Migration: Tracking Resources through Space and Time.* Cambridge University Press, Cambridge, UK.

FAO (1992) *The Desert Locust Guidelines. III. Information and Forecasting.* FAO, Rome.

FAO (1994) *The Desert Locust Guidelines. II. Survey.* FAO, Rome.

Farrow R. A. (1979) Population dynamics of the Australian plague locust, *Chortoicetes terminifera* (Walker), in central New South Wales. I. Reproduction and migration in relation to the weather. *Aust. J. Zool.* 27, 717–745.

Greenstone M. H., Eaton R. R. and Morgan C. E. (1991) Sampling aerially dispersing arthropods: A high-volume, inexpensive, automobile- and aircraft-borne system. *J. Econ. Entomol.* 84, 1717–1724.

Gregg P.C., Fitt G. P., Coombs M. and Henderson G. S. (1993) Migrating moths (Lepidoptera) collected in tower-mounted light traps in northern New South Wales, Australia: Species composition and seasonal abundance. *Bull. Ent. Res.* 83, 563–578.

Gunn D. L. and Rainey R. C. (1979) (Eds) *Strategy and Tactics of Control of Migrant Pests.* The Royal Society, London. *Phil. Trans. R. Soc. Lond.* B 287, 245–488.

Halbert S., Connelly J. and Sandvol L. (1990) Suction trapping of aphids in western North America (emphasis on Idaho). *Acta Phytopathol. Entomol. Hung.* 25, 411–422.

Hamilton J. G. and Bryceson K. P. (1993) Use of enhanced GMS weather satellite data in locust forecasting, pp. 444–448. In *Pest Control and Sustainable Agriculture* (Edited by S. A. Corey, D. J. Dall and W. M. Milne). CSIRO Publications, Melbourne.

Hardie J. (1993) Flight behaviour in migrating insects. *J. Agric. Entomol.* 10, 239–245.

Harrington R. and Stork N. E. (1994) (Eds) *Insects in a Changing Environment: Proceedings of the 17th Symposium of the Royal Entomological Society.* Academic Press, London.

Hielkema J. U. (1990) Satellite environment monitoring for migrant pest forecasting by FAO: The ARTEMIS system. *Phil. Trans. R. Soc. Lond.* B 328, 705–717.

Hirao J. (1979) Forecasting brown planthopper outbreaks in Japan, pp. 101–112. In *Brown Planthopper: Threat to Rice Production in Asia.* International Rice Research Institute, Los Baños, Philippines.

Hirao J. (1985) Recent trends in the occurrence and forecasting procedures in the brown planthopper. *Chin. J. Entomol.* 4, 65–76.

Johnson C. G. (1969) *Migration and Dispersal of Insects by Flight.* Methuen, London.

Johnson C. G., Crosskey R. W. and Davies J. B. (1982) Species composition and cyclical changes in the numbers of savanna blackflies (Diptera: Simuliidae) caught by suction traps in the Onchocerciasis Control Programme area in W. Africa. *Bull. Ent. Res.* 72, 39–64.

Joyce R. J. V. (1981) The control of migrant pests, pp. 209–229. In *Animal Migration* (Edited by D. J. Aidley). Cambridge University Press, Cambridge, UK.

Kennedy J. S. (1985) Migration, behavioural and ecological, pp. 5–26. In *Migration: Mechanisms and Adaptive Significance* (Edited by M. A. Rankin). *Contrib. Marine Sci.* 27, suppl.

Kisimoto R. (1968) Yellow pan water trap for sampling the small brown planthopper, *Laodelphax striatellus* (Fallén), a vector of the rice stripe virus. *Appl. Ent. Zool.* 3, 37–48.

Kisimoto R. (1991) Long-distance migration of rice insects, pp. 167–195. In *Rice Insects: Management Strategies* (Edited by E. A. Heinrichs and T. A. Miller). Springer-Verlag, New York.

Kitenda K. R. A. (1990) Training: The missing link in pest control. *Phil. Trans. R. Soc. Lond.* B 328, 673–677.

Lindquist D. A., Abusowa M. and Hall M. J. R. (1992) The New World screwworm fly in Libya: A review of its introduction and eradication. *Med. Vet. Entomol.* 6, 2–8.

Liu C.-H. (1985) Study on the long-distance migration of the brown planthopper in Taiwan. *Chin. J. Entomol.* 4, 49–54.

Lopez J. D., Shaver T. N. and Dickerson

W. A. (1990) Population monitoring of *Heliothis* spp. using pheromones, pp. 473–496. In *Behaviour-Monitoring Chemicals for Insect Management* (Edited by R. L. Ridgway, R. M. Siverstein and M. N. Inscoe). Marcel Dekker, New York.

Magor J. I. (1995) Forecasting migrant insect pests, pp. 399–426. In *Insect Migration: Tracking Resources through Space and Time* (Edited by V. A. Drake and A. G. Gatehouse). Cambridge University Press, Cambridge, UK.

Meinzingen W. F. (1993) (Ed.) *A Guide to Migrant Pest Management in Africa.* FAO, Rome.

Milford J. R. and Dugdale G. (1990) Monitoring rainfall in relation to the control of migrant pests. *Phil. Trans. R. Soc. Lond.* B 328, 689–704.

Ministry of Agriculture and Forestry (Japan) (1971) *General and Detailed Rules for the Enforcement of Disease and Insect Outbreak Forecast Work for Ordinary Crops in Japan.* Agricultural Administration Bureau, Ministry of Agriculture and Forestry, Tokyo.

Morton R., Tuart L. D. and Wardhaugh K. G. (1981) The analysis and standardisation of light-trap catches of *Heliothis armigera* (Hübner) and *H. punctiger* (Wallengren) (Lepidoptera: Noctuidae). *Bull. Ent. Res.* 71, 207–225.

Muirhead-Thomson R. C. (1991) *Trap Responses of Flying Insects.* Academic Press, London, UK.

National Co-ordinated Research Group for White Back Planthoppers (1981) Studies on the migration of white back planthoppers (*Sogatella furcifera* Horvath). *Sci. Agric. Sin. 1981* No. 5, 25–31.

Ooi P. A. C. (1982) A surveillance system for the rice planthoppers in Malaysia, pp. 551–565. In *Proceedings of the International Conference on Plant Protection in the Tropics* (Edited by K. L. Heong, B. S. Lee, T. M. Lim, C. H. Teoh and Y. Ibrahim). Malaysian Plant Protection Society, Kuala Lumpur, Malaysia.

Ooi P. A. C. and Heong K. L. (1988) Operation of a brown planthopper surveillance system in the Tanjung Karang Irrigation Scheme in Malaysia. *Crop Prot.* 7, 273–278.

Padgham D. E. (1983) The influence of the host plant on the development of the adult brown planthopper, *Nilaparvata lugens* (Stål) (Hemiptera: Delphacidae), and its significance for migration. *Bull. Ent. Res.* 73, 117–128.

Pedgley D. E. (1981) (Ed.) *Desert Locust Forecasting Manual* Volumes 1 and 2. Centre for Overseas Pest Research, London.

Pedgley D. E. (1982) *Windborne Pests and Diseases: Meteorology of Airborne Organisms.* Ellis Horwood, Chichester, UK.

Pedgley D. E. (1993) Managing migratory insects pests — A review. *Int. J. Pest Manage.* 39, 3–12.

Perfect T. J., Cook A. G. and Padgham D. E. (1985) Interpretation of the flight activity of *Nilaparvata lugens* (Stål) and *Sogatella furcifera* (Horváth) (Hemiptera: Delphacidae) based on comparative trap catches and field monitoring with rubidium. *Bull. Ent. Res.* 75, 93–106.

Perfect T. J. (1986) Techniques for insect sampling in relation to forecasting pest outbreaks, pp. 42–46. In *Proceedings of the Seminar on Agrometeorology and Pest Forecasting, Fulmer Grange, UK, 24–28 June 1985.* CTA, Wageningen & TDRI, London.

Porter J. H., Parry M. L. and Carter T. R. (1991) The potential effects of climatic change on agricultural insect pests. *Agric. For. Meteorol.* 57, 221–240.

Rabb R. L. and Kennedy G. G. (1979)

(Eds) *Movement of Highly Mobile Insects: Concepts and Methodology in Research*. North Carolina State University, Raleigh.

Rainey R. C. (1958) Some observations on flying locusts and atmospheric turbulence in eastern Africa. *Q. J. R. Met. Soc.* 84, 334–354.

Rainey R. C. (1963) Aircraft reconnaissance and assessment of locust populations, pp. 228–233. In *Report of the 2nd International Agricultural Aviation Congress, 19–22 September 1962*, Grignon, France.

Rainey R. C., Browning K. A., Cheke R. A. and Haggis M. J. (1990) (Eds) *Migrant Pests: Progress, Problems and Potentialities*. The Royal Society, London. *Phil. Trans. R. Soc. Lond.* B 328, 515–755.

Reissig W. H., Heinrichs E. A., Litsinger J. A., Moody K., Fiedler L., Mew T. W. and Barrion A. T. (1985) *Illustrated Guide to Integrated Pest Management in Rice in Tropical Asia*. International Rice Research Institute, Los Baños, Philippines.

Reynolds D. R. and Riley J. R. (1988) A migration of grasshoppers, particularly *Diabolocatantops axillaris* (Thunberg) (Orthoptera: Acrididae), in the West African Sahel. *Bull. Ent. Res.* 78, 251–271.

Riley J. R. (1989) Remote sensing in entomology. *Annu. Rev. Entomol.* 34, 247–271.

Riley J. R. (1993) A radar technique for automatically monitoring insect migration and biodiversity, pp. 310–314. In *Proceedings of Twelfth International Symposium on Biotelemetry*, Ancona, 1992 (Edited by P. Mancini, S. Fioretti, C. Cristalli and R. Bedini). Litografia Felici, Pisa, Italy.

Riley J. R. and Reynolds D. R. (1993) Radar monitoring of locusts and other migratory insects, pp. 51–53. In *World Agriculture 1993* (Edited by A. Cartwright). Sterling Publications, London.

Riley J. R., Armes N. J., Reynolds D. R. and Smith A. D. (1992) Nocturnal observations on the emergence and flight behaviour of *Helicoverpa armigera* (Lepidoptera: Noctuidae) in the post-rainy season in central India. *Bull. Ent. Res.* 82, 243–256.

Riley J. R., Reynolds D. R., Mukhopadhyay S., Ghosh M. R. and Sarkar T. K. (1995) Long-distance windborne migration of aphids and other small insects in north-east India. *Eur. J. Entomol.* 92, 639–653.

Robert Y. (1987) Aphid vector monitoring in Europe, pp. 81–129. In *Current Topics in Vector Research. Vol. 3* (Edited by K. F. Harris). Springer-Verlag, New York.

Robinson T. P. (1995) Geographic information systems and remotely sensed data for determining the seasonal distribution of habitats of migrant insect pests, pp. 335–352. In *Insect Migration: Tracking Resources through Space and Time* (Edited by V. A. Drake and A. G. Gatehouse). Cambridge University Press, Cambridge, UK.

Rose D. J. W., Dewhurst C.F. and Page W. W. (1997) *The African Armyworm Handbook: Its Status, Biology, Ecology, Epidemiology and Management, with Particular Reference to Eastern Africa*. Desert Locust Control Organisation for Eastern Africa, Nairobi (in press).

Ruesink W. G. and Kogan M. (1994) The quantitative basis of pest management. Sampling and measuring, pp. 355–391. In *Introduction to Insect Pest Management* (3rd Edition) (Edited by R. L. Metcalf and W. H. Luckman). John Wiley & Sons, New York.

Sellers R. F. (1980) Weather, host and vector—Their interplay in the spread of insect-borne animal virus diseases. *J. Hyg., Camb.* 85, 65–102.

Sellers R. F. and Pedgley D. E. (1985) Possible wind-borne spread to western Turkey of bluetongue virus in 1977 and of Akabane virus in 1979. *J. Hyg., Camb.* 95, 149–158.

Service M. W. (1993) *Mosquito Ecology: Field Sampling Methods* (2nd Edition). Elsevier Applied Science, London.

Smith A. D., Riley J. R. and Gregory R. D. (1993) A method for routine monitoring of the aerial migration of insects by using a vertical-looking radar. *Phil. Trans. R. Soc. Lond.*, B 340, 393–404.

Southwood T. R. E. (1978) *Ecological Methods with Particular Reference to the Study of Insect Populations* (2nd Edition). Chapman and Hall, London.

Steedman A. (1990) (Ed.) *Locust Handbook* (3rd Edition). Natural Resources Institute, Chatham.

Tang J. Y., Cheng J. A. and Norton G. A. (1994) HOPPER—An expert system for forecasting the risk of white-backed planthopper attack in the first crop season in China. *Crop Prot.* 13, 463–473.

Tatchell G. M. (1991) Monitoring and forecasting aphid problems, pp. 215–230. In *Aphid–Plant Interactions: Populations to Molecules* (Edited by D. C. Peters, J. A. Webster and C. S. Chlouber). Oklahoma Agricultural Experiment Station Miscellaneous Publication No. 132.

Taylor J., Padgeham D. E. and Perfect T. J. (1982) A light trap with upwardly directed illumination and temporal segregation of the catch. *Bull. Ent. Res.* 72, 405–431.

Tucker M. R., Mwandoto S. and Pedgley D. E. (1982) Further evidence for windborne movement of armyworm moths, *Spodoptera exempta,* in East Africa. *Ecol. Ent.* 7, 463–473.

Tucker M. R. and Pedgley D. E. (1983) Rainfall and outbreaks of the African armyworm, *Spodoptera exempta* (Walker) (Lepidoptera: Noctuidae). *Bull. Ent. Res.* 73, 195–199.

Wall C. (1990) Principles of monitoring, pp. 9–23. In *Behaviour-Modifying Chemicals for Insect Management* (Edited by R. L. Ridgway, R. M. Siverstein and M. N. Inscoe). Marcel Dekker, New York.

Walsh J. F., Davies J. B. and Cliff B. (1981) World Health Organisation Onchocerciasis Control Programme in the Volta River Basin, pp. 85–103. In *Blackflies: The Future for Biological Methods in Integrated Control* (Edited by M. Laird). Academic Press, London, New York.

Wang S.-S. and Yen F.-C. (1985) Analysis of the data of brown planthopper (*Nilaparvata lugens* (Stål)) with light trap in Taiwan. *Chin. J. Entomol.* 4, 13–22.

Wightman J. A. and Ranga Rao G. V. (1993) Pheromone trapping in South Asia: Review and requirements. *IOBC/WPRS Bull.* 16 (10), 149–156.

Woiwod I. P. and Harrington R. (1994) Flying in the face of change—The Rothamsted insect survey, pp. 321–342. In *Long-Term Research in Agricultural and Ecological Sciences* (Edited by R. A. Leigh and A. E. Johnson). CAB International, Wallingford.

Zhou B.-H., Wang H.-K. and Cheng X.-N. (1995) Forecasting systems for migrant pests. I. The brown planthopper in China, pp. 353–364. In *Insect Migration: Tracking Resources through Space and Time* (Edited by V. A. Drake and A. G. Gatehouse). Cambridge University Press, Cambridge, UK.

New Perspectives in the Behaviour and Chemical Ecology of Tropical Insects

Convenor: *Dr R. K. Saini*
ICIPE,
Nairobi, Kenya

PLENARY LECTURE

Semiochemicals 2001

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Abstract—In the latter half of the 20th century, we have had considerable success in identifying pheromones for many insect species, in characterising perception and response mechanisms, and determining how pheromones are biosynthesised. Successful applications include disruption of mating by moths that use sex pheromones, mass trapping of beetles that use aggregation pheromones, and the use of pheromone-baited traps to monitor insect pests as part of integrated pest management (IPM) programmes. However, most successes have been in the temperate zone; many pheromones are incompletely characterised, and applications have not been as routinely effective as those for chemical insecticides. New technology and new thinking are both required. In the future, coupled gas chromatographic-electroantennographic analysis will revolutionise and refine the identification of pheromones, and other semiochemicals. Delivery of this technology to the tropics could be achieved by setting up three networks, one each in Africa, Asia and the tropical Americas, to process insects from throughout a representative region. Thinking must expand to include types of communication largely neglected until now, e.g. between eggs or larvae and adults. And instead of focusing on one phenomenon, e.g. sex attraction, entomologists must examine the role of multiple semiochemicals that insects use in the process of making decisions regarding host selection and reproduction. These will include host plant kairomones and semiochemicals from heterospecific insects, as well as pheromones produced by conspecifics. This new approach will lead to an ability to sabotage key aspects in the life history of an insect pest and to apply all possible types of semiochemical-based controls. However, semiochemical-based applications will be only one of numerous types of factors used in the integrated, species-specific management of insect pests. The widespread adoption of semiochemicals in pest management will demand a commercial environment receptive to developing and delivering species-specific products, with correspondingly limited profitability, and will also require a benevolent registration system for these products.

Key Words: IPM, semiochemicals, pheromones, host plant kairomones

Introduction

In the latter half of the 20th century, entomologists and chemists have had remarkable success in the identification of message-bearing chemicals, now widely known as semiochemicals, after the Greek word *semeon,* which means a mark or signal (Nordland, 1981). For example, by 1992 there were known sex pheromones for 397 species and subspecies of Lepidoptera (Arn et al., 1992). Many attractive sex or aggregation pheromones, as well as attractive host kairomones for insects in other orders have also been identified (Meyer and McLaughlin, 1988). Diversity in semiochemical-based communication is manifest in such intriguing examples as the honeybee queen mandibular gland pheromone that maintains a queen's retinue (Slessor et al., 1988), trail-following pheromones in ants (Morgan, 1984), multifunctional defensive and alarm pheromones of bugs (Aldrich, 1988), maturation pheromone for the desert locust (Mahamat et al., 1993) and even death recognition signals ('necromones') for cockroaches (Rollo et al., 1994).

The arsenal of new semiochemicals has found increasing practical use, primarily in the detection and monitoring of insect pests, in disruption of their mating, and in reduction of populations through mass trapping (Ridgway et al., 1988). However, most of the applications have been on insect pests in temperate zones, on worldwide pests of major economic crops, e.g. cotton, or on pests of a few major tropical crops, e.g. oil palms. Few applications have been developed for most tropical crops, and almost none has been developed for subsistence farmers. In addition to uneven applications of known semiochemicals, many applications are not very efficacious, particularly in pheromone-based disruption. There is a growing realisation that some of this inadequate efficacy may be due to the fact that key minor components for many insect pheromones are yet to be discovered. Finally, the chemical ecology of many important insects, especially in the tropics, remains an unstudied mystery.

I perceive five needs for the study and use of insect semiochemicals in the next century: (1) a willingness to seek and adopt new technology; (2) learning to pursue new patterns of thinking, perhaps like an insect; (3) a need to incorporate the use of semiochemicals into integrated pest management (IPM) systems; (4) a commercial environment receptive to developing, marketing and delivering semiochemical-based products and services; and (5) a benevolent registration system for species-specific, naturally-derived materials.

New Technology and Its Implementation in Tropical Countries

There are many examples where new technology could apply to furthering the study and use of semiochemicals in the next century. These range from employing enzymes to synthesise chirally-pure pheromones (Stokes and Oehlschlager, 1987), to the use of biodegradable plastics for pheromone release devices. But there is one technology, coupled gas chromatographic electroantennographic detection (GC-EAD) (Struble and Arn, 1984), that could greatly change our knowledge of and ability to use semiochemicals against insect pests. With the current sophistication of gas chromatography and electrophysiology, volatile samples containing only a small portion of the contents of a single pheromone gland from a calling female moth can be routinely analysed by GC-EAD.

The system relies on twin detection systems. One is an insect antenna suspended between two electrodes, or with minute insects' antennae that are impaled by a recording electrode, while a reference electrode is placed somewhere in the haemocoel. The sample extract is injected onto a split-stream capillary gas chromatographic column so that compounds separated by the column arrive at identical times at the antennal preparation, and at the flame ionisation detector (FID) of the gas chromatograph. The FID records everything, while the antenna responds electrochemically by a depolarisation of olfactory receptors only when the compound in question is one that they are preprogrammed to smell. Thus the antenna filters out all the chemical noise that the FID records, leaving the investigator only a few potentially behaviourally-active compounds to identify, synthesise and bioassay.

In many cases GC-EAD can result in the immediate identification of a new pheromone. For example, antennae of the African palm weevil, *Rhyncophorus phoenicis* L., detected a single-component aggregation pheromone, 3-methyl-4-octanol (phoenicol), in a 'sea' of FID-active compounds (Gries et al., 1993). In such cases, it may be only days between the time that an investigation begins and a new pheromone candidate is ready for field testing.

The situation encountered by our research group with the eastern hemlock looper, *Lambdina fiscellaria fiscellaria* (Guenee) was much different (Gries et al., 1991). The male antenna responded to four compounds in the female gland extract, but the compounds were in such minute quantity that there was no FID response at all. However, expert inferences as to the gas chromatographic retention characteristics of the candidate compounds, and some fine synthetic chemistry, validated by GC-EAD, and GC-mass spectroscopic analyses, resulted in identification of the four antennally-active compounds. Two of the synthetic compounds were verified to be active in field tests run only six weeks after the investigation began.

We have also used GC-EAD analysis to determine that minute amounts of antennally-active unknown compounds, that are below the detection threshold of the most sensitive gas chromatograph, occur in the volatile extracts of several lepidopteran pests. We are beginning to demonstrate that these trace components are in fact key sex pheromone components in these insects. I suggest that in the next era of insect chemical ecology, every insect for which we think we know the complete pheromone blend should be reanalysed by GC-EAD. These analyses would determine if there are as yet unknown pheromone components that could potentially increase the efficacy of pheromones used to monitor or manage insect pests. For insects that have yet to be studied in this and the next century it is absolutely essential that they be subjected to GC-EAD analysis.

One might ask, who will study the chemical ecology of tropical insect pests in the next century? I propose the establishment of three networks for research on semiochemicals of tropical insects, one each in Africa, Asia, and the tropical Americas. One centre for such a network already exists at the International Centre of Insect Physiology and Ecology (ICIPE) in Nairobi, Kenya. A fine group of world class African scientists from locust-affected countries at ICIPE have recently employed GC-EAD technology in the identification of a whole suite of new pheromones for the desert locust, *Schistocerca gregaria* (Forskal) (Hassanali, 1995). This landmark study undoubtedly puts the ICIPE group firmly on the world semiochemical map. The centres of the Asian and American networks should also have an appropriate combination of expertise, stability, interest and established worldwide liaisons with other scientists.

In my vision of a working network, it would be the initial responsibility of the centre laboratory to establish contacts with scientists in other countries within the network region. As the existence of the network became known, new participants would be expected to join the network voluntarily. The target insects would be ranked in order of economic, social or biotic importance, and a manageable group of insects would be selected. Entomologists in participating countries would be responsible for collection of insect and plant material, as well as bioassays in the laboratory and the field. Chemists and electrophysiologists at the centre laboratory would perform GC-EAD analysis, as well as the analytical and synthetic chemistry needed for correct identification of active materials. They would also synthesise highly pure compounds of verified authenticity for field testing. Once semiochemicals are known, it would be the responsibility of scientists in the network countries to develop pest management strategies and tactics based on the potential uses of the new materials. With completion of work on one insect, the one ranked next in importance would take its place in the target group.

Such networks do not occur spontaneously. They need leadership, commitment, expertise, international goodwill, and long term funding. Some expert advice might also be required. It is usually one or a few determined and courageous individuals (not a committee) that launch such a venture and see it through to completion.

New Thinking

Let me now turn to new thinking. In fact, it is old thinking, that I advocate, because I believe that we should return to thinking like the old time naturalists, who in turn, did a good job of thinking like insects. I recently analysed the decision-making pathway that bark beetles needed to negotiate in the process of host selection (Borden, 1996). I then proposed how we could turn each decision around and use our knowledge to disrupt the beetles' behaviour. Herein, I examine the Lepidoptera.

The most often used and most efficacious way in which sex pheromones are used to manage lepidopteran pests is in mating disruption (Cardé, 1990), as depicted in Fig. 1. Dispersing males in search of mates are confronted with an artificial environment in which broadcast dispersion of synthetic sex pheromone creates the false impression that a habitat is loaded with pheromone-producing, conspecific females. Provided that the release rate is high enough and that the right materials are used in a blend of adequate complexity, males are unable to find and mate with females. This likely occurs due to a combination of false trail following, habituation and sensory adaptation. The technique works, and it has taken us a long way into a new era of pest management.

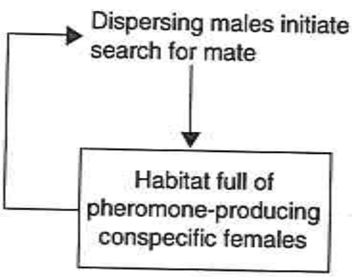

Fig. 1. Model depicting use of broadcast female sex pheromone to disrupt mating behaviour of male moths, and to maintain these males in a dispersive state.

But how would a naturalist look at the opportunities for the use of semiochemicals? I like to think that he or she would examine all of the possible opportunities for semiochemical-based communication with host and non-host plants and with all life stages of both con- and heterospecifics (Borden, 1993). Ensuing from this examination would be the construction of a decision-making pathway for female moths (not males), that depicts how a dispersing female would eventually find a suitable host plant (Fig. 2). This is, of course, a generalised model, and as for all such models, exceptions to it abound.

There are five critical decisions in the pathway (Fig. 2). A wrong decision can potentially result in not being mated, or in laying eggs that have a poor chance of survival. The first two decisions

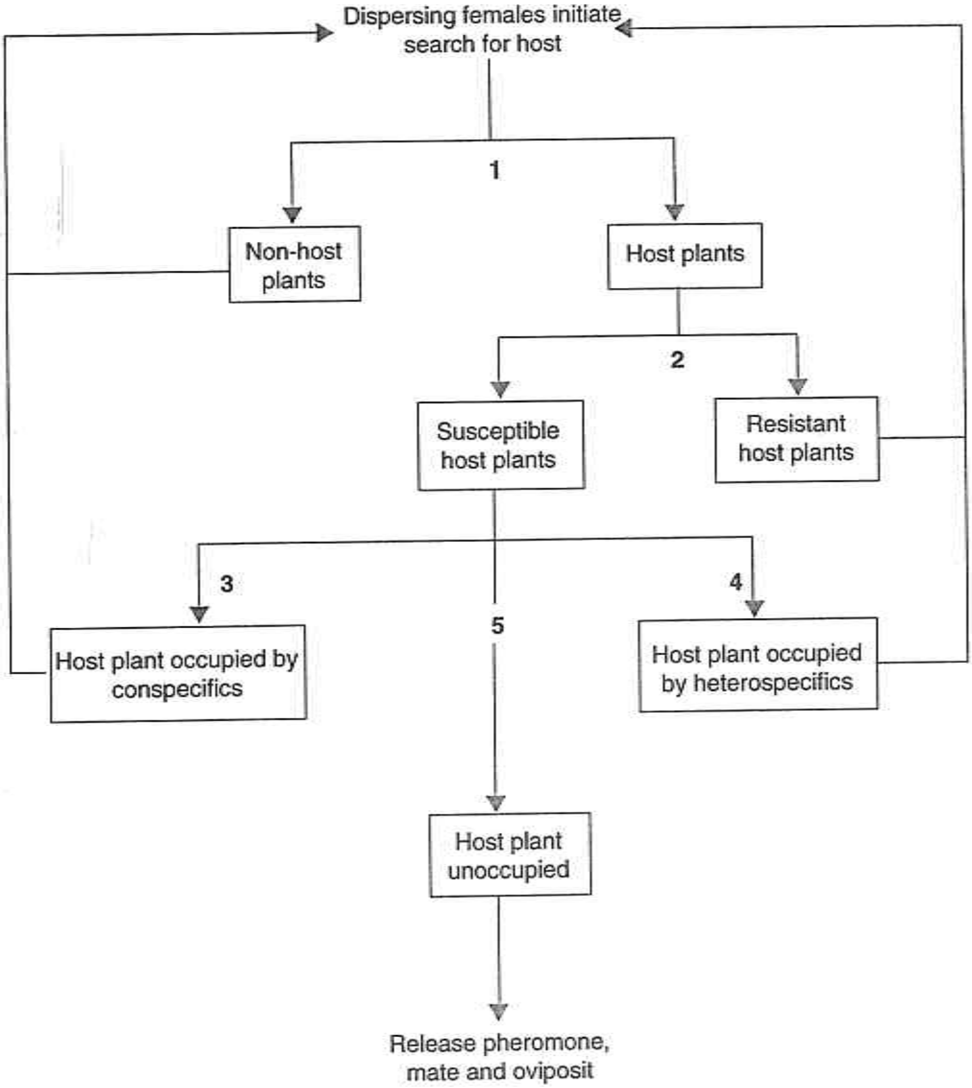

Fig. 2. Hypothetical decision-making pathway in which female moths must make four critical choices that lead to rejection of non-hosts or unfavourable hosts, prior to a fifth 'take-it-or-leave-it' choice whether or not to attack a suitable unoccupied host (or unoccupied portion of an occupied host).

involve initially perceiving the difference between host and non-host plants, and second, between resistant and susceptible host plants. Even within a natural population, there are plants that are more (or less) resistant than others, or are resistant at one stage of their lives, but not at another, and the insect must be able to tell the difference. The next two decisions involve the avoidance of host plants (or parts thereof) that are occupied by individuals of another species (decision 3), or their own species (decision 4). These individuals may be eggs, larvae or adults. In any of these cases, a territorial semiochemical signal may be perceived that would tell the host-seeking female that if she settles here, there is a good chance that her eggs will be eaten, or that the larvae ensuing therefrom will be outcompeted by larvae of the first-arriving hetero- or conspecifics. The final decision (number 5) is obviously a 'right' decision, the selection of an unoccupied host plant (or a sufficiently large unoccupied portion of an occupied plant) that will allow the female to release pheromone, mate and oviposit where her larvae have an excellent chance of survival.

If one continues to think like a naturalist, he or she can then begin to construct various tactics of increasing complexity, that could potentially be used in the disruption of female behaviour. I stress that this is primarily a *thinking* exercise at present, although hints derived from hard data are beginning to appear that suggest that this is the right track for the next century.

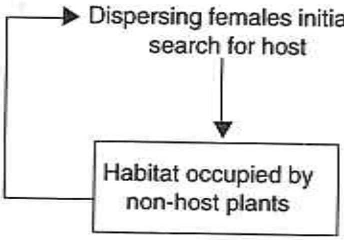

Fig. 3. Desired decision-making pathway in which a single semiochemical treatment is used to create the false message that a habitat is full of non-host plants, disrupting the host selection behaviour of female moths, and maintaining them in a dispersive state.

Taking the first decision, the most obvious disruptive tactic would be to give host-seeking females a false semiochemical message that a habitat was occupied by non-host plants (Fig. 3). This would of course demand that research be done to determine the semiochemical signals by which females avoid non-host plants.

Jumping a few steps, one could elucidate all the negative semiochemical stimuli associated with wrong decisions in the pathway (Fig. 2), and theoretically combine them in a single disruptive treatment (Fig. 4). The bogus semiochemical message would then be that a habitat was occupied by resistant, non-hosts populated by both con- and heterospecifics. The plant-associated stimuli might, for example, be various terpenoid substances, the heterospecific stimulus a sex pheromone component, and the conspecific stimulus an oviposition-deterrent pheromone associated with eggs. We do not yet know if such a tactic would work, but it would be most stimulating to do the research.

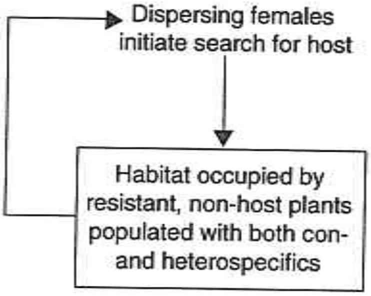

Fig. 4. Desired decision-making pathway in which multiple semiochemical treatments are used to create the false message that a habitat is full of resistant, non-host plants fully populated by both con- and heterospecific insects, disrupting the host selection behaviour of female moths, and maintaining them in a dispersive state.

Carrying this scenario to a final step, a 'push-pull' tactic could be invoked, whereby the disruptive combination ('push') was matched by an attractive stimulus, e.g. from a preferred host plant, that 'pulled' the disrupted females to their doom in traps or a trap crop (Fig. 5). Although microbial or hormonal insecticides would potentially work in the limited area occupied by a trap crop, there would be a good case in applying this tactic to use an acutely toxic, moderately persistent insecticide in a highly restricted and

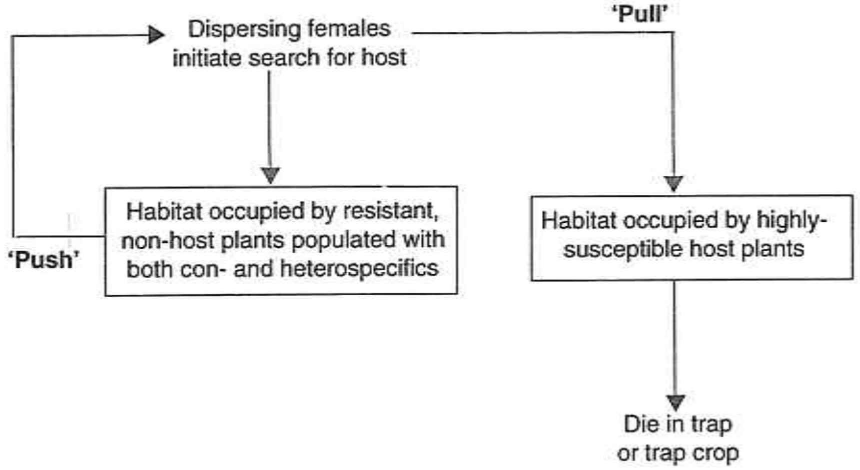

Fig. 5. Optimal desired decision-making pathway integrating all possible negative stimuli in Fig. 2 to 'push' female moths from a habitat to be protected, coupled with a lethal alternative, an apparent source of highly susceptible host plants that 'pull' them away.

environmentally-sensitive manner. Push-pull tactics are now beginning to gain favour for other taxa, including root-feeding Diptera such as onion maggots, *Delia antigua* (Meigen) (Miller et al., 1990), and bark beetles such as the mountain pine beetle, *Dendroctomus ponderosae* Hopkins (Lindgren and Borden, 1993).

The possible use of attractive host kairomones to trap female moths in a push-pull tactic (Fig. 5) raises yet another naturalist type question. If female sex pheromone could be used to disrupt mating behaviour by males, could attractive host plant kairomones be used to disrupt host selection behaviour by females (Fig. 6)? Recent studies indicate that long-range kairomonally-mediated host finding does occur in moths (Phelan et al., 1991), just as it occurs in flies (Hawkes and Coaker, 1974; Judd and Borden, 1989), locusts (Kennedy and Moorehouse, 1969), and beetles (Chapman, 1963). A disruptive tactic using attractive host plant kairomones might be particularly applicable against females that must find point-source hosts such as flowers or fruits.

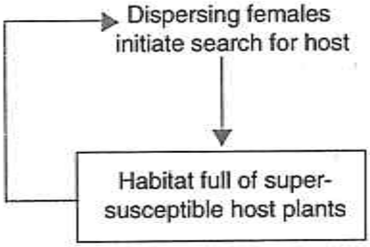

Fig. 6. Model depicting the hypothesised use of attractive host plant kairomones to disrupt host-selection behaviour by female moths in much the same manner as female sex pheromone is used to disrupt mating behaviour by males (Fig. 1).

The above considerations tempt one to wonder even further. If a host-based attractant could be used to disrupt female host-selection behaviour, what would be the effect of using such an attractant along with female sex pheromone to disrupt male behaviour (Fig. 7)? Would males follow false trails more diligently if the sex pheromone and attractive host kairomones were combined, or would sensory adaptation and habituation be more pronounced, thus increasing the disruptive effect?

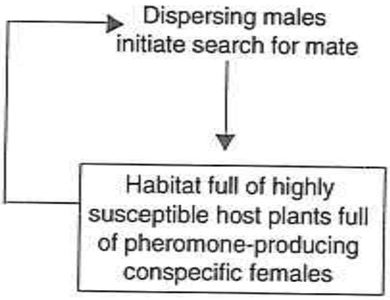

Fig. 7. Model depicting the proposed addition of attractive host plant kairomones to a female sex pheromone treatment in an attempt to enhance the disruption of mating behaviour of male moths.

Role of Semiochemicals in Integrated Pest Management

The third need for advancing the use of insect semiochemicals in the next century is to incorporate semiochemicals into IPM programmes. I have been dismayed to find that in many cases we are using semiochemicals against insects in a persistent and repetitious manner (Trumble and Alvarado-Rodriguez, 1993), in much the same way that has resulted in resistance to other insecticides, most recently, *Bacillus thuringiensis* Berliner (Tabashnik et al., 1990). It may seem improbable that insects will develop resistance to semiochemicals. However, laboratory studies attempting to select for altered amounts of pheromone production, or shifted ratios of pheromone components, suggest that resistance to broadcast disruptants could develop in the field (Collins and Cardé, 1989; Collins et al., 1990).

To develop true resistance to a female-produced sex pheromone, it may be necessary for the female to produce a different blend at the same time that the male sensory receptors adapt to perceive the new pheromone component(s) (Butlin and Trickett, 1996). But there are numerous other ways that an insect species could develop resistance, or otherwise 'resist' the use of a pheromone. These include:

1. immigration of mated, gravid females into a treated area;
2. immigration into a treated area of a new 'pherotype' that uses a different blend or a different ratio of the same components used by the target population;
3. selection for: (a) individuals that produce such high amounts of pheromone that they can be perceived over a background treatment, (b) females that mate away from the crop to be protected and immigrate into a treated area, (c) males that perceive or respond to only the complete, natural blend and are thus resistant to an incomplete, generic blend, (d) new pherotypes based on: females producing a new compound that the males can already smell, males perceiving a compound that the females already produce, ability to respond to a female-produced compound that the males can already smell, or different ratios of components than are found in the target population; and
4. adaptation to find mates by visual or other signals.

To avoid the development of resistance is sufficient reason alone to use semiochemicals along with other tools and tactics. In most cases, however, pest management will be most efficacious and enduring if various tactics are integrated in achieving the objectives of a given strategy.

A Commercial System Receptive to the Development and Marketing of Semiochemicals

Another of my needs for the next century is a receptive commercial system. Big companies that demand gross sales for a product that exceed \$5 million per year will only be interested in semiochemicals of major pests. While there may be a need for refinement, the delivery of semiochemical-based treatments for these pests is already locked up by commercial concerns.

Most semiochemicals are species-specific, either in their natural occurrence, or in their use. And species-specificity severely limits profitability. The markets for most pheromones, for example, will probably fall somewhere between \$5,000 and \$500,000 per year, depending on the type, extent, and regularity of use. Thus, companies that get into the semiochemical business must be prepared to grow in small, species-specific increments, in a far different way than conventional manufacturing or service companies, and even new molecular biotechnology companies.

In the tropics, such companies will need chemical expertise and good manufacturing facilities, but overheads will be much cheaper than in other parts of the world. Thus if a product works it may well fall within the purchasing power of small growers and local cooperatives. For many pests in agricultural systems run by large corporations, e.g. bananas, pineapples, and oil palms, it may be of advantage to the corporation to purchase and supply semiochemicals to small growers to lessen the danger of pests from small holdings invading their operations. For many resource-poor farmers, however, semiochemical-based technologies may be beyond their reach.

One might ask, how will semiochemical-based companies develop in the tropics in the next century? Companies with their home offices in Japan, North America, or Europe are in the tropics now. I suggest that within tropical countries, local entrepreneurs will eventually take over local operations, either as subsidiaries of the parent companies, or as separate small firms. Another possibility is for technology delivery companies to develop as arms-length spin-off enterprises from research institutes.

Rational Registration Policy

Lastly there will be the problem of registration, probably following models developed in Europe or North America. Registration of any chemical agent (even a semiochemical) is in the best interest of human and environmental health. This will be of particular concern for the many new and different chemicals that will be found in host plants as well as insect eggs and larvae.

Because new semiochemicals will be species-specific, often with small to minute potential markets, there will be little economic incentive for companies to pursue new registrations. Thus wise governments will adopt reasonable registration requirements. These may include: (1) region-wide, rather than national, registrations, with several countries working together; (2) limited testing requirements for certain types of chemicals; (3) generic registrations of certain compounds that may occur in numerous products or blends; (4) compensation for companies that make generic registrations, by companies that subsequently use the registered materials; and (5) possible subsidisation of registration by local governments or government consortia, with provision for repayment of the subsidy as a small percentage of gross sales of the registered product.

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The above examples are but a few of the concerns that must be addressed and solved if semiochemicals are to be integrated into the pest management systems of the 21st century. It should be clear that the study of insect semiochemicals, in both its basic and applied phases, is really in its infancy. We have countless discoveries to make, and many of these will lead us into more and more inventive ways of turning nature to our advantage, without damaging nature itself. A young entomologist beginning a career in the year 2001, with the ability to conduct research on semiochemicals and to use them in the management of insect pests, will have a very exciting, challenging, and rewarding professional life.

References

Aldrich (1988) Chemical ecology of the Heteroptera. *Annu. Rev. Ent.* 33, 211–238.

Arn H., Tóth M. and Priesner E. (1992) *List of Sex Pheromones of Lepidoptera and Related Attractants* (2nd edition). International Organization for Biological Control, Montfavet, France.

Borden J. H. (1993) Strategies and tactics for the use of semiochemicals against forest insect pests in North America, pp. 265–279. In *Pest Management: Biologically Based Technologies* (Edited by R. D. Lumsden and J. L. Vaughn). Am. Chem. Soc., Washington, DC.

Borden J. H. (1996) Disruption of semiochemical-mediated aggregation in bark beetles, pp. 421–438. In *Pheromone Research: New Directions* (Edited by R. T. Cardé and A. K. Minks). Chapman and Hall, New York.

Butlin R. and Trickett A. J. (1996) Can population genetic simulations help to interpret pheromone evolution? pp. 548–562. In *Pheromone Research: New Directions* (Edited by R. T. Cardé and A. K. Minks). Chapman and Hall, New York.

Cardé R. T. (1990) Principles of mating disruption, pp. 47–71. In *Behaviour-Modifying Chemicals for Insect Management* (Edited by R. L. Ridgway, R. M. Silverstein and M. N. Inscoe). Marcel Dekker, New York.

Chapman J. A. (1963) Field selection of different log odours by scolytid beetles. *Can. Ent.* 95, 673–676.

Collins R. D. and Cardé R. T. (1989) Heritable variation in pheromone response of the pink bollworm, *Pectinophora gossypiella* (Lepidoptera: Gelechiidae). *J. Chem. Ecol.* 15, 2647–2659.

Collins R. D., Rosenblum S. L. and Cardé R. T. (1990) Selection for increased pheromone titre in the pink bollworm moth, *Pectinophora gossypiella* (Lepidoptera: Gelechiidae). *Physiol. Ent.* 15, 141–147.

Gries G., Gries R., Borden J. H., Li J., Slessor K. N., King G. G. S., Bowers W. W., West R. J. and Underhill E. W. (1991) 5, 11-dimethylheptadecane and 2, 5 dimethylheptadecane: Sex pheromone components of the geometrid moth, *Lambdina fiscellaria fiscellaria*. *Naturwissenschaften* 78, 315–317.

Gries G., Gries R., Perez A. L., Oehlschlager A. C., Gonzales L. M., Pierce H. D. Jr., Kouda-Bonafos M., Zebeyou M. and Nanou N. (1993) Aggregation pheromone of the African palm weevil, *Rhyncophorus phoenicis* F. *Naturwissenschaften* 80, 90–91.

Hassanali A. (1997) Semiochemical modulation of the gregarious phase desert locust: An overview of current research status. Paper presented at the *Third International Conference on Tropical Entomology, 30 October–4 November 1994, Nairobi, Kenya.*

Hawkes C. and Coaker T. H. (1979) Factors affecting the behavioural responses of the adult cabbage root fly, *Delia brassicae,* to host plant odour. *Ent. Exp. Appl.* 25, 45–58.

Judd G. J. R. and Borden J. H. (1989) Distant olfactory response of the onion fly, *Delia antigua,* to host-plant odour in the field. *Physiol. Ent.* 14, 429–441.

Kennedy J. S. and Moorehouse J. E. (1969) Laboratory observations on locust responses to windborn grass odour. *Ent. Exp. Appl.* 12, 487–503.

Lindgren B. S. and Borden J. H. (1993) Displacement and aggregation of mountain pine beetles, *Dendroctonus ponderosae* (Coleoptera: Scolytidae), in response to their antiaggregation and aggregation pheromone. *Can. J. For. Res.* 23, 286–290.

Mahamat H., Hassanali A., Odongo H., Torto B. and El Bashir E.-S. (1993) Studies on the maturation-accelerating pheromone of the desert locust *Schistocerca gregaria* (Orthoptera: Acrididae). *Chemecology* 4, 159–164.

Mayer M. S. and McLaughlin J. R. (1991) *Handbook of Insect Pheromones.* CRC Press, Boca Raton, Florida.

Miller J. R. and Cowles R. S. (1990) Stimulo-deterrent diversion: A concept and its possible application to onion maggot control. *J. Chem. Ecol.* 16, 3197–3212.

Morgan E. D. (1984) Chemical words and phrases in the language of pheromones for foraging and recruitment, pp. 13–28. In *Insect Communication* (Edited by T. Lewis). John Wiley and Sons, New York.

Phelan P. L., Roelofs C. J., Youngman R. R. and Baker T. C. (1991) Characterization of chemicals mediating ovipositional host-plant finding by *Amyelois transitella* females. *J. Chem. Ecol.* 17, 599–613.

Ridgway R. L., Silverstein R. M. and Inscoe M. N. (Eds) (1990) *Behaviour-Modifying Chemicals for Insect Management.* Marcel Dekker, New York.

Rollo C. D., Czyzewska E. and Borden J. H. (1994) Fatty acid necromones for cockroaches. *Naturwissenschaften* 81, 409–410.

Slessor K. N., Kaminski L.-A., King G. G. S., Borden J. H. and Winston M. L. (1988) Semiochemical basis of the retinue response to queen honey bees. *Nature* 332, 354–356.

Stokes T. M. and Oehlschlager A. C. (1987) Enzyme reactions in apolar solvents: The resolution of (+)-sulcatol with porcine pancreatic lipase. *Tetrahedron Lett.* 2091–2094.

Struble D. L. and Arn H. (1984) Combined gas chromatography and electroantennogram recording of insect olfactory responses, pp. 161–178. In *Techniques in Pheromone Research* (Edited by H. E. Hummel and T. A. Miller). Springer-Verlag. New York.

Tabashnik B. E., Cushing N. L., Finson N. and Johnson M. W. (1990) Field development of resistance to *Bacillus thuringiensis* in the diamondback moth (Lepidoptera: Plutellidae). *J. Econ. Ent.* 83, 1671–1676.

Trumble J. T. and Alvarado-Rodriguez (1993) Development and economic evaluation of an IPM program for fresh market tomato production in Mexico. *Agric. Eco. Syst. Environ.* 43, 267–284.

Pheromones for Three Beetle Pests of Asian Palms

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Abstract—Two Asian palm weevils, *Rhynchophorus ferrugineus* (Oliv.) and *R. vulneratus* (Panz.), and the coconut rhinoceros beetle, *Oryctes rhinoceros* L., inflict major damage on palms. Palm weevil larvae mine in the trunk of trees, eventually killing their hosts. *Rhynchophorus ferrugineus* has been introduced to the Arabian peninsula and Africa, where insecticidal controls have failed to halt its spread. *Oryctes rhinoceros* defoliates mature palms and causes major deformation and sometimes death of young oil palms. Studies on other *Rhynchophorus* spp. had determined previously that males produce aggregation pheromone. Laboratory bioassays in a two-choice olfactometer determined that *Oryctes* males do the same. The identity of aggregation pheromones was determined by coupled gas chromatographic-electroantennographic (GC-EAD) detection, GC - mass spectrometry, and field testing of synthetic candidate pheromones. Palm weevil antennae of both species gave significant positive responses to 4-methyl-5-nonanol and its corresponding ketone, 4-methyl-5-nonanone. Weevils of both sexes responded to bucket traps baited with the alcohol but the ketone was inactive. The antennae of *O. rhinoceros* detected ethyl 4-methyloctanoate, ethyl 4-methylheptanoate and 4-methyloctanoic acid. In a newly-designed vane trap, the octanoate was highly attractive to beetles of both sexes, while the heptanoate was weakly attractive, but still significantly more so than the previously known attractant, ethyl chrysanthemumate. Potential applications for these new pheromones are: monitoring the spread of and mass-trapping exotic palm weevils, mass-trapping of rhinoceros beetles in young oil palm plantations, and using rhinoceros beetle pheromone to attract beetles to sources of baculovirus.

Key Words: Rhynchophorus ferrugineus, R. vulneratus, Oryctes rhinoceros, pheromones pest management

Introduction

The Asian palm weevil, *Rhynchophorus ferrugineus* (Oliv.) and the red stripe palm weevil, *R. vulneratus* (Panz.), are pests damaging palm in South and Southeast Asia (Sivapragasam et al., 1990; Sadakathulla, 1991). Throughout much of the same range, and extending into the South Pacific, the coconut rhinoceros beetle, *Oryctes rhinoceros* L., also causes major economic losses (Zelazny, 1979; Liau and Ahmad, 1991,1993).

Palm weevils are attracted to oviposit in wounded palms, wherein the larvae mine, causing death of fronds; if attack is in the growing points of young trees or in boles of mature trees, they can kill the tree (Kalshoven, 1981).

Rhynchophorus ferrugineus has been introduced into the Arabian peninsula (Bokhari and Abuzuhira, 1992) and Egypt (M. M. Taher, FAO, Cairo, Egypt, pers. commun.), where it has become a severe pest of date palms and is partially controlled by the application of organophosphate insecticides.

Adult coconut rhinoceros beetles mine in the growing points of palms, causing the photosynthetic area of the new, unfolded fronds to be greatly reduced, and causing stem deformation and death in young palms. Heavy losses of coconut production may occur as a result of defoliation (Zelazny, 1979). Immature oil palms in Indonesia and Malaysia are inspected frequently, rhinoceros beetles are manually removed, and the trees are treated with granular carbofuran (Ho and Toh, 1982). Even with such careful surveillance and control, many mishappen and stunted trees must be replaced, and further expense is often incurred because of the need to remove dead trunks from replaced plantations and from adjacent mature stands (Liau and Ahmad, 1991).

Aggregation pheromones are known for most *Rhynchophorus* spp. and for the African rhinoceros beetle, *Oryctes monoceros* (Table 1). Rhynchophorol, the aggregation pheromone for the American palm weevil, *R. palmarum,* has proven to be highly effective in mass-trapping this species in Costa Rican oil palm plantations, and correspondingly controlling red ring disease caused by a weevil-vectored, lethal nematode (Oehlschlager et al., 1993).

Palm weevils and the coconut rhinoceros beetle are major pests of palms in Indonesia (Kalshoven, 1981). Our research in Indonesia has been directed toward identifying the aggregation pheromones, and on investigating the efficacy of pheromone-based mass-trapping of these beetles.

Identification of New Pheromones

For all three species, air was passed through glass or nalgene chambers containing groups of field-collected adult males or females, or adults reared from field-collected larvae. The volatiles were trapped in Porapak Q, extracted in pentane, and subjected to coupled gas chromatographic-electroantennographic detection analysis (GC-EAD) as described by Oehlschlager et al. (1992) and Gries et al. (1994a). For *O. rhinoceros,* laboratory bioassays in a Y-tube olfactometer showed that males produce an aggregation pheromone, and suggested that females produce a sex pheromone. Such bioassays were not done with the two weevils.

GC-EAD analysis disclosed two antennally-active compounds, 4-methyl-5-nonanol (ferrugineol) and 4-methyl-5-nonanone in both *R. ferrugineus* and *R. vulneratus* (Hallett et al., 1993a). Both racemic compounds and their separate stereoisomers were synthesised (Hallett et al., 1993a; Perez et al., 1996), and tested in the field in white bucket traps (Oehlschlager et al., 1993) attached 2 m high to the boles of mature palms. The field experiments (Hallett et al., 1993a; Perez et al., 1996) demonstrated that: (1) racemic ferrugineol alone was equally attractive to weevils of both sexes at release rates ranging from 0.3–3.0 mg per 24 h; (2) racemic ferrugineone caused no increase in response by either species when released as a minor component with ferrugineol; (3) the 4(*S*), 5(*S*) stereoisomer of ferrugineol, is behaviorally active, while the other three isomers have no biological activity; and (4) as yet unknown palm tissue volatiles are produced at peak amounts five days after cutting, and act as attractive synergists to ferrugineol.

Table 1. Summary of known pheromones and their isomeric specificity and known or indicated host kairomones for six *Rhynchophorus* spp. and two *Oryctes* spp.

Species and common names	Pheromones, trivial names, and isomeric specificity (if known)	Kairomones identified or source indicated	References
Rhynchophorus palmarum L. American palm weevil	6 - methyl-2 -*(E)* - hepten-4-ol (rhynchophorol). *(S)*-(-) enantiomer active, antipode inactive	Palm tissue or sugarcane	Oehlschlager et al. (1992, 1993)
Rhynchophorus phoenicis L. African palm weevil	3-methyl-4-octanol (phoenicol)	Ethyl propionate	Gries et al. (1993, 1994b) Rochat et al. (1993)
Rhynchophorus cruentatus (F.) Palmetto weevil	5-methyl-4-octanol (cruentol)	Ethyl acetate, *(S)*-(-) ethyl lactate, ethyl iso-butyrate, ethyl butyrate, ethanol	Weissling et al. (1994) Giblin-Davis et al. (1994)
Rhynchophorus ferrugineus (Oliv.), Asian palm weevil and *Rhynchophorus vulneratus* (Panz.), red stripe palm weevil	4-methyl-5-nonanol (ferrugineol) 4(*S*),5(*S*) stereoisomer active, other 3 benign	Palm tissue	Hallett et al. (1993b) Perez et al. (1996)
Rhynchophorus bilineatus (Montr.)	4-methyl-5-nonanol (ferrugineol)	Sugarcane	Oehlschlager et al. (1995)
Oryctes monoceros (Oliv.) African rhinoceros beetle	ethyl 4-methyloctanoate (oryctelure)	Not investigated	Gries et al. (1994a)
Oryctes rhinoceros L. Coconut rhinoceros beetle	ethyl 4-methyloctanoate (oryctelure)	Palm tissue	Hallett et al. (1995)

The antennae of both sexes of *O. rhinoceros* responded in GC-EAD analysis primarily to one compound, ethyl 4-methyloctanoate (Hallett et al., 1995), the same compound found to be an aggregation pheromone in *O. monoceros* (Oliv.) and given the trivial name oryctelure (Gries et al., 1994a). Also found in the volatiles of male beetles were 4-methyloctanoic acid and ethyl 4-methylheptanoate. In a Y-tube olfactometer, a 100:1 blend of the octanoate and heptanoate, the two most antennally-active compounds, was highly attractive to both sexes at a dose of 612 ng per individual bioassay beetle, confirming earlier results with the Porapak Q-captured volatiles of male beetles.

Field experiments on *O. rhinoceros* were conducted in North Sumatra in newly established oil palm plantations (Hallett et al., 1995). They demonstrated that: (1) oryctelure released at 30 mg per 24 h from plastic-bucket, pitfall traps was equally attractive to beetles of both sexes; (2) a 'vane' trap with two interlocking, crossed barriers fitted above a plastic bucket resting on the soil surface was significantly more effective in capturing O. *rhinoceros* than a similar trap with one barrier, which in turn was superior to the pitfall trap (all further experiments were in vane traps); (3) a dose of 9 mg per 24 h was as effective as 30 mg per 24 h, and was used in all subsequent experiments; (4) synthetic 4-(*S*)-ethyl 4-methyloctanoate attracted both sexes of beetles, while the 4-(*R*) isomer was inactive, supporting chiral chromatographic analyses that found the 4-(*S*) isomer to be the only one produced by male beetles; (5) when the three antennally-active compounds in male volatiles, and the best previously-known attractant, ethyl chrysanthemumate, were tested alone, oryctelure was highly attractive, the heptanoate appeared to be marginally attractive, and neither the octanoic acid nor ethyl chrysanthemumate attracted significant numbers of beetles; (6) no combination of the above components improved the potency of the baits over that to oryctelure alone; and (7) combination of oryctelure with the odour of freshly-milled empty oil palm fruit bunches caused a significant increase in trap captures, demonstrating the occurrence of as yet unknown kairomones.The odour of rotting palm tissue was inactive.

A final experiment disclosed that there was neither inhibition nor enhancement of response of *O. rhinoceros* or *R. vulneratus* when pheromones of the two species were combined.

Discussion

In combination with the results of other studies, the above results demonstrate that all *Rhynchophorus* species utilise methyl-branched, secondary alcohols as aggregation pheromones, while the two main world species of *Oryctes* employ the same compound, ethyl 4-methyloctanoate (Table 1). For both genera, volatiles from deteriorating palm tissue cause an increase in attraction over that to the pheromone alone, and for *R. phoenicis* and *R. cruentatus* the active host kairomones are known to be ethyl propionate and ethyl acetate, respectively. The combined action of host kairomones and insect-produced pheromones to form an attractive semiochemical blend in palm-infesting beetles is consistent with the use of similar semiochemicals by other Coleoptera to mediate aggregation on food sources (Borden, 1985).

The complete lack of species specificity between *R. ferrugineus* and *R. vulneratus* in pheromone production and response, as well as the capture of colour intermorphs with characteristics of both species (Hallett et al., 1993a), suggests that the validity of these widely sympatric species should be questioned. In the scolytid genus *Ips,* closely related species are cross attractive, but maintain reproductive isolation through allopatric or parapatric distributions (Lanier and Wood, 1975), unlike the palm weevils (Hallett et al., 1993a). Isolation in pheromone production and response by sympatric species in the Scolytidae is often achieved by structural and chiral specificity, and species-specific ratios of components (Birch et al., 1980; Borden et al., 1980; Camacho et al., 1993). It is thus noteworthy that *R. ferrugineus* and *R. vulneratus* are sympatric, and have identical pheromone components, with identical chirality and identical ratios between components.

There is excellent potential for the practical use of these new pheromones. The palm weevil pheromone may be used to monitor the spread and frequency of *R. ferrugineus* in the Arabian peninsula and Africa. The possibility that geographic variation in pheromone production and response could lead to aberrant results is dispelled by the fact that there is no difference in response to synthetic pheromone by *R. ferrugineus* from Indonesia and the United Arab Emirates (Hallett et al., 1993b). In attempts to eradicate the new weevil infestations, and to control established populations throughout the range of *R. ferrugineus* and *R. vulneratus,* mass trapping programmes could be implemented, similar to the programme used so effectively to control *R. palmarum* in Costa Rica (Oehlschlager et al., 1993). *Oryctes rhinoceros* could also be mass trapped, particularly in newly established oil palm plantations. Such a tactic could be used to replace hand labour and the frequent application of carbofuran where labour is expensive, e.g. in Malaysia. In Indonesia, where labour is cheap, mass trapping might supplement manual removal of beetles, replacing the use of insecticides. Because the baculovirus introduced to control *O. rhinoceros* (Bedford, 1986) is not uniformly established, is inconsistent and incomplete in its effectiveness (Zelazny, 1979; Zelazny and Alfiler, 1987, 1991), and may require repeated introductions, oryctelure could be used to enhance the impact of the virus. Semiochemical baits of short duration could be placed on a non-trapping surface laced with baculovirus so that beetles would become contaminated on landing and on departure would re-inoculate the virus into the indigenous population. For all of the above tactics, efficacy would be optimised by the inherently low populations of these large insects.

References

Bedford G. O. (1986) Biological control of the rhinoceros beetle *(Oryctes rhinoceros)* in the South Pacific by baculovirus. *Agric. Ecosyst. Environ.* 15, 141–147.

Birch M. C., Light D. L., Wood D. E., Silverstein R. M., Bergot G., West J. R. and Young J. C. (1980) Pheromonal attraction and allomonal interruption of *Ips pini* in California by the two enantiomers of ipsdienol. *J. Chem. Ecol.* 6, 703–717.

Bokhari U. G. and Abuzuhira R. (1992) Diagnostic tests for red palm weevil, *Rhynchophorus ferrugineus* infested date palm trees. *Arab J. Sci. Res.* 10, 93–104.

Borden J. H. (1985) Aggregation pheromones, pp. 257–285. In *Comprehensive Insect Physiology, Biochemistry and Pharmacology* Vol. 9 (Edited by G. A. Kerkut and L. I. Gilbert). Pergamon Press, Oxford.

Borden J. H., Handley J. R., McLean J. A., Silverstein R. M., Chong L., Slessor K. N., Johnston B. D. and Schuler H. R. (1980) Enantiomer-based specificity in pheromone communication by two sympatric *Gnathotrichus* species (Coleoptera: Scolytidae). *J. Chem. Ecol.* 6, 445–456.

Camacho A. D., Pierce H. D. Jr and Borden J. H. (1993) Geometrical and optical isomerism of pheromones in two sympatric *Dryocoetes* species (Coleoptera: Scolytidae) mediates species specificity and response level. *J. Chem. Ecol.* 19, 2169–2182.

Giblin-Davis R. M., Weissling T. J., Oehlschlager A. C. and Gonzalez L. M. (1994) Field response of *Rhynchophorus cruentatus* (Coleoptera: Curculionidae) to its aggregation pheromone and fermenting plant volatiles. *Florida Ent.* 77, 164–177.

Gries G., Gries R., Perez A. L., Oehlschlager A. C., Gonzalez L. M., Pierce H. D. Jr, Kouda Bonafos M., Zebeyou M. and Nanou N. (1993) Aggregation pheromone of the African palm weevil, *Rhynchophorus phoenicis* F. *Naturwissenschaften* 80, 90–91.

Gries G., Gries R., Perez A. L., Oehlschlager A. C., Gonzalez L. M., Pierce H. D. Jr, Zebeyou M. and Kouame B. (1994a) Aggregation pheromone of the African rhinoceros beetle, *Oryctes monoceros* (Olivier) (Coleoptera: Scarabaeidae). *Z. Naturforsch.* 49c, 363–366.

Gries G., Gries R., Perez A. L., Gonzales L. M., Pierce H. D. Jr, Oehlschlager A. C., Rhainds M., Zebeyou M. and Kouame B. (1994b) Ethyl propionate: Synergistic kairomone for African palm weevil, *Rhynchophorus phoenicis* L. (Coleoptera: Curculionidae). *J. Chem. Ecol.* 20, 889–897.

Hallett R. H., Gries G., Gries R., Borden, J. H., Czyzewska E., Oehlschlager A. C., Pierce H. D. Jr, Angerilli N. P. D. and Rauf A. (1993a) Aggregation pheromones of two Asian palm weevils, *Rhynchophorus ferrugineus* and *R. vulneratus*. *Naturwissenschaften* 80, 328–331.

Hallet R. H., Oehlschlager A. C., Gries G., Angerilli N. P. D., Al Shareqi R. K., Gassouma M. S. and Borden J. H. (1993b) Field testing of aggregation pheromones of two Asian palm weevils. In *Proc. PORIM Int'l Oil Palm Congress,* 20–25 September, 1993, Kuala Lumpur, Malaysia, P35, 1–11.

Hallett R. H., Perez A. L., Gries G., Gries R., Pierce H. D. Jr, Yue J., Oehlschlager A. C., Gonzalez L. M. and Borden J. H. (1995) Aggregation pheromone of the coconut rhinoceros beetle, *Oryctes rhinoceros* L. (Coleoptera: Scarabaeidae). *J. Chem. Ecol.* 21, 1549–1570.

Ho C. T. and Toh D. Y. (1982) Some investigations into the control of *Oryctes rhinoceros* L. in coconut plantings. *Planter* 58, 492–506.

Kalshoven L. G. E. (1981) *The Pests of Crops in Indonesia* (revised and translated by P. A. van der Laan). P. T. Ichtiar Baru-Van Hoeve, Jakarta.

Lanier G. N. and Wood D. L. (1975) Specificity of response to pheromones in the genus *Ips* (Coleoptera: Scolytidae). *J. Chem. Ecol.* 1, 9–23.

Liau S. S. and Ahmad A. (1991) The control of *Oryctes rhinoceros* by clean clearing and its effect on early yield in palm to palm replants, pp. 396–403. In *Proc. PORIM Int'l Oil Palm Congress,* 9–14 September, 1991, Kuala Lumpur, Malaysia.

Liau S. S. and Ahmad A. (1993) Simulated defoliation and crop loss in young oil palm, A31, pp. 1–25. In *Proc. PORIM Int'l Oil Palm Congress,* 20–25 September, 1993, Kuala Lumpur, Malaysia.

Oehlschlager A. C., Chinchilla C. M., Gonzalez L. M., Jiron L. F., Mexzan R. G. and Morgan B. (1993)

Development of a pheromone-based trapping system for *Rhynchophorus palmarum* (Coleoptera: Curculionidae). *J. Econ. Ent.* 86, 1381–1392.

Oehlschlager A. C., Pierce H. D. Jr, Morgan B., Wimalaratne P. D. C., Slessor K. N., King G. G. S., Gries G., Gries R., Borden J. H., Jiron L. F., Chinchilla C.M. and Mexzan R. G. (1992) Chirality and field activity of rhynchophorol, the aggregation pheromone of the American palm weevil. *Naturwissenschaften* 79, 134–135.

Oehlschlager A. C., Perez A. L., Pierce H. D. Jr, Gonzalez L. M., Prior R. N. B., Gries R. and Gries G. (1995) Aggregation pheromone of the Asian palm weevil, *Rhynchophorus bilineatus* (Montr.). *J. Chem. Ecol.* (Submitted).

Perez A. L., Hallett R. H., Gries R., Gries G., Oehlschlager A. C. and Borden J. H. (1996) Pheromone chirality of the Asian palm weevils, *Rhynchophorus ferrugineus* (Oliv.) and *Rhynchophorus vulneratus* (Panz.) (Coleoptera: Curculionidae). *J. Chem. Ecol.* 22, 357–368.

Rochat D., Malosse C., Lettere M., Ramirez L. P., Einhorn J. and Zagatti P. (1993) Identification of new pheromone-related compounds from volatiles produced by males of four Rhynchophorine weevils (Coleoptera: Curculionidae). *C.R. Acad. Sci. Paris Ser. II,* 316, 1737–1742.

Sadakathulla S. (1991) Management of the red palm weevil, *Rhynchophorus ferrugineus* F., in coconut plantations. *Planter* 67, 415–419.

Sivapragasam A., Arikiah A and Ranjit C. A. (1990) The red stripe palm weevil, *Rhynchophorus schach* Olivier (Coleoptera: Curculionidae): An increasing menace to coconut palms in Hilir Perak. *Planter* 66, 113–123.

Weissling T. J., Giblin-Davis R. M., Gries G., Gries R., Perez A. L., Pierce H. D. Jr and Oehlschlager A. C. (1994) Aggregation pheromone of the palmetto weevil, *Rhynchophorus cruentatus* (F.) (Coleoptera: Curculionidae). *J. Chem. Ecol.* 20, 505–515.

Zelazny B. (1979) Loss in coconut yield due to *Oryctes rhinoceros* damage. *FAO Plant Prot. Bull.* 27, 65–70.

Zelazny B. and Alfiler A. R. (1987) Ecological methods for adult populations of *Oryctes rhinoceros* (Coleoptera: Scarabaeidae). *Ecol. Ent.* 12, 227–238.

Zelazny B. and Alfiler A. R. (1991) Ecology of baculovirus - infected and healthy adults of *Oryctes rhinoceros* (Coleoptera: Scarabaeidae) on coconut palms in the Philippines. *Ecol. Ent.* 16, 253–259.

Farmer Participatory Strategies for Technology Transfer in Pest Management

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Methods for Farmer Participation and Progress in Adaptive Research for Crop Pest Technology Development: ICIPE's Experience

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Abstract—Since mid-1980s ICIPE has made efforts to develop IPM technology with intercropping practices, insect pest resistant cultivars and biological control as the main components.

The development of IPM technology has been done in collaboration with resource-limited farmers, as well as extensionists and researchers of the Kenya National Programme in testing and adapting the technology to the agroecological and socioeconomic conditions of local communities.

This has been done in the context of three major projects that ICIPE has been implementing in recent years. These have focused on sustainable pest management in food crops, mainly against stemborers of maize and sorghum while attention has also been paid to insect pests on companion crops as well.

The methodologies that have been used in the implementation of these projects include: (1) diagnostic surveys aimed at understanding entomological, agronomic and socioeconomic conditions of communities and at providing a basis for selection of project sites and farmers; (2) mobilisation and involvement of farmers in learning, adopting and adjusting IPM technology to their situations; (3) periodic interviews of farmers using focused questionnaires; and (4) workshops and meetings with farmers and extensionists at which various aspects of IPM are discussed and farmers' perceptions are sought.

Key Words: farmer participation, IPM, resource-limited farmers, extensionists, researchers, ICIPE

Background

The International Centre of Insect Physiology and Ecology (ICIPE) launched its pilot project on integrated pest management (IPM) in Oyugis and Kendu Bay areas of western Kenya in 1987. A second IPM project entitled the Kwale and Kilifi Adaptive Research Project (KKARP) was launched in coastal Kenya in 1992. In 1993, ICIPE launched the Interactive Socioeconomic Research for Bio-Intensive Pest Management (ISERIPM) project. These projects being participatory have necessitated work with farming communities (e.g., villages) and individual farmers on a continuous basis. This paper outlines the methodological approaches that have been used in: (a) identifying and selecting on-farm trial sites and farmers; and (b) promoting participation of the farmers in the projects.

The approach consists of three phases: mission-oriented basic research at which technologies are developed by researchers at research stations and on-farm farmer-managed trials. The implementation of the subsequent IPM projects, particularly the ISERIPM project added farmers' evaluation of technologies both on-station as well as on-farm researchers' managed trials. These IPM projects that are being undertaken by the Centre will enable an assessment of whether the approach is valid or needs to be modified on the basis of experience from practical field activities.

When working with this approach to IPM technology development, it is worth noting that effort has been made to move away from the 'transfer of technology model'. According to this model, farm technologies are developed by researchers mainly at research stations and are passed on to extension agents to pass on to farmers (Roling, 1983). Many resource-limited farmers in eastern Africa and elsewhere have never had the opportunity to apply effectively or even had access to such technologies owing to their varied socioeconomic circumstances and the inability of the Extension Service to communicate the technologies to them and assert their application. This limitation in the 'transfer of technology model' has led to adoption of the participatory research approach which emphasises involvement of farmers, extension agents and other relevant parties in the process of development of farm technologies (Volken et al., 1985).

There are, however, various models of participatory research that are labelled as contractual, consultative, collaborative and collegiate which need to be borne in mind when working with farmers (Biggs, 1987). The contractual approach is one in which the land and services of farmers are borrowed or hired to make possible the verification under various agroecological conditions of technologies developed on-station. This approach can be described as participatory only to the extent that a link is created between the researcher and the farmer.

The consultative approach is said to be analogous to the doctor-patient relationship. Farmers are consulted at various stages of the research process, but most of the decisions regarding the content and methods of research are made by the researchers alone.

The collaborative method is one which involves a more continuous interaction between the researcher and farmer, the latter being consulted even on ways in which research might effectively be conducted at the community level.

The collegiate approach goes further and seeks to strengthen local capacities to conduct informal research at the community level so as to complement the formal research system.

It should be added that Robert Chambers (Farrington and Martin, 1990) has described the importance of farmer-first-and-last approach, which visualises the role of the farmer at all stages of research, as it would involve learning by the scientists from farmers, and then generating technologies on-farm.

A recent compilation of abstracts of 340 papers in farmer-participatory research (Amanor, 1990) reflects the highly diverse experiences in farmer-participatory research. It was evident that no two projects or experiments documented are identical in all respects; nevertheless, it is being acknowledged, in recent years, that farmers can contribute actively in the research process in various ways towards developing acceptable and sustainable technologies.

The IPM Projects: An Overview

The ICIPE/UNECA Project

The ICIPE/UNECA pilot IPM project was implemented in Oyugis and Kendu Bay areas of western Kenya during 1987–92. It was the first IPM project to be undertaken collaboratively by crop pest and social science researchers. Forty-nine (49) farmers whose homesteads were located alongside major roads were selected as project farmers and they evaluated the technologies in about 1 acre of land each season. The main IPM components tested were insect pest resistant cultivars of maize and sorghum and cultural practices, especially intercropping of the above crops with cowpea and/or beans. The experiences gained during implementation of the project included the following:

(i) Most of the farmers preferred maize and sorghum cultivars that were high yielding. Other traits that influenced farmers' preferences included height of plants, palatability and colour of seed.

(ii) Intercropping single maize rows alternated with cowpea/beans rows within a spacing of 75–90 cm between rows and 15–30 cm between plants increased labour demand and necessitated further research into alternative planting patterns that could help minimise labour costs.

(iii) Some diffusion of IPM technologies from project to non-project farmers occurred, but the adoption of the various components was inadequate and pinpointed to the need for minimal guidance of the non-project farmers to help enhance the level of adoption.

(iv) The approach used in working with farmers was individual contact and it was only towards the end of the project that effort was made to organise the farmers and work with them both as individuals and in groups. An expanded phase of the project was planned, and a community-based approach was used in selection of a few villages and farmers of the areas for participation in the project, but this phase did not materialise owing to funding difficulties.

These experiences in working with farmers in the ICIPE/UNECA project provided the basis for planning the subsequent projects.

The KKARP Project

The KKARP is a Government of Kenya initiative. It was conceived as an adaptive research component of a wider development project, the Kwale and Kilifi Districts Development Project (KKDDP), which aims at enhancing food security in the region by identifying and developing sustainable methods of minimising yield losses caused by insect pests on some targeted food crops.

The project is being implemented by the ICIPE for and on behalf of the Government of Kenya in partnership with the Kenya Agricultural Research Institute (KARI) which is the executing agency representing the Ministry of Research, Technical Training and Technology (MRTTT).

The objectives of the project are to: (a) assist in enhancing food production and in improving the income levels of the 'resource-poor' farmers in Kwale and Kilifi districts (in coastal Kenya) by developing and adapting sustainable technologies for the management of the major insect pests on chosen food crops; and (b) undertake capacity building of the National Agricultural Research System (NARS) in adaptive research on pest management on food crops.

The project's mandate was to evaluate control technologies for insects affecting crops and livestock for ecological adaptability and socioeconomic suitability in the region. The technologies consisted of pest resistant varieties of maize, sorghum and cowpea; cultural practices for the control of stemborers on maize/sorghum, and trapping for the control of tsetse flies.

The project staff was constituted into three sub-teams, namely crop pests; tsetse; and social science research. Each sub-team was led by an ICIPE specialist, while the NARS counterpart played the role of deputy leader. Other professionals as well as technical and support staff were all from the NARS. This arrangement provided for a close working relationship between ICIPE and NARS colleagues as well as facilitating on-the-job training and implementation of farmer participatory evaluation of technologies.

The ISERIPM Project

The ISERIPM project was jointly conceived and developed by ICIPE's social science and crop pest researchers. It is a collaborative and participatory research project in which ICIPE's scientists work closely with the Kenya Agricultural Research Institute (KARI) researchers, MOALDM's extensionists and the farming community in developing IPM technology.

The project has two main objectives: First, to undertake adaptive and evaluative research on pest and vector management technologies pertaining to selected staple food crops and livestock, respectively, in appropriate agroecological zones of Kenya; and second, to develop interactive socioeconomic interface methodologies for crop pest management. This paper deals with the crop pests component of the adaptive research being implemented in the Kenya coast (Kwale and Kilifi districts). The livestock component is under implementation on Rusinga Island.

Originally the project had three phases of the main crop pests component of the project: (i) on-station scientist-managed trials and farmers' evaluation which was implemented in 1993; (ii) on-farm researcher-managed trials which are being implemented in 1994; and finally, on-farm farmer managed trials which will be implemented in 1995. Later, two more phases of modified technology evaluation by farmers and promotion of technology adoption were added.

The IPM components being developed are: (a) insect-pest resistant cultivars of maize and sorghum; (b) cultural practices with emphasis on relay and strip intercropping; and (c) biological control using *Bacillus thuringiensis (Bt)*. In addition, an appropriate stemborer monitoring technique is being developed with a view to training farmers in its effective application.

The Methods Used in Implementing the IPM Projects

ISERIPM's main focus is on developing methodologies that can facilitate adaptation of farm technologies to local conditions to enhance their chances of adoption and sustainability. The methods include: (i) identifying and selecting on-farm trial sites and farmers; and (ii) involving the farmers in the trials. The methods are community-based and seek widespread participation of both the community and individual farmers in the trials. The methods have been, to some extent, used in the ICIPE/UNECA and the KKARP projects. The following discussion is, however, based primarily on the ISERIPM methodologies under implementation.

Diagnostic Methods Used in the Selection of Project Sites and Farmers

At conception, the projects usually select districts or administrative divisions where there is a severe problem of damage by insect pests, especially stemborers of the main food crops. The areas are selected by biologists in consultation with social scientists.

Once these larger areas have been chosen, then several methods are used to select smaller areas within them for on-farm trials. The methods that are employed are diagnostic in nature and are as follows: In the ISERIPM project, GIS characterisation of the areas on the basis of agroecological and socioeconomic parameters was carried out. The areas that are identified by GIS are those which are suitable for growing of the project's target crops: maize, sorghum, cowpea/beans and cassava. The GIS characterisation was based on rainfall and to some extent on soils.

Second, a macro-level survey was undertaken in areas perceived by the research team to have potential for growing of the target crops. These are areas that have either been or are likely to be identified by GIS. The survey entailed reconnaissance visits to the potential areas and discussions with the local leaders and frontline extension agents. Documentary sources of information such as annual reports of the MOALDM, maps and other relevant documents were also used.

The survey permitted collection of baseline information which included names of locations, sub-locations and villages; main crops grown and those that are intercropped; population size, density, settlement patterns and ethnic composition; and farm organisations. This baseline information helped in the selection of much smaller areas such as sub-locations and villages for the on-farm trials.

Additional reconnaissance visits were made to potential areas that had been identified both by GIS and macro-level surveys. The visits permitted collection of more detailed agronomic and socioeconomic data necessary for selection of specific areas such as sub-locations and villages for the on-farm trials. The visits were made by the social science field team which held discussions with local leaders including MOALDM's extension agents.

The reconnaissance visits permitted selection of six sub-locations: Jego, Mrima and Kundutsi in Kwale district; and Murimani, Pingilikani and Magogoni in Kilifi district. The visits also permitted identification and selection of 24 villages (4 villages from each of the above sub-locations) in which the village-level surveys were carried out.

Third, a village-level survey was undertaken by sub-teams of social and biological scientists assisted by the project's field staff and MOALDM's extension agents. The survey was done at village meetings at which a group of 5–7 leaders of each village were interviewed using a questionnaire prepared by social scientists in consultation with biologists. The survey provided detailed information about the villages which included: (i) rainfall range; (ii) importance of maize production and other crops such as sorghum, cowpea and cassava; (iii) extent of stemborer problem; (iv) landholding system, availability of fairly flat area and average farm holdings of 2 acres each, enough for experimental plots; and (v) accessibility. This information served as a basis for ultimate selection of sub-locations and villages for on-farm trials.

The village-level survey helped in the selection of 4 of the above sub-locations (Jego, Mrima, Pingilikani and Magogoni) and 8 villages (2 villages from each of the chosen sub-locations) as on-farm trial sites.

Fourth, a household-level survey was carried out by the social science field staff aimed at providing baseline information about the households. This information was used as the basis for selection of farmers for participation in the project and would later be used as baseline for impact assessment. It involved interviews of homestead heads (each representing a farmer) using a questionnaire prepared by the social scientists in consultation with the biologists. Information collected included: (i) personal and household characteristics such as occupation, gender, formal education, household size and composition, size of land owned, etc.; (ii) crop production activities including types of crops grown and acreages, income from crop sales and self-sufficiency in food; (iii) farm resources owned and used including ox-ploughs and hand hoes; (iv) costs of production of farm inputs such as seed, fertiliser and farm labour; (v) amount of family labour available and how used; (vi) access to extension sources of information, knowledge and adoption of farm inputs and practices including access to credit; and (vii) membership in farm organisations and leadership positions held.

In the household-level survey, 228 household heads were sampled using systematic random sampling method. Because resources were limited, it was decided to select less than half of the farmers to participate in the project. To do this, two types of criteria were used to select farmers to participate in the project. The criteria were: (i) general criteria which included willingness to provide land for the IPM trials, time spent on the farm, indication of stemborer as a problem and main crops grown; and (ii) resource-endowment criteria which included, maize production, number of livestock owned, amount of income from off-farm sources; and education, knowledge and adoption. Based on these criteria, a total of 89 farmers were identified as participants in the project. About 75% of these were ranked as low and very low in resource endowment; the rest were ranked as medium, and high in resource endowment.

In the KKARP, some of these methods have been used, with slight modifications, in the selection of project sites and reconnaissance visits made to gather relevant information from all potential sites. The potential sites were those which fell within certain agro-ecological conditions, where the target crops were produced, and were accessible. Regarding agroecological conditions, the sites selected were representative of the high, medium and low-medium zones. Lists of villages within these potential areas were compiled by the research team helped by the MOALDM's extension staff and from the lists, six villages (half from Kwale and half from Kilifi districts) were randomly selected as research sites.

The project also carried out a household-level survey which covered 180 household heads of the project villages; each represented by a farmer. Information gathered from the households included demographic characteristics, cropping and cattle keeping practices, knowledge of crop pests and their disease vectors and level and impacts of extension and other support services.

Awareness Creation and Farmers' Involvement in the Projects

Different types of educational forums and participatory activities have been used to make farmers aware and to involve them in the projects. First, periodic farmers' meetings were held in the project villages. Initial meetings permitted the project teams to make members of the villages aware of the projects, its objectives and components and the need for them to participate in them. Subsequent meetings were held as need arose, for example, when there was need to teach the farmers about a particular IPM component such as intercropping.

Second, focused interviews were used when farmers were evaluating the IPM components such as crop cultivars and intercropping practices. They were also used in certain narrowly conceived studies, e.g., those of farmers' perceptions of assistance provided by the project and, enhancement of their knowledge of IPM components.

Third, workshops were held between the social and biological scientists both for farmers and MOALDM's extension staff. Their main aim was to familiarise the farmers and the extension staff about the IPM projects, their objectives and IPM components. During each of the workshops tours were made to one of the IPM trial sites where the participants observed the various IPM components and discussed them with the project team.

Fourth, farm education tours were arranged for the project farmers with the help of the MOALDM's extension staff. They were aimed at increasing the awareness of the farmers about improved farming methods. They entailed exchange of ideas between the participants and their hosts and extension staff.

It should be noted that tours were exchanged by farmers between districts and were used mainly by farmers to learn from each other and to share crop production skills. Through such tours, project and non-project farmers were introduced to crop varieties and practices. On two occasions farmers were able to visit ICIPE's Mbita Point Field Station which is located in western Kenya and observed research activities that were being undertaken there.

Fifth, field days have been used to expose both project and non-project farmers to various aspects of the trials and to share ideas among themselves and the project team and MOALDM extensionists.

Finally, project meetings between biologists and social scientists, and NARS, and farmers' representatives have been held regularly.

Additionally, farmers participated by providing information for the different surveys of the ISERIPM project, in the selection of trial farmers, and more important in the management of the trials.

In the KKARP, there were three types of project meetings: First, the local coordination committees brought together senior officials of the MOALDM/KARI/ICIPE scientists as well as farmers' representatives. At these meetings, the project activities were reviewed and plans for the future discussed, and where necessary, adjustments and modifications to the objectives and activities of the project were made. Opinions and suggestions of farmers were solicited and incorporated as appropriate. Second, planning/review meetings were held at the beginning and midway through the season, and were used to plan details of the season's activities. They involved farmers, frontline extension workers and researchers at the various sites, and were held with the purpose of reviewing the project's progress in order to make any necessary modifications in their implementation. Finally, Consultative meetings were held at the beginning of every season. They involved project and NARS scientists, district and provincial level MOALDM officials and farmers' representatives to discuss the technology options and methodological issues.

Concluding Remarks

A number of conclusions can be drawn from the above discussion. First, the approach of technology development that guides in the implementation of the IPM projects provides scope for farmer participation mainly in evaluating the components during the first phase of on-station trials, some involvement mainly in the form of learning about IPM technology during on-farm scientist-managed trials, and a high level of involvement during the third phase of on-farm farmer-managed trials.

However, experience in the ISERIPM project suggests the need for additional phases during which adoption and sustainability, and issues related to availability of farm inputs and diffusion of IPM technology components can be evaluated.

Second, whereas a systematic method has been used in the selection of project farmers, in many of the villages, owing largely to the community-based nature of the IPM projects, a number of non-project farmers have also participated with project farmers and in the education tours as well. This shows the interest of the non-participating farmers, but more importantly the strength of the participatory research approach.

Third, a community-based participatory approach has been made possible through choice of smaller areas (villages) as project sites. It is easier to organise members of each of the villages and work with them as a group. It is also easier to develop leadership within each of the villages through exposing their members to various educational activities.

Fourth, diffusion of proven IPM technologies from the project to non-project farmers promises to be more effective, especially due to the involvement of some of the latter in the IPM project activities. With the holding of educational forums like field days both for project and non-project farmers during on-farm farmer-managed trials phase, there is greater scope for diffusion of proven IPM technologies to occur.

Finally, the extension phase is beyond the scope of these projects, but experience suggests that more and more members of each of the project villages could be gradually involved in the project, especially as they benefit or see their neighbours benefiting from it. From these few villages, more and more neighbouring villages could be involved in the project. As some of the villages acquire capacity to manage the newly acquired technologies on their own, extension agents could move on to help other needy villages. Frontline extension agents of the project areas are being trained both in the technical aspects of IPM and in the participatory research methods and this provides promise for the extension phase of the project.

References

Amanor K. (1990) Analytical Abstracts on Farmer Participatory Research. Agricultural Administration Unit, *Occasional Paper* 9, Overseas Development Institute, London.

Biggs S. D. (1987) Proposed methodology for analyzing farmer participation in the ISNAR OFCOR Study. *Agricultural Administration (Research and Extension) Network, Newsletter No. 17,* ODI, London.

Farrington J. and Martin A. (1990) Farmer participation in agricultural research: A review of concepts and practices. *Agricultural Administration Unit, Occasional Paper 9,* Overseas Development Institute, London, pp. 10–13.

Roling N. (1983) Agricultural knowledge: Its development, transformation, promotion and utilisation. Paper for Third Expert Working Group on Information, Analysis and Consolidation, Kuala Lumpur, Malaysia, 12–16 September.

Volken H., Kumar A. and Kaithathara R. (1985) *Learning from the Rural Poor.* Indian Social Institute, New Delhi.

Natural Products in Pest Management

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Natural Pesticides in Africa with Special Reference to Botswana, Zambia and Tanzania

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Abstract—In spite of the considerable amount of publications from workshops, individual research studies, policy reports and project descriptions which underline the importance of plant-derived pesticides in plant protection it has been unclear how much of this information has disseminated to the grassroots level. Within the regional Plant Protection Improvement Programme (PPIP) the question rose as to what extent people are concerned with natural pesticides in the region, working as researchers, advisors or growers? How is this implemented in practice? Finally, in what way can PPIP strengthen these activities? A study was carried out in 1993 and the results are presented in a report. Information is given about activities on the use of natural pesticides with special reference to Botswana, Zambia and Tanzania (Mainland and Zanzibar). Plants of particular interest such as neem (*Azadirachta indica*), tephrosia (*Tephrosia vogelii*), milk bush (*Euphorbia tirucalli*), basil (*Ocimum* spp.) and *Neorautanenia* spp. are described in more detail as well as the use of ash in stored products. Suggestions are given for how to strengthen the work on natural pesticides with the ultimate goal to support the smallscale farmers.

Key Words: natural pesticides, *Azadirachta indica, Tephrosia vogelii, Euphorbia tiruccali Ocimum* spp., *Neorautanenia* spp., ash in stored products

Introduction

The Plant Protection Improvement Programme (PPIP) funded by the Swedish International Development Authority (SIDA) is a regional programme covering Botswana, Tanzania and Zambia. The aim of PPIP is to increase the capacity of the region to solve its plant protection problems with particular emphasis on the needs of smallscale farmers. In spite of the considerable amount of publications from workshops, individual research studies, policy reports and project descriptions which underline the importance of plant-derived pesticides in plant protection, it has been unclear how much of this information has disseminated to the grassroots level. Within the Coordinating Committee of PPIP the question rose as to what extent people are concerned with natural pesticides in the region, working as researchers, advisors or farmers? How is this implemented in practice? Finally, in what way can PPIP strengthen these activities?

A compilation of information on the use of natural pesticides in Africa was done partly by advertising in *Tanzania Agricultural Research & Training Newsletter*, vol. VIII: 1–2 and partly by writing to private persons and organisations. More than 20 replies were received from various African countries providing valuable information about traditional practice on natural crop protection, on-going experiments and contacts to other persons and organisations known to be involved in work related to natural pesticides. This was followed by a three-weeks visit to Botswana, Mozambique, Zambia and Tanzania in November–

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December 1993. A literature search was also carried out. The investigation resulted in a report (Berger, 1994) which includes a historical background to the use of natural pesticides, a detailed description of on-going activities in the region, a focus on some particular plants, suggestions for the future and a pesticide network. Parts of the report will be presented in this paper.

Possibilities and Limitations

There is an urgent need to build up reliable food production systems in developing countries, not the least in Africa, where people regularly are faced with harsh environmental constraints of drought and pest outbreaks and a constant lack of agricultural inputs and limited financial means. Under the paradigms of sustainable agriculture and self-reliance, different aid organisations have tried to channel their help to smallscale farmers in the tropics in order to facilitate their use of resources which are locally available and can be cheaply maintained. From this perspective natural crop protection could have an important role to play in the many situations where pests seriously hamper agricultural production. The possibility of making raw extracts from plants grown in the neighbourhood where the farmer lives assists self sufficiency and gives him/her a cheap alternative to conventional pesticides which often are imported using foreign exchange. Large-scale production (for local use) of natural pesticides based on crude or purified extracts could also provide an income for people in the countryside.

Today there is considerable interest among biochemists and botanists to screen plants for secondary chemical compounds, which could be used for developing medicals and pesticides, particularly in the tropical rain forests where plant species are numerous but threatened with extinction (Downum et al., 1993). However, it is an expensive and difficult process to isolate and identify the active ingredients and further to produce them in formulations which can be commercialised. Further, natural pesticides are not uniform products but rather consist of different active ingredients which often vary in concentration from sample to sample. This makes toxicological tests difficult and costly to run (Latum and Gerrits, 1991). Therefore one can expect that the interest of the chemical industry in developing new biopesticides is rather limited.

Shared Problems in Botswana, Zambia and Tanzania

A combination of a constrained economy and an increasing awareness of the negative effects of synthetic pesticides highlights some pest–crop complexes which appear to catch peoples' interest in their work with natural crop protection.

Insect Pests on Vegetables

Vegetables are important supplements to staple crops and they are also a resource of income for people living near the towns. Crop rotation and the use of resistant varieties are important methods for reducing pest damage but not always enough in order to control insects. There seems to be a widespread misuse of chemical pesticides in vegetables. Pesticides which are left-overs from locusts campaigns, as in Botswana, or used in cash crops like cotton (DDT and organic phosphour compounds are still common) or coffee as in Tanzania are used indiscriminately on vegetables. Many of these pesticides have a medium to high persistency taking a long time to break down. In vegetables the period between chemical application and harvest is usually short. The risk of pesticide contamination in the products which are sold on the market is obvious affecting the health of both producers and consumers.

Storage Pests

Post-harvest losses are often more significant than crop losses which occur in the field. In Africa as much as 20–50% of the grain can be lost in maize and pulses because of infestations from weevils, bruchids and other insects (FAO, 1985). Healthy products and clean storage structures are essential to prevent pest damage but may not be enough, in particular if the storage period is long. Chemicals for fumigation or seed treatment are sometimes available but have become less attractive due to the costs. There is a common tradition among farmers at the subsistence level to use natural products such as ash instead and these alternatives appear to have increased their importance. An enquiry in Zimbabwe showed that the number of farmers who used natural pesticides in addition to chemicals changed from 20% before 1989 to 80% after (Giga and Mvumi, pers. commun.). Maize has usually been stored as cobs which makes it more difficult for weevils, *Sitophilus* spp. to penetrate the grains. However, this common practice has been challenged by the larger grain borer, *Prostephanus truncatus*, a newly introduced storage pest in Africa, which prefers maize cobs rather than grains.

Termites in Tree Plantations

Agroforestry is today extending to many areas of Africa. Growing annual crops together with perennial trees or shrubs increases the versatility of the cultivation system as a whole and hence spreads the risk for the farmer. Trees are an important resource for fuel and have a beneficial effect on soil conservation. Tree plantations are of special interest in marginal areas where living conditions are hard owing to a combination of poor soils, dry climate and population pressure which have led to degradation of soils and severe shortage of wood for burning. The establishment of tree seedlings may be seriously hampered by termites. Seedlings can be protected with insecticides before planting but many farmers cannot afford to buy the products. An improper handling of these chemicals, usually persistent organochlorines, can cause negative effects both on the health of the user and on the environment.

Activities Concerning Plant-Derived Pesticides

Briefly, activities in Botswana, Zambia and Tanzania occur on four different levels. (1) Collection of information about traditional use of plants with particular reference to crop protection. (2) Simple on-farm trials or demonstrations which usually do not include replications for statistical analyses. (3) Experimental work in field and laboratory using crude plant extracts. (4) Chemical analyses of active ingredients and bioassays of crude or purified plant extracts. Documentation so far is scarce but some examples are given in the more detailed description below. Extension seems to take place in close contacts with farmers who are involved in surveys and on-farm trials.

Many different plant species are used traditionally as natural pesticides and/or have been explored experimentally. Some plants seem to be more popular or tested more often than others. For instance, experiments on the effect of plant extract from tephrosia, *Tephrosia vogelii,* occurred in six different places in Zambia. Similarly, species of the family Euphorbiaceae appeared to be commonly used in Tanzania. A brief description of some of these plants is given below.

Plant Material of Particular Interest

The Neem Tree and Other Meliaceae

Neem, *A. indica,* Persian lilac, *Melia azedarach,* and *Trichilia emetica* do all belong to the mahagony family Meliaceae. Neem is widely distributed throughout tropical Africa in both dry and humid areas (FAO, 1988). It is grown in many West African countries such as Niger, Sierra Leone, Ghana, in plantations in Sudan and Ethiopia and in East and southern Africa with a predominance in the Swahili dominated areas along the coast.

There is an immense documentation on the neem tree, including the pesticidal properties of neem products (Jacobson, 1989; Schmutterer, 1990; National Research Council, 1992; Saxena, 1993). In spite of this there seems to be a rather limited documentation in Africa of how it should be exploited in practical crop protection with regard to methods of application, dosages and target pests. The most common method seems to be to let dried and crushed kernels soak in water and spray the solution on the crop. This is also the way neem is used in Zanzibar and Kenya (Said and Jro, pers. commun.).

For storage protection neem is usually used as a powder from crushed seeds which is mixed with the grain at various concentrations. This gives protection of many insect pests (Golob and Webley, 1980; Saxena et al., 1989); however, contradictory results are also obtained. Larger grain borer, *Prostephanus truncatus,* is less sensitive to neem than the weevils, *Sitophilus* spp. (Tierto Niber, 1989; Tierto Niber et al., 1992). Silos with maize are therefore treated with a combination of powder and slurries of neem and pyrethrum (Tierto Niber, 1994). The neem product gives a bitter smell and taste which can reduce its attractiveness as a protectant in food grain particularly in areas where there is shortage of water for rinsing the produce (Tierto Niber, pers. commun.). The risk of aflatoxin contamination in the grain owing to neem fruits which have not been dried properly should also be considered (Latum and Gerrits, 1991).

Neem leaves contain much less of the major active ingredient, azadirachtin, than seed kernels and are apparently not used as commonly. Nevertheless leaf powder mixed with beans at a concentration of 5% was shown to be effective against Mexican bean weevils *Zabrotes subfasciatus* (Busungu and Mushobozy, 1991). Further, water extract from fresh leaves gave a good control of stemborers (*Chilo partellus*) in maize, when applied into the plant whorls in Mozambique (Segeren, 1993).

The azadirachtin content in seed kernels and the antifeedant activity the plant extract gives can vary between plant material from different locations (Ermel et al., 1987; Singh, 1987). The fact that the concentration of the active compounds may vary between different plant materials is probably one reason for the sometimes ambivalent results reported from the field. This was also experienced in Mozambique and Zambia.

In Nicaragua, within a project supported by Germany and Sweden, it has been possible to establish tree plantations and a small factory for producing crude neem products which are then commercialised. The practical experience from this project could be useful if similar projects are going to be developed elsewhere. The published material includes manuals for plantation procedure, technique for processing the plant extract and application methods against various pests (Gruber and Mendez, 1992; Gruber and Miranda, 1993).

The Persian lilac or chinaberry appears to be a common alternative to neem and there is occasionally a confusion of which of the two plants has actually been used. During a neem planting programme in Ethiopia it was revealed that the seeds used were from the Persian lilac and not from the neem. There is hence a risk that the two species can be mixed up with consequences for the interpretation of experimental results.

Stoll (1988) suggested to use powder of dried leaves and seeds in stored grain. In addition, bark has been used as powder against bruchids (Javaid, in prep.) or soaked in water for spraying against termites (Mandola, pers. commun.). Leaf extract in water was not as effective as neem leaves against the stemborers in maize (Segeren, 1993).

A third species of the Meliaceae family, *Trichilia emetica,* is reported to be used in Mozambique. Treatment with crushed seeds mixed with cowpea at a dosage of 1% gave a 98% protection of the grain and no weight loss after 90 days (Segeren, 1993).

Tephrosia vogelii

The legume *T. vogelii* is a shrubby plant indigenous to Africa but distributed to many other parts in the tropics where it is used as shelter, cover crop, fish poison and as a pesticide. It was introduced to the United States in the sixties for the purpose of commercial production of rotenone and regarded as a more promising plant than *Derris* and *Lonchocarpus* spp. which were the main sources of the pesticide (Barnes and Freyre, 1966). In eastern and southern Africa *T. vogelii* and other related species have been grown in small plantations by smallholders for their use in crop protection (Watt and Breyer-Brandwijk, 1962). The principle active ingredient is rotenone but there are also other rotenoids such as tephrosin and deguelin which are toxic to mammals. The insecticidal effects have been shown on several different insect species (Grainge and Ahmed, 1988). In bioassays, extracts of these compounds had stronger antifeedant effect on armyworms, *Spodoptera exempta,* sugarcane borer, *Eldana saccharina* and pod borers, *Maruca testulalis* than extracts of azadirachtin (Hassanali and Lwande, 1989).

The most common application method is to let fresh and crushed leaves soak in water at a concentration of 10% and then spray the liquid on the crop. Farmers in Malawi use tephrosia as a dip to protect cattle from ticks and as a fish poison (CIMMYT, 1991). Similar practices are reported from Zambia (Kaposhi, 1992). On the other hand, farmers in the Mansa region were said not to be satisfied with the plant used as a botanical pesticide in crop protection (Thord Karlsson, pers. commun.). Powder of tephrosia leaves can also be used to protect stored products. In Congo, powder mixed with groundnuts at a ratio of 1:40 gave a 98.8% mortality of the groundnut borer, *Caryedon serratus,* after 13 days (Delobel and Malonga, 1987).

Euphorbia tirucalli

The milk bush, *E. tirucalli,* is a succulent shrub or tree of several metres height which occurs in grassland and savanna woodland throughout tropical Africa including Madagascar as well as in the Arabian peninsula, India and the Far East (Polhill, 1988). It is easy to propagate with branch cuttings and is often planted in hedges around villages in eastern Africa. Stem, branches and buds have insecticidal and repellent properties against aphids, grasshoppers and mosquitoes (Grainge and Ahmed, 1988). The plant is also used as a fish poison. The plant sap, latex, can be applied as a seed dressing against the plant parasitic nematodes *Tylenchorhynchus brassicae* and *Rotylenchus reniformis* to protect vegetables (Siddiqui and Alam, 1988a, b). Leaves, seeds and roots are soaked in water and the solution is sprayed to protect vegetables from caterpillars and seedlings from termites (Said and Mandola, pers. commun.). Because the latex is harmful to the eyes and causes irritation of the skin the plant material must be handled carefully when preparing the crude extracts.

Finger euphorbia is planted near coconut trees to prevent attack by rhinoceros beetle, *Oryctes* spp. in Kenya (Onyango Jro, pers. commun.) and similar practice to protect coconut trees against termites occurred with another Euphorbiaceae *Pedilanthus cucullatus* in the coastal region of Tanzania before the second world war. The plant is now used in Handeni to protect tree seedlings from termites (von Ramdohr, pers. commun.).

Ocimum spp.

Sweet basil, *O. basilicum* (syn. *americanum*) was reported by Irvine (1955) for its potential as a pesticide. Leaves and seeds are rich in essential oils which are repellent, toxic or growth inhibitory to many insects (Grainge and Ahmed, 1988). In field and laboratory experiments treatments with seed extracts against bugs in turnip, *Bagrada cruciferarum*, the American bollworm, *Helicoverpa armigera* and aphids, *Aphis gossypii* increased mortality between 50–90% (Pandey et al., 1983a, b).

There are other wild *Ocimum* species such as *O. suave* and *O. canum* which have been used traditionally against pests in Tanzania. Branches of *O. suave* are often placed around windows and doors to keep mosquitoes away. Chemical analyses of the essential oils from the plant revealed that the principle compound was eugenol which was shown to have a strong repellent effect on mosquitoes (Chogo and Crank, 1981). Linalool is another terpenoid found in hoary basil, *O. canum*. This chemical compound is responsible for the toxic effect of dried leaves to the bruchid *Zabrotes subfasciatus* and other storage pests (Weaver et al., 1991). Extracts from *O. suave* have shown promising results in bioassays on maize weevils, *Sitophilus zeamais,* carried out at ICIPE, Kenya. The plant was going to be in focus for future evaluation of botanical pesticides in stored grain at the village level (Hassanali and Lwande, 1989).

Eugenol and other isolates of essential oils have also a strong inhibitory effect on the growth of many fungi (Garg and Siddiqui, 1992).

Neorautanenia spp.

This plant is a perennial non-climbing leguminose (Phaseolae) weed creeper with long stems. It is common in eastern Africa from the Zambezian bushland to the grasslands of the Somali-Masai region (Lock, 1989). The thick root is cut into pieces and these are soaked in water. The extract is effective against ticks in Zambia (Kaposhi, 1992) and was also used in Handeni, Tanzania *(N. mitis)* for stemborer control in maize (Ramdohr, pers. commun.).

Ashes

To treat the stored grain with ash is a common method of protection against insect pests (Golob and Webley, 1980). The ash is either mixed thoroughly with the grain or added to the stored product in various layers. Ashes seem to be used both indiscriminately and from a particular product. In Zimbabwe undefined ashes and ashes from maize cores and mopane tree, *Colophospermum mopane* are predominant in Mashonaland provinces while ashes from cattle and goat droppings and from the lead wood, *Combretum imberbe,* are preferred in Matabeleland provinces (Giga and Mvumi, pers. commun.). Lead wood is very heavy and burns down to an almost floury ash. It is also used by people in Botswana and was shown to be fairly effective against bruchids in cowpea (Javaid, in prep.). Wood ash, as well as sand, tobacco dust and dolomite, provided a good protection of maize stored for six months in Malawi (Golob, 1984).

The protectant mechanisms of ash is unclear. Desiccation and suffocation are two possible ways of how insects are affected. There may be a variation in how effective different ash products are owing to differences in texture and chemical composition. Although the choice of ash products is likely to be dependent on what is available for the people in a particular area, it could be of interest to carry out comparative experiments of several ash products against the most common storage pests.

Ashes are usually used in stored grain but can also be applied to field crops. Stoll (1988) gives several recipes for protection of vegetables against insects and diseases. In Kenya ash is applied against stemborers in maize (Jro, pers. commun.) and in Uganda farmers use ash to protect against sweetpotato clear wing, *Synanthedon dasysceles,* aphids, banana weevils and blight in tomatoes; there are, however, some doubts about the effect (Brehony, pers. commun.).

Suggestions for the Future

The constrained economy of many smallscale farmers together with the problems of health risks and environmental pollution owing to chemical pesticides provide strong arguments for carrying out studies on plants with pesticidal properties. These studies can of course be of interest in themselves because they may contribute to scientific knowledge in general making it easier to predict the outcome of different interactions between plants and pests.

However, if the aim is to improve the natural crop protection there must also be an awareness of and response to the experience of the farmers. Current knowledge and new findings about promising plant products need to be transformed into practical applications which are accepted by the users. Neglecting this can lead to a negative feedback from the farmers which results in a decreasing interest to use natural pesticides. Some general suggestions are given below for how to strengthen the current work with natural pesticides with the ultimate goal of helping the smallscale farmers.

Collection of Information

Information about plants with pesticidal properties can be collected in two ways, either from surveys at the grassroots level or from existing databases and current knowledge about the flora in the country.

Surveys can be an important means for getting to know about traditional plant protection methods and has already given results. Within the Handeni Agroforestry Project in Tanzania, the research team walks through the bush together with both young and old villagers, the latter would then point out useful plants which the younger people could learn about. To ask a farmer about plant protection methods may not be the best way to get the right information. Many farmers have been too involved in the use of chemical pesticides and see these as the only method to protect the crop. Although traditional methods are used they are not brought up as a source for plant protection.

There are databases which supply information about potential plants. One example is Grainge and Ahmed's *Handbook of Plants with Pest-Control Properties* (1988). A database has also been developed in Zimbabwe (Elwell, pers. commun.) and could provide a valuable source for the region. This database is the basis for a forthcoming joint publication by PPIP and Natural Farming Network in Zimbabwe (Elwell and Maas, 1995: Natural pest and disease control). A bibliographic database dealing with storage pests has recently been published by Natural Resources Institute (Rees et al., 1993). Linking the information obtained from the database to the knowledge of the indigenous flora could draw rings on the most promising plants which deserve further studies. Important aspects to consider are not only pesticidal properties of the plants but also their distribution, abundance and easiness to be propagated. Cooperation with botanists at the National Herbaria and Universities would facilitate the work. Help is also needed with the identification of plants used traditionally but only known by their local names.

Comparative Studies with Emphasis on the Mechanisms

In several studies comparisons have been made between extracts from different plants and their effect on a particular organism (Busungu and Mushobozy, 1991; Sohati and Sithanantham, 1992; Poswal et al., 1992). The reason for choosing these plants is often that they have been used locally for medical treatment, in tick control, as fish poison, etc. Sometimes a more detailed description is given about the active ingredients.

A common limitation is that the results are seldom discussed in relation to the mechanisms which are thought to be responsible. The mechanisms behind an extract's protectant properties are of course not always understood, nor easy to observe in the field. Bioassays with crude or purified extracts could contribute with information about insect behaviour and development and thus facilitate to interpret the results. Antifeedant activity assay with leaf discs in a choice situation has been used at ICIPE and is described by Kubo (1993); other examples of bioassays on fecundity and development are given from the neem tree (Schmutterer and Ascher, 1987; Saxena, 1993).

The target pest of most studies is one single species. However, crops are often hosts for several insects and in the case of vegetables there is a wide range of aphids, bugs, caterpillars and beetles which feed on the plants. It would be useful to carry out comparative studies testing one or a few promising plant materials against various insects with different feeding behaviour.

Most studies of natural pesticides are concerned with the effects on insects. Plants or crude extracts can also be used against many other organisms (Grainge and Ahmed, 1988) and some examples on the nematicidal and fungicidal effects of *E. tirucalli* and *Ocimum* spp. were given above. Marigold plants, *Tagetes* spp., are known for their nematicidal properties and field experiments in Tanzania have shown that intercropping tomatoes with marigold significantly reduced number of root-galls and increased the yield (Ijani and Mmbaga, 1988). Similar results are reported from Kenya (Oduor-Owino, 1993). In laboratory experiments in Botswana, extract from the stem of *Dichapetalum cymosum* completely inhibited the mycelium growth of the rot pathogen *Macrophomina phasealina* and fungicidal effects were also found in extracts from *M. azaderach* (seed and bark), *Solanum nigrum* (berries) and *Pavetta harborri* (stem)(Poswal et al., 1992).

Concentration to Some Important Plants

There is a need to concentrate the work on certain plants in order to cover them as well as possible at different levels. A systematic approach is required. This includes documentation of the botanical aspects of the plants, the growing conditions and how they can be propagated. Further, it includes research in laboratory and field taking into account the need of chemical identification of active ingredients and testing for toxicity to mammals and beneficial insects. Extraction and application methods ought to be assessed (and improved) with the feedback from the farmers. Finally, if the arguments are good enough, extension material should be produced. A system of leaflets, one for each plant, may give enough flexibility to cope with several products at the same time in spite of heterogeneity in the scientific and practical knowledge of the plants. In addition, leaflets can be easily updated in the light of new findings.

The Need for Cooperation

There is a widespread interest among researchers and extension officers to incorporate natural pesticides into the integrated pest management. A shortcoming seems to be that most of the work is carried out on a scattered ad-hoc basis, with little background information and few horizontal and vertical links to other people who study the same plants somewhere else. The description of the various on-going activities on plant-derived substances which is given in the report (Berger, 1994), should be seen as a first attempt to create a network of people interested in natural pesticides. Together with the network presented on neem (National Research Council, 1992) it could provide possibilities for developing a mutual exchange of ideas and experiences, concentration on relevant research topics and an avoidance of unnecesssary duplications of experiments. As a result of this study, cooperation has already been initiated in Zambia (Berger and Mugoya, 1995).

References

Barnes D. K. and Freyre R. H. (1966) Recovery of natural insecticide from *Tephrosia vogelii*. I. Efficiency of rotenoid extraction from fresh and oven-dried leaves. *Economic Botany* 20, 279–284.

Berger A. (1994) Using Natural Pesticides—Current and Future Perspectives. A report for the Plant Protection Improvement Programme in Botswana, Zambia and Tanzania. Rapport 2, Sveriges lantbruksuniversitet, Institutionen för växtskyddsvetenskap, Alnarp, Sweden.

Berger A. and Mugoya C. F. (1995) *Natural Plant Products as Pesticides.* Proceedings from the First National Symposium in Zambia held in Lusaka, 2–5 August, 1994. Report 4, Swedish University of Agricultural Sciences, Alnarp, Sweden.

Busungu D. G. and Mushobozy D. M. K. (1991) The efficacy of various protectants against *Zabrotes subfasciatus* (Boh) Coleoptera, Bruchidae in common beans. *Bean Research* 6, 62–67.

Chogo J. B. and Crank G. (1981) Chemical composition and biological activity of the Tanzanian plant *Ocimum suave*. *J. Natural Products* 44, 308–311.

CIMMYT (1991) *Farming Systems Bulletin,* Eastern and Southern Africa, no. 9.

Delobel A. and Malonga P. (1987) Insecticidal properties of six plant materials against *Caryedon serratus* (Ol.) (Coleoptera: Bruchidae). *J. Stored Product Research* 23, 173–176.

Downum K. R., Romeo J. T. and Stafford H. A. (Eds)(1993) *Phytochemical Potential of Tropical Plants. Recent Advances in Phytochemistry* (Volume 27). Plenum Press, New York.

Elwell H. and Maas A. (1995) *Natural Pests and Disease Control.* Natural Farming Network, Zimbabwe.

Ermel K., Pahlich E. and Schmutterer H. (1987) Azadirachtin content of neem kernels from different geographical locations, and its dependence on temperature, relative humidity, and light, pp. 171–184. In *Natural Pesticides from the Neem Tree and Other Tropical Plants* (Edited by H. Schmutterer and K. R. S. Ascher*).* GTZ, Eschborn, Germany.

FAO (1985) *Handling and Storage of Food Grains.* Food and Agriculture Organisation of the United Nations, Rome.

FAO (1988) *Traditional Food Plants.* Food and Agriculture Organisation of the United Nations, Rome.

Garg S. C. and Siddiqui N. (1992) Antifungal activity of some essential oils isolates. *Pharmazie* 47, 467–468.

Golob P. (1984) Improvements in maize storage for the smallholder farmer. *Tropical Stored Products Information,* no. 50, 14–19.

Golob P. and Webley D. J. (1980) The use of plants and minerals as traditional protectants of stored products. Tropical Products Institute G 138. Now Post Harvest Pest and Quality Section, Natural Resources Institute, Chatham, United Kingdom.

Grainge M. and Ahmed S. (1988) *Handbook of Plants with Pest-Control Properties.* Resource Systems Institute, East-West Centre, Honolulu, Hawaii. John Wiley & Sons, New York.

Gruber A. K. and Mendez M. (Eds) (1992) Arbol Nim en Nicaragua. Cultivo y aprovechamiento como fuente de insecticidas botánicas. Proyecto Insecticida Botánico nim, Impreso en Editorial Evangélica, CIEETS, Managua, Nicaragua.

Gruber A. K. and Miranda F. (Eds)(1993) Memoria del primer taller de intercambio de experiencias y conocimientos sobre el cultivo del arbol nim en America Latina. 2–6 Novembre, Managua, Nicaragua.

Hassanali A. and Lwande W. (1989) Antipest secondary metabolites from African plants, pp. 78–96. In *Insecticides of Plant Origin* (Edited by J. T. Arnason, B. J. R. Philogene, and P. Morand). ACS symposium series 387. American Chemical Society, Washington, DC.

Ijani A. S. M. and Mmbaga M. T. (1988) Studies on the control of root knot nematodes (*Meloidogyne* species) on tomatoes in Tanzania using marigold plants (*Tagetes* species), ethylene dibromide and aldicarb. *Trop. Pest Manage.* 34, 147–149.

Irvine F. R. (1955) West African insecticides. *Colon. Pl. Anim. Prod.* 5, 34–38.

Jacobson M. (Ed.) (1989) *The Neem Tree. Focus on Phytochemical Pesticides* (Volume 1). CRS Press, Boca Raton, Florida, USA.

Kaposhi C. K. M. (1992) The role of natural products in integrated tick management in Africa. *Insect Sci. Applic.* 13, 595–598.

Kubo I. (1993) Insect control agents from tropical plants. In *Phytochemical Potential of Tropical Plants. Recent Advances in Phytochemistry* (Volume 9) (Edited by K. R. Downum et al.). Plenum Press, New York.

Latum E. B. J. van and Gerrits R. (1991) *Bio-Pesticides in Developing Countries. Prospects and Research Priorities.* ACTS Press, African Centre for Technology Studies, Nairobi, Kenya and ACTS Biopolicy Institute, Maastricht, The Netherlands.

Lock J. M. (1989) *Legumes of Africa—A Check List.* Royal Botanical Gardens, Kew, UK.

National Research Council (1992) *Neem: A Tree for Solving Global Problems.* National Academy Press, Washington, US.

Oduor-Owino P. (1993) Effects of aldicarb, *Datura stramonium, Datura metel* and *Tagetes minuta* on the pathogenicity of root-knot nematodes in Kenya. *Crop Protection* 12, 315–317.

Pandey U. K., Srivastava A., Lekha C. and Singh A. (1983a) Efficacy of certain plant extracts against brinjal aphid *Aphis gossypii* Glover. *Indian J. Entomol.* 45, 313–314.

Pandey U. K., Srivastava A., Singh A. and Pandey M. (1983b) Evaluation of some plant origin insecticides against gram caterpillar, *Heliothis armigera* Hubn. *Indian J. Entomol.* 45, 211–212.

Polhill R. M. (Ed.) (1988) *Flora of Tropical East Africa. Euphorbiaceae I–II.* A. A. Balkema, Rotterdam.

Poswal M. A. T., Masunga G., Javaid T. and Kwerepe B. C. (1992) Comparative evaluation of the inhibitory effects of different plant extracts on the charcoal rot pathogen *Macrophomina phaseolina* in Botswana. In *Proceedings of the First National Workshop on Plant Genetic Resources,* 24–26 June, 1992, Gaborone (Edited by S. M. Mathodi et al.).

Rees D. P., Dales M. J. and Golob P. (1993) Alternative methods for the control of stored-product insect pests. A bibliographic database. Natural Resources Institute, Chatham, United Kingdom.

Saxena R. C. (1993) Neem as a source of natural insecticides—An update. In *Botanical Pesticides in Integrated Pest Management.* Indian Society of Tobacco Science, Rajahmundry, India. IRRI, Manilla, Philippines.

Saxena R. C., Jilani G. and Kareem A. A. (1989) Effects of neem on stored grain insects. In *The Neem Tree. Focus on Phytochemical Pesticides* (Volume I). CRS Press, Boca Raton, Florida.

Schmutterer H. (1990) Properties and potential of natural pesticides from the neem tree, *Azadirachta indica. Annu. Rev. Entomol.* 35, 271–297.

Schmutterer H. and Ascher K. R. S. (Eds) (1987) *Natural Pesticides from the Neem Tree and Other Tropical Plants.* Proceedings from the third international neem conference, Nairobi, Kenya, 10–15 July 1986. GTZ, Eschborn, Germany.

Segeren P. (1993) Pesticidas naturais: Uma alternativa para o sector familiar? Extra - Revista para o desenvolvimento e a extensao rural, 12, 34–38. Centro de Formaçao Agrária e de Desenvolvimento Rural, Maputo, Moçambique.

Siddiqui M. A. and Alam M. M. (1988a) Effect of seed dressing with plant latex on *Tylenchorynchus brassicae* and plant growth of cabbage and cauliflower. *Pakistan J. Nematol.* 6, 65–71.

Siddiqui M. A. and Alam M. M. (1988b) Effect of latex on *Rotylenchus reniformis* and plant growth of some vegetables. *Nematologia Medeterranea* 16, 129–130.

Singh R. P. (1987) Comparison of antifeedant efficacy and extract yields from different parts and ecotypes of neem (*Azadirachta indica* A. Juss) trees, pp. 185–194. In *Natural Pesticides from the Neem Tree and Other Tropical Plants.* (Edited by H. Schmutterer and K. R. S. Ascher). GTZ, Eschborn, Germany.

Sohati P.H. and Sithanantham S. (1992) Exploratory field testing of plant extracts against some pests on cowpea in Zambia. Paper presented at the SADCC/IITA Cowpea Workshop for Southern Africa, 26–27 September, 1991, Harare, Zimbabwe.

Stoll G. (1988) *Natural Plant Protection in the Tropics.* AGRECOL, Margraf Publishers Scientific Books, Weikersheim, Germany.

Tierto Niber B. (1989) Evaluation of some indigenous Ghanaian plants for insecticidal, repellent or antifeedant effects on four species of stored product pests. MSc thesis, Dept of Applied Zoology, University of Helsinki, Finland.

Tierto Niber B. (1994) The ability of powders and slurries from ten plant species to protect stored grain from attack by *Prostephanus truncatus* Horn. (Coleoptera: Bostrichidae) and *Sitophilus oryzae* (Coleoptera: Curculionidae). *J. Stored Prod. Res.* 30, 297–301.

Tierto Niber B., Helenius J. and Varis A.-L. (1992) Toxicity of plant extracts to three storage beetles (Coleoptera). *J. Appl. Ent.* 113, 202–208.

Watt J. M. and Breyer-Brandwijk M. G. (1962) *The Medicinal and Poisonous Plants of Southern and Eastern Africa.* Livingstone, London.

Weaver D. K., Dunkel F. V., Ntezurubanza L., Jackson L. L. and Stock D. T. (1991) The efficacy of linalool, a major component of freshly-milled *Ocimum canum* Sims (Lamiaceae), for protection against postharvest damage by certain stored product Coleoptera. *J. Stored Prod. Res.* 27, 213–220.

Crop Pest Management

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Implementation and Economic Impact of Cotton Integrated Pest Management in The Sudan

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Abstract—The FAO/ARC project entitled Development and Application of Integrated Pest Control in Cotton and Rotational Food Crops in The Sudan was initiated in 1979. The Food and Agricultural Organisation of the United Nations was designated as the executing agency and the Ministry of Agriculture through the Agricultural Research Corporation as the implementing agency. The main objectives were to reduce the escalating number of insecticide sprays (average 7–8 sprays per season) and minimise both the cost of production and the environmental contamination by pesticides. The research was carried out mostly as on-farm large-scale trials. A new IPM package was recommended and has been already adopted by all cotton producing schemes in the country.

As a result, the number of sprays in cotton in the Gezira Scheme has dropped from 5–6 in the 1980s to 4.9 in 1992/93 and 3 in the 1993/94 season. This means a saving of approximately 6.77 x 10^6 US$ (calculation using the 1993/94 cotton areas and current exchange rate) only in the 1993/94 season. In the Rahad Scheme, the number of sprays in cotton was reduced from 4.55 in 1992/93 to 3.1 in 1993/94. This means a saving of 1.15 x 10^6 US$. The total donor contribution to the FAO/ARC project amounts to 8.17 x 10^6 US$ for the four respective project phases from 1979 to 1995. From these data (including savings on wheat spraying) it can be concluded that the donor contribution to the project approximates the savings in pesticides of one year of IPM implementation in cotton and wheat in the Gezira and Rahad Schemes.

In addition to the measurable economic return, the project staff and the ARC counterparts noticed the positive effect of reducing aerial spraying on the occurrence of natural enemies on the other crops in the cotton based agroecosystem in the Rahad and Gezira Schemes, indicating an improvement of environmental quality in both agricultural schemes.

Key Words: cotton IPM, ETL, *Jacobiasca lybica, Bemisia tabaci, Helicoverpa armigera, Aphis gossypii*

Introduction

Chemical control of cotton pests in the Gezira scheme, the largest agricultural scheme under gravity irrigation and the main cotton producing area in The Sudan, started in 1950. During the past four decades there has been dramatic change in both the species composition of the pests complex and the number of spray applications per season (Eveleens, 1983; El-Bashir et al., 1978).

The key pest, against which the commercial insecticide application started in the Gezira Scheme in 1950, was the cotton jassid, *Jacobiasca lybica* (de Berg). The total reliance on insecticides to control this species resulted in the resurgence of the cotton whitefly, *Bemisia tabaci* Genn. in the late fifties and the American bollworm *Helicoverpa armigera* (Hubn.) in the early sixties. The cotton aphid, *Aphis gossypii* Glov., which had been a late-season pest was converted into an all-season pest since the late seventies (Eveleens, 1983; Abdelrahman and Munir, 1989).

The number of sprays on cotton was only one during the fifties, increased steadily till it reached eight rounds per season during the late seventies. The trend of the number of sprays and that of the cotton yield is shown in Fig. 1. The lower yield in 1992/93 season is attributed to the incomplete cotton picking of the medium staple varieties due to the low prices announced by the authorities.

The FAO/ARC Integrated Pest Management (IPM) Project entitled "Development and Application of Integrated Pest Management in Cotton and Rotational Food Crops" was initiated in 1979. The project underwent three phases devoted mostly to cotton. The fourth phase which started in January 1993 was designed to cover three years with main emphasis on vegetable IPM. The four phases have been generously sponsored by the Government of the Netherlands and executed by FAO and the Agricultural Research Corporation (ARC) of the Sudan (Table 1).

In the first phase of the IPM project, most of the activities were devoted to the study of the seasonal occurrence of the main pests as well as their natural enemies. The effect of the important agronomic practices on the population densities of the key pests were studied (Eveleens and Abdelrahman, 1980; Eveleens 1983). Breeding for resistance

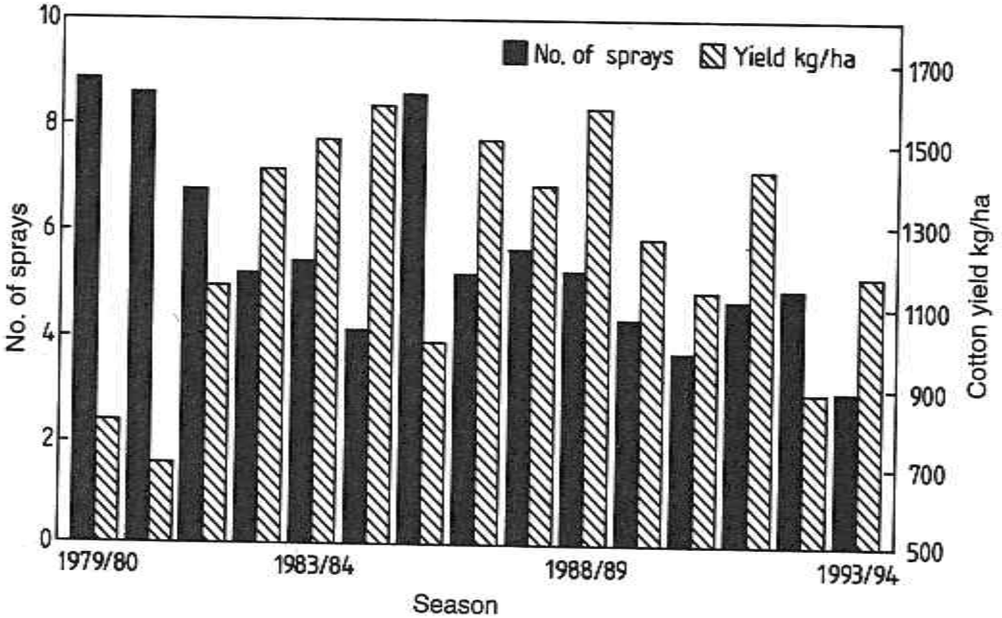

Fig. 1. Cotton yield and number of sprays in Gezira 1979–1994.

Table 1. Duration and budget of the consecutive stages of the FAO/ARC integrated pest management project in the Sudan

Phase	Duration	Budget (in US$)
I	May 1979–September 1983	991,330.00
II	September 1985–April 1989	1,376,000.00
III	May 1989–June 1992	2,892,470.00
IV	January 1993–December 1995	2,910,980.00

to major pest species resulted in releasing Sudac-K variety (Sippell et al., 1987), a whitefly-resistant super-okra glabrous *Gossypium hirsutum*.

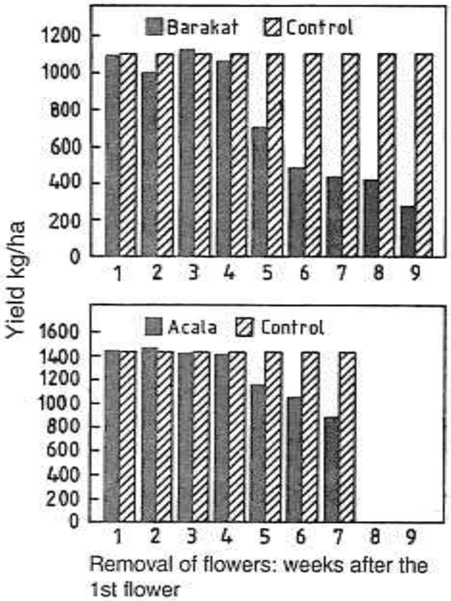

Fig. 2. The compensatory ability of the commercial cotton varieties (Barakat and Acala) to simulated 100% damage by bollworms, Gezira 1988–1991.

During the second phase a large-scale trial was conducted in the commercial cotton fields of the Gezira scheme. An area of 333 ha of cotton was left completely unsprayed throughout the 1986/87 season. This trial showed the conditions which were prevailing in the Gezira before the introduction of insecticides application. The basic insect problems of cotton were thus illuminated and the impact of the insecticides was convincingly demonstrated. The key pest of cotton in the unsprayed cotton fields was again found to be the jassid. Both the whitefly and the bollworm *H. armigera* pests were created by the continuous use of insecticides. The most important finding was that, in the absence of insecticides, the indigenous natural enemies were capable of suppressing both whitefly and aphids below the economic threshold levels throughout the season (Abdelrahman and Munir, 1989). The importance of delaying the first insecticide application which was suggested by Eveleens and Abdelrahman (1980) was verified. As a result during the third phase (1985–1992) a series of trials to raise the ETLs for the four pests were conducted in different localities (Stam et al., 1994). Another series of experiments were also conducted to reveal the maximum age of the cotton plant at which it can fully compensate simulated 100% damage of bollworms in the Gezira environment (Fig. 2). It was found that all the commercial cotton varieties could compensate 100% of such damage up to four weeks after the initiation of flowering (Abdelrahman, 1995). The newly proposed higher ETLs (Stam et al., 1994) were accepted by the National Pests and Diseases Committee and were released for all cotton growing areas (Table 2). These new ETLs have been fully adopted in all cotton areas in the Sudan since the 1993/94 season.

The early cotton pests which might pose some difficulty when the first application of insecticides is delayed are *H. armigera* and *J. lybica*. For the former species, the egg parasitoid, *Trichogramma pretiosum* Riley was introduced from Texas, USA; mass-bred in Holland and released in cotton fields at Rahad, Gezira and New Halfa during 1988–1990 period. The species became established and is regularly recovered since then (Munir et al., 1995). Nevertheless chemical control is still needed because the incidence of parasitism is rather low at the beginning of the cotton growing season. The cotton jassid can be effectively controlled by a selective single insecticide treatment if the need arises.

At the end of the three phases of research and validation of cotton IPM it was possible to reduce the use of the insecticides on cotton from av. six to av.

Table 2. Newly recommended economic threshold levels for cotton pests

Pest	Former ETLs	New ETL
Bemisia tabaci	200 adults/100 leaves	600 adults/100 leaves
Jacobiasca lybica	50 nymphs/100 leaves	70 nymphs/100 leaves in *Gossypium hirsutum* and 100 nymphs/100 leaves in *G. barbadense*
Aphis gossypii	20% infested plants	40% infested plants
Helicoverpa armigera	10 eggs and/or larvae per 100 plants	30 eggs or 10 larvae per 100 plants. No insecticide spraying before advanced flowering

four sprays in all IPM experimental areas. This was achieved by:

(a) Delaying the first application of insecticides to permit the establishment of the local natural enemies in the cotton canopy;
(b) Raising the economic threshold levels for the four important pests;
(c) Introduction and successful colonisation of the egg parasitoid, *Trichogramma pretiosum* to control *H. armigera* which appeared early in the season and required early spraying upsetting natural biological control;
(d) Optimising cultural practices, e.g. timely sowing, regular irrigation and good weed control;
(e) Intensive extension and training programmes on the recognition of hazards of insecticides for both the agriculturists and the farmers.

The Economic Impact

The adoption of the IPM recommendations, particularly the raised ETLs has significantly reduced the number of sprays in all the IPM areas since the 1990/91 growing season (Table 3). The IPM experimental areas received four sprays in the two seasons 1992/93–1993/94 whereas the conventionally treated areas received six sprays. In the 1992/93 season the management of the Rahad Scheme (second to the Gezira Scheme in cotton production) implemented the new ETLs on the total cotton production area (26,000 ha). The Gezira Scheme management tested the new ETLs during this season on about 12,600 ha. Since the 1993/94 growing season, all the cotton areas in The Sudan have implemented the IPM recommendation. The mean cost of pesticides used was equal to US$ 24.53 per ha. The cost of the aerial application was US$ 5.95 per ha for 1994/95. Hence the cost of one spray/ha averaged US$ 30.48. It was calculated that in all the cotton fields in Sudan two sprays have been saved every season in the last two seasons (1992/93 and 1993/94) in which the new ETLs have been adopted. The monetary value of the saving was equal to 14.89 million US$ according to the cotton areas shown in Table 4. The number of sprays on cotton had been further reduced to 2.8 in the Gezira from the 1994/95 season.

The cotton quality has also improved as judged by the increase in the percentage of the higher lint grades which mean higher prices for the farmer (Fig. 3). The lint stickiness which is one of the major factors affecting the cotton grades has significantly dropped in the

Table 3. Cotton production and protection in the Gezira Scheme during 1979–1994 (Source: Sudan Gezira Board)

Season	No. of sprays	Yield	(Kg/ha)	Crop protection cost as % of total production costs
		LS	MS	
1979–80	8.87	796	1189	34
1980–81	8.61	696	1059	32
1981–82	6.78	1316	887	26
1982–83	5.22	1410	1927	24
1983–84	5.45	1388	2093	26
1984–85	4.14	1427	2476	23
1985–86	8.60	1112	1765	33
1986–87	5.20	1537	1825	30
1987–88	5.67	1258	1862	24
1988–89	5.27	1420	2067	22
1989–90	4.34	1215	1664	15
1990–91	3.72	930	1508	10
1991–92	4.75	1628	1895	19
1992–93	4.93	1420	1069	35
1993–94	3.02	1469	1404	30

LS and MS: Long and medium staple cotton varieties, respectively.

Table 4. The cost of chemical control of cotton pests in the irrigated sector in Sudan (1981/82–1993/94)

Season	Irrigated cotton (ha)	Cost of one spray (in 1000 US$)
1981/82	331,656	10,108.874
1982/83	359,341	10,952.713
1983/84	368,781	11,240.444
1984/85	346,012	10,546.445
1985/86	314,019	9,571.299
1986/87	334,279	10,188.823
1987/88	306,229	9,333.860
1988/89	303,110	9,238.793
1989/90	281,407	8,577.285
1990/91	178,795	5,449.672
1991/92	151,099	4,605.497
1992/93	127,275	3,879.342
1993/94	117,002	3,566.221

Average cost of one spray/ha during last ten years = 30.48 dollars.

last few years, particularly in the 1994/95 season. Lint stickiness is caused by the honeydew secreted by the whitefly and the aphids.

During the last four seasons the cotton area has been significantly reduced in order to increase wheat production in the country. However, the policy now is very much in favour of cotton which is regaining its normal rotational space. If we take an area of 315,000 ha of irrigated cotton per season (Table 4), the cost of two sprays would be US$ 19.2 million.

The large-scale cotton IPM trials of the 1986–1990 growing season was subjected to a comprehensive economic evaluation by Faki (1992) who

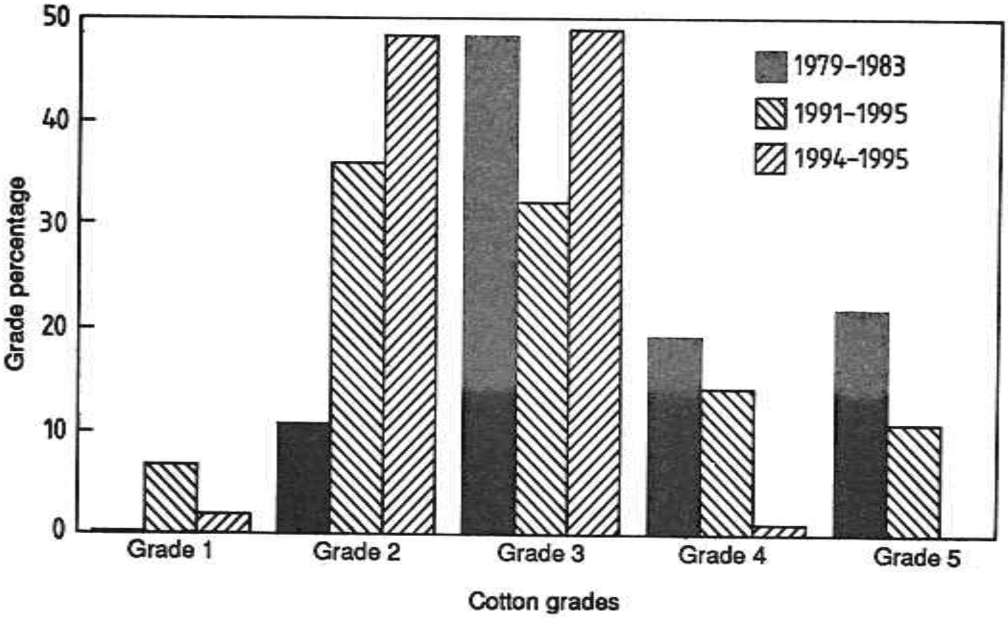

Fig. 3. Cotton grade percentage in Gezira Scheme (Block Om Shadida) during 1979–1995. (Source: Sudan Gezira Board).

concluded that the evaluation with a foreign exchange scenario showed highly comparable profitability of the IPM practice; and that the IPM fields enjoyed better consistency in yields than those of the conventional regime. He added that the reduction in cotton prices or the increase in the cost of pest control would induce a shift in profitability in favour of the IPM practice.

The Indirect Economic Impact

The indirect economic impact of the pesticides through the pollution of the agroecosystem, although difficult to measure in monetary terms, should not be ignored. In the Gezira the poisoning of cattle and goats is very common during the spraying months. Intoxicated canal fish, birds and farm animals are a familiar feature of the spraying season.

Although the magnitude of the effect of pesticides on human health is well known, accurate or even reasonable data on the number of pesticide poisonings and deaths in The Sudan do not exist. The people who are affected by toxic dosages of pesticides do not usually seek medical attention. Many of the symptoms of pesticide poisoning are generally non-specific and could easily be attributed to other causes, most important of which is malaria or the consumption of decayed food.

An important factor which is not always calculated in the economic impact of IPM implementation is the positive impact of the practice on the crops other than the target crop. In The Sudan, most of the important pests of vegetables are the same species which attack cotton and entail chemical treatments (e.g. *Bemisia tabaci, Helicoverpa armigera* and *Jacopiasca lybica*). The decimation of the natural enemies of these pests in the area and the acceleration of the development of resistance to chemicals among the populations of these species will undoubtedly increase the cost of the vegetable production through increased pesticide applications.

During the last two seasons 1992/93 and 1993/94 the reduction of insecticide applications on cotton must have had a positive impact on the promotion of the role of the natural enemies in the cotton-based agroecosystem in the Rahad and Gezira schemes. This impact is evaluated now through comprehensive studies in both schemes. There are at present some indications to this positive impact. The wheat crop which is part of the rotation in both schemes is usually given two sprays per season against aphids. The number of sprays on wheat has dropped from 1.7 in 1992/93 to 0.9 in 1993/94 in the Gezira. In Rahad, the wheat crop has been introduced in the rotation only in 1992/93 season. In both seasons, 1992/93 and 1993/94, wheat in Rahad received no spraying. This coincided with adoption of the IPM package in Rahad.

References

Abdelrahman A. A. (1995) Delaying chemical control for *Helicoverpa armigera* (Hb.) in cotton in Sudan to promote IPM. *Crop Protection* (in press).

Abdelrahman A. A. and Munir B. (1989) Sudanese experience in integrated pest management of cotton. *Insect Sci. Applic.* 10, 787–794.

El-Bashir S., El-Tigani K. B., El-Tayeb Y. M. and Khalifa H. (1978) Crop pest management in the Sudan. *Proc. Symp. Khartoum,* Feb. 1978. Ministry of Agriculture and University of Khartoum, Sudan.

Eveleens K. G. and Abdelrahman A. A. (1980) The cotton whitefly problem: Can the tide be turned? Working paper No. 5; FAO/UNEP African Programme for the Development and Application of Integrated Pest Control in Cotton Growing prepared for the 44th Meeting of the National Pests and Disease Committee, ARC Gezira Research Station, Mimeograph 12 pp.

Eveleens K. G. (1983) Cotton-insect control in the Sudan Gezira: Analysis of a crisis. *Crop Protection* 2, 273–287.

Faki H. (1992) Economic evaluation of integrated pest control in cotton: Gezira and Rahad, 1986/87–1989/90. Consultancy Report; the FAO/ARC IPM Project GCP/SUD/025/NET Wad Medani, Mimeograph, 25 pp.

Munir B., Abdelrahman A. A., Mohammed A. H. and Stam P. A. (1995) Introduction of *Trichogramma pretiosum* Riley against *Helicoverpa (Heliothis) armigera* (Hb.) in the Sudan. *Entomophaga* (in press).

Sippell D. W., Bindra O. S. and Khalifa H. (1987) Resistance to whitefly (*Bemisia tabaci)* in cotton. *Crop Protection* 6, 171–178.

Stam P. A., Abdelrahman A. A. and Munir B. (1994) Comparison of control action thresholds for *Heliothis armigera, Bemisia tabaci* and *Aphis gossypii* on cotton in the Sudan Gezira and Rahad regions. *Crop Protection* 13, 503–512.

Farmers' First Approach in Developing IPM on Vegetable Crops in The Sudan

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Abstract—In developing a new strategy for vegetable IPM in the Sudan, the FAO/ARC IPM Project has drawn on the experience of other FAO IPM projects, particularly in Southeast Asia, and has adopted the IPM Farmer Field School (FFS) approach. In this approach, on-farm research is integrated with extension: farmers are trained in IPM by validating technical options for pest control at farm level. The results of FFS are analysed to provide feed-back to the process of IPM technology development.

First IPM options ('menus', 'tool boxes') for tomato and onion, the major vegetable crops grown in central Sudan were prepared based on regular pest surveys and critical evaluation of presently used production systems of vegetable crops and their effect on pest damage on 140 vegetable farms. Additional IPM options were recommended by six working groups comprising researchers, extensionists and vegetable farmers (tomato, onion, eggplant and okra, cucurbits, legumes and root and tuber crops) during the National Workshop on Integrated Vegetable Crop Management in the Sudan, Wad Medani, 5–7 December 1993.

Survey of current status of farmer's knowledge (KAP), particularly, vegetable production and protection and assessment of the extension services capability to implement a comprehensive IPM extension programme was carried out in 1993/94 by 22 extensionists in three areas by interviewing 330 vegetable farmers. The results of the KAP survey were used to formulate research and extension priorities for the project's activities.

Nineteen FFS were established and vegetable farmers were trained in pest and natural enemy recognition and monitoring, understanding of pest damage–crop loss relationships, and pest control operations including the safe use of pesticides. In addition to FFS, the project organised group training courses on IPM approaches and options for 669 agricultural cadre (extensionists, horticulturalists, plant protectionists); 2786 farmers; 892 rural women and 2125 students in the 1993/94 growing season.

Key Words: vegetable IPM, tomato IPM, onion IPM, Farmer Field Schools (FFS), participatory approach

Introduction

The research project on development of integrated pest control in cotton in the Sudan started in December 1979 and went through three successive phases all financed by the Netherlands Directorate General for International Cooperation and implemented through the Food and Agricultural Organisation of the United Nations (FAO) and the Sudanese Agricultural Research Corporation (ARC). In January 1993 the project entered its IVth Phase with a substantial shift from cotton to vegetables and cereals. The project has also a new title which is "Development and Application of Integrated Pest Management in Vegetables, Wheat and Cotton".

During the first three phases the main thrust was to develop and introduce IPM in cotton, particularly through the use of raised ETLs for the four main insect pests. This approach did not involve major extension activities since pest monitoring, decision making and pest control operations are executed by the Schemes (Gezira and Rahad) and not by farmers. The same can be said for wheat IPM. However, with the shift in the fourth project phase from cotton and wheat to vegetable IPM, the project had to change its approach because in vegetable crops, all pest control operations are carried out by farmers. This means that farmers need to be trained in pest and natural enemy recognition and monitoring, understanding of pest damage–crop loss relationships, and pest control operations including the use of pesticides. Moreover, very few technical options were available for vegetable IPM. This situation has obliged the project to develop a new strategy for IPM development on vegetables.

One of the major problems of implementing IPM strategies in Africa, common with other regions, is the functionally separate structure of research and extension service as had been noted by participants of the Regional Seminar on the Development and Application of Integrated Pest Management on Vegetables in Africa; 23–30 November 1992, Dakar, Senegal (FAO, 1993). The top-down transmission of research results, first to extension staff and then to the farmer, is the norm. Considering the current availability of traditional pest control methodologies at the farmer level, this approach obviously needs to be modified. What is needed is a multidisciplinary mechanism that encompasses full farmers involvement and recognises their role as producers and developers with the farmers participating in the technical evaluation of the IPM procedure used (Schulten 1989; Ikin et al., 1993; Schulten, 1994; Dabrowski et al., 1994).

The Sudan situation is not different than in other countries in the region and Africa. Dr Abdalla Ahmed Abdalla, the present chairman of the Board of Directors of the Agricultural Research Corporation confirmed that there is an urgent need of bringing together as much as possible the agricultural education, agricultural research and extension in the Sudan. He emphasised that there are "certain structural deficits in the agricultural system itself; partly because of lack of strong linkage between agricultural research and extension, because each is in a separate structural area.., and the extension service is in the Ministry of Agriculture but very isolated from agricultural research and education... (Abdalla, 1993).

The FAO/ARC IPM Project in The Sudan had addressed the problem by directing its activities towards on-farm research and farmers involvement in developing and validation of IPM on vegetables. Much emphasis is given to the essential close cooperation between research and extension. Extensionists were involved from the beginning in the project developments, especially on-farm research and participatory training of vegetable farmers; and not only in the end-users phase.

All IPM-related activities are carried out in the active participation, interaction and sharing of available resources with the Sudanese collaborators at the Agricultural Research Corporation (ARC); Gezira and Rahad Schemes, Plant Protection and Extension Departments of the Gezira and Khartoum State and the Khartoum and Gezira University.

Present Production and Plant Protection Practices by Vegetable Farmers

Central Sudan occupies a leading position in vegetables production in the country. There are many problems however, in the production of these crops. Management practices are diverse and the risk of crop failure is high. Input supply and marketing aspects are often mentioned as important constraints. Pests and diseases are major problems of vegetables production (Yassin, 1983; Siddig and Sharaf Eldin, 1990). There is evidence of irrational use of pesticides with the many environmental and health hazards. Improper pest management may be due to lack of adequate information on pesticide use, scarcity of the right types of pesticides and legislative shortcomings in their transactions. Constraints in vegetables production could be alleviated through an integrated pest management approach. Provision of information on the status of vegetables production aids decisions on the nature of research and extension work within this approach.

A survey of current status of farmers' knowledge, attitude and production practices (KAP approach) was carried out in 1993 by 22 extensionists in three important areas of vegetable production in central Sudan: Rahad and Gezira Schemes and along the Blue Nile (Gezira State). This survey data provided information on the following four main aspects:

(a) general characteristics of farmers and production patterns;
(b) farmers' knowledge, attitudes and practices on crop management;
(c) characteristics of pest management practices;
(d) marketing of vegetables and their returns.

It was found that farmers' experience with agriculture and vegetables production was high, particularly along the Nile in central Sudan. Such experience was the major source for crop rotation information, as well as for important management practices. Extension information was, however, more utilised by Rahad and Nile farmers, though confined to certain practices such as weeding, irrigation and crop harvesting. Farmers' initiative to seek extension help was substantial, being more frequent in Rahad and along the Nile, and less often in Gezira. Most farmers reported past visits of extension agents, mainly providing technical information. They were highly receptive to extension advice. Farmers' organisations, especially along the Nile and to a lesser extent in Gezira and Rahad constitute another important source of technical information and other services. Research and extension activities should utilise existing potentialities such as farmers motivations to accept technological changes and encourage support for existing farmer organisations.

Farmers' attitudes towards vegetables production methods were diverse. Traditional methods were believed by about half of the farmers in Gezira, one-third along the Nile and by a small percentage of Rahad farmers. However, almost all farmers believed in intensive daily follow-up of vegetables production practices. Extension will be an important factor to expose farmers to improved technology. Differences in attitudes towards such technology may indicate that farmers in Rahad and along the Nile would be more responsive to technological improvements.

Vegetables in the Gezira were always preceded, and mostly followed, by field crops. In Rahad, the sequence was almost full alternation of vegetable crops. Along the Nile, alternation of vegetables with fallow or legume crops as well as with vegetables was reported. Rotation aspects should be given due attention in both research and extension, particularly in Rahad and Gezira.

Generally, the vegetables production calendar continued almost all the year round. Onion sowing extended from

July to December, with a forward shift in Rahad, while harvesting spreads from November to March. Tomato planting extends from May to December in Gezira and Rahad, and goes up to February along the Nile. Its harvest ranged between August and April in all areas. Cucumber is sown and harvested throughout the year. Pepper and eggplant are planted during June–July in the Gezira and harvested during August–March. In other areas, production of the two crops extends over a longer time in discrete periods. Problems related to off-season production need to be addressed, especially in connection with the high probability of the incidence of pest and disease attack.

Pests and diseases were leading causes of vegetables losses in the three areas. Improper management practices were nevertheless important reasons in all areas, while low-quality seed and input shortages were of some significance, especially in Gezira (Table 1).

Farmers' knowledge of pests and disease types was limited. Aphids, tomato yellow leaf curl virus disease, American bollworm and wilt were the types identifiable by farmers, though at varying degrees. These were the observed pests in the 1993/94 season.

The types of pesticides commonly known were Kafil 10, Sevin, Sumicidin, Rogor and Danitol. Those widely used were, however, Sevin, Rogor and Sumicidin. Kafil 10 and Folimat were more applied in Gezira and along the Nile, while Danitol use was common among both Rahad and Nile producers. More pesticide types were known and used along the Nile. There was considerable consistency between knowledge and actual use of pesticides, but there were some discrepancies, especially in the Nile area. Hazards in pesticides use and limitation in their effectiveness would be expected with the reported limited range of known and used pesticides and farmers limited ability to identify and differentiate among vegetables pests. Extension services need to be intensified for the application of the right type of pesticides to control specific pests in different vegetable crops.

There was high discrepancy between pesticides and information sources on their use, particularly with respect to market purchases. Market sources may lack the necessary specialisation to offer the right type of information. This may again result in hazardous use.

Chemicals were the best means of pest management in the opinion of most farmers in the three areas. Good

Table 1. Perception of farmers of major factors responsibile for vegetables crop losses (% farmers) in three vegetable growing areas in central Sudan

Reasons for crop loss	Gezira		Rahad		Nile	
	(1)	(2)	(1)	(2)	(1)	(2)
Low-quality seeds	9	19	4	4	21	-
Improper management practice	13	48	31	35	10	15
Input shortages	4	22	8	-	12	-
Theft	4	-	2	4	1	-
Pests and diseases	70	11	40	42	29	61
Others	-	-	14	15	27	24

(1) First rank (2) Second rank.

management practices were mentioned by some, but the combination of pesticides and good management practices was highly favoured. Resistant varieties, either alone or in combination with good management and pesticide were advocated by some farmers (Table 2). Integrated pest management, involving biological control and good management practices will constitute an important means to utilise farmers favourable current behaviour with respect to pest management.

Pest management practices were mainly chemical use. Good crop management was important in the Gezira, while Rahad and Nile farmers believed in fertilisers as another means of pest control. The cultivation of tolerant varieties was limited and needs more emphasis in extension (Table 3).

Use of sprayers was rated as the best method of pesticides application. Actual methods used were, however, diverse in the Gezira. Tree branches and brooms, although favoured methods by a negligible portion of farmers, use was considerable (25% for Gezira farmers; and only 3% for Rahad and the Nile bank's farmers). This indicates farmers' low access to improved spraying techniques. For pesticides mixing, a stick was preferred but some farmers did not practice mixing.

With respect to safety measures, most farmers carried out spraying without special clothing but, nevertheless, awareness about using old or other clothes was considerable. Farmers were also keen about soap and clean water availability in the field. However, relatively more Nile farmers took drinks and did not care to be

Table 2. Farmers' opinions on the best methods of pest control (% of farmers) in three vegetable growing areas in central Sudan

Control method	Gezira	Rahad	Nile
1 Resistant varieties	6	5	8
2 Good management practices	10	16	9
3 Biological factors (Farmers' friends)	1	-	-
4 Pesticides	29	40	33
5 Other			6
6 (2)+(4)	28	22	36
7 (1)+(2)+(4)	23	3	3
8 (1)+(2)+(3)	3	14	5

Table 3. Methods used by farmers for effective pest control (% of farmers) in three vegetable growing areas in central Sudan

Control method	Gezira	Rahad	Nile
Pesticides	79	83	94
Good management practices	58	2	2
Fertiliser use	21	58	45
Tolerant varieties	12	8	-
Smoke	3	2	4

accompanied by children. Both attitudes pose hazards in pesticide use. Post-spray precautions such as disposal of empty pesticides containers were satisfactory. Body cleaning was common in Gezira and Rahad, but highly neglected along the Nile. Due to the considerable variability in farmers' use of safety measures during chemical application, detailed identification of such measures needs to be made and conveyed to farmers.

Production costs may be one indicator of the management level. Crops that were expensive to produce were respectively: tomato, onion, pepper and eggplant. Cucumber and okra were relatively cheaper to produce. The overall production costs were similar for Gezira and the Nile area, and significantly lower at Rahad where emphasis was on low-cost crops. Lower yields relative to production costs along the Nile could be attributable to the high water and transport costs.

Farmers' ranking of management practices according to their costs revealed that tomato practices were the most expensive, followed by those of onion. Pepper was the least expensive according to the farmers' judgment while eggplant, cucumber and okra were of more or less similar ranking. Due to high costs of producing certain vegetables, particularly tomato and onion, variability in their yields should be minimised for reduction in risk to farmers. Work on identification and extension of proper management practices are conducive to yield improvement and its stability. This will result in higher and more stable profitability that reduces risks to vegetable growers.

Vegetables contribution to the farmers' total income was about one-third. They, however, constituted the largest portion of income from agriculture. Comparison of production costs and revenues revealed encouraging and comparable profitability in the three areas. Due to the high variability, high profits would be realised by some farmers and losses by others. High profitability of vegetables represents an encouraging factor according to which the high responsiveness of farmers to improvements is expected. On-farm research is a useful tool to improve production practices and to provide important feedback to research and extension.

Formulation of the IPM Strategies

The FAO/ARC IPM Project in The Sudan seeks to consolidate the achievements of the Green Revolution (when the inputs were available and cheap) but to remove its negative consequences by reducing cost of production and helping farmers become better managers. It seeks to incorporate natural processes into farming, and reduce off-farm inputs, leading to a more profitable and efficient production, and to better human and environmental health.

IPM relies on farmers' increased knowledge, active monitoring and analytic decision making with respect to pest management, active use of improved genetic and biological potential of cultivars, and in some areas, to better rotation. Pest control decision making is based on frequent and systematic field monitoring considering pest populations, natural control factors, crop status and climate conditions (Schulten, 1989; Schulten, 1994).

As the field surveys showed, up to 100% of Sudanese vegetable farmers have been using pesticides, some in weekly intervals and the costs of their applications did not surpass 25% of the total production input costs in 1989–1990 (Anon, 1986; Siddig and Sharaf

Eldin, 1990; Faki et al., 1994). The production conditions are, however, changing with the introduction of free market economy in the Sudan and the World Bank policy of withdrawing assistance for subsidising the pesticide purchases. The necessary inputs are imported which means spending more scarce foreign currency and much higher prices for imported pesticides for farmers. Trapped between the farmers' financial limitations and the presently available information provided mainly by the agrochemical industry, the extension services are unable to bring any real changes to this situation based on present recommendations for vegetable pests' control.

The large number of vegetable species being attacked by various pests and diseases in the Sudan requires a broad range of treatments in an integrated approach; including a combination of hygienic measures (crop rotation; field sanitation); the choice of resistant varieties; curative chemical treatments and biological control.

Two-year regular field surveys of approximately 140 vegetable farms in central Sudan confirmed previously published reports that the onion thrips, *Thrips tabaci* Lind, is the major pest on onion in the entire country where onion is grown. The cotton whitefly, *Bemisia tabaci* (Genn.) is a major pest, mainly as the vector of tomato yellow leaf curl virus (TYLCV) on tomato. TYLCV can reduce yield up to 75% or more, especially during the summer growing season (Yassin, 1983). The American bollworm, *Helicoverpa (Heliothis) armigera* (Hb.) is the second insect pest on tomato, damaging also cotton, okra, sorghum, beans and other crops. Seedling stages of tomato crop are often attacked by the leafminer, *Liriomyza trifolii* (Burgess) and the two-spotted cricket, *Gryllus bimaculatus* Deg. (a polyphagous pest).

Powdery mildew, caused by *Levillula taurica* (Tev.) is the second most important disease, and has become the most common and destructive fungal disease on the winter tomato crop (Ahmed E. Nafisa, in press).

The main pest of eggplant is the cotton jassid, *Jacobiasca (Empoasca) lybica* (De Berg) causing yellowing and drying up of the leaves. Two other species are commonly observed in specialised vegetable growing areas: the stemborer *Enzophera asseatella* Treit, which causes decline and death of plants; the bud borer worm, *Scropipalpa heliopa* Low attacking flower buds and reducing the yield, and the fruit borer worm, *Sceliodes laisalis* Wck., damaging fruits. The cotton aphid, *Aphis gossypii* (Glover) is a major pest of okra and also occurs all over the country on cotton, eggplant, tomato, cowpea, etc.

Potato tuber moth, *Phthorimaea operculella* (Zeller) is a major pest of potato causing considerable damage to tubers, reaching 60% (Siddig, 1982).

Although the main vegetable pests have been identified in the Sudan, and some research results were available on resistant tomato and onion varieties as well as on natural enemies and effectiveness of pesticides, rational pest management was hardly practised by Sudanese vegetable growers.

The FAO/ARC IPM Project initiated a national activity on developing and implementing the vegetable IPM programme by organising a workshop on Integrated Vegetable Crop Management in the Sudan: Present Status and Future Alternatives, 5–7 December 1993 in cooperation with the Agricultural Research Corporation, Gezira. The workshop objectives were as follows:

(i) promotion of sound agricultural and integrated pest management

practices in vegetable crops in The Sudan;
(ii) reviewing of findings of horticultural and crop protection researchers and practitioners; and
(iii) formulation of IPM recommendations for the horticulture extension services in The Sudan.

H. E. Prof. Ahmed Ali Geneif, the Minister for Agriculture, Natural Resources and Animal Wealth gave his strong support for IPM as the governmental policy; farmers involvement and 'empowerment' of farmers. Between 250–300 participants attended the three-day conference comprising one day on general introductory papers on integrated vegetable production and protection in the tropics (some papers concentrated exclusively on The Sudan); during the second day five working groups identified for the first time what is known on IPM on vegetables (emphasising the effect of proper cultural practices) in The Sudan and during the third day farmers gave their views on the actual needs.

Debates on the scope and understanding of an IPM programme on vegetables in The Sudan resulted in the following conclusions:

- The overall objective should be to establish sustainable, cost-effective vegetable production and protection technologies which are within the reach of the farmers and do not harm pesticide users, consumers and the environment;
- The immediate goal should be to help farmers in raising their yields without misuse or over-use of pesticides but by developing integrated crop production and pest management options aiming at non-chemical pest and disease control.

Further improvements of the IPM strategies suitable for Sudanese vegetable farmers were based on the results of on-farm and participatory research conducted by the IPM Project staff and more than 20 counterparts in four areas: Gezira, Rahad, Kanana and Khartoum in the 1993 and 1994 growing seasons (Tables 4 and 5).

Table 4. IPM options for tomato+

General:

1. Avoid overlapping between seasons.
2. Sanitation measures.
   - removal of crop residues, disposal of volunteer plants, burning chaff stack is useful to control, e.g. American bollworm;
   - do not grow seedlings near the previous season's crop;
   - do not grow tomatoes close to okra (the vital host of tomato yellow leaf curl virus) (TYLCV).
3. Rotation.
4. Khareef season cultivation shows lower TYLCV incidence.
5. Old tomato crops should be destroyed soon after harvesting.

Specific:

1. Seed dressing with systemic fungicide triadimenol to reduce number of regular spraying with foliar fungicides against the powdery mildew infections (especially important for the winter growing season).
2. Planting high yielding and tolerant tomato varieties to TYLCV as Peto 86 (Peto-seed or Sluis & Groot); Strain B of known origin (e.g. California Seed Co. and Pop Vriend); Sinnar 1 and Sinnar 2 (recently registered by the ARC); Fiona F1 (TYLCV) (Sluis & Groot). New heat

Contd.

Table 4. Contd.

and TYLCV tolerant advanced lines are under final on-farm testing by breeders from the Gezira University.

3. Production of 3–4 week-old seedlings under low insect-proof netting restricting the vector, *Bemisia tabaci* infestation.
4. Sowing/transplanting in well-prepared soil, followed by proper cultural practices and regular irrigation.
   Optimal watering intervals and nitrogen fertilisation to minimise the blossom end rot of fruits (an excess of nitrogen rate and long watering intervals are highly conducive to the disease).
5. Intercropping with following plants:
   - winter crop: fenugreek, coriander, as non-hosts for *Bemisia* and TYLCV;
   - summer crop: lubia bean; pigeon pea as *Bemisia* trap crops, non-hosts to TYLCV and hot and dry windbreaks.
6. Removal of weeds, potential alternative hosts of TYLCV:

Acalypha indica	*Datura stramonium*
Hibiscus ficulneus	*Solanum dubium*

7. Regular chemical control against the vector, *Bemisia tabaci*, during early seedling stages on seed-beds with pyrethroids at recommended doses.
8. Mixing mineral/organic oils with low doses of insecticides or using single oils (see also Sharaf and Allawi, 1981; Butler et al., 1988). Natural oils are toxic to both eggs and larvae, and repellent to adults for 7 days.
9. Insecticide treatment against the whitefly should be stopped at the fruit setting (later TYLCV infections have little effect on tomato yield).

[+] The recommendations have been developed based on deliberations of the National Workshop on Integrated Vegetable Crop Management, 5–7 December 1993, Wad Medani and unpublished results of on-farm and participatory research supported by the FAO/ARC IPM Project in the Sudan.

Table 5. IPM options for onion

1. Proper preparation of seedbed.
2. Pre-watering before sowing and transplanting; regular irrigation in 7–10-day intervals.
3. Early sowing in July, transplanting in September so that the crop is well established before thrips develop. Thrips infestation increases between January and March. Seedlings transplanted in December and January are still small when the thrips infestation develops rapidly soon after transplanting.
4. Transplanting into rows (in light basin soils, 20 cm between rows and 10 cm in the row or in heavy soils—60 cm between ridges and 5–10 cm between plants) improves hand weeding.
5. Optimal dose of fertilisers and regular weeding.
6. Regular irrigation in 7–10-day intervals after transplanting significantly reduces thrips population.
7. Chemical treatment only at 20 thrips/plant as the economic threshold level.
8. Elimination of regular preventive (prophylactic) spraying by training of farmers in recognition of the onion thrips and their damage level on plants.
9. Restriction of using Lannate (class 1 toxicity) insecticide in favour of other less toxic insecticides as malathion and Cidial (phenthoate) recommended by the Pests and Diseases Committee.

IPM Farmer Field School Approach

To start a successful IPM movement, farmers must feel a need for IPM—or minimally—a need for some sort of change or improvement. It is also imperative that research scientists and extension agents can provide at least some appropriate and reliable IPM information (concepts) and techniques and are willing to work with farmers in their fields to develop and adapt technologies (Schulten, 1994).

Table 6. Number of cadres, farmers, rural women and students trained in integrated pest management in the Sudan (1989–1993)

Year	Cadre	Rural women	Students	Farmers general IPM training	Farmer field schools
1989	201	-	-	240	-
1990	561	-	120	464	-
1991	1284	871	319	1863	-
1992	2574	1994	6109	5148	-
1993	3583	2836	8667	8700	178

This new participatory approach in research and training has been included and emphasised in group training courses organised for extensionists and plant protection and horticulture officers by the IPM project in The Sudan.

The number of cadres (extensionists, horticulturists, entomologists, plant protectionists); farmers; rural women; students; and IPM Project technicians trained in integrated pest management during in-service courses are shown in Table 6. A large number of extension and training materials has been released by the project (Table 7).

The training focused on the following topics:

- The effect of cultural practices on vegetables pests control;
- Identification of main vegetable pests and their natural enemies;
- Operation and maintenance of knapsack sprayers and safe use of pesticides, safety measures, safety (withholding) periods for pesticides, and first aid;
- The importance of interaction between researchers, farmers, extensionists and specialists in participatory research and training;
- Orientation of the general public on the IPM objectives, practices and elements;
- The importance of producing healthy agricultural products.

The group training courses facilitated undertaking the next step by the IPM project staff with close cooperation from counterparts of the national agriculture system—initiation of IPM Farmer Field Schools in central Sudan.

The IPM project has adopted the Farmer Field School (FFS) approach first developed by the other FAO IPM projects, particularly in Southeast Asia (Schulten, 1989; Kenmore, 1991; van de Fliert, 1993). In this approach, on-farm research is integrated with extension: farmers are trained in IPM by validating technical options for pest control at farm level. The results of FFS

Table 7. Extension materials published by the FAO/ARC IPM Project

Title	Author	Language	No. of Pages	Year
Integrated Pest Management	Asim A. A. Rahman and A. Alsaffar	Arabic	13	1991
Pest Insects on Cotton	IPM Project	Arabic/ English	Poster	1991
Natural Enemies of Cotton Pest	IPM Project	Arabic/ English	Poster	1991
"Farmers' Friends" (Natural Enemies)	IPM Project	Arabic/ English	Poster	1991
IPM Lecture Notes for Agricultural Cadres	IPM Project	Arabic	188	1992
IPM Lecture Notes for Entomologists in the Sudan	IPM Project	English	132	1992
Guide for Vegetable Production in Gezira	Mirghani Khogali	Arabic	59	1992
How to Use Pesticides	IPM Project	Arabic	Poster	1992
Guide on Training Organization and Management	A. Alsaffar; M. Izzeldin	Arabic	18	1992
Effect of Improved Cultural Practices on Vegetable Pest Control	A. Alsaffar; S. M. Saad and M. Izzeldin	Arabic	12	1993
Basic Cultural Practices for Main Vegetable Crops (Tomato, Onion, Okra and Eggplant)	Mirghani Khogali	Arabic	22	1993
IPM Development in the Sudan	A. A. A. Rahman and A. Alsaffar	Arabic	6	1993
Operation and Maintenance of Knapsack Sprayers	M. Izzeldin Mahgoub	Arabic	12	1994
"Farmer's Friend" (Natural Enemies)	B. Munir	Arabic	34	1994
Vegetable Insects (pamphlet for farmers	Dieya Eldin Alagwah	Arabic	38	1994
Safe Use of Pesticides	F. Alagabani and A. Alsaffar	Arabic	6	1994

are analysed to provide feedback to the process of IPM technology development. Key principles of the IPM Farmer Field Schools include:

(a) practising proper cultural practices to grow a healthy crop, resistant to local diseases and able to compensate for pest damage;
(b) a good knowledge of pests and their natural enemies, not in terms of their Latin names, but in terms of function, what they do to plants and to each other at what stage of the crop. Such knowledge also includes the developmental stages of a pest and their recognition. This knowledge is expected to be updated and improved by farmers' own observation and experimentation, and by farmer - to - farmer exchange of experience;
(c) regular and systematic observation in the field, using systematic procedures (random selection of sampling) to assess the occurrence of pests and natural enemies in relation to the crop's development stage;
(d) sound decision making and discussion with other farmers about such decisions. The process of decision making is more important than the decision itself;
(e) experimentation with planting times, varieties, soil cultivation practices, fertilisation, rotations and biological control for their effect on pest populations;
(f) use of relevant, science-based knowledge, such as cultivar tolerance and regenerative capacity after pest damage, or in parasites in pest eggs or larvae (Kenmore, 1991; van de Fliert, 1993).

Farmers' Field Schools as a new method in the IPM participatory training were established for the first time in The Sudan in 19 villages of the Gezira and Rahad Schemes and the Gezira, Sennar and Khartoum States in 1993 and 1994. The school activities included weekly meetings in the field throughout the whole growing season with a group of 10–20 farmers (the groups increased late in the season to 25–35 farmers who learned about the field meetings) and concentrated on optimal cultural practices, identification and biology of main vegetable pests and their natural enemies ('farmer's friends') and on proper selection of pesticides and their safe application.

The following indicators could prove that the farmers training has been successful in 1993/94 season:

- The high attendance of farmers indicating a sound training methodology, qualifications of the training staff, materials used and realistic programme;
- The great willingness and readiness of the farmers to learn and improve their knowledge and skills in using sprayers and safety measures.
- Repeated requests to continue the FFS activities with the project staff.

The direct effect of the farmers' increased knowledge gained in the Farmers' Field Schools was measured by a significant yield increase of onion and tomato crops managed by participating farmers; e.g. the implementation of crop rotation for controlling the pinky rot disease in onion increased the yield threefold.

Discussion

The above activities of the FAO/ARC IPM Project in the Sudan show that the recommendations of the Regional Seminar on the Development and Application of Integrated Pest Management on Vegetables in Africa (23–30 November 1992, Dakar, Senegal) had been implemented as the Project's priorities as follows:

- (i) formulating strategies for IPM based on available information and implementing IPM on vegetables grown by farmers;
- (ii) organising locality-specific workshops on IPM with emphasis on joint activities involving researchers, farmers, extensionists and policy makers;
- (iii) involving policy makers and technical development agencies in workshops, field demonstrations and pilot programmes to convince them that IPM is an essential component in the development of sustainable agriculture;
- (iv) providing training in IPM development and implementation based on interactions between farmers, extensionists, researchers and those from other disciplines;
- (v) preparing extension materials for identified beneficiary groups with due attention paid to pretesting and local dialects (FAO, 1993).

The seminar members noted, however, that there is no universally applicable strategy of vegetable IPM available for Africa because of the widely differing agrogeographic zones and socioeconomic conditions (FAO 1993).

Development of IPM for vegetables is a complex undertaking, because it is a heterogenous group of crops which are produced on small acreage by individual small farmers, not frequently reached by the extension service.

IPM is not a technology and is therefore, not something that can be transferred using conventional approaches. Instead, it is a process—ideally catalysed and supported by extensionists (plant protection services) and researchers—that engages farmers in experiential learning and dynamic local research that continuously reshapes solutions to their problems of the moment. These problems, as perceived and defined by farmers within their local ecological context, knit farmers, extension agents (plant protectionists) and research workers into IPM implementing groups. This approach automatically leads to a new perception of research and extension. Research can no longer be seen as an outsider's activity which attempts to optimise the value of externally defined inputs and externally verified knowledge. Similarly, extension moves away from traditional models, for example those embedded in diffusion theory, and moves towards the robust principle of putting "farmers first" (Chambers et al., 1989). When the fundamental role of farmers as the owners and implementors of IPM is recognised, it focuses efforts of research, extension and other external activities in a way that leads to successful IPM implementation.

A fundamental message is that IPM is implemented by farmers. Researchers and extension agents provide essential support to the IPM enterprise, usually through training or development projects. Successful IPM programmes evolve through a continuous and dynamic interaction of farmer–trainer initiative and researcher response. Farmers are especially successful innovators when extension agents and scientists are committed to simultaneously affirming local knowledge and adding to that knowledge (Chambers, 1992).

References

Abdalla Ahmed Abdalla (1993) Sudan's farmers achieve grain surplus/send food relief abroad. *Sudan-Now,* 18,14–17.

Anonymous (1986) Master Plan for Fruits and Vegetables in the Sudan. Republic of the Sudan, Ministry of

Agriculture and Natural Resources Khartoum, Sudan and Deutsche Gesellschaff fur Technische Zusammenarbeit (GTZ).

Butler G. D., Coudriet D. L. and Henneberry T. J. (1988) Toxicity and repellency of soy-bean and cotton seed oils to the sweet potato whitefly and the cotton aphid in green-house studies. *The South Western Entomologist* 13, 81–86.

Chambers R. (1992) Scientist or resource-poor farmer—Whose knowledge counts? In *Proceedings of a Seminar on Crop Protection for Resource-Poor Farmers* (Edited by R. W. Gibson and A. Sweetmore). Technical Centre for Agricultural and Rural Co-operation and Natural Resources Institute.

Chambers R., Pacey A. and Thripp L. A. (1989) *Farmer First. Farmer Innovation and Agricultural Research.* Intermediate Technology Publications, London.

Faki Hamid, Ahmed T. Abdelmoneim and Alsaffar Ahmed (1994) KAP Survey on Vegetables Production in Gezira and Rahad Schemes and Private Farmers along the Blue Nile. Consultancv Report. Integrated Pest Management Project (IPM); GCP/SUD/025/NET. Mimeograph, 40 pp.

Fliert E. van de (1993) Integrated pest management: Farmer field schools generate sustainable practices. A case study in Central Jawa evaluating IPM training. PhD thesis. Agricultural University Wageningen, the Netherlands, 304 pp.

Food and Agriculture Organisation (FAO) (1993) Report. Regional Seminar on the Development and Application of Integrated Pest Management on Vegetables in Africa, Dakar, Senegal, 23–30 November 1992. FAO Regional Office for Africa, Accra, Ghana, 79 pp.

Ikin R., Schulten G. G. M. and de Borhegyi (1993) Development and application of IPM on vegetables in Africa: Highlights of a regional seminar. *FAO Plant Protection Bulletin* 41(3–4), 155–160.

Kenmore P. E. (1991) Indonesia's integrated pest management—A model for Asia. A lecture presented during the workshop: Rice Farmers' Environment, Conservation, Production, Profits, 1991. Mimeograph, 56 pp.

Sharaf N. S. and Allawi T. F. (1981) Control of *Bemisia tabaci* Genn., a vector of tomato yellow leaf and virus disease in Jordan. *Zeitschrift fur Planzenkrankheite and Planzenschutz* 88, 123–131.

Schulten G. G. M. (1989) The role of FAO in IPM in Africa. *Insect Sci. Applic.* 10, 795–807.

Schulten G. G. M. (1994) The need for integrated pest management in vegetables and its implementation, pp. 20–23. In *Integrated Vegetable Crop Management in the Sudan* (Edited by Z. T. Dabrowski). The FAO/ARC IPM Project, Wad Medani, Sudan.

Siddig Ahmed Siddig (1982) Evaluation of some cultural practices for the control of cutworms and potato tuber moth damage. Annual Report. Entomology Section, Shambat Research Station.

Siddig Ahmed Siddig and Nasr Eldin Sharaf Eldin (1990) Consultancy on Vegetable Production, Present Insect Pest Status and their Control, Integrated Pest Management in Cotton and Rotational Food Crops; GCP/SUD/025/NET; Agricultural Research Corporation, Wad Medani. Mimeograph, 96 pp.

Yassin A. M. (1983) A review of factors influencing control strategies against tomato leaf curl virus disease in the Sudan. *Trop. Pest Manage.* 29, 253–256.

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