WORKSHOP

RESEARCH PRIORITIES FOR MIGRANT PESTS IN SOUTHERN AFRICA

Natural Resources Institute

ARC • LNR

DFID Department for International Development

CPP Crop Protection Programme

Natural Resources Institute (NRI)
University of Greenwich, UK

Agricultural Research Council (ARC)
Plant Protection Research Institute
(PPRI) South Africa

Department for International Development

Crop Protection Programme

Workshop on Research Priorities for Migrant Pests of Agriculture in Southern Africa

Plant Protection Research Institute, Pretoria, South Africa
24–26 March 1999

Edited by
R.A. Cheke, L.J. Rosenberg and M.E. Kieser

Natural Resources Institute (NRI)
University of Greenwich, UK

Agricultural Research Council (ARC)
Plant Protection Research Institute
(PPRI) South Africa

Department for International Development

Crop Protection Programme

The Natural Resources Institute (NRI) of the University of Greenwich is an internationally recognized centre of expertise in research and consultancy in the environment and natural resources sector. The Institute carries out research and development and training to promote efficient management and use of renewable natural resources in support of sustainable livelihoods.

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Participants at the Workshop on Research Priorities for Migrant Pests of Agriculture in Southern Africa, Pretoria, 24–26 March 1999

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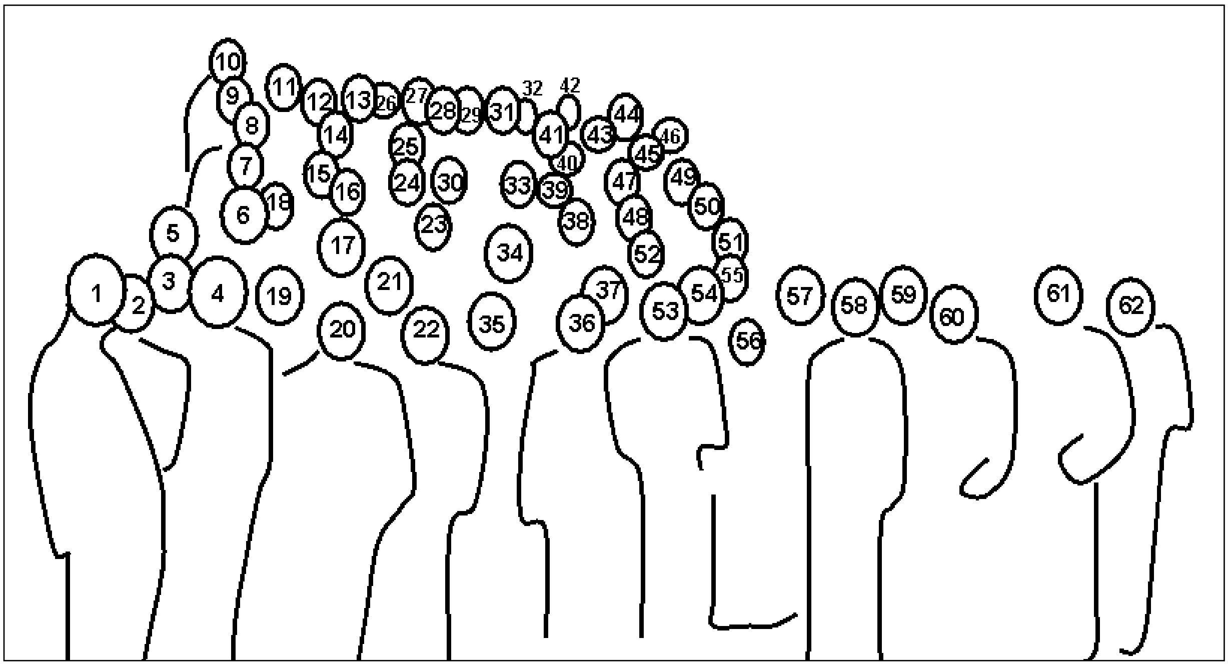

Number	Name	Country	Number	Name	Country
1	Clive Elliott	FAO	**32**	Johan Möhr	South Africa
2	Roger Price	South Africa	**33**	Thys Botha	South Africa
3	Gert Greyvenstein	South Africa	**34**	Rob Toms	South Africa
4	Jaco Willemse	South Africa	**35**	Bob Cheke	UK
5	Colin Bourke	South Africa	**36**	Afete Gadabu	IRLCO-CSA
6	Peter Mundy	Zimbabwe	**37**	Harriett Thindwa	Malawi
7	Shirley Hanrahan	South Africa	**38**	Morrison Mbuli	Swaziland
8	Dave Keetch	South Africa	**39**	Helen Altshul	UK
9	Dieter Oschadleus	South Africa	**40**	Tom Mabesa	South Africa
10	Les Underhill	South Africa	**41**	Johan Olivier	South Africa
11	Mark Anderson	South Africa	**42**	Nic Basson	South Africa
12	Terry Newby	South Africa	**43**	Aldo Berruti	South Africa
13	Peter Jones	UK	**44**	Henk Bouwman	South Africa
14	John Tladi	South Africa	**45**	Robin Jones	South Africa
15	Mariana van Jaarsveld	South Africa	**46**	Gustav Engelbrecht	South Africa
16	Craig Whittington-Jones	Southa Africa	**47**	Richard Allan	UK
17	Stephan Badenhorst	South Africa	**48**	Sergei Mutahiwa	Tanzania
18	Jannette Mitchell	South Africa	**49**	Geoffrey Kirenga	Tanzania
19	Luka Geertsema	South Africa	**50**	George Rhodes	Namibia
20	Thadeo Tarimo	Tanzania	**51**	Barbara Adolf	Namibia
21	Louis van Dyk	South Africa	**52**	Elizabeth Müller	South Africa
22	John Katheru	IRLCO-CSA	**53**	Simon Sithole	Zimbabwe
23	Etienne van der Walt	South Africa	**54**	Margaret Kieser	South Africa
24	John Holt	UK	**55**	Rebecca Kolare	Botswana
25	Anneke Thackrah	South Africa	**56**	Jane Rosenberg	UK
26	Jon Venn	UK	**57**	Dick Brown	South Africa
27	Mike Jarvis	South Africa	**58**	John Bahana	IRLCO-CSA
28	Lean van der Westhuizen	South Africa	**59**	Matt Thomas	UK
29	Keith Jones	UK	**60**	Kenneth Sibolile	Namibia
30	Albertine Tjitombo	Namibia	**61**	John Terry	UK
31	Wilfred Mushobozi	Tanzania	**62**	Simon Eden-Green	UK

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FOREWORD

In some years migrant pests cause extensive, occasionally devastating, damage to the crops of subsistence farmers in sub-Saharan Africa, Asia and elsewhere but in other years their impacts are minimal. In southern Africa, Red Locusts, Brown Locusts, the African Armyworm and quelea birds are the most significant of these pests which move extensively, cross boundaries and often seem to appear 'out of nowhere'. However, research has shown that many of the outbreaks and directions of movements are related to prevailing climatic conditions, providing hope that forecasting methods can be devised to help plant protection departments and farmers to prepare for the pest onslaughts.

Whether the outbreaks can be predicted or not, they need to be controlled with as little environmental damage as possible. So better forecasting and improved control methods are urgently needed. The Workshop described in these proceedings sought to bring together many of those concerned with management of migrant pests in southern Africa, in order to develop and review priorities for research to ameliorate these problems. It was convened primarily to prioritise support for research under the Crop Protection Programme (CPP) of the UK Department for International Development (DFID), working in collaboration with other donors and the affected countries themselves. It also sought to foster regional strategies against migrant pests, in response to the unique challenge that control is often most needed in areas remote from those where the pests are likely to have greatest impact, and hence to generate greatest demand. Within this framework of regional co-operation, priorities for research are to develop technologies likely to achieve greatest impact on improving the livelihoods of the poorest and most disadvantaged sections of communities in southern Africa.

The Workshop on Research Priorities for Migrant Pests of Agriculture in Southern Africa, took place at the Plant Protection Research Institute (PPRI), Pretoria, South Africa, during 24–26 March 1999. It was hosted by the PPRI, jointly organised by them and the Natural Resources Institute (NRI), and sponsored by Natural Resources International Ltd (NRIL) who manage the CPP under the DFID's strategy for research on renewable natural resources. We looked to the workshop to provide ideas and concrete, realisable, plans for future work on migrant pests to help the CPP to achieve its objectives of minimising the impact of migrant pests on crop production through improved pest control strategies for locusts, grasshoppers, armyworm, and quelea.

I thank the Director and staff of PPRI for providing a very welcoming atmosphere for our deliberations and for making the workshop a great success. In particular, special thanks are due to Margaret Kieser for bearing the brunt of the organisation, for her indefatigable efforts to ensure the smooth running of the workshop at PPRI, and for continuing with editorial burdens afterwards. I would also like to thank Claire Troy for her help in assisting the NRI organisers, the editors, Bob Cheke and Jane Rosenberg and those who refereed the manuscripts, without whom production of these diligently edited proceedings would not have been possible.

Dr Simon Eden-Green
Manager, DFID Crop Protection Programme
Natural Resources International Ltd
Chatham, Kent, UK

Editors' Preface

AIMS OF THE WORKSHOP

Migrant pests such as locusts, quelea birds and armyworm are major threats to agriculture in southern Africa, causing considerable losses when large numbers descend and feed on farmers' crops and pasture. They pose a particular control problem because of their ability to destroy or severely damage crops in one locality and then fly hundreds of kilometres to repeat the damage elsewhere. These pests are no respecters of district, provincial or national boundaries, and plant protection teams rely heavily on co-ordinated monitoring, forecasting and control strategies.

Work is being carried out in southern Africa and elsewhere to help reduce both crop losses and control costs by improving forecasting and promoting the use of efficient and environmentally safer control methods.

The Agricultural Research Council-Plant Protection Research Institute[1], South Africa, and the Natural Resources Institute, University of Greenwich[2], UK, organised a Workshop to identify and prioritise issues related to migrant pests of agriculture in southern Africa. The aim of the Workshop was to bring together scientists, research managers and crop protection specialists to clarify the main lines along which strategies could be developed and promoted to improve forecasting and reduce the impact of migrant pests for the benefit of resource-poor people. The Workshop paid particular attention to:

- summarising the current state of knowledge regarding the principal migrant pests affecting the region (armyworm, locusts and quelea)
- identifying the priorities for future migrant pest research
- identifying linkages and partnerships to address the research priorities and implementation
- assessing the pathways by which research outputs can be implemented to help resource-poor farmers improve their livelihoods.

The Workshop was sponsored by the UK Government's Department for International Development[3] Crop Protection Programme, the largest of 12 centrally funded programmes which support research in farming, fisheries and forestry, particularly in Asia and sub-Saharan Africa.

SUMMARY OF WORKSHOP PROCEDURES

The Workshop was held at the Agricultural Research Council – Plant Protection Research Institute, Pretoria, from 24 to 26 March 1999 and was attended by 66 delegates from

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[1]The **Plant Protection Research Institute** of the ARC was established in 1962 and has developed into a leading research organisation with a strong complement of scientists and technical support teams. The Institute concentrates on excellence in the component disciplines of integrated pest management and provides expert support services on national, regional and international levels to agricultural and environmental concerns. The Institute is also mandated to address certain pests of national importance such as locusts, quelea and termites.

[2]The **Natural Resources Institute** of the University of Greenwich is an internationally recognized centre of expertise in research and consultancy in the environment and natural resources sector. The Institute carries out research and development and training to promote efficient management and use of renewable natural resources in support of sustainable livelihoods.

[3]The **Department for International Development** (DFID) is the UK government department responsible for promoting development and the reduction of poverty. DFID seeks to work in partnership with multilateral institutions, governments, business, civil society and the research community to encourage progress which will help alleviate poverty, especially in the developing countries in Asia and sub-Saharan Africa.

Botswana, Malawi, Namibia, South Africa, Sudan, Swaziland, Tanzania, United Kingdom, Zimbabwe, the International Red Locust Control Organisation for Central and Southern Africa (IRLCO-CSA) and the Food and Agriculture Organization of the United Nations (FAO) (see pages xiii–xvi for list of delegates).

The first day focused on presenting a synopsis of current research on the three main migrant pests in southern Africa – armyworm, locusts and quelea – and described the national, regional (IRLCO-CSA, Southern African Development Community, SADC) and international (FAO) infrastructures for dealing with them. On the second and third days, after consideration of the issues to be addressed to ensure uptake of research findings by resource-poor farmers, the Workshop divided into three groups according to pest species. Each group adopted a generalised Logical Framework approach to identifying research priorities, constraints, risks and linkages.

Four Logical Frameworks, covering armyworm, locust, quelea and cross-cutting research priorities were developed and an informal *ad hoc* steering committee (names annotated in list, pages xiii–xvi) undertook to bring together the Workshop's findings in a Summary Report and to make recommendations on further actions.

ADDRESSING THE NEEDS OF BENEFICIARIES AND THE POVERTY FOCUS

Donors increasingly emphasise that research must be focused on improving the livelihoods of poor people, and the use of participatory approaches in identifying and prioritising research requirements is particularly encouraged. A number of factors have to be addressed to ensure that the research is relevant to the needs of resource-poor farmers, and that research outputs are successfully used by institutions that will deliver benefits to these farmers or their communities (global, national, village, household scales).

Issues to be considered for strategic and applied research from micro- to macro-scales

Synchronisation of efforts (e.g. sovereignty – who has the authority to impose the control strategy?, concerted actions between countries)
Economics (e.g. who pays for the control?, off-site effects)
Research extension linkages (e.g. role of farmers' groups, extension services, dissemination and linkages)
Appropriateness (e.g. perceptions of the problem and the solutions used)
Data sources (e.g. farmers' roles as providers of data)
Participatory monitoring and evaluation (e.g. involvement implies ownership, particularly at farmers' group level)
Awareness (methods of educating farmers, e.g. taking them to see pest damage on other farms)
Feedback (from farmers to the extension service and along the line of responsibilities)
Accountability (e.g. consideration of pesticide safety).

Migrant Pest Workshop website – http://www.arc.agric.za/lnr/main/migrant/main.htm

Workshop on Research Priorities for Migrant Pests of Agriculture in Southern Africa, Plant Protection Research Institute, Pretoria, South Africa, 24–26 March 1999. R. A. Cheke, L. J. Rosenberg and M. E. Kieser (eds) (2000) Natural Resources Institute, Chatham, UK.

WELCOME AND OFFICIAL OPENING ADDRESS

M. C. Walters

Director, Agricultural Research Council-Plant Protection Research Institute (ARC-PPRI), Private Bag X134, Pretoria 0001, South Africa
(email: nipbnw@plant2.agric.za)

The ARC-Plant Protection Research Institute is an organisation that has long-standing links with the problems of migrant pests such as locusts, quelea and armyworm. Those links go back to the establishment of the Division of Entomology in the newly formed Department of Agriculture in 1910.

For many years the Division of Entomology, and its successor PPRI, housed both the research and the control functions with regard to locusts. After these two functions were separated in the early 1970s, liaison and co-operation were maintained between PPRI and the Directorate: Agricultural Resource Conservation (now the Directorate Land and Resource Management) – the latter being responsible for the control of declared national pests.

It is my privilege to welcome you to our facility. We thank the Natural Resources Institute (NRI) for initiating this Workshop and arranging the sponsorship by the Department for International Development (DFID).

An important aim of the ARC is to build links to other African countries, and together with international institutions such as NRI and DFID, to deploy relevant capacity and technology in the interest of agricultural and economic development. Networking with African and international role players is essential to move the continent to a future of self-sufficiency and prosperity. The ARC is already linked to various such networks, for example, SAFRINET, the South African part of BioNET-International, and the African Water Hyacinth Initiative.

The need for networks is emphasised by:

- a decline in the ability to refine and transfer methods and knowledge as technology
- erratic population dynamics
- declining interest by governments in programmes
- dwindling scientific budgets.

The need for expertise is illustrated by:

- the recent migratory locust plague in Madagascar
- persistent outbreaks of locusts and grasshoppers in countries of the former Soviet Union (CIS)

- more than 50% forage loss in the western USA to grasshoppers
- build-up of desert locusts in North Africa – emphasising the importance of the creation of alternative networks between African countries and international role players.

The recommendations from this Workshop will be followed with interest.

DELEGATES
(* = Steering Committee Members)

BOTSWANA

KOLARE, Mrs Rebecca – Pest Management Section, Plant Protection Division, P/Bag 003, **Gaborone**

FAO

*ELLIOTT, Dr Clive – Plant Protection Service AGPP, FAO, Via delle Terme di Caracalla 00100, **Rome**
email: clive.elliott@fao.org

MALAWI

THINDWA, Dr Harriet – Ministry of Agriculture, Bvumbwe Research Station, PO Box 5748, **Limbe**

NAMIBIA

ADOLPH, Dr Barbara – NRI Social Sciences Department, Kavango Farming Systems Research and Extension Project, c/o DEES, P/Bag 2096, **Rundu**
email: badolph@tsu.namib.com

RHODES, Mr George – Ministry of Agriculture, Water and Rural Development, Agricultural Extension Department, P/Bag 13184, **Windhoek**

SIBOLILE, Mr Kenneth – Ministry of Agriculture, Water and Rural Development, Agricultural Extension Department, Subdivision Agriculture and Law, P/Bag 13184, **Windhoek**

TJITOMBO, Mrs Albertine – Ministry of Agriculture, Water and Rural Development, Agricultural Extension Department, P/Bag 13184, **Windhoek**

SOUTH AFRICA

ANDERSON, Mr Mark – Northern Cape Nature Conservation Service, P/Bag X6102, **Kimberley** 8300

BADENHORST, Mr Stephan – National Department of Agriculture, P/Bag X120, **Pretoria** 0001

BASSON, Mr Nic – ARC-Plant Protection Research Institute, P/Bag X134, **Pretoria** 0001
email: rietcvv@plant2.agric.za

BERRUTI, Dr Aldo – Birdlife South Africa, PO Box 515, **Randburg** 2125
email: blsa05@iafrica.com

*BOTHA, Mr Thys – National Department of Agriculture, P/Bag X120, **Pretoria** 0001
email: T_C@yebo.co.za

BOUWMAN, Dr Henk – ARC-Plant Protection Research Institute, P/Bag X134, **Pretoria** 0001
email: nipbhb@plant1.agric.za (Present address: Prof. H. Bouwman, School of Environmental Sciences and Development, Potchefstroom University for CHE, Potchefstroom, South Africa
email: drkhb@puknet.puk.ac.za)

BROWN, Dr Dick – Locust Management Solutions, 501 Charles Street, **Menlo Park** 0081
email: rietdb@plant2.agric.za

BURKE, Mr Colin – National Department of Agriculture, P/Bag X120, **Pretoria** 0001

ENGELBRECHT, Mr Gustav – Department of Tourism and Evironmental Conservation, NW Province, PO Box 5396, **Kockspark** 2523
email: tecpotch@iafrica.com

GEERTSEMA, Mr Luka – National Department of Agriculture, P/Bag X120, **Pretoria** 0001
email: luka@narc.agric.za

GREYVENSTEIN, Mr Gert – National Department of Agriculture, P/Bag X120, **Pretoria** 0001

HANRAHAN, Prof Shirley – Zoology Department – WITS, P/Bag X03, **WITS** 2050
email: shirley@gecko.biol.wits.ac.za

JARVIS, Dr Mike – PO Box 292, **Wellington** 7654, Cape Province
email: mjarvis@iafrica.com

JONES, Dr Robin – Rhone-Poulenc, PO Box 12447, **Onderstepoort** 0110
email: robin.jones@rhone-poulenc.com

KALULE-SABITI, Dr Margaret – Department of Tourism, Environment and Conservation, P/Bag X 90, **Mmabatho** 2735

KEETCH, Dr David – FAO, c/o Goldamer Exports, PO Box 39763, Faerie Glen, **Pretoria** 0043

*KIESER, Mrs Margaret – ARC-Plant Protection Research Institute, Locust Research Unit, P/Bag X134, **Pretoria** 0001
email: rietmek@plant2.agric.za

MABESA, Mr Tom – AVCASA, PO Box 1995, **Halfway House** 1685

MITCHELL, Mrs Jannette – ARC-Plant Protection Research Institute, Termite Research Unit, P/Bag X134, **Pretoria** 0001
email: rietjm@plant2.agric.za

MÖHR, Dr Johan – ARC-Plant Protection Research Institute, P/Bag X134, **Pretoria** 0001
email: nipbjdm@plant1.agric.za

MULLER, Mrs Elizabeth – ARC-Plant Protection Research Institute, Locust Research Unit, P/Bag X134, **Pretoria** 0001
email: rietejm@plant2.agric.za

NEWBY, Mr Terry – ARC-Institute for Soil, Climate and Water, P/Bag X79, **Pretoria** 0001
email: terry@igkw2.agric.za

OLIVIER, Mr Johan – Uniroyal Chemical (Pty) Ltd, PO Box 2089, **Kempton Park**

OSCHADLEUS, Mr Dieter – SAFRING, University of Cape Town, **Rondebosch** 7701
email: dieter@maths.uct.ac.za

PRICE, Mr Roger – ARC-Plant Protection Research Institute, Locust Research Unit, P/Bag X 134, **Pretoria** 0001
email: rietrep@plant2.agric.za

SMELT, Mr Richard – AgrEvo, 16st street, Hoechst High Chem Park, **Midrand** 1605

THACKRAH, Mrs Anneke – ARC-Institute for Soil, Climate and Water, P/Bag X79, **Pretoria** 0001
email: a_thack@igkw2.agric.za

TLADI, Mr John – National Department of Agriculture, P/Bag X120, **Pretoria** 0001
email: user22@narc.agric.za

TOMS, Dr Rob – Transvaal Museum, PO Box 413, **Pretoria** 0001
email: Toms@tm.up.ac.za

UNDERHILL, Prof. Leslie – Avian Demography Unit, Department of Statistical Sciences, University of Cape Town, **Rondebosch** 7701
email: LGU@maths.ac.za

VAN DER WALT, Mr Etienne – ARC- Plant Protection Research Institute, P/Bag X134, **Pretoria** 0001
email: nipbevdw@plant1.agric.za

VAN DER WALT, Dr Pieter – SA National Parks, PO Box 787, **Pretoria** 0001
email: peet@parks-sa.co.za

VAN DER WESTHUIZEN, Dr Lean – University of the Orange Free State, Department of Entomology, PO Box 339, **Bloemfontein** 9300
email: vdwestmc@dre.nw.uovs.ac.za

*VAN DYK, Dr Louis – ARC-Plant Protection Research Institute, P/Bag X134, **Pretoria** 0001
email: nipblpvd@plant1.agric.za

WALTERS, Mr Mike – Director ARC-Plant Protection Research Institute, P/Bag X134, **Pretoria** 0001
email: nipbnw@plant.agric.za

WHITTINGTON-JONES, Mr Craig – Rhodes University, **Grahamstown** 6140
email: g92w5516@giraffe.ru.ac.za

WILLEMSE, Mr Jaco – National Department of Agriculture, P/Bag X120, **Pretoria** 0001

SUDAN

BASHIR, Dr Elsadig – PO Box 1580, Postal Code 14411, **Omdurman**

SWAZILAND

MBULI, Mr Morrison – Plant Protection Unit, Crop Production Section, PO Box 501, **Manzini**

TANZANIA

*KIRENGA, Mr Geoffrey – Ministry of Agriculture, Plant Protection Division, PO Box 9071, **Dar Es Salaam**

MUSHOBOZI, Mr Wilfred – Plant Protection – Ministry of Agriculture, Pest Control Services, PO Box 7473, **Arusha**
email: avrdc-arp@cybernet.co.tz

MUTAHIWA, Mr Sergei – Ministry of Agriculture and Co-operatives, Plant Protection Department, PO Box 9091, **Dar Es Salaam**
email: ipm@ipm.africaonline.co.tz

*TARIMO, Dr Thadeo – Ministry of Agriculture, PO Box 7473, **Arusha**
email: avrdc-arp@cybernet.co.tz

UNITED KINGDOM

ALLAN, Richard Grant – Quelea Management Consultant, Easdale, **Isle of Seil,** Argyll PA3 4RF, Scotland
email: richardallan@compuserve.com

ALTSHUL, Ms Helen – Natural Resources International Ltd, Central Avenue, **Chatham Maritime,** Kent ME4 4TB
email: h.j.altshul@gre.ac.uk

*CHEKE, Prof. Robert – Department of Pest Management, Natural Resources Institute, University of Greenwich, Central Avenue, **Chatham Maritime,** Kent ME4 4TB
email: r.a.cheke@greenwich.ac.uk

*EDEN-GREEN, Dr Simon – Natural Resources International Ltd, Central Avenue, **Chatham Maritime,** Kent ME4 4TB
email: s.j.eden-green@gre.ac.uk

HOLT, Dr Johnson – Department of Pest Management, Natural Resources Institute, University of Greenwich, Central Avenue, **Chatham Maritime,** Kent ME4 4TB
email: hj30@gre.ac.uk

JONES, Dr Keith – Department of Pest Management, Natural Resources Institute, University of Greenwich, Central Avenue, **Chatham Maritime,** Kent ME4 4TB
email: K.A.Jones@gre.ac.uk

JONES, Dr Peter – Edinburgh University, ICAPB (Ashworth Labs), Kings Buildings, **Edinburgh** EH9 3JT
email: peter.jones@ed.ac.uk

*ROSENBERG, Dr Jane – Department of Environmental Sciences, Natural Resources Institute, University of Greenwich, Central Avenue, **Chatham Maritime,** Kent ME4 4TB
email: l.j.rosenberg@gre.ac.uk

*TERRY, John – IACR Long Ashton, Long Ashton, **Bristol** BS41 9AF
email: john.terry@bbsrc.ac.uk

THOMAS, Dr Matt – NERC Centre for Population Biology and CABI Bioscience, Silwood Park, **Ascot,** Berkshire, SL5 7PY
email: m.thomas@cabi.org

VENN, Dr Jon – Department of Pest Management, Natural Resources Institute, University of Greenwich, Central Avenue, **Chatham Maritime,** Kent ME4 4TB
email: j.f.venn@greenwich.ac.uk

ZAMBIA

*BAHANA, Dr John – International Red Locust Control Organisation for Central and Southern Africa, PO Box 240252, **N'dola**
email:locust@zamnet.zm

GADABU, Dr Afete Divelia – International Red Locust Control Organisation for Central and Southern Africa, PO Box 240252, **N'dola**
email: locust@zamnet.zm

KATHERU, Mr John Ngondi – International Red Locust Control Organisation for Central and Southern Africa, PO Box 240252, **N'dola**
email: locust@zamnet.zm

ZIMBABWE

MUNDY, Dr Peter – Parks and Wildlife Conservation Fund, PO Box 2283, **Bulawayo**
email: bfa@telconet.co.zw

SITHOLE, Dr – SADC Food Security Unit, PO Box 4046, **Harare**
email: smachiri@fanr-sadc.org.zw

SESSION 1 INTERNATIONAL PERSPECTIVES

Workshop on Research Priorities for Migrant Pests of Agriculture in Southern Africa, Plant Protection Research Institute, Pretoria, South Africa, 24–26 March 1999.
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1 DFID-sponsored Migrant Pest Research, 1989–99

Robert A. Cheke

Natural Resources Institute, University of Greenwich, Central Avenue,
Chatham Maritime, Kent, ME4 4TB, UK
(email: r.a.cheke@greenwich.ac.uk)

ABSTRACT

In 1989 the UK Government's Overseas Development Administration (ODA), now the Department for International Development (DFID), launched its Renewable Natural Resources Research Strategy (RNRRS) for the allocation of funds in support of development priorities. This scheme included an initiative on pest control, the Integrated Pest Management Strategy Area (IPMSA), which funded projects on the biology and control of migrant pests. The Crop Protection Programme (CPP) followed in 1995 and was based on different production systems reflecting differences between agro-ecological zones. The CPP has continued to support work on migrant pests, but with increasing emphasis on southern Africa.

Given the current focus of research programmes on discrete communities of beneficiaries or on localised improvements in livelihoods, it is necessary to align them with the need for international initiatives on pests, which eschew boundaries as spectacularly as do locusts or quelea birds. Migrant pests are also difficult to reconcile with some bilateral aid programmes when their control in one country may benefit that country's neighbours more than the community bearing the control costs.

The species constituting migrant pests, which qualify as targets within the RNRRS, are briefly described. The ways in which DFID-supported projects on migrant pests have sought, during the 1989–99 period, to increase knowledge of their biology, means of controlling them, ways of coping with environmental effects of control measures, the economics of control, monitoring their environments and modelling and forecasting outbreaks are reviewed. Finally, thoughts on future research priorities within the developmental context of southern Africa are considered.

INTRODUCTION

The UK Aid Programme, in its various guises, has supported research into the biology and control of migrant pests in Africa for much of this century. The discussion here will be restricted to the period from 1989, when the then Overseas Development Administration's (ODA) Renewable Natural Resources Research Strategy (RNRRS) initiated an Integrated Pest Management Strategy Area (IPMSA) which included migrant pests in its brief, until 1999. Highlights of the IPMSA have been summarised by Hillocks and Eden-Green (1998). The IPMSA was replaced in 1995 by the Crop Protection Programme (CPP) of the

Department for International Development (DFID). The DFID Strategy for Research on Renewable Natural Resources aims to generate new knowledge in natural and social sciences and to promote the uptake and application of this knowledge to sustain livelihoods of poor people through better management of renewable natural resources. In addition to initiatives under the Research Strategy, DFID also has a Strategy for Aid to Locust Activities, which seeks to maintain a capacity to enable the UK to contribute towards national, regional and international efforts for the cost-effective and environmentally sound control of locusts. It functions through existing institutional structures and funding mechanisms, in order to enhance food security in low-income developing countries.

The DFID emphasis on a research- and knowledge-based strategy follows similar initiatives by the World Bank (1998), which uses the word knowledge to encompass both technical know-how and attributes, be they the quality of a worker or the credit-worthiness of a company (Anonymous, 1998). Such attributes allow the generation of knowledge, which coupled with sustainable capacity building and recognition of intellectual property rights (Butler, 1998), can be used to harness scientific knowledge towards achieving social and economic goals, in other words development, within increasingly knowledge-based economies (Anonymous, 1999). The trends are clear and information technology, the internet and radically improved global communication networks are already helping to bridge the knowledge gaps between rich and poor countries (Butler, 1999).

Until the advent of the internet, information about pest outbreaks could take too long to reach Europe-based migrant pest forecasters and by the time their predictions reached the pest-infested countries it was often too late for the forecasts to be put to good use. Now, however, satellite-derived information on rainfall can be sent regularly from the UK to Tanzania by email, and used at once in a model for forecasting likely armyworm outbreaks with almost no delay (Holt *et al.*, 2000 *or* see page 151). If control measures can be taken, then an immediate benefit will be won for the rural poor whose livelihoods will have been improved by the application of knowledge. Such examples will constitute steps towards the goal of poverty elimination.

A consensus is needed on what are the most appropriate steps to be taken on the road to reducing the impact of crop losses, caused by migratory pests, which contribute to rural poverty within southern Africa. The extent of potential damage is illustrated by the depredations of the most infamous migratory pest, the Desert Locust, *Schistocerca gregaria*, which caused US$ 160,000,000 worth of damage at 1990 prices during the 1950–59 period (FAO, 1998). Annual losses in Africa due to Red-billed Quelea birds, *Quelea quelea*, have been estimated as US$ 45,000,000 (Elliott, 1989). The damage by migratory pests is often sporadic, localised and may be of little significance to some national economies, but to those small-scale farmers whose crops are completely destroyed their effects are catastrophic and can cause famine. Because of the general and widespread occurrence of migratory pests, the uptake pathways of research on them are, by necessity, through national and international crop protection authorities rather than through identified groups of farmer stakeholders. The international dimension of some of the pests predicates co-operation between countries and some altruism, in the spirit of African unity, as successful control in one country may make all the difference to the harvests of its neighbours.

MIGRATORY PESTS IN SOUTHERN AFRICA

It is problems related to the biology and control of locusts and grasshoppers, noctuid moths, quelea birds and the environmental effects of the control methods, which are of most concern. The main migratory pests in southern Africa are the Brown Locust, *Locustana pardalina*, the Red Locust, *Nomadacris septemfasciata*, the Migratory Locust, *Locusta migratoria*, the Desert Locust, *Schistocerca gregaria gregaria* (which reaches Tanzania in some plague years), the southern form of the Desert Locust, *Schistocerca gregaria flaviventris* (found in Angola, Ascension Island, Botswana, Namibia and South Africa, but is seldom a pest now), the African Armyworm, *Spodoptera exempta*, the American Bollworm, *Helicoverpa armigera* and Red-billed Quelea birds, *Quelea quelea lathamii*.

Other candidates for migrant pest status include some aphid species, which are vectors of economically important virus diseases of crops. The sudden appearance of symptoms of such diseases, and the lack of known alternative host plants for the virus complexes, has led to speculation that the aphid vectors may migrate long distances carrying the viruses with them, as they are known to do in temperate regions. Migration is thought to occur with Barley Yellow Dwarf Virus and several vector species in Kenya (Wanjama, 1990) and with Groundnut Rosette Disease in Malawi, spread by *Aphis craccivora* (Adams, 1967; Davies, 1972), a known migrant in Australia (Gutierrez *et al*., 1971). Support for the possibility of long distance dispersal of aphids in Africa comes from the trapping of aphids in air-borne nets at heights up to 150 m over Côte d'Ivoire (R. C. Rainey, M. J. Haggis and R. A. Cheke, unpubl.). Also, 491 *A. craccivora* have been caught at dusk 15 m above groundnut, cotton, sorghum and fallow fields in the southern Gezira, Sudan, at aerial densities of $0.24/m^3$, the highest insect density ever recorded in more than 100 h of aircraft trapping in tropical Africa (Rainey, 1983, 1989). This and other catches were made of *A. craccivora* as high as 1200 m above the ground, and in suction traps (J. Bowden in Rainey, 1983) when the Inter-Tropical Front (ITF) was passing. Other pest aphids caught in aeroplane-borne traps in the same area included *A. gossypii* and *Rhopalosiphum maidis* (Rainey and Haggis, 1980).

Many plant-disease vectors other than aphids are known to be migrants outside Africa, and it is possible that some of these and related insects may be migratory, albeit for short distances only, within Africa too. Examples include: (a) whiteflies, which spread African Cassava Mosaic Disease and several other important viruses such as Cotton Leaf Curl, Okra Leaf Curl and Tomato Leaf Curl, since movements by *Bemisia tabaci* are of importance in American cropping systems (Allen *et al*., 1994, Byrne *et al*., 1994); (b) Homoptera such as leafhoppers, since some are long-distance migrants in Asia (Kisimoto, 1976) and there is evidence that *Cicadulina* spp., the vector of Maize Streak Disease in Africa (also the subject of CPP projects, Cooter *et al*., 1999), may travel as far as 118 km (Rose, 1973; Thresh, 1983), but there are regional differences with Ugandan populations being more sedentary than those in Zimbabwe (Downham and Cooter, 1998); (c) thrips, which transmit Tomato Spotted Wilt Virus amongst others, the migrations of which have been discussed by Johnson (1969) and Thresh (1983); (d) beetles, which transmit Cowpea Chlorotic Mottle (Thresh, 1983); and (e) mealybug vectors of Cocoa Swollen Shoot Disease (Thresh, 1983).

DFID-FUNDED RESEARCH ON MIGRANT PESTS

During the 1989–99 period there have been few DFID-funded research projects on locusts and grasshoppers in southern Africa, but there have been projects there on African Armyworm moths, Migratory Locusts and quelea birds. These, and other projects on migratory pests elsewhere, have included work on basic biology, on population dynamics, on environmental aspects related to forecasting tools, and on control methods, including their environmental impacts. There have also been studies of the economics of migratory pest control strategies. The following sections summarise some of these studies.

Locusts and Grasshoppers

The critical difference between a locust and a grasshopper is the former's ability to change its phase from a solitary insect to a gregarious one with associated changes in morphology, physiology and behaviour (Uvarov, 1966, 1977). Thus, a goal of locust control would be to develop a means to prevent the gregarisation process. In order to achieve this it is necessary to understand the process itself, in order to try and manipulate it. The way that Desert Locusts become gregarised and revert to the solitarious phase has been investigated by laboratory experiments, which have demonstrated the time course of the changes and the stimuli promoting them (Roessingh *et al.*, 1993; Roessingh and Simpson, 1994; Simpson *et al.*, 1999). The importance of the insects' recent history, including the phase status of the parents, in determining readiness to shift phases has been emphasised. It is also now known that a chemical in the foam part of an egg-pod has gregarising properties (Tickell, 1996, McCaffery *et al.*, 1998). Eggs, which would normally be expected to hatch as gregarious nymphs, emerged as solitarious insects when deprived of the foam plug. When the foam from gregarious females was applied to eggs expected to hatch as solitaries, these emerged gregariform. It has also been demonstrated that a semiochemical which attracts gravid females to common egg-laying sites is deposited in the egg froth (Saini *et al.*, 1995) and topical treatment of Desert Locusts and Migratory Locusts with azadirachtin-enriched neem oil has a solitarising effect (Schmutterer and Freres, 1990; Langewald and Schmutterer, 1995).

The role of such phase changes in Desert Locust population dynamics was investigated in an IMPSA modelling project. It was known that the intrinsic rate of increase (r) of populations of the gregarious phase of the Desert Locust is potentially much higher than the solitarious phase with faster development rates of the gregarious insects compensating for their lower fecundities (Cheke, 1978). Indeed estimates of r were so high that theory predicted that the dynamics might be chaotic (Cheke and Holt, 1993, 1996). If so, this would mean that forecasting and predictions would only be possible over short periods, if at all, with important implications for the feasibility of forecasting. Analyses of time series of the numbers of territories infested have been unable to resolve this issue, with chaotic dynamics remaining a possibility and, indeed, some models including chaos gave good agreement with empirical trends. Further analyses using only the West African data confirmed a relationship with rainfall but the pattern was heteroscedastic, such that high rainfall did not always yield locusts. Interestingly, this pattern emerged from a model with chaotic parameters but did not from the same model with r in the stable domain. Analyses of the time-series data revealed evidence for a 2-year lag in the dynamics (Cheke and Holt, 1993), a possibility also supported by theory (N.-C. Stenseth, R. A. Cheke and X.-S. Zhang, unpubl.). Further research on the dynamics of phase changes, and how shifts from one phase to another can be modelled to give realistic output, supports assumptions that locust dynamics are complex and that this complexity can be addressed with models incorporating phase shifts (Holt and Cheke, 1996a). However, quite simple rule-based models can also have predictive value (Holt and Cheke, 1996b). It would be instructive to apply similar analytical methods to data on Red, Brown or Migratory Locusts in southern Africa.

The importance of phase changes in the generation and termination of plagues has been investigated further in a project, co-ordinated by Jane Rosenberg and Richard Healey, on identification of the factors which lead to changes in Desert Locust populations at the beginning and end of recession periods. DFID has also supported research on the application of GIS and remote sensing techniques for the development and transfer of technology for Desert Locust management on the Red Sea coast of Eritrea, involving a computer-based system known as the Reconnaissance and Management System for the Environment of *Schistocerca* (RAMSES). This, coupled with the FAO *Schistocerca* Warning Management System (SWARMS) (Cressman, 1997), should lead to improved forecasting abilities (Rosenberg, 2000; see page 165) and could be developed and adapted for other migrant pests including those infesting southern Africa.

DFID has also supported research into the use of radar for detecting and tracking migrant pests which has been tested successfully in the field with locusts, grasshoppers, armyworm, American Bollworm and other pests including aphids (Reynolds and Riley, 1997; Riley *et al.*, 1995). Indeed, it is now practicable to have an early warning of the occurrence of locusts using a vertical-looking radar (Riley and Reynolds, 1997) which could act as an adjunct to traditional scouting methods and the monitoring of vegetation by satellite.

The optimal locust control strategy is prevention of gregarisation and swarming, through timely control of the hoppers. In the past, this was possible using the organochlorine insecticide dieldrin, but this was rightly withdrawn because of its potential adverse impact on human health, non-target organisms, and its accumulation in the environment. An alternative to full coverage insecticide spraying is the barrier technique in which insecticide is sprayed on to strips of vegetation, separated by wide spaces which are not sprayed. Marching hoppers encounter the sprayed barriers as they move around searching for food, and acquire a lethal dose of the insecticide. DFID-funded field trials in Madagascar showed that barriers treated with diflubenzuron, which is one of the first generation of insect growth regulators (IGRs) successfully controlled migratory locust hoppers (Cooper *et al.*, 1995). Optimum barrier width and spacing is not known, nor is the potential usefulness of some of the more recent products for use in barriers, such as newer IGRs and fipronil, a phenyl pyrazole insecticide which is relatively new to locust control. A current CPP project is addressing barrier performance by developing a mathematical model, which incorporates the movement and feeding behaviour of four different species of locusts (J. Holt and J. F. Cooper, unpubl.). However, further work is needed to increase the efficiency and effectiveness of the technique and in particular to validate the model under field conditions. This work will be in collaboration with locust control departments which will be end-users of the technology.

A research programme on the environmental effects of control against the Migratory Locust *Locusta migratoria capito* occurring in Madagascar, where large-scale aerial spraying operations are continuing, is underway. The United States Agency for International Development (USAID) is currently supporting and helping to build national capacity in environmental monitoring, impact assessments and quality control of the spraying operations through the Office National pour l'Environnement (ONE). Staff from NRI are providing technical assistance in environmental monitoring, environmental impact assessment and quality control of locust spraying, and training in the principles of locust control, quality control of spray equipment, calibration, control techniques, navigation, weather conditions and droplet distribution. A more efficient monitoring system is now needed in Madagascar to provide quality control of locust spraying operations and thus an improved information management, analysis and archiving system.

Research on environmental monitoring has also included development of methods of pesticide residue analysis appropriate to less-developed countries, which can be used to assess effects of migrant pest control (Cox, 1993, 1994; NRI, 1993). Another DFID-sponsored project has been maintaining a database known as ENVIRON, which compiles information on the toxicity of pesticides, which can be freely accessed on request. Simple, inexpensive and portable equipment for environmental monitoring has also been developed

(Grant, 1998) and the environmental effects of Desert Locust control operations have been reviewed by Ritchie and Dobson (1995).

DFID has supported biological approaches to the control of locusts and grasshoppers by contributing to the LUBILOSA project (Paraso *et al.*, 1997; Thomas, 2000 *or* see page 173) and other research on use of fungal pathogens (Caudwell and Gatehouse, 1994).

A project on the effects of drought stress on food plants of locusts and how the insects respond concluded that the palatability to locusts of *Schouwia purpurea* increases with drought stress, possibly through the combined increase in sugar and proline content of the leaves.

Studies of the population dynamics and the egg-diapause of the Senegalese Grasshopper *Oedaleus senegalensis* have confirmed that outbreaks tend to occur after droughts (Colvin, 1997). Such studies are of interest to entomologists in southern Africa, given the parallels between the ecology of this species and that of the Brown Locust.

The economics of Desert Locust control policies have been evaluated in a recent workshop (Joffe in FAO, 1998), with an approach which could also be applied to southern African migratory pests.

Armyworm Moths

Models of populations of gregarious phase African Armyworm showed that, like Desert Locusts, they also have higher intrinsic rates of increase than the solitarious phase, with synchronisation of development and faster development rates of the gregarious phase being contributing factors (Cheke, 1995). Thus, a means of preventing gregarisation could also be a goal applicable to this pest. As is the case with all other migratory pests, rainfall is an important determinant of armyworm activity. A project based in Tanzania combines rainfall estimates, based on remote sensing data on Cold Cloud Duration (CCD), with data from a network of pheromone traps into a model to predict outbreaks (Holt *et al.*, 2000 *or* see page 151). Data used in the derivation of the models were collected during earlier DFID-supported work which included the compilation of armyworm occurrences in a database (WORMBASE, Day *et al.*, 1996), work on movements in relation to weather patterns (Tucker, 1993, 1994), and estimates of probabilities of movements to different destinations based on outbreaks in known source areas (Cheke and Tucker, 1995). A parallel project has been developing and testing the use of nuclear polyhedrosis viruses (NPV) as an alternative to pesticides for the control of armyworm (Cherry *et al.*, 1997, D. Grzywacz and M. A. Parnell, unpubl.).

The control of armyworm, be it by pesticides or NPVs, has been based on the idea of strategic control, whereby initial outbreaks are deemed worthy of control whether they are on a crop or not, in order to prevent further outbreaks developing perhaps far distant from the controlled point. The economics of this strategic control approach were investigated and it was concluded that for some outbreak areas, but not all, strategic control would be cost-effective in terms of the values of crops saved in relation to armyworm control costs (Cheke and Tucker, 1995).

American Bollworm Moths

The IPMSA funded several projects on insecticide resistance in American Bollworm. The studies showed how best to detect and manage pyrethroid-resistance (Armes *et al.*, 1994) and how it varied with the season and availability of non-crop food plants (Madden *et al.*, 1995). Both the presence of non-cultivated hosts and diapause provided opportunities for conserving insecticide susceptibility. A simple bio-assay technique was developed enabling local staff to monitor the resistance (De Souza *et al.*, 1995). Research on microbial methods of control of this pest was also conducted with evaluations of the efficacy of formulations of *Bacillus thuringiensis* and NPVs (Cherry *et al.*, 1996, 2000). Other work included predictions of oviposition in relation to rainfall (Madden *et al.*, 1993).

Quelea Birds

There had been little support from DFID for research on Red-billed Quelea birds *Quelea quelea* following the intensive research programme in the 1970s (Ward, 1971; Jones, 1989a,b,c,d) until the continuing importance of these pests led to renewed interest in 1995. A project on the southern African subspecies *Q. q. lathamii*, investigated its taxonomy (Jones *et al.*, 1998, 2000b), genetic variability and movements in relation to environmental variables (Jones *et al.*, 2000a *or* see page 139). Field work has been undertaken in Botswana, Namibia, South Africa and Zimbabwe to collect samples of DNA from different populations to help elucidate migration patterns. A database on quelea occurrences has also been compiled, which will be used in combination with rainfall and vegetation data to devise a predictive model of the birds' likely movements under different circumstances.

Quelea control is still dependent on the use of explosives or the organo-phosphate avicide fenthion (Queletox). Both control methods have effects on the wider environment in general but on non-target organisms in particular. Thus there is a need for new control techniques, but until their development it is imperative to minimise the effects of fenthion and to this end the DFID project has been examining the possibility of bio-remediation of fenthion-contaminated soil using the fungus *Phanerochaete chrysosporium* to breakdown residues. By-products of the breakdown process have been identified, the speed of degradation measured and key variables influencing it identified, suggesting that it is worthwhile to proceed with field trials (Zacchi *et al.*, 2000 *or* see page 191). The possibility of exploiting the bio-remediation of sites contaminated in control activities with other chemicals against other migrant pests would be worth examining too.

RESEARCH PRIORITIES AND POSSIBILITIES FOR THE FUTURE

There are several general themes applicable to most of the migrant pests discussed.

1. Novel environment-friendly control methods are required for all the pests discussed. Progress has been made with biological agents for use against locusts, grasshoppers, armyworm and American bollworm, but the methods all need refinements and further tests before they can become the control means of universal and widespread choice. There is an urgent need for a new means of controlling quelea birds to replace fenthion and explosives.

2. The consolidation, expansion and refining of existing knowledge-based computer applications such as the RAMSES system for Desert Locust in Eritrea, WORMBASE and forecasting models for African armyworm in eastern Africa and the quelea database for *Q. q. lathamii* in southern Africa. The development of parallel systems for the same pest species elsewhere and for additional pests such as Brown Locusts, within the southern African context, would also be worthwhile.

3. Knowledge of soil moisture levels is important for assessing the likelihood of orthopteran outbreaks. Research should be conducted to assess possibilities for estimating soil

moisture levels 5 cm or more below ground, which is feasible using satellite imagery based on radar (D. Archer, pers. comm.), to help predict hatching times by diapausing migrant pests such as Brown Locusts in southern Africa (and Senegalese Grasshoppers in West Africa) and the suitability of breeding grounds for others such as the Desert Locust.

4. Further work on the search for solitarising chemicals or other behaviour-modifying agents, which could be developed as sprays against hopper bands or swarms of locusts.

5. Standardisation and agreement on protocols for assessing the environmental effects of pesticides.

6. The development of bio-remediation techniques, which could be used as a follow-up to control methods, to reduce environmental contamination by pesticides.

7. Investigations of the migrations of vectors of plant diseases such as *A. craccivora*, whiteflies and thrips, and their possible epidemiological implications.

Research priorities not mentioned above specific to particular pests or groups of pests include for locusts: time-series analyses of long-term data on Red, Brown and Migratory Locusts and consolidation of progress with barrier methods of hopper control with IGRs. For quelea: investigations of Integrated Pest Management approaches, involving judicious use of planting times, resistant crops, fast-growing varieties and training of farmers regarding the need for rapid reporting of bird arrivals and nest-building.

It is also important to decide on the best ways to maintain national capacities and international organisations dedicated to migrant pest control, and how to co-ordinate responses from diverse sources efficiently. Without well-equipped and well-trained control teams, most forecasts are of little value.

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2 FAO's Perspective on Migratory Pests

Clive C. H. Elliott

Migratory Pests, Plant Protection Service, AGPP, FAO, Rome, Italy
(email: clive.elliott@fao.org)

ABSTRACT

FAO has a global mandate to provide development/emergency assistance on locusts to its 176 member nations, to provide fora for meetings on locusts and to collect, analyse, forecast and disseminate information on locusts. FAO is recognised as having a comparative advantage over other bodies in this work because success in combating locusts depends on international collaboration, which FAO can most easily foster. Up to now, the focus of attention has been the Desert Locust because it is perceived as posing the greatest threat to the greatest number of countries, but FAO has also recently provided assistance with problems caused by five other species of locust, and also by armyworm and by quelea. For this group of migratory pests, FAO's priorities are to provide a satisfactory service to member countries and to limit the effect of the pests on food security. In respect of the Desert Locust, these priorities are expressed through a Special Programme EMPRES (Emergency Prevention System for Transboundary Animal and Plant Pests and Diseases – Desert Locust component). The Locust and Other Migratory Pests Group at FAO HQ also includes a Desert Locust Information Service which produces a monthly Bulletin plus Updates and Alerts. Emphasis in the field is on achieving preventive control at the least cost and most environmentally friendly manner, and to implement this through strengthened national locust units. For quelea, the introduction of Integrated Pest Management approaches, which does not rule out but limits pesticide use, is seen as the best way forward. For armyworm, the strategy developed by the Regional Armyworm Programme under the Desert Locust Control Organisation for Eastern Africa (DLCO-EA) is supported. The various ways in which FAO can provide assistance is also described.

INTRODUCTION

As the Agency of the United Nations that specialises in food and agriculture, FAO has three main roles within its specialisation. One is to provide development/emergency assistance, including independent advice, to its 176 member nations. The second is to provide fora for its members to meet, discuss and agree on how to approach different agricultural problems. The third is to provide a service to them by collecting, analysing and disseminating global information on agriculture. In the realm of migratory pests, this same principle applies.

In terms of priorities, in recent years it has become important for UN agencies to identify the areas in which they have a comparative advantage over other international or national bodies concerned with development assistance, such as bilateral agencies, research institutions and non-governmental organizations. Some effort was made to do this when the current FAO Director-General was elected in 1994. Among other topics, it was agreed that transboundary pests and diseases, i.e. those that regularly cross national frontiers and require collaboration between countries to combat them successfully, were particularly appropriate to FAO. This recognition led to the establishment of a Special Programme, the Emergency Prevention System for Transboundary Animal and Plant Pests and Diseases, otherwise known as EMPRES. This programme has two elements, one on animal diseases and one on the Desert Locust, *Schistocerca gregaria*.

The comparative advantage that FAO has as a co-ordinator of work on migratory pests, specifically locusts, has been in existence at least since about 1955, when the FAO Desert Locust Control Committee first met. For example, in 1972 the Anti-Locust Research Centre in London agreed to devolve its role as collector, collator and forecaster of Desert Locust outbreaks, and transferred its Desert Locust Information Service to FAO in Rome. The General Assembly of the United Nations also formally gave the mandate for co-ordination of locust management to FAO. Given this background, this paper will review FAO's present-day perspective on migratory pests.

WHICH MIGRATORY PESTS?

FAO, as an international organisation, has in theory a global mandate, insofar as any of its member nations may ask for help. If one wanted to prepare a list of migratory pests globally, the first step of course would be to define what is meant by the term. Normally migration is defined as a two-way movement with some directional element, which distinguishes it from nomadism and species' irruptions or expansions. It is usually used to describe long-distance movements of several hundred kilometres. There are plenty of exceptions to these generalities such as altitudinal migration which may involve a movement of only a few hundred metres, and the point at which migration ends and nomadism begins has always been uncertain. For example, the movements of gregarious Desert Locusts (COPR, 1982; Steedman, 1990) certainly cover hundreds, sometimes thousands, of kilometres, and there is a directional element since the swarms fly downwind and the winds tend to blow in a certain direction at a certain season. The movement is not strictly two-way as swarms may only return to their place of origin after several generations or may never return at all if ecological conditions do not favour repeated breeding and the wind does not carry them there. In the place of origin, a permanent population of the species in its solitary form maintains the locusts' presence.

The Red-billed Quelea, *Quelea quelea*, qualifies as a migrant by distance, and in other aspects of its biology such as pre-migratory fattening, but the direction taken appears to be to some extent adjustable according to rainfall patterns (Bruggers and Elliott, 1989). Areas suffering from drought are probably over-flown and the species ranges widely to find suitable breeding locations. Even so, breeding sites, if they receive adequate rains around them, will be used regularly and seasonally, giving a directional element to the movements. The African Armyworm, *Spodoptera exempta*, again qualifies by distance, with a similar directional element to the Desert Locust, caused by the winds tending to blow in a certain direction at a certain season (Rose *et al.*, 1997). A return migration does not occur.

Because migration usually involves long distances, the species concerned typically crosses several national frontiers, and can be defined as transboundary. Again there are exceptions, such as the African Migratory Locust in Madagascar, *Locusta migratoria capito*, which remains within the island but moves several hundred kilometres with regularity to the direction of its movements. The Australian Plague Locust, *Chortoicetes terminifera*, and the Spur-throated Locust, *Austracris guttulosa*, are similar examples.

In practice, the term 'migratory pest' is used somewhat loosely in that the species to which it is applied may not strictly be migratory according to the precise definition. It is usually used for only three faunal types, locusts, armyworms and birds. Some pest species of grasshopper, for example the Senegalese Grasshopper, *Oedaleus senegalensis*, show regular seasonal movements, but for convenience are not grouped with the migratory pests. FAO has a Locust and Other Migratory Pests Group, which has provided regular assistance for the following pests:

- Desert Locust *Schistocerca gregaria*
- Red Locust *Nomadacris septemfasciata*
- African Migratory Locust *Locusta migratoria migratoria*
- Madagascar Migratory Locust *L. m. capito*
- Moroccan Locust *Dociostaurus maroccanus*
- Italian Locust *Calliptamus italicus*

- African Armyworm *Spodoptera exempta*

- Red-billed Quelea *Quelea quelea*.

This list is not all-inclusive in that it does not list all the species that could for practical purposes be considered migratory pests. The Australian locusts are not mentioned because the Australian Plague Locust Commission is fully capable of looking after the problem, without any help from FAO. On the other hand, if FAO receives a request for assistance from a member nation or a group of nations for a migratory pest not listed, such requests would always be considered and evaluated. A species not listed, but which is an obvious candidate for inclusion is the Brown Locust, *Locustana pardalina*. To date, probably for historical reasons, FAO has not received any direct requests for assistance in combating the Brown Locust, although it has supported improvements in plant protection in Botswana, which has included Brown Locust control. On a few occasions in the past 20 years, though not recently, FAO has also provided assistance in South and Central America for control of the local locust species.

For the armyworms, only *S. exempta* (covering the Arabian Peninsula south to southern Africa) is listed. Other species such as *S. litura* (India and the Far East) and *S. frugiperda* (North America and the Caribbean) have not, to date, been covered.

FAO'S PRIORITIES AND APPROACHES ON MIGRATORY PESTS

It could be said that FAO has two major priorities in respect of migratory pests, one to provide a satisfactory service to its member nations and the other to limit the effect of migratory pests on food security. Another important role is the provision of fora for discussion and agreement on migratory pest problems, leading towards these two priorities. The EMPRES (Desert Locust) Programme is identified as a specific priority within these general ones, by its classification as a Special Programme of the FAO Director-General. The Desert Locust receives much more attention than any other species of migratory pest, through EMPRES, but also as the main species covered by the FAO Desert Locust Information Service (DLIS). The reason for this is partly because the Desert Locust is perceived as posing the greatest threat to the greatest number of countries, but also because of limitations in capacity and resources. The notoriety of the species (COPR, 1982) has been recorded since about 1300 B.C. Between 1860 and 1999, there have been eight major plagues, each lasting from 4 to 22 years. The most recent plague from 1986 to 1989 cost donors more than US$300 million in assistance, and affected countries probably invested a similar amount from their own resources. Since 1989, upsurges in Desert Locust populations have re-occurred in 1992–94 and 1995–98, each requiring further intervention and giving rise to a degree of donor fatigue. Hence the development of EMPRES was perceived as a necessity to try to find a solution to the problem.

FAO headquarters' input into migratory pests comes from its Locust and Other Migratory Pests Group within the Plant Protection Service (AGPP). The Group has four full-time permanent posts, two of which cover any aspect of migratory pests and two (from the DLIS, which is part of the Group) focus mainly on information collection, analysis, forecasting and dissemination. The functions of the Group cover the production by the DLIS of a monthly Bulletin on the Desert Locust situation and forecast. The Bulletin is based on reports received from affected countries, plus analysis of remotely sensed locust habitat condition, weather reports, rainfall and wind directions. The Bulletin is supplemented by Updates and Alerts, when Desert Locust outbreaks or upsurges begin to develop. There is also an Internet home-page, which gives the latest information and the most recent Bulletin. The staff carries out emergency assessments of reported outbreaks of migratory pests and promotes joint activities by affected countries such as joint surveys along border areas affected by locusts. Staff provide training in making assessments of migratory pest outbreaks to affected countries and train locust officers to carry out improved surveying or control operations.

From time to time, the Group is reinforced by additional staff funded out of Trust Funds supporting emergency programmes (for example, the current outbreak of Migratory Locust in Madagascar) or research-orientated programmes (for example, Belgium's recent support for research on remote-sensing evaluation of locust habitats). It is also sometimes supported on a temporary basis out of its own funds, for example to strengthen EMPRES implementation. This small staff complement has a limited physical and technical capacity to deal with migratory pest problems other than the Desert Locust. During important upsurges in the Desert Locust population, almost all attention goes on that species. When a recession period occurs, more time can be spent on the other species listed above. Technically, the Group's expertise reflects the Desert Locust priority, but it also has some expertise in the other species listed, including the Migratory Locust, the Red Locust and quelea birds. FAO is also fortunate, through its status as an international agency, to be able to draw on consultant expertise from anywhere in the world. It is thereby able to fill gaps in the individual technical abilities of its Locust and Other Migratory Pests Group, for example in armyworm management, by recruiting well-qualified consultants, provided the funds are available.

In the field, FAO implements projects, which are supported by donor Trust Funds and by its own Technical Co-operation Programme (TCP). For EMPRES, in addition to these, an allocation is also made from FAO's core resources (the Regular Programme). The Locust and Other Migratory Pests Group is co-ordinating a major multi-donor programme on the Desert Locust in the nine countries around the Red Sea, designated as the EMPRES Central Region Programme. A similar programme is under formulation for the Western Region (West and Northwest Africa). The Central Region has six international and national staff working closely with Government-appointed Liaison Officers from eight of the nine countries. The Western Region currently has only one donor-supported project with two staff, but will expand when/if the multi-donor programme gets off the ground. The only other on-going Trust Fund project involving migratory pests is LOCUSTOX, based in Senegal, which is looking at environmental problems in relation to the side-effects of locust control, and, more recently, to pesticide residues in general.

Technically, the priority in the Desert Locust is, through EMPRES, to limit the possibility that plagues may develop and to eliminate expensive crisis management as the means by which plagues are combated. This is to be achieved primarily through strengthening, in a sustainable way, the capacities of national plant protection departments to carry out effective locust surveys ('early warning') and to practise rapid preventive control ('early reaction') using the least costly and most environmentally friendly methods that can be developed. In addition, the programme is expected to catalyse and promote research that is likely to contribute to these objectives. While these principles are easy to state, they are highly complex to achieve. Individual donor-supported projects within EMPRES are reviewing locust control strategies to work out when intervention should begin, and examining how to reduce the quantities of pesticide needed for effective control. Emphasis is also being given to alternatives to conventional pesticides especially bio-pesticides and barrier spraying.

Sustainability of capacity is likely to be achieved through sharing resources between the richer countries, which stand to lose heavily in the case of a plague, and the poorer ones, from which many plagues are thought to originate, using FAO's Desert Locust Commissions as the bodies through which such arrangements are made. All of these topics could be considered as among FAO's major interests.

For the other species of locusts listed above, it is conceivable that FAO would consider developing an EMPRES Programme for the Red Locust or the Brown Locust, but several provisos would need to be met. These would include a co-ordinated, high-level, request from the affected countries, an indication that donors might be prepared to support such a programme and the willingness of FAO to increase the staff of the Locust and Other Migratory Pests Group, so that the necessary support could be provided.

As a reflection of the importance which FAO attaches to the correct use of pesticides in locust control, an independent group, the Pesticide Referee Group (PRG) was established to review studies on the efficacy of locust pesticides. The Group meets about once a year and is composed of five members who are selected on a personal basis for their knowledge of different aspects of pesticides. They are expected to provide FAO, and, through FAO, all interested parties, with advice on the efficacy of the pesticides. Their report is widely circulated to locust-affected countries and donors. At its Sixth Meeting in 1997, the Group included a first effort at estimating the suitability of the different pesticides in various habitat types in terms of the environmental side-effects. In 1998, this was developed further. The Group is also attempting to expand its advice to include species other than the Desert Locust. It should be noted that the PRG is **not** a registration body; registration remains a matter for each country's sovereignty. FAO provides advice on efficacy and countries use that advice as they choose.

In respect of quelea birds, FAO is currently encouraging the use of Integrated Pest Management (IPM) approaches to the problem of bird attacks on cereal crops. This means working with farmers in examining all aspects of farming practices in relation to quelea damage, and seeking to minimise external inputs, especially pesticides. It includes modifying crop husbandry, planting time, weed reduction, crop substitution, bird scaring, exclusion netting, etc., and only using lethal control for birds directly threatening crops when the other methods have failed. It is also important for farmers to be aware of the costs of control using pesticides, and in the case of commercial farmers, for them to bear some or all of the costs. A major likely benefit of IPM is reduced environmental side-effects resulting from decreased pesticide use. Although some elements of IPM have been tried in bird pest management, a major effort has yet to be made, for quelea, to focus on farmers in all aspects of the problem. FAO has a draft project prepared for quelea management in the Senegal River valley which will attempt to investigate the problem using IPM techniques, if donor support is eventually forthcoming.

In terms of FAO's role in providing fora, at present almost all of the effort goes into the Desert Locust. The major forum is the Desert Locust Control Committee which meets about once every 2 years and has over 60 countries listed as members. Its subsidiary Technical Group discusses technical questions handed down to it by the Committee. FAO also has three regional Desert Locust Commissions, one for North-west Africa, one for the Central Region and one for South-west Asia.

WHAT ASSISTANCE DOES FAO PROVIDE?

Misconceptions are often held about what assistance FAO can and cannot support. FAO is primarily an agency designed to provide its member countries with development assistance, but it also has a role to play in giving emergency assistance. Development assistance tends to be longer-term and is normally aimed at building up national capacities, while emergency assistance is always short-term and intended to assist with an immediate crisis caused in this case by a migratory pest. For both sorts of assistance, FAO's **own** resources are strictly limited and are provided through one channel only, namely its Technical Co-operation Programme (TCP). TCP assistance funds individual projects for which there is a fixed ceiling budget for all projects and a maximum duration of 24 months. In emergency outbreaks of migratory pests, and following a request from a high level (the Minister of Agriculture or higher) from the affected country, TCP projects can be created and approved very rapidly, in exceptional circumstances in as little as a week, but usually within about a month. Their approval depends in part on a technical evaluation which agrees that a genuine emergency exists. TCP assistance for development projects may take several months to be approved and its approval will depend on a number of factors including the availability of funds and the extent to which a particular country has received other TCP assistance already.

FAO is not an organisation which directly funds research or training, but both of these may be funded if they are an intrinsic part of development TCP projects, or if in the case of training, they are part of the action plan to deal with an emergency. FAO is therefore not normally able to respond to individual requests for funds to cover degree level training, to cover participation by outside staff in research meetings, or to fund research, which is not built in to projects. In connection with its role in collecting and disseminating information on agriculture, which falls under what is nowadays called FAO's HQ **normative** activities (as opposed to its **operational** activities, implementing or supporting agricultural development or emergencies in the field), FAO has a role in disseminating guidelines on correct practices and methodologies for dealing with particular agricultural problems. In this context, if methodologies are lacking or need improving, normative TCP projects can sometimes be approved to support such developments. FAO also has a small budget under its core Regular Programme funding which is allocated to its different specialist Groups, such as the Locust and Other Migratory Pests Group, to cover the operating costs of its normative activities. These funds can be used to a very limited extent to support field activities, which are linked to the priorities of the Group, such as holding experts' consultations on technical questions deemed to have critical importance. Experts from anywhere in the world can be invited to contribute to such meetings.

FAO also provides support to projects funded by external donors, which choose to channel their funds through FAO, under what is called the Trust Fund system. Donors usually decide to support such projects because they consider that FAO has more expertise in a particular field than they possess themselves, or because they consider that FAO, because of its mandate and role as an international organisation, is the most appropriate body to execute such projects. Migratory pests are a case in point because they cover several different countries and FAO can often handle the inter-country arrangements more easily.

Trust Fund projects can also be either development or emergency projects, and can incorporate research and training elements into them. Occasionally, Trust Fund projects can be almost purely research orientated, if the donor feels that the technical support that FAO can provide will help to keep the research well directed or if the research is part of a greater whole and is better for its integration into that whole. Finding a donor to support a Trust Fund is often not easy, especially in the present day climate of economic constraint. It is usually most successful when a donor has a demonstrated sympathy with a recipient country and an interest in a particular field. For example, certain donors have a history or tradition of supporting development or research in migratory pests and will take an interest in proposals. On the other hand, new donors may develop from a swing in the political pendulum and can be persuaded to support work on migratory pests, which fit with certain priority interests, such as environmental concerns.

The range of possibilities for FAO to support work on migratory pests is, in conclusion, quite wide. Obtaining approval of TCP or Trust Fund support, however, is an exacting process, which is often not successful because of funding shortages or a failure to develop a convincing justification.

CONCLUSION

The technical cornerstones of FAO's perspective on locusts is how to achieve preventive control for the least cost and in the most environmentally friendly manner. On quelea, it is how to achieve an IPM approach such that lethal control with pesticides is the option used minimally. For armyworm, FAO supports the strategy of rapid reaction and monitoring developed by the Regional Armyworm Programme under DLCO-EA. Underlining these perspectives is the Organisation's concern with improving food security.

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3 The Role of the International Red Locust Control Organisation for Central and Southern Africa (IRLCO-CSA) in the Management of Migratory Pests

J. W. Bahana

IRLCO-CSA, PO Box 240252, N'dola, Zambia
(email: locust@zamnet.zm)

ABSTRACT

The International Red Locust Control Organisation for Central and Southern Africa (IRLCO-CSA) has existed since 1949 (when known as the International Red Locust Control Service, IRLCS) after its establishment by an international convention. The formation of IRLCO-CSA was partly a result of nearly 15 years' work to identify sources of Red Locust (*Nomadacris septemfasciata* Serville) plagues and to prevent their re-occurrence. A plague of Red Locusts, which started in 1929 and ended in 1944, had affected most of Africa south of the equator and some areas further north. For the organisation to achieve its objectives, its strategy was first to identify the source of the plague and then to control hopper bands and incipient swarms. For more than 40 years this strategy was effective. Consequently, the organisation expanded its mandate to include the management of other migratory pests, viz. African Armyworm, *Spodoptera exempta*, and quelea birds, *Quelea quelea*.

This paper reviews the historical development of methodologies for the control of Red Locusts and other migratory pests and appraises current techniques. The role of ecological and weather factors in Red Locust upsurges is briefly examined. The quantitative study of such factors may lead to more accurate forecasts of outbreaks, which in turn would lead to more judicious use of pesticides. The search for alternatives to pesticides is advocated in view of the sensitive nature of the environment in the outbreak areas of the Red Locust.

INTRODUCTION

The International Red Locust Control Organisation for Central and Southern Africa (IRLCO-CSA) is an inter-governmental institution and is the successor to the International Red Locust Control Service (IRLCS) which was established by a convention in 1949. The formation of IRLCS was partly the result of concerted research efforts, over nearly 15 years, to identify the sources of a plague of Red Locusts (*Nomadacris septemfasciata* Serville) which started in 1929 and ended in 1944. There had been at least two previous plagues and the 1929–44 plague affected the whole of Africa south of the equator and some areas further north (Figure 1). More importantly, IRLCS was mandated to prevent

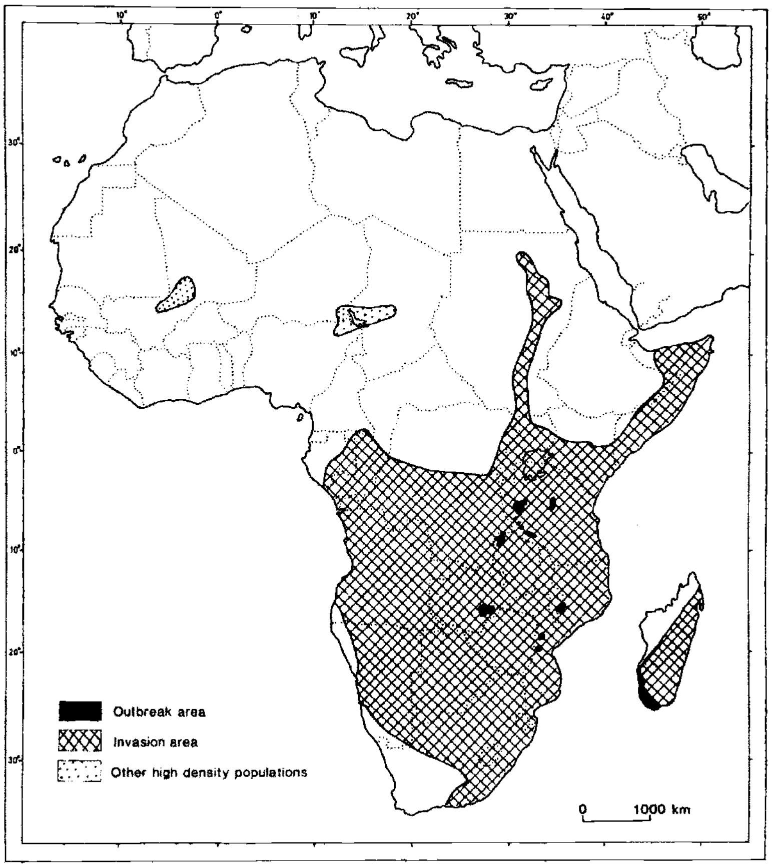

Figure 1 Distribution of the Red Locust.

re-occurrence of such plagues. For IRLCS to achieve its objectives, its strategy was first to identify the source of the plagues, and secondly to control hopper bands and incipient swarms in the source areas.

In 1970, however, IRLCS gave way to the formation of IRLCO-CSA under a new convention but with similar goals. The current member states are Kenya, Malawi, Mozambique, Swaziland, Tanzania, Uganda, Zambia and Zimbabwe. The principal mandate is, as for its predecessor, the prevention of Red Locust plagues, with the additional responsibility of monitoring and forecasting other migratory pests, such as the African Armyworm, *Spodoptera exempta* and Red-billed Quelea birds, *Quelea quelea.*

Plagues of Red Locust are known to have affected large parts of Africa at least three times in recent recorded history, lasting more than 50 years altogether. Following Uvarov's phase theory, the sources of Red Locust plagues or outbreak areas, were initially identified through the work of two pioneer scientists, A. P. G. Michelmore and H. J. Bredo (Gunn, 1957). It was subsequently realised that the ratio of the size of the outbreak areas compared to the whole invasion area was 1:1500. The task of controlling locusts in the outbreak areas was, therefore, much easier than policing the whole invasion area and led to the adoption of the concept of preventive control.

This paper reviews the development of methodologies for the control of Red Locust and other migratory pests and appraises current techniques. The role of ecological and weather factors in the development of Red Locust plagues is briefly examined. The paper also

Table 1 Outbreak areas of the Red Locust

Outbreak Area	Country
Wembere Plains	TANZANIA
Malagarasi Basin	TANZANIA
Iku-Katavi Plains	TANZANIA
Rukwa Valley	TANZANIA
Mweru wa Ntipa	ZAMBIA
Kafue Flats	ZAMBIA
Lake Chilwa/Chiuta Plains	MALAWI/MOZAMBIQUE
Buzi-Gorongosa Plains	MOZAMBIQUE

highlights the fact that close monitoring of such factors is crucial to the accurate forecasting of outbreaks.

ECOLOGY OF RED LOCUST OUTBREAK AREAS

An 'outbreak area' can be defined as a region capable of producing a swarm from an indigenous and, at some time, non-swarming locust population (Symmons, 1964). Earlier, Key (1945) working on *Chortoicetes terminifera* Wlk defined an outbreak area as an aggregate of outbreak centres.

There are eight recognised outbreak areas of the Red Locust in the IRLCO-CSA's region (Table 1). Some of these areas are believed to have been the sources of the last and earlier plagues (Gunn, 1960). However, swarms which originated from Mweru wa Ntipa and the Rukwa Valley initiated the plague of 1929–44 (Michelmore, 1949). At the time, the other outbreak areas were not yet known and, therefore, their contribution to the plague was not documented. Swarms have, however, been recorded in all these areas since (Figure 2).

The characteristics of Red Locust outbreak areas have been reviewed by Materu (1984) and Gunn (1956). Vesey-Fitzgerald (1955) also carried out extensive studies of the vegetation of the outbreak areas, which are generally all flood plains with a number of other common characteristics including:

- impeded or closed drainage systems;
- extensive grasslands mainly of the species of *Echinochloa pyramidalis*, *Cynodon dactylon*, *Hyparrhenia* spp.;
- *Sporobolus* spp., *Cyperus* spp., etc. forming mosaics of short and tall grasses;
- one rainy season: November to April; and
- fairly wide diurnal temperature fluctuations.

Outbreak areas are unstable environments where there are always permanent locust populations. During upsurges, changes in the ecological conditions lead to more successful breeding and gregarisation. From the inception of IRLCS, it was accepted that better knowledge of the ecology of the outbreak areas would greatly contribute to the understanding of the causes of plagues. Unfortunately, there have been no studies undertaken either prior to or during a Red Locust plague to understand the causes of such plagues. Indeed, as there has been no plague since 1944, the causes can only be deduced from circumstantial

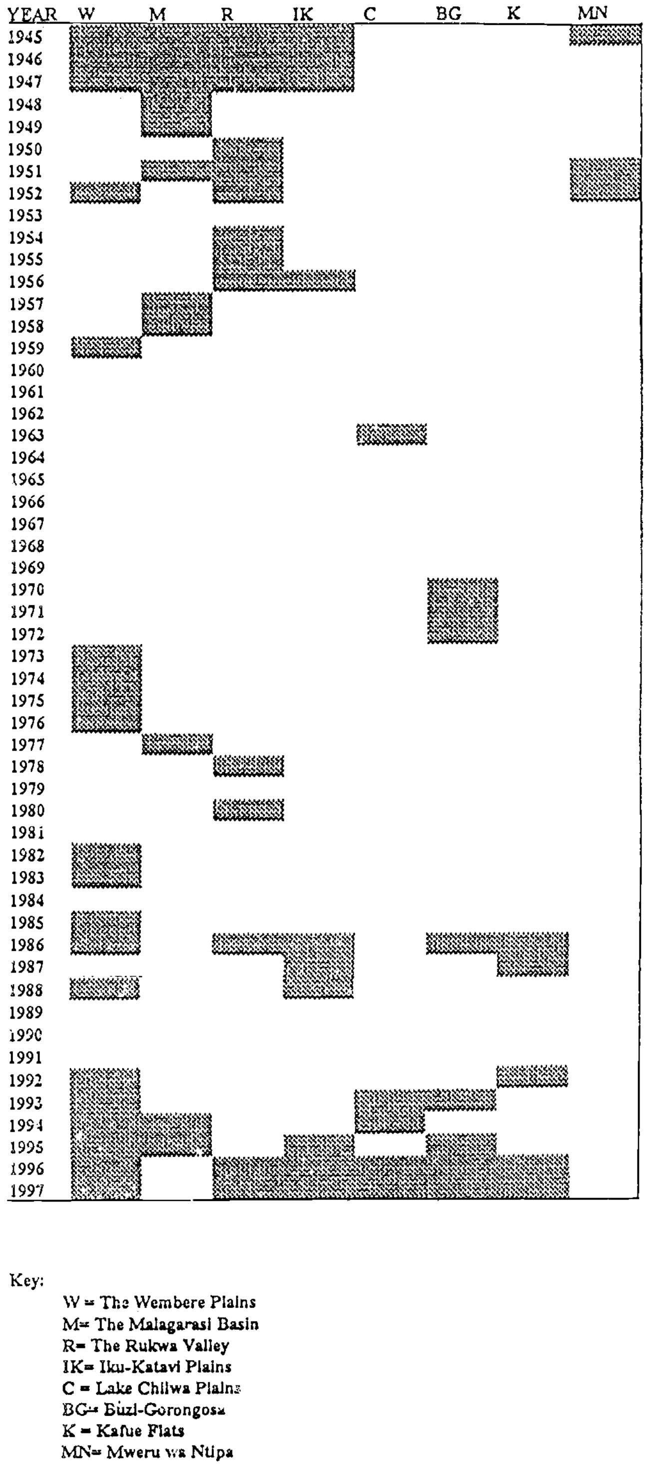

Figure 2 Frequency of swarm formation in Red Locust outbreak areas in 1945–97 (courtesy: A. D. Gadabu).

evidence (Symmons, 1964). Research efforts in outbreak areas have largely been concentrated on control in conformity with the mandate of the organisation. Thus, the need to fully understand the role of ecological changes in outbreak areas as major contributing factors to Red Locust plagues has remained largely unrealised.

PREVENTIVE CONTROL STRATEGIES

Unlike other plague locusts such as the Desert Locust, *Schistocerca gregaria* or Migratory Locust, *Locusta migratoria*, the Red Locust is univoltine. The eggs are laid at the beginning of the rains, around November–December in southern Africa, and hatch after about 30 days. Development to the adult stage takes about 60 days. The adults remain immature until the onset of the next rains. Consequently, the control regime for this locust is closely tied to its life history; first to control the hopper population and secondly to reduce the breeding potential of the adult population. The objective is to prevent swarm formation and population migration out of the breeding areas.

Two concepts evolved from work by IRLCS: (1) insecticidal control and (2) modification of the environment in the outbreak areas. The basis for these concepts is that if control of incipient swarms and hopper bands is carried out in outbreak areas, this would reduce reproductive potential, thus preventing the development of plagues. On the other hand, by transforming the environment of outbreak areas, factors that favour population increase would presumably be eliminated so that locust breeding is inhibited.

Insecticidal Control

The most rudimentary control methods were practised in Red Locust control during the last plague. Thus, hoppers were trapped in ditches and beaten to death or burnt, and adults were whipped with tree branches, but such methods were clearly ineffective (Gunn, 1960). Later, in common with general locust control, there has been a progressive increase in chemical applications against the Red Locust, ranging from extremely poisonous compounds such as arsenic, to more environmentally acceptable formulations. While Red Locust habitats differ from those for other species of locust in Africa, recommendations for the control of the Desert Locust have generally also been accepted for Red Locust. It is only recently that these recommendations are being examined in view of the efficacy on Red Locust of some pesticides that have been found less than optimum for Desert Locust control. In the absence of better control methods, the IRLCO-CSA continues to rely on chemical pesticides.

The outbreak areas are wetlands with a rich flora and fauna. They are, therefore, sensitive to pesticide contamination. Continuous application of pesticides in the same localities could seriously harm the ecological balance of such areas and so there is a need to continue the search for much safer acridicides. A biological control project is presently under consideration, involving the International Institute for Biological Control (IIBC) and IRLCO-CSA, through the LUBILOSA project, in which the feasibility of the use of myco-pesticides for the control of Red Locusts will be determined. The possibilities of using myco-pesticides in the control of Red Locusts are far reaching as an element of preventive control. As naturally occurring pathogens, myco-pesticides offer the opportunity for self-perpetuation and the ability to hold locust populations below swarming levels. Red Locust outbreak areas appear to be better suited for the self-propagation of myco-pesticides than Desert Locust habitats in much more arid areas.

Ecological Control

Flooding levels

Red Locust outbreak areas are periodically flooded. Persistent high water levels in the plains usually coincide with low locust populations. There is evidence that upsurges of Red Locust took place when the lakes in the Rukwa Valley were dry, while recessions occurred when the lake levels were high (Gunn, 1956). Analysis of climate data by Symmons (1959) showed that a high water table in the Rukwa Valley was correlated with poor locust breeding. The results also showed that the amount of rain falling in the catchment area of Rukwa in one season was inversely correlated with locust breeding success of the following generation.

Similarly, studies of lake levels and incidences of swarm formation in Mweru wa Ntipa, one of the sources of the last plague, have also concluded that flooded plains are not favourable to locust population upsurges (Gunn, 1955).

Since the 1960s, the Rukwa Valley has mostly been flooded with high lake water levels. Coincidentally, no serious locust outbreaks have been reported. Similarly, Mweru wa Ntipa, has also been largely flooded. Again, there has been very little recent locust activity in this area. Attempts were made at making some outbreak areas unfavourable for locust breeding through flooding (Gunn, 1957), but they were discontinued because of their costs and the impact such an undertaking would have on the surrounding areas.

Vegetation in locust habitats

Red Locust outbreak areas have common vegetation features (Vesey-Fitzgerald, 1955). The most abundant and common plant species are grasses that colonise different niches depending on soil types, drainage, and water levels. The influence of these grass types on locust population dynamics is yet to be fully understood. However, it is known that the different grass mosaics provide various locust habitats, including food and shelter (Materu, 1984).

The outbreak areas undergo periodic grass burnings that are usually started by pastoralists. Grass burning has the effect of increasing oviposition sites without seriously affecting food and shelter for the locusts. Grass fires have, thus, been found to influence locust populations (Gunn, 1957). In the Rukwa Valley swarms occurred in 10 out of 16 years, a proportion which dropped considerably when controlled burning was introduced (Vesey-Fitzgerald, 1964). The influence of cattle ranching on the grass cover was also tested there but, for various reasons, including mineral content of the drinking water for the animals, tsetse flies (*Glossina* spp.) and marketing, the success of this project was limited (Gunn, 1956; Materu, 1984).

At the height of floods, grass seeds are carried around with flood-waters within the plains. When the flood subsides, the seeds germinate wherever they are deposited, creating a new niche. Thus, over a period, there are noticeable vegetation shifts in the outbreak area but the influence of this shift on locust populations has not been investigated.

Afforestation, as a means of reducing the breeding habitats and therefore influencing locust populations, was also tried in the Rukwa Valley (Robertson, 1958). A number of tree species were planted but did not survive, apparently because the soils were unsuitable for tree survival. Those that grew subsequently died out because of bush fires.

OTHER MIGRATORY PESTS

African Migratory Locust (*Locusta migratoria migratorioides*)

The mandate of IRLCO-CSA has continually been revised to take into account the needs of the member countries and the situation pertaining to locusts in the region. While the organisation was formed to prevent the re-occurrence of Red Locust plagues, in the 1980s, it became apparent that the African Migratory Locust, *Locusta migratoria migratorioides* R & F, was becoming a serious problem to a number of countries. Extensive outbreaks in 1988–90 occurred in Botswana, Malawi, Swaziland, Zambia and Zimbabwe, causing the organisation to include this locust species in its mandate.

No research has been undertaken on this locust by the organisation except for insecticide trials. It was never understood, therefore, why there was a sudden upsurge of the species in the late 1980s. It is possible, however, that the comparatively dry decade of the 1980s may have contributed to the upsurge (Bahana and Byaruhanga, 1988).

African Armyworm (*Spodoptera exempta*) and Quelea birds (*Quelea quelea*)

One of the important changes in the convention governing IRLCO-CSA was for the organisation to assist its member countries to manage other migratory pests, particularly the armyworm, *S. exempta*, and Red-billed Quelea birds, *Q. quelea*. It was recognised that these are trans-boundary pests and that, therefore, a regional intelligence system would be an important ingredient in the management of such pests. In this regard, the organisation would operate a regional database from which long-term forecasts could be made.

The armyworm programme was initially well received by extension departments apparently because it coincided with widespread outbreaks in the region. Training was undertaken and an armyworm pheromone trap system was established in all the member countries. Computers to handle the databases were provided. Unfortunately, the system appears to have ground to a halt for various reasons including:

- the sporadic nature of armyworm outbreaks – the importance of such pests tends to be relegated when there are no outbreaks;
- the cost of back-up service was high, hence computers could not be maintained;
- high staff turnover, common in national extension agencies, so that trained and experienced personnel tended to be lost;
- generally unreliable communication systems in the region.

As for quelea, some of the problems have included: transfers of personnel, reluctance to exchange data by National Plant Protection Units and lack of funds for research into areas of regional relevance, such as migrations of birds.

CONCLUSION

The existence of the IRLCO-CSA is a reminder of the vulnerability of southern Africa to Red Locust plagues. But while the organisation may have succeeded in carrying out its mandate, the paradox is that resources may no longer be made available for this insurance scheme, simply because the threat of locusts is not immediately apparent to planners. Red Locusts are killed in their outbreak areas to avert crop damage. Moreover, outbreak areas are inaccessible except to the organisation's staff and pastoralists, the latter feeling no direct impact of locusts. There is, therefore, a problem of awareness. Because of the economic crises that have beset countries in the region in the 1980s and 1990s, budgetary allocations are continually going to emergencies. Preventive control of locusts is unlikely to be seen, therefore, as a priority.

In view of these economic problems, the need to revisit the strategies for Red Locust plague prevention is more urgent than ever before. Chemical control, which has played an important role hitherto, must be seen in the wider context of environmental concerns, given that Red Locust habitats are sensitive wetlands. The search for biological control and other novel methodologies must be intensified.

The idea of a permanent solution to locust problems is still attractive to many. There are a number of examples of locust species that have been permanently controlled through ecological changes of breeding habitats such as the Mountain Locust in north America (*Melanoplus spretus*), and the Moroccan Locust (*Dociostaurus maroccanus*) in Cyprus (Ashall, 1970).

But the Red Locust may not necessarily lend itself to such control, even if there are indications that flooding could change breeding areas into unsuitable habitats. A number of reasons, both economic and ecological would mitigate against its success.

- As human population increases, outbreak areas are no longer the remote and uninhabitable zones they used to be. Cultivated areas are now slowly encroaching, and human habitation is common in some of these hitherto wild plains.
- Many of the outbreak areas are also game reserves or national parks with many wild animals. Drastic changes of the ecosystem to make them unsuitable as outbreak areas would result in the relocation or death of such animals. This would have serious negative influences on the economies of the countries concerned.
- Outbreak areas are also wetlands with rich flora and fauna. Changes would have serious impacts on the present ecological balance.

It seems, therefore, that research must move faster, to find a permanent solution to the problem of locust plagues before the member governments completely cut financial grants. When the cuts finally come, it will not take long for a Red Locust plague to re-surface. Then to the planner, this will be an emergency worth financing!

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SESSION 2 MIGRANT PESTS AND THEIR IMPACTS

Workshop on Research Priorities for Migrant Pests of Agriculture in Southern Africa, Plant Protection Research Institute, Pretoria, South Africa, 24–26 March 1999.
R. A. Cheke, L. J. Rosenberg and M. E. Kieser (eds) (2000) Natural Resources Institute, Chatham, UK.

4 A Century of Locust Control in South Africa

R. E. Price and H. D. Brown

Locust Research Unit, Agricultural Research Council-Plant Protection Research Institute, Private Bag X134, Pretoria 0001, South Africa
(email: rietrep@plant2.agric.za)

ABSTRACT

It is just over 100 years since the chemical control of locusts began in South Africa when sodium arsenite dust was first applied by hand to Red Locust hopper bands and roosting swarms in Natal (Anonymous, 1906). Although our knowledge of locust outbreak dynamics, insecticide technology, application techniques and intervention strategies has made great advances, locusts remain a serious problem. Outbreaks of Brown, African Migratory and Red Locust still threaten sustainable agricultural production in southern Africa. Due to insufficient early warning and limited operational capacity, Brown Locust outbreaks are only contained after emergency campaigns have been launched. Such a curative control response involves vast expenditure, high insecticide usage and increased risk of environmental contamination. This paper briefly describes the biology and outbreak dynamics of the four species of plague locust occurring in southern Africa and focuses on the Brown Locust – a species of great economic importance for the SADC Region. The status of the Brown Locust in South Africa, the advances made, the current control strategy and operational tactics are highlighted. Whether major locust upsurges can in fact be effectively managed and locust control re-inforced, will be reviewed.

INTRODUCTION

Four species of plague locust occur in southern Africa, namely the Brown Locust, *Locustana pardalina*, the Red Locust, *Nomadacris septemfasciata*, the African Migratory Locust, *Locusta migratoria migratorioides* and the Southern African Desert Locust, *Schistocerca gregaria flaviventris*. All have recently produced outbreaks within the region and have been the target of chemical control campaigns. The species each have different life histories and population outbreak dynamics, inhabit widely contrasting environments, ranging from deserts to flooded grasslands, and thus present unique problems for locust control operations.

Brown Locust

Endemic to the semi-desert Karoo areas of South Africa and southern Namibia, the Brown Locust poses by far the most serious economic problems within the region (Faure and Marais, 1937; Lea, 1958a). With its drought-resistant egg stage, short life cycle with 2–4 generations per year, high fecundity and highly gregarious behaviour, the Brown Locust regularly produces intense outbreaks (Smit, 1939; Lea, 1964, 1970). Eggs are usually laid

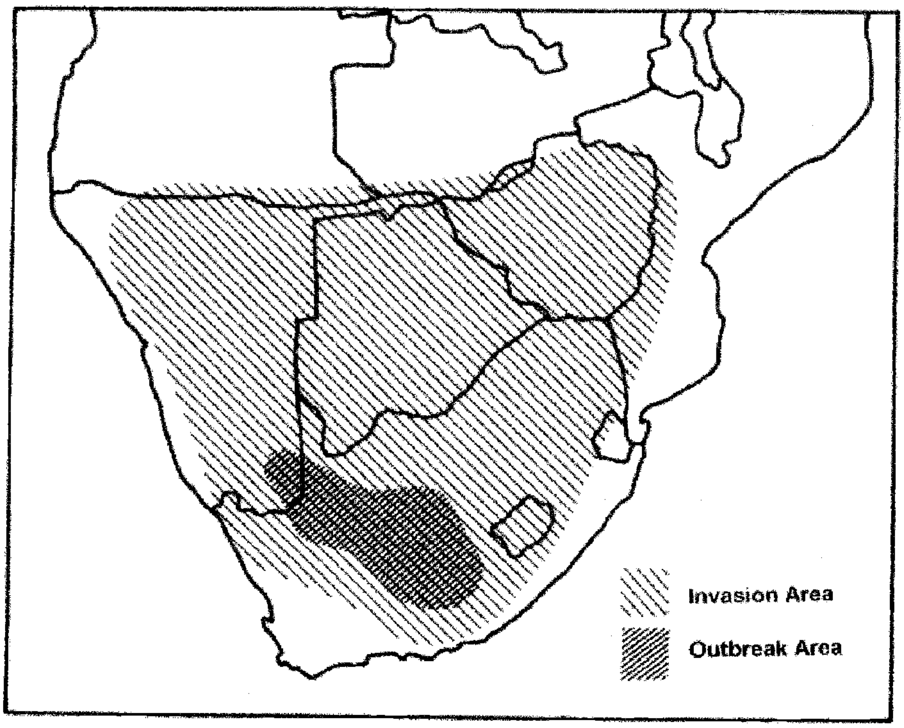

Figure 1 Outbreak and invasion area of the Brown Locust.

in dry soil and during the summer months will hatch approximately 10 days after 15–25 mm of rain has fallen (Smit, 1939). Under drought conditions, eggs enter various states of diapause and quiescence and can remain viable for up to 3 years (Matthée, 1951; Botha, 1967).

Incipient outbreaks generally arise following the end of droughts and are characterised by the dramatic increase in the density of the solitary phase adult population over wide areas of the Karoo (Smit, 1939, 1941; Lea, 1969). Hatching hoppers then aggregate and develop into thousands of small, discrete, highly gregarious hopper bands. For example, over 250,000 hopper bands and 40,000 fledging adult swarms were controlled in the massive 1985–86 upsurge. Swarming populations can then perpetuate themselves for a number of years, requiring an intense control effort, before gradually dying out during another drought cycle. The most recent outbreak cycle (1985–97) was typical of this pattern.

The outbreak and invasion area of the Brown Locust is shown in Figure 1, with the high intensity outbreak area situated in the Northern Cape Province of South Africa. Uncontrolled outbreaks in the past used to threaten agriculture throughout the entire southern African region up to the Zambezi river (Lea, 1970).

Red Locust

The recognised outbreak areas of the Red Locust occur in eight or nine relatively small, seasonally flooded, grassland areas in Central and East Africa (Gunn, 1960; Bahana and Byaruhanga, 1991). With only one generation per year the Red Locust is vulnerable to chemical control and the last major plague cycle (1927–44) ended when the first organochlorine insecticides became available (Gunn, 1960). However, recent population upsurges in southern Africa have demonstrated that outbreaks are difficult to detect in the remote and often inaccessible flooded grasslands (Brown and Price, 1997). Once adult swarms have escaped from these outbreak areas, the highly mobile swarms are difficult to track down and control in the vast invasion area. For example, swarms escaping from an intense outbreak in the Buzi river flood plain grasslands in Mozambique in 1996 flew over 2000 km through Zimbabwe, Botswana and South Africa, with swarms observed over Pretoria for the first time in 50 years.

African Migratory Locust

The Migratory Locust is widespread in grassland areas south of the Sahara and has its main outbreak area in the middle Niger flood plain in Mali where the last plague (1928–41) originated (Steedman, 1990). Over the past 30 years, numerous small-scale outbreaks have developed in various countries in southern Africa, but none of these outbreaks has been large enough to initiate a plague cycle. Outbreaks have occurred in natural grasslands, such as in the east Caprivi in Namibia, but outbreaks have been more commonly reported from cereal crop-producing areas where the adaptable locust has been able to utilise the man-made cropland environment (Farrow, 1974; Brown, 1986). For example, the green feed provided by the winter wheat crop in the Orange Free State in South Africa enhances the dry season survival and allows the locust to produce an early generation in spring which was previously not possible in the original grassland habitat (Brown, 1986). This extra generation and the high fecundity achieved in the summer maize crop enables the locust to produce localised swarming populations during autumn (Price and Brown, 1990). Populations can cause economic damage to newly planted winter wheat before dispersing and largely dying out during the cold and dry Orange Free State winter.

Southern African Desert Locust

This locust is a subspecies of the well-known plague Desert Locust from north Africa and occasionally produces small outbreaks following good rainfall in the red sand dune areas of the Kalahari desert, along the border between Namibia and South Africa. Outbreaks are generally of novelty value only, although small-scale damage has been recorded to irrigated crops along the Orange River in the past (Botha, 1969; Waloff and Pedgley, 1986).

Since the Brown Locust produces regular outbreaks and causes the most serious economic problems in the southern African region this paper will discuss the past, current and possible future control of this species.

PAST ACHIEVEMENTS

Plague Prevention

During the past 50 years, swarming populations of the Brown Locust have largely been confined to the Karoo, with only short-term invasions of neighbouring countries reported, such as in 1986. Virtually no crop damage outside the Karoo has been reported and the threat to food security within the SADC region has been averted. Although large-scale locust control campaigns have been regularly conducted in the Karoo, the actual prevention of plagues has been a success.

Outbreak Frequency

Outbreaks of the Brown Locust develop almost annually somewhere or other in the Karoo. The high outbreak frequency, measured by the number of Magisterial districts in South

Africa, Botswana and Namibia where locusts were chemically controlled each year, shows that there have only been 5 years in the past 50 when no chemical control was undertaken (Figure 2). Outbreak cycles have generally lasted 10–12 years with short drought-induced recession periods between the population upsurges.

Locust Control

The history of Brown Locust control during the past 100 years is summarised in Table 1.

Control strategy

Locusts have traditionally been combated at source in the Karoo before migrating swarms can escape and threaten the cereal crop-producing areas. Farmers are legally required to report the presence of locusts on their land and locust control is the responsibility of the National Department of Agriculture. Most control action is directed at late-instar hopper bands, with spot spraying of the generally small-sized (0.1–1 ha) individual bands taking place shortly after sunrise while still densely aggregated on their overnight roosts. Ultra low volume (ULV) insecticide is applied from backpacks or vehicle-mounted motorised sprayers (Brown, 1988). Roosting adult swarms, which vary in size and may be hundreds of hectares in extent, are usually sprayed from vehicles at night, which allows a longer time to complete the task. Spray aircraft are sometimes used to combat the larger targets.

Acridicides

Regular outbreaks and the relatively easy access to gregarious locust targets have made the Karoo an ideal venue to evaluate new acridicides. During the past 25 years, at least 34 products have been evaluated in laboratory bioassays and in hundreds of field trials by PPRI (Table 2), with 28 products evaluated in the past 12 years alone. Dose range-finding trials are typically undertaken against 5th instar hopper bands in a variety of Karoo habitats and are repeated at different seasons so that the minimum effective dose rate can be established over a range of application conditions (Brown, 1988).

A number of the products listed in Table 2 have now been commercially registered for locust control in South Africa under the Agricultural and Stock Remedies Act (Act 36 of 1947).

With regard to insecticide application technology, South Africa pioneered the use of insecticide baits for locust control and rapidly introduced the organochlorine insecticide BHC when it became available. The first aircraft spray trials were undertaken as early as the 1930s, when arsenic dust was simply emitted into the slip-stream of the aircraft. South Africa also developed its own stacked disc ULV sprayer, the ‘Frans Hugo’, back in the 1970s.

Locust Biology and Outbreak Dynamics

Over 150 scientific articles on the biology and control of the Brown Locust have been published. Important advances in the science of acridology have been made by a number of South African scientists. Professor Faure from Pretoria University, working with caged Brown Locusts, was the first to provide evidence for Uvarov’s theory of the phase transformation of locusts (Faure, 1932), while Matthée’s comprehensive work on egg diapause (Matthée, 1951) is still considered to be a classic study. Work on a wide range of topics, from locust biochemistry to the impact of natural enemies, have been investigated to some extent. The outbreak area has been defined and the frequency and intensity of outbreaks recorded. Smit (1939, 1960) made extensive observations on the behaviour of solitarious

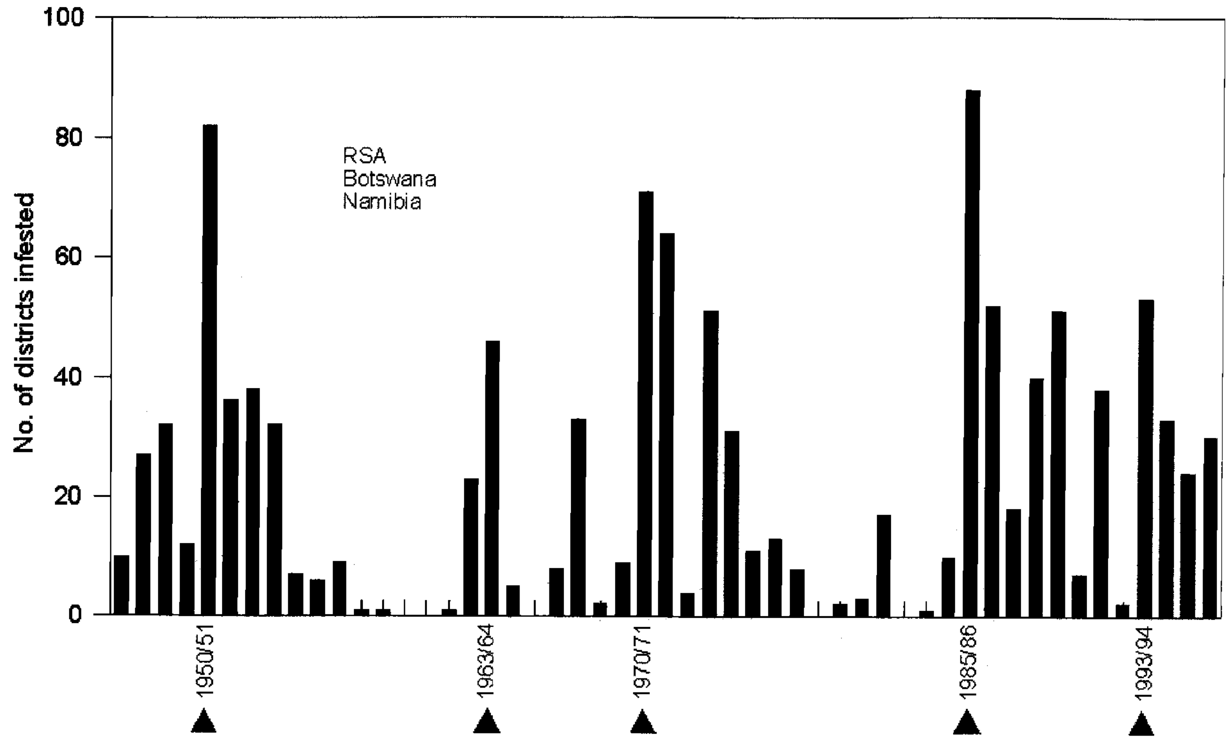

Figure 2 Frequency and intensity of Brown Locust outbreaks 1947–97 (solid bars represent the number of districts infested in the Republic of South Africa, Botswana and Namibia; triangles point to serious Brown Locust plague years).

Table 1 History of Brown Locust control in South Africa

Before 1906	Mechanical and cultural control (trampling, beating, burning pastures, digging up egg beds)
1906–34	Sodium arsenite (liquid and dusting powder)
1934–44	Sodium arsenite baits (bran bait applied by hand to hopper bands)
1945–86	Benzene hexachloride (BHC) (mainly applied as a dusting powder)
1975–94	Organophosphate insecticides (diazinon and fenitrothion applied as a ULV spray)
1990–to date	Synthetic pyrethroids (esfenvalerate and deltamethrin ULV sprays)
Future	New products continue to be registered, e.g. alpha cypermethrin, fipronil, Green Muscle

populations and the development of incipient outbreaks, while Lea (1958b, 1964) described the population dynamics and environmental factors triggering outbreaks.

Outbreak Forecasting

Regular locust population surveys undertaken at fixed sites by locust officers throughout the Karoo from the 1940s up until the mid-1960s allowed an accurate forecasting service to be provided (Smit, 1941; Lea, 1969). However, financial cutbacks have severely reduced the ability to undertake such comprehensive surveys and our ability to forecast outbreaks has deteriorated. Until 1996 there was also a good network of technical contact with neighbouring countries regarding migratory pests under the auspices of the regional Southern African Regional Commission for the Conservation and Utilisation of the Soil (SARCCUS) organisation. However, this organisation has since been disbanded and regional collaboration has consequently deteriorated.

Environmental Impact

South Africa has had a proactive history of introducing safer and more environmentally benign acridicides. Arsenic dust was phased out in the 1930s due to numerous cases of stock poisoning and was replaced by the more target-specific arsenic bait. In the 1970s, the organochlorine BHC was found to persist unduly in the Karoo environment and to have accumulated in the human population (Botha *et al.*, 1974), which led to it being phased out. The high toxicity of the organophosphate insecticides, especially the bird kills and the high number of hospital cases amongst locust officers due to cholinesterase inhibition, led to this class of insecticide being withdrawn in the mid-1990s. The environmental impacts of the synthetic pyrethroids, such as deltamethrin and esfenvalerate, as well as the insect growth regulator, diflubenzuron, have been evaluated in the Karoo. No long-term impact on non-target invertebrates was demonstrated, with most of the fauna rapidly re-colonizing spray plots within a few weeks after treatment (Stewart and Seesink, 1996; Roux, 1998).

A recent highlight has been the field evaluation and commercial registration of the locust-killing fungus, *Metarhizium anisopliae* var. *acridum* (Bateman *et al.*, 1994; Price *et al.*, 1997). This oil-based myco-insecticide, trade name Green Muscle, only kills locusts and grasshoppers and is seen as a viable, ecologically safer alternative to conventional insecticides, especially for use in National Parks and other conservation areas in the Karoo.

Table 2 Acridicides screened against the Brown Locust over the past 25 years

Organochlorines	BHC gamma BHC DNOC DDT
Carbamates	bendiocarb propoxur
Organophosphates	malathion dichlorvos diazinon fenitrothion pyridafenthion phoxim chlorpyrifos
Pyrethroids	deltamethrin fenvalerate esfenvalerate alpha cypermethrin lambda cyhalothrin silafluofen tralomethrin
Combinations	deltamethrin + fenitrothion deltamethrin + pyridafenthion esfenvalerate + fenitrothion
IGRs	diflubenzuron teflubenzuron flufenoxuron
Other compounds	fipronil etofenprox
Botanicals	Neem Syringa oil
Biopesticides	*Metarhizium anisopliae* *Beauveria* sp. *Bacillus thuringiensis* entomopox virus

CURRENT SITUATION

Control Tactics

Locust control in the Karoo continues to be outbreak suppression or the 'fire brigade' approach. The periodic nature of the locust problem excludes the existence of a permanent control infrastructure and control relies on the temporary recruitment of an army of farmers and labourers during a locust outbreak. This so-called 'commando system' has proved effective over the past 50 years as there is a good network of farms, roads and communications in the Karoo. However, the system is becoming inefficient due to high transport costs, and the depressed farming situation has resulted in an increased number of absentee farmers and locked farm gates. This lack of survey and reporting from the more remote areas now means that the control organisation can become overwhelmed during a big outbreak.

The motorised mist-blower spray equipment currently used is effective, although the technology is almost obsolete and should be replaced gradually with more modern spinning disc and spinning cage equipment. Some of this controlled droplet application equipment has already been evaluated under trial conditions with favourable results.

Recurring Outbreaks

The frequency and intensity of Brown Locust outbreaks over the past 50 years, shown previously in Figure 2, suggests that more intense outbreaks occurred during the past 15 years than occurred previously, despite the extensive use of modern insecticides. There now seem to be fewer years with low locust activity and it is possible that the control action is actually preventing the outbreaks from fully gregarising, and burning themselves out, by breaking up the locust populations, as postulated by De Villiers (1987). Are we actually perpetuating a locust problem in the Karoo by preventing the locust 'pot from boiling over'?

Detailed situation maps of Brown Locust outbreaks and control actions recorded each year during the recent outbreak cycle, dating back to 1984, show that there is a definite pattern of swarm movements around the Karoo (PPRI, unpublished). Locust populations are able to utilise the various winter and summer rainfall areas in different parts of the Karoo and there is a seasonal displacement of swarms on the prevailing winds; swarms generally fly in a northerly direction during summer and then east and south-east during the autumn. The maps suggest that although hundreds of thousands of targets were energetically controlled since 1984, the campaign action actually had little effect on the basic pattern of outbreaks. Enough gregarious swarms would evidently escape control in one area of the Karoo to seed the next area where another hopper control campaign would then be waged the following generation or season. Although control action obviously greatly dampened this pattern, insufficient locusts were controlled to actually break the pattern.

The fact that a large-scale Brown Locust outbreak is almost impossible to stop by chemical means alone is supported by evidence from North Africa and Australia, where it is believed that environmental conditions play by far the greatest role in bringing locust outbreaks under control.

Monitoring and Forecasting

There has been recent progress towards developing a Brown Locust situation bulletin and outbreak early warning service, using GIS technology. However, without funding to undertake regular field surveys to obtain accurate information on the status of the locust population the computerised outbreak warning system will be of little value.

Cost of Locust Control

Controlling the Brown Locust has cost the South African taxpayer millions of Rands annually. The massive outbreak in 1985–86 cost over R50 million to control (equivalent to US$25 million at the time), while the recent outbreak in 1995–96 cost approximately R14 million (US$3.5 million). Control costs are bound to escalate in future, especially as expensive insecticides have to be imported. Also, less money is available to undertake research on the development of alternative control strategies than there used to be.

FUTURE OPTIONS

The research priority must be to develop more efficient, cost-effective and environmentally benign methods of controlling the Brown Locust. Whether this entails bolstering the current control system, or incorporating new alternative control methods into a comprehensive Integrated Pest Management (IPM) strategy, must be determined. Various options are discussed below.

Spot Application

The current spot application of insecticide to roosting locust targets can be very effective and has a relatively low environmental impact, although too few targets may be located to stop the outbreak process. How effective is the current commando system and what proportion of locust targets are actually controlled? Scouting for targets could possibly be improved by using micro-light aircraft to monitor remote areas or where access to farms is currently difficult. The search for targets could also be concentrated in specific areas highlighted by an effective locust early warning system.

Blanket Spraying

The aerial spraying of blocks of land infested by locusts is the main technique used during most locust control campaigns around the world. However, the discrete nature of Brown Locust hopper bands would possibly result in the wasteful and environmentally damaging spraying of large areas with no locusts. Blanket treatment against the Brown Locust could, however, be used as a control tactic once a certain threshold number of targets has been reported.

Target-Specific Locust Control

The repeated application of conventional insecticides for locust control in the unique Karoo biome is a cause for concern and there is an increasing demand for more environmentally acceptable methods of controlling locusts, especially in ecologically sensitive areas. Although conventional insecticides are likely to remain the mainstay of locust control for some time, there is an urgent need to develop an IPM strategy for Brown Locust control, which can accommodate alternative control methods, for use in specific areas where a reduced environmental impact is required. Products such as the Green Muscle myco-insecticide and various insect growth regulators have already been evaluated against the Brown Locust and are commercially available.

Other target-specific control options, such as entomopox viruses, botanicals and insecticide baits, require more evaluation. Poison baits were extensively used in the Karoo in the 1930s before being phased out when BHC became available. However, a recent re-evaluation of baiting, using small doses of modern stomach-acting insecticides incorporated into a wheat bran carrier, showed that baiting was an effective and highly target-specific method of hopper band control (Price and Brown, 1997). However, the logistics of bait storage and transport could present problems.

Insecticide Barrier Treatments

The technique of spraying persistent organochlorine insecticides, such as dieldrin, on to narrow strips of vegetation as a barrier against hopper bands was extensively used in Central and North Africa in the past against the Red Locust and the Desert Locust, but was never used against the Brown Locust. However, a new generation of insecticides, with good persistence on vegetation but without the bio-accumulation problems associated with the organochlorines, is now available. Promising candidates include fipronil and some of the insect growth regulators.

The efficacy of barrier treatments against the fast-marching Brown Locust bands in the Karoo, with its sparse vegetation cover, needs to be evaluated. Treatment thresholds also need to be established since barrier spraying, if not judiciously applied, can result in the wasteful spraying of many square kilometres of habitat where there are few locusts. Barriers can also only be used against hopper bands and provide no control of adult swarms.

Target Adults Only

Abandoning the current hopper band control strategy and concentrating the control effort against the fledgling swarms once they aggregate is a tactic that has long been advocated as a more effective use of resources in the Karoo (Cilliers *et al.*, 1964). However, this strategy may require a large number of aircraft to be readily available as the 'window' of opportunity for control is short before swarms start to migrate out of the Karoo. The control of hundreds of swarms once outside the Karoo would cause huge logistical problems.

Direct Crop Protection

Before synthetic insecticides became available the uncontrolled migration of swarming populations from the Karoo led to a long recession period between outbreaks (Lea, 1970). Swarming activity outside the Karoo also soon died out as the locusts were outside their optimum breeding habitat. Due to the escalating costs of locust control, the economic option of suspending locust control in the remote outbreak areas and only concentrating on direct crop protection instead is an idea that has been considered as a cost-effective option in other locust affected regions (Herok and Krall, 1995). However, it is unlikely that this strategy will be adopted in southern Africa due to the national responsibilities regarding migrant pest control and the political sensitivity regarding food security within the region.

CONCLUSION

Despite over 100 years of systematic locust control campaigns in the Karoo, the Brown Locust still has the ability to produce outbreaks that can overwhelm the control capacity. Even though the modern insecticides currently applied are highly effective, the control strategy is still basically how it was 50 years ago. Perhaps Brown Locust outbreaks have been controlled as efficiently as possible and attempts to improve the current system or to implement alternative control methods will not be cost-effective. However, the future aim must be to strive for effective, environmentally benign and cheaper ways of managing locust populations. Whether this is possible is what time and the results of more focused research can tell us.

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5 Quelea Management in Eastern and Southern Africa

Clive C. H. Elliott

Migratory Pests, Plant Protection Service, AGPP, FAO, Rome, Italy
(email: clive.elliott@fao.org)

ABSTRACT

The paper argues that the context of management of the Red-billed Quelea, *Quelea quelea*, in 1999 is significantly different from the context that has occurred in any of the previous five decades. Economic constraints are making it increasingly difficult for some countries to sustain expensive management practices. 'Green' politics in most major donor countries is restricting the availability of donor support, either completely or unless a link to reduced pesticide usage and/or Integrated Pest Managment approaches is evident. 'Green' lobbies in certain quelea-affected countries are pressing for more environmentally friendly techniques as research shows that secondary poisoning is more of a problem than realised hitherto. In this relatively new context, it is proposed that research is urgently needed to create a different range of management options that better fit the economic and environmental concerns of the present day.

INTRODUCTION

Traditional methods to combat depredations of cereal crops by the Red-billed Quelea, *Quelea quelea*, have no doubt existed in eastern and southern Africa since man began cultivating cereal crops. Official management most probably started during the Second World War, when efforts were made to increase grain production to feed troops. Fifty or more years later, with hundreds of scientific papers produced, and, relatively recently, three books published on the quelea (Bruggers and Elliott, 1989; Mundy and Jarvis, 1989; Allan, 1997), one might expect that the subject would have been exhaustively covered and management practices well established. While the general principle applying to any living creature, that the more you know about it the more questions about its biology arise, applies equally to the quelea, the context of the depredations, including knowledge about aspects of management practices, has not remained static but has gradually evolved. It is suggested that the context of quelea management in 1999 is substantially different from the contexts that applied in any of the previous four or five decades.

My own view is that two elements of the context are relatively new. One is that economic constraints are exerting a more and more powerful brake on what can be done, on the amount that governments are prepared or able to invest in quelea management, and therefore what activities are practicable. The other is a combination of stronger 'green' political influences among major donor countries, the beginnings of 'green' lobbies in certain quelea-affected countries, and the greater knowledge we now have indicating that the standard management practice of controlling quelea with organophosphate sprays, leads to more secondary poisoning than was generally supposed (van der Walt *et al.*, 1998). The consequences of this new context are that some donors have taken quelea off their list of priorities while others are willing to support quelea control activities only if they are clearly aimed at reduced pesticide usage and/or introducing Integrated Pest Management (IPM) approaches, and are obviously sustainable. Another result, specific to South Africa, has been an increase in the use of the environmentally cleaner fire-bomb technique, despite its considerably higher cost, in preference to pesticide sprays. It is suggested, that in the light of these developments, there is an urgent need for quelea management to be re-examined and re-orientated, through suitably directed research, to fit the resources and concerns of today.

EXISTING MANAGEMENT PRACTICES

Quelea management by government authorities (as opposed to individual efforts by subsistence or commercial farmers) is, to a greater or lesser extent, currently and regularly practised in eastern and southern Africa by Botswana, Ethiopia, Kenya, South Africa, Sudan, Tanzania, and Zimbabwe. Other countries in the region that previously identified quelea as a problem (Malawi, Mozambique, Somalia, Swaziland, Uganda, Zambia; FAO, 1980) have apparently stopped quelea control for lack of political stability, for lack of resources or for lack of priority, or carry it out only very infrequently. Two additional countries, Eritrea and Namibia, have not yet established regular quelea control, although Eritrea carried out its first operation against quelea in recent times in 1998, with the help of aircraft from the Desert Locust Control Organisation for Eastern Africa.

If only the seven major countries are considered, it appears that most of the control is by the aerial spraying of the organophosphate fenthion against breeding colony and non-breeding roost targets. Only Kenya and South Africa use the fire-bomb technique, and only Zimbabwe (high-volume tractor-borne and handheld ULV machines) and Botswana (vehicle-mounted ULV sprayers) use ground-sprayers. In four of the seven countries, obtaining the resources to continue regular quelea control is becoming more and more difficult. Only in Zimbabwe, Botswana and South Africa, and perhaps Kenya, do resources remain sufficient for control. In Zimbabwe, this is achieved because commercial farmers contribute substantially to the cost. In Zimbabwe and South Africa, it is likely that in future a higher proportion of the resources will go into controlling quelea populations attacking subsistence farming in austral summer. Up to now in these countries, the emphasis has been on protecting commercial farming in winter.

None of the countries attempts to make any routine assessment of the damage caused to cereal crops by measuring the losses incurred in the fields. Some countries make assessments if particularly heavy damage occurs, for example in Tanzania (T. M. C. Tarimo, pers. comm.). Others try to justify the expense of control by calculating the amount of crop that the birds killed would have consumed, e.g. Zimbabwe (Winkfield, 1989), South Africa (Geertsema, 1998). Such calculations often assume that all the birds killed would have eaten cereals on the standing crop, and make assumptions of daily consumption and wastage caused by each bird. The total damaged per bird per day, if the bird is exclusively feeding on cereal crops, has been variously estimated at 8 g (Winkfield, 1989) and 10 g (Elliott, 1989). Estimates based around this level are probably reasonable. Geertsema (1998) assumed only 4 g, which may be correct for the amount consumed but does not take account of the amount of crop wasted. On the other hand, he assumed that all the birds killed had been eating cereal crops. If he had used a damage level of 10 g/bird/day, but had assumed that only 40 % of the birds killed had eaten crops exclusively, he would have reached the same conclusion. The assumption that all birds killed were exclusively eating cereals from the standing crop is likely to lead to large over-estimates of the cost-benefit because quelea almost always include wild grass seed in their diet (Erickson, 1989; Jarvis and Vernon, 1989) and, in any given roost, a significant number will usually eat only grass seed. Recent studies of the food eaten by quelea collected in two provinces in South Africa during control operations showed that none of the quelea had eaten commercial grain (Soobramoney *et al.*, 1998).

Quelea management policy in the seven countries varies, but all of the countries would probably agree that quelea are only targeted when they are perceived to threaten crops or have already started to attack them. None would hold to the view, which was held in some quarters in the 1960s and subsequently discredited for ecological and economic reasons, that an effort should be made to eradicate the quelea from the face of the Earth. In the case of breeding colonies, sometimes the degree of threat is difficult to evaluate. If breeding colonies are near substantial areas of crop, which has become accepted to mean within 30 km (Elliott and Allan 1989; Allan, 1997), they would be controlled in Sudan, Ethiopia, Tanzania and Botswana, if the resources to do so are available. In Kenya, colonies normally occur only in areas relatively remote from agriculture, where they are not usually controlled and only those close to crops are controlled in South Africa. Although colonies occur close to subsistence farming in Zimbabwe, traditionally they have not been controlled there by spraying. Sometimes local people raid them to collect nestlings, but this appears to be done more to obtain some good quality protein food, than as a crop protection measure. The Zimbabwe colonies are remote from commercial cereal farms.

Management policy on roosts would be to control those that have already started to attack crops or that occur at certain times of year when crops are vulnerable and in traditional sites from which such attacks usually develop. Roosts occurring during seasons in which no crops were ripening would normally be left alone.

The policy on the choice of tactic varies from country to country. In eastern Africa, it appears to follow a tradition in that aerial spraying is used at certain times of year in certain areas. In Kenya, fire-bombs are used later in the cropping season when roosts form close to cultivation in tall eucalyptus plantations which are often less than a hectare in area. In Zimbabwe, the cost of the tactic is taken into account and the cheapest effective method chosen (Jarvis and Mundy, 1989). Interest in cutting costs has led to the development of the 'trap-roost' concept whereby stands of napier grass (*Pennisetum purpureum*) were grown near crops in such a way that they could easily be accessed with a tractor-borne mist-blower. It was hoped that the napier grass would be chosen as a roost by quelea, allowing easy and cheap control. In the event, this idea has not been widely adopted because the quelea did not choose the site prepared for them often enough. The policy has also tried to take into account the potential damage which a quelea roost can cause. Farmers are encouraged to count the birds and to assess whether there are sufficient numbers of birds to make an impact on the crop. Aerial operations were only carried out if the estimated number of birds reached about one million. The method for making such an estimate (Jarvis, 1989) is highly approximate. My own observation in Zimbabwe suggests that over-estimates may have often resulted, leading to aerial spraying taking place when it was not justified according to the official criteria. Aerial sprays are now done only when roosts are either too large or too difficult of access to be controlled with ground-sprayers (P. J. Mundy, pers. comm.). Allan (1997) suggested that only quelea in concentrations of more than 250,000 birds, which are a threat to crops, constitute legitimate targets, but gave no explanation as to why this number should be chosen rather than a higher or lower one.

In South Africa, in response to concerns about secondary poisonings, a policy decision has been taken to control roosts with explosives whenever possible. In effect, the technique can only be applied to small roosts usually of up to about 4 ha in eucalypts or acacia and up to 2 ha in reed beds (L. Geertsema, pers. comm.). The proportion of control actions with fire-bombs has risen to about half of all the interventions made, although the proportion varies somewhat from season to season. Although the fire-bomb costs significantly more than aerial spraying, the number of birds killed is often considerably higher which makes the difference in cost smaller (L. Geertsema, pers. comm.).

In making the decision to control or not to control, apart from the threat to a cereal crop and the cost/benefits mentioned above, Elliott and Allan (1989) suggested that the policy on the decision should include an assessment of the importance of the crop. Importance was subdivided into local, national and political. While these factors would seem still to be valid, they are usually not articulated, especially the political element.

One last aspect of quelea management policy concerns environmental aspects. The fact that non-target birds and, occasionally, other vertebrates may be killed by quelea control operations is well-established (Meinzingen *et al*., 1989; Keith *et al*., 1994; van der Walt *et al*., 1998; Verdoorn, 1998). The impact of this knowledge on management practice in eastern and southern Africa is variable from country to country. In most countries, the pressures to carry out control in situations in which serious crop damage is underway are sufficiently heavy that environmental considerations will have little impact. Despite appropriate training, many quelea control staff may not easily recognise that controlling a particular target will endanger a significant number of non-target birds.

Colonies that have attracted unusually large numbers of predators, or roosts that are adjacent to wetland habitats, are cases in point. Disasters involving the deaths of hundreds of raptorial or other non-target birds have been recorded from time to time. To keep the problem in perspective, it should be remembered that, compared to other forms of agricultural spraying, the areas of quelea concentrations sprayed are very small. For example, South Africa controlled annually an average of 185 sites, with an average size of 7.3 ha during the years 1987/88–1997/98 (Geertsema, 1998); Ethiopia, 37 sites of 41 ha (Abdurahman Abdullahi, pers. comm.); Sudan, 145 sites of 205 ha (Ali Mohamed Ali, pers. comm.). While some of these may sometimes cause ecological disasters, the impact on non-target bird populations is likely to be minimal. Most governments in principle support efforts to minimise side-effects, but only a few, primarily in southern Africa, have the resources, skills or priority to implement them.

DISCUSSION

In the past, efforts have been made to estimate the extent of crop damage caused by quelea (Elliott, 1989). The collecting of crop damage data directly from the standing crop has always been an arduous, time-consuming and costly exercise, with the result that data for making estimates are limited. When damage is underway or perceived to be imminent, priority is given to control action. There is seldom an opportunity to measure damage in circumstances in which no control at all has taken place. When resources are limited for control, they are likely to be non-existent for damage measurement. Such a situation is typical for migratory pests in general and makes it difficult to assess economic impact (see Joffe, 1998, for the Desert Locust, *Schistocerca gregaria*).

The conclusion reached previously by the author on the quelea was that on average annual losses suffered by major affected countries amounted to one or two million US dollars per country, but that these losses were probably less than 5% of national production of the cereals concerned (Elliott, 1989). Nevertheless individual farmers, groups of farmers or large farms could occasionally suffer catastrophic damage to their crops. As has been said many times, the situation is complicated in quelea, as it often is with other migratory pests, by farmers' perceptions and their tendency to exaggerate their losses. Because quelea flocks are so conspicuous, farmers often over-estimate the numbers of birds in their fields and over-estimate the threat they pose. Their concerns are transposed into political pressure for quelea control teams to take action against the birds, partly to reduce the farmers' complaints. An important element in the equation is that in most countries, quelea control is carried out by the government at no cost to the farmers. Farmers have nothing to lose financially if they complain to government and vociferously demand action, and they may gain a little more yield if the quelea are removed. Sometimes, of course, their complaints are fully justified and, if nothing is done, serious damage will result. It appears that this outcome is more often the exception than the rule. If so, the quelea problem is as much caused by farmers' perceptions as it is by the birds.

In summary, it could be said that the first element of the quelea problem is that the species eats cereal seeds from the standing crop, in addition to its natural diet of wild grass seeds. The second is farmers' perceptions and as an extension of this, the fact that control operations are normally conducted for them free of charge. The third is the environmental side-effects produced by all forms of control, but particularly by the aerial spraying of pesticides. On the last, the occasional disasters that occur can be very bad publicity for a government that espouses conservation and promotes ecotourism.

What does this summary mean in terms of defining research/development priorities? For quelea ecology, it would suggest that emphasis should be given to two elements. One is to understand more about what factors cause quelea populations to feed more on cereal crops in one year than another. Is the proposal, originally made by Ward (1965), that the quelea turns to cereal crops only when its natural food is short still valid? Given a situation such as in Zimbabwe, where irrigated winter wheat always provides a food source during the dry season when it is presumed that the quelea's natural food is becoming short, is the pressure on the crop always the same each year? In some years, only nuisance-level damage might occur, and control could be minimised. Answers to such questions might allow the years in which severe damage would occur to be identified, in which case control with pesticides would be justified. Furthermore, if it was known where quelea that cause damage were coming from, and how their population distribution changed during the year, it might be possible to identify certain times of the year when most of the population later causing damage was concentrated in one region. This might offer the possibility of strategic control of major roosts or colonies, such that bird pressure later in the year would be reduced. It would also justify another effort among southern African countries to establish a quelea population monitoring network. Standard monitoring forms are available and a network of observers who live and work in quelea areas (agricultural extension staff, game scouts, tsetse officers, etc.) could be established in the region. Resources would also have to be made available to collect and analyse the data.

In respect of farmer perceptions, it was proposed at the 22nd International Ornithological Congress that Integrated Pest Management (IPM) approaches should be investigated for quelea management (Elliott and Craig, 1998). The core of this approach, which is being used increasingly successfully in Asia to reduce pesticide usage, is to work with farmers to minimise as far as possible the vulnerability of their crop to quelea attacks. In so doing, farmers are encouraged to understand where bird damage fits into the spectrum of all the factors that affect the final yield. The process is intended to help farmers recognise when quelea pose a serious threat and when they are merely a nuisance and likely to have little impact on the yield. The different IPM elements have been tried with quelea in the past in many different situations sometimes with success, but as a package combined with IPM techniques such as farmer field schools and demonstration farms, it would be a new development. Part of the IPM package is to give serious consideration to charging some of the cost of control to commercial farmers and to exerting pressure on subsistence farmers to follow directives on reducing crop vulnerability. Another aspect of IPM that deserves a new emphasis is the possibility of harvesting quelea for food. While present indications are that harvesting is probably not an option as a crop protection technique, it offers the possibility of providing income to rural populations in compensation for crop losses. It may also make a contribution psychologically, as farmers who are catching some birds for food may feel that they are combating the problem rather than doing nothing. Further research on the economics of quelea damage may help to clarify the issue, but it is suggested that the quelea problem, for governments, will not go away as long as many farmers perceive quelea as a problem and therefore complain.

There is also a strong case for further research on how to carry out control, especially pesticide control, in such a way as environmental side-effects are minimised. In the last 20 years, the direction of control improvements has tended to be towards decreasing the quantity of pesticide used per hectare treated by using smaller spray droplets. When quelea were first controlled aerially, fenthion was mixed 50:50 with diesel and larger droplets were used. Apparently, the following dawn, almost all of the quelea were dead (R. G. Allan, pers. comm.). Current techniques mean that 30% or more of the birds are still fluttering in the trees the next morning and a significant number, partially contaminated, are able to fly away from the roost and distribute themselves over a large area, very much extending the potential secondary poisoning. Research is needed on how to achieve a complete knockdown by the following morning with no movement away from the target site. In eastern Africa, investigation is also needed into target definition to find out why targets, in Ethiopia and Sudan for example, are reported as being six times and 30 times bigger, respectively, than those in South Africa, and whether this reflects a real difference in quelea biology or poor estimates of the size or location of the aggregation. Another element that requires investigation is how to make the fire-bomb easier and cheaper to use, so that it may be employed more often as an alternative to pesticides.

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6 Institutional Co-operation to Address Socio-economic Aspects Related to Migrant Pests of Agriculture in the Southern Africa Region

M. J. Botha

NDA – Directorate Land and Resource Management, P/Bag X120, Pretoria 0001, South Africa
(email: T_C@yebo.co.za)

ABSTRACT

The southern African region referred to in this paper comprises the 14 member countries of the Southern African Development Community (SADC). The influence of migratory pests such as locusts and Red-billed Quelea on agricultural production and its contribution to the alleviation of rural poverty in the region is highlighted. Networking in a co-ordinated manner among present institutional structures to address research needs and migratory pest control measures to enhance food security, which in turn contributes to poverty relief, is an essential goal. In the past the Southern African Regional Commission for the Conservation and Utilisation of the Soil (SARCCUS) Sub-Committee for the Control for Migratory Pests played a major role in the southern African region, to achieve such a goal. The incorporation of SARCCUS's Sub-Committee for the Control of Migratory Pests into the new SADC Crop Sector opens new horizons and offers new challenges to achieve this goal.

INTRODUCTION

The aims of this workshop are to identify the key issues for promoting the uptake and impact of research on migrant pests in southern Africa. The participants include a variety of institutional managers, an experienced body of scientists, researchers, and also last, but not least, experienced managers and operators of crop protection. I classify myself under this last category and will address the topic of *Institutional Co-operation to Address Socio-economic Aspects Related to Migrant Pests of Agriculture in the Southern African Region*, as seen in the eyes of such a manager. Furthermore when referring to southern Africa, I am referring to the sub-regional body of Africa known as the Southern African Development Community (SADC), comprising the 14 following countries in alphabetical order: Angola, Botswana, Comoros, Democratic Republic of Congo, Lesotho, Malawi, Mauritius, Mozambique, Namibia, South Africa, Swaziland, Tanzania, Zambia, Zimbabwe.

SOCIO-ECONOMIC ASPECTS

Migrant pests are a natural phenomenon and only when they threaten man's livelihood do they pose a problem. Through grain crop production practices for example, man has

Table 1 1996 land use dynamics of SADC countries (World Bank, 1998a)

Country	**Total area ($km^2 \times 1000$)**	**Arable land area ($km^2 \times 1000$)**	**% Arable land**
Angola	1247	37.4	3
Botswana	582	5.7	1
Comoros	3	0.7	35
Dem. Rep. Congo	2267	68.0	3
Lesotho	30	3.0	1
Malawi	94	16.9	18
Mauritius	2	1.0	52
Mozambique	784	31.4	4
Namibia	823	8.2	1
South Africa	1221	39.7	13
Swaziland	17	2.0	11
Tanzania	884	35.4	4
Zambia	743	52.0	7
Zimbabwe	387	30.9	8
Total	9084	332.3	3.7
United States	9159	1923.0	21

disturbed nature's sensitive balance, by simultaneously increasing the availability of food sources for pests. Table 1 reflects the distribution of arable land in the SADC region (World Bank, 1998a). The arable land includes land defined by the Food and Agricultural Organisation of the United Nations (FAO), as land under temporary crops (doubled cropped areas are counted once), temporary meadows for mowing or for pasture, land under market or kitchen gardens, and land temporarily fallow. Land abandoned, as a result of shifting cultivation is not included, nor is land on which trees are grown for wood or timber. From the table it is very clear how scarce the SADC countries' arable land sources are. Only 3.7% of the total land area consists of arable land, compared to 21% of a developed country such as the USA, whose total land area is of the same proportions as the SADC region. In the past, demand for food was met by growth in arable land area under cultivation. For the last 10 years, however, global growth in arable land area has been zero. The world is almost entirely dependent on increased yields to expand agricultural production.

The SADC countries are no exception to this rule. The rural population indicated in Table 2 is the difference between total and urban population. The table clearly indicates that migrant pests such as Red-billed Quelea, *Quelea quelea*, locusts and African Armyworm, *Spodoptera exempta*, threaten 122.9 million people in the SADC region (67% of the total population) whose livelihoods depend on agriculture and subsequent food production. The poor food security position of the region is highlighted by comparisons. The 0.18 ha/capita arable land is meagre in comparison with a country such as the United States, which has 0.71 ha of arable land per capita, with which to feed its population and also to contribute to its Gross Domestic Product (GDP) with exports. The rural population density (i.e. the rural population divided by the arable land area), of 370 people/km^2 for the SADC region, is more than tenfold that of a developed country such as the United States, where there are 34 people/km^2. The potential economic loss caused by migrant pests on a crop in the SADC region, and on the livelihoods of the rural population there, is therefore also more than tenfold that of their counterparts in the USA.

Table 2 1996 population and land use dynamics of SADC countries (World Bank, 1998a)

Country	Total population (millions)	Rural population (millions)	Rural of total population (%)	People/km^2 arable land (number)	Arable land (ha/capita)
Angola	13.3	9.3	70	248	0.28
Botswana	2.1	0.9	46	168	0.27
Comoros	0.6	0.4*	67	400*	0.17*
Dem. Rep. Congo	40.0	29.2	73	429	0.17
Lesotho	1.9	1.4	74	470	0.16
Malawi	10.0	8.5	85	505	0.17
Mauritius	1.1	0.7	64	668	0.09
Mozambique	18.5	12.3	66	391	0.17
Namibia	1.6	1.0	63	121	0.51
South Africa	39.7	20.3	51	128	0.40
Swaziland	0.9	0.6*	67	300*	0.22*
Tanzania	32.2	25.7	80	728	0.11
Zambia	8.9	5.1	57	97	0.59
Zimbabwe	11.4	7.5	66	244	0.27
Total	182.2	122.9	67	370	0.18
United States	270.8	65.4	24	34	0.71

*Extrapolated
Total average used because actual figures not available

The Gross Domestic Product (GDP) figures (Table 3) represent the sum of total consumption and gross domestic savings per country (World Bank, 1998b). Although the contribution of agricultural production to GDP of the SADC region weighted average (wm), only amounts to 12.8%, its contribution varies from as little as 4.5% for Botswana, to as much as 59.4% for Tanzania (J. A. Radebe, pers. comm.). Similarly, GDP per capita

Table 3 Gross Domestic Product (GDP), agriculture's contribution, and GDP/capita of SADC countries (World Bank, 1998b)

Country	GDP (US$ Billion)	Agriculture (% GDP)	GDP/capita (US$)
Angola	10.0	15.7	752
Botswana	4.6	4.5	2190
Comoros	0.4	40.0	685
Dem. Rep. Congo	18.0	59.0	450
Lesotho	0.9	11.3	461
Malawi	2.2	39.8	220
Mauritius	3.2	9.7	2909
Mozambique	1.4	35.0	76
Namibia	2.8	15.3	1750
South Africa	130.0	4.7	3275
Swaziland	1.0	9.1	1097
Tanzania	2.3	59.4	71
Zambia	3.3	18.1	370
Zimbabwe	6.3	13.9	550
Total	186.4	12.8 (wm)	1022 (wm)
United States	8083.0	2.0	30200

weighted average for the SADC region amounts to US$1022 but is as low as US$71 in Tanzania. The values for nine of the SADC region countries are below the average GDP per capita income of US$1022, which is only 3.4% of the GDP per capita income of a developed country such as the United States, whose GDP per capita income is US$30,200. Countries such as Comoros, Democratic Republic of the Congo, Malawi, Mozambique and Tanzania whose majority of per capita income is derived from agriculture, are therefore very vulnerable to impoverishment because of the threat of migrant pests of agriculture. The fact that the other SADC countries have other alternative sources of income however, does not alter the fact that they too are vulnerable to impoverishment as a result of migrant pest damage to agricultural production, if you take into consideration their relative low per capita income.

INSTITUTIONAL CO-OPERATION

Migrant pests in the southern regions of the African continent do not recognise political boundaries and it is also a fact that agricultural resources such as rivers and indigenous vegetation are not subject to territorial delimitation. Just as national boundaries cannot prevent the spread of plant and animal diseases, so do migrant pests such as locusts and quelea traverse countries of southern Africa with total disregard of territorial distinction. There is, therefore, inter-dependence and a need for territorial co-operation with regard to the management of migrant pests and their possible control and further research.

Many countries were aware of this fact and in 1948 various territories in southern Africa met at the Inter-African conference at Goma, to discuss issues such as land utilisation incorporating migrant pest control (Bridgens, 1989). Shortly after the Goma meeting, a conference was held in London where it was unanimously agreed that an inter-Governmental Commission for Technical Co-operation in Africa South of the Sahara (CCTA) be set up. The CCTA was to function as an overall policy forming and administrative body, to promote inter-territorial co-operation in all fields of social and economic development in Africa South of the Sahara. In the same year, at an African Regional Scientific Conference held in Johannesburg, South Africa, the Scientific Council of Africa South of the Sahara (CSA) was brought into being as a purely scientific body to act as adviser to CCTA.

The subject of liaison and inter-relationships between sub-continent organisations such as CCTA/CSA and regional organisations such as Regional Committees is a complicated one. Suffice it to say, that it followed that technical work best undertaken on a sub-continent scale was undertaken by CCTA/CSA, while technical work focused more on local issues at regional level was undertaken by the Regional Committees. Proceedings and recommendations of Regional Committee meetings were distributed amongst CCTA, CSA and other Regional Committees to sustain an inter-communication process. One of the Regional Committees, which originated from this milieu, was the Southern African Regional Commission for the Conservation and Utilisation of the Soil (SARCCUS), which held its inaugural meeting in Pretoria, South Africa, on 5 June 1950. After 12 years, during which SARCCUS functioned by way of rapporteurs, six, and later ten, Standing Committees were initiated. With the cessation of CCTA in 1964, the change of SARCCUS to that of an autonomous Regional Commission was ratified. The SARCCUS Region's northern boundary was determined as the sixth latitude line of mainland Africa and adjoining Islands. However, not all the countries within that boundary joined the organisation. The following countries (in alphabetical order) were active members: Angola, Botswana, Lesotho, Malawi, Mozambique, South Africa, South-west Africa/Namibia, Swaziland.

SARCCUS's aim was to promote technical co-operation with a view to achieving tangible benefit for all member countries whilst ignoring any political differences that might have existed amongst member countries. This purely technical, non-political, stance facilitated many significant contributions which the Commission made to southern Africa during its time.

A subcommittee for Migratory Pests addressed aspects of migrant pests of southern Africa under the Standing Committee for Plant Protection. This subcommittee convened once a year on a rotational basis amongst the member countries during which every country reported on the scope of control of migrant pests and also relevant research project findings of the previous year. The member countries also established a reporting network, administered by the SARCCUS Secretariat, on migrant pest movements throughout the region, which functioned as an early warning system. The tenth and last meeting of this subcommittee was held in Windhoek, Namibia, during June 1997. Since then SARCCUS has been in the process of being incorporated into the SADC structure.

The SADC Ministers of Food, Agriculture and Natural Resources (FANR) have approved the proposed Terms of Reference for the new SADC Crop Sector, which has been allocated to Zimbabwe for co-ordination (M. Molope, pers. comm.). According to the terms of reference, the main objectives will be to promote the output, protection, processing, storage and utilisation of all crops, including perennial crops, as a means of enhancing food security and promoting trade and economic development. The ministers also agreed that the new Sector Co-ordinating Unit for Agricultural Research and Training should concentrate on co-ordinating research in crops and livestock, working closely with the Crop Production and Livestock Sectors.

CONCLUSION

The importance of co-operation and networking amongst SADC countries and international institutions to address rural poverty alleviation was highlighted at a workshop held in Cape Town, South Africa, during February 1996, sponsored by the SADC Secretariat, the World Bank and the International Fund for Agriculture and local authorities (IFAD, 1996). The influence that migrant pests of agriculture have on agricultural production, food security, GDP per capita and poverty alleviation programmes speaks for itself. The strong foundation that has been created by the amalgamation and streamlining process to form a broader SADC body offers the opportunity to network migrant pests of agriculture aspects in order to obtain the set goal of poverty alleviation.

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SESSION 2A CURRENT MIGRANT PEST RESEARCH BASED IN SOUTHERN AFRICA: LOCUSTS

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7 Modelling Brown Locust Outbreaks

D. Tilch and S. A. Hanrahan

Department of Zoology, University of the Witwatersrand, WITS 2050, South Africa
(email: SHIRLEY@gecko.biol.wits.ac.za)

ABSTRACT

South Africa has a long tradition of locust research and control. The life history and biology of the Brown Locust, *Locustana pardalina*, are documented, but little is known of the species' population dynamics. To understand the mechanisms driving population fluctuations of the Brown Locust, a model for simulating plague events was developed using MATLAB (MATLAB, 1992). A rule-based model that determined the transitions between stages of the locust life-cycle, contingent on daily rainfall and temperature records, was enhanced by migration probability functions based on distance between stations, wind speed, locust flight duration and wind heading.

In order to test simulation effectiveness, simulations for specific stations were compared with data on swarms eradicated in each magisterial district. This information had been collected to pay locust control officers and was used despite the limitations of its accuracy. Rainfall, temperature and wind data were supplied by the South African Weather Bureau.

It was assumed that incorporation of wind-facilitated migration into the basic model would increase the accuracy of predictions. The inclusion of migration tracking routines improves the simulation of outbreak events with respect to timing.

INTRODUCTION

South Africa has a long tradition of locust research and control. The life history and biology of the Brown Locust, *Locustana pardalina*, are documented, but little is known of the species' population dynamics.

The research described here was part of a collaborative project between various departments of the Agricultural Research Council, namely the Locust Research Unit of the Plant Protection Research Institute (PPRI), the Institute for Soil, Climate and Water (ISCW), the Directorate: Land and Resource Management (DLARM) and University of the Witwatersrand (WITS). The project aims included the development of an early warning system for the Brown Locust. The broader aims of the collaboration were to:

- collect and collate locust data in the outbreak region
- carry out retrospective analysis and mapping of locust outbreaks
- improve locust monitoring systems
- analyse weather data for the outbreak region

- model locust outbreaks
- develop an early warning system using weather data, vegetation indices and locust data, integrated into a Geographic Information System (GIS).

The specific aim of the work presented here was to build a locust life-cycle model from information derived from the literature and from the practical experience of staff of Wits and the Locust Research Unit of PPRI.

The Brown Locust is restricted to the more arid regions of southern Africa, to which it is well adapted. Features of the life cycle have recently been reviewed by Price (1988) and Hanrahan (1988). A resident population of the solitary form provides a constant base from which swarming populations can develop, apparently with little warning (Lea, 1958). Eggs are particularly well adapted to arid conditions. They can survive long periods in the dry sandy soils (Matthée, 1951; Price, 1988) and over-winter. The eggs have a complex diapause, which allows a small proportion of them to remain unhatched even after the normal diapause period is broken and ideal hatching conditions have been experienced (Matthée, 1951). This allows large populations of eggs to build up in the soil over several seasons (Du Plessis, 1938). The eggs can begin embryonic development but suspend the process and survive up to 45% dehydration and later re-hydrate to continue development when the next rains occur. The process of dehydration and re-hydration can be repeated several times (Matthée, 1951). Embryos have survived for as long as 3 years in this way (Lounsbury, 1910), but in the field viability declines with time (Botha, 1967).

Extensive marching of hopper bands occurs, but this has been ignored as only short distances are covered. Adult gregarious Brown Locusts undertake largely low altitude flight, 10–20 m above ground. Migration generally starts after sunrise and is temperature-dependent, but night flying also occurs. Factors causing cessation of flight are not clearly established. The important features for the model are locust readiness for flight and wind conditions on a particular day.

The area in which outbreaks are common has an erratic rainfall, and is thought to be influenced by El Niño effects on the Southern Oscillation. Efforts to show a direct correlation between deviation in rainfall and locust 'boom and bust' patterns have not been successful.

MATERIALS AND METHODS

Information on swarms eradicated in each magisterial district, collected to pay locust control officers, were used despite the limitations of its accuracy. Data were accumulated into monthly totals for each magisterial district. Rainfall, temperature and wind data were supplied by the South African Weather Bureau. The rainfall and temperature data are recorded daily figures whereas the wind data are generated from wind model data used by the Weather Bureau. Records were searched to find reasonably uninterrupted data series for particular stations that matched a particular locust outbreak. Data from 1986–89 were used, when the last severe outbreak occurred. Efforts were concentrated on four areas namely Douglas, Pofadder, Graaff Reinet and De Aar (Figure 1).

The model consists of two fairly independent sections. The first part is based on the locust life cycle and is derived from an earlier version of the model (Nailand and Hanrahan, 1993). The second section deals with migration (Tilch, 1998).

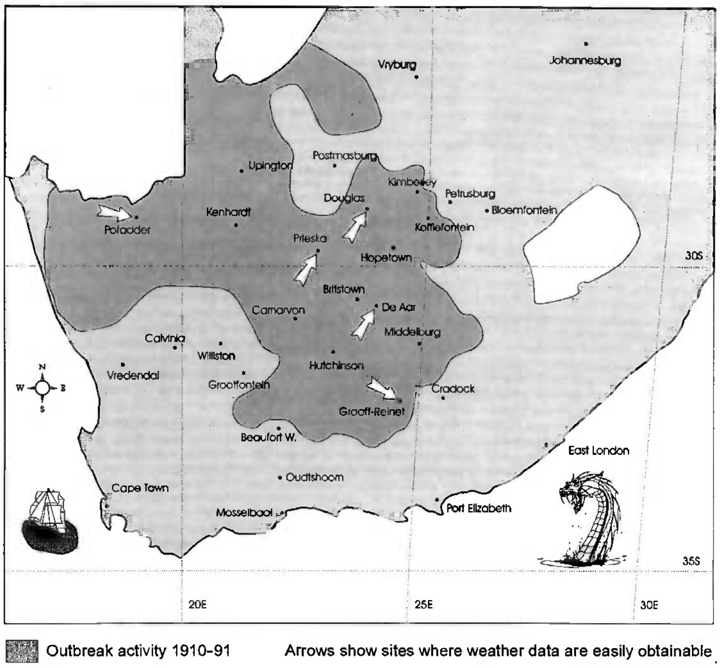

Figure 1 Map of South Africa showing main locust outbreak area 1910–91. Locust control data are catalogued according to magisterial district and weather data according to weather station, mainly located in towns and on specific farms.

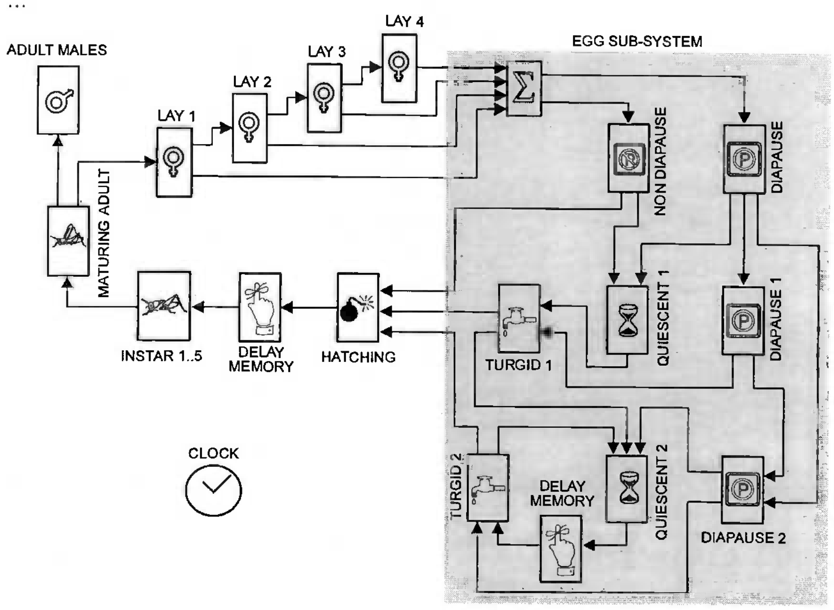

Figure 2 The model of the Brown Locust life cycle set out as a block diagram. The shaded area represents the egg stages of the life cycle, showing the complexity of two levels of diapause as well as the cycling between quiescence when eggs dehydrate during dry spells, and turgidity when eggs rehydrate after rain. Eggs only hatch once diapause is broken and they have acquired enough moisture to remain turgid while they complete embryonic development. The clear section on the left of the diagram represents post-hatching instars. Males are noted but not modelled further. Females are shown laying a maximum of four egg packets at fixed time intervals.

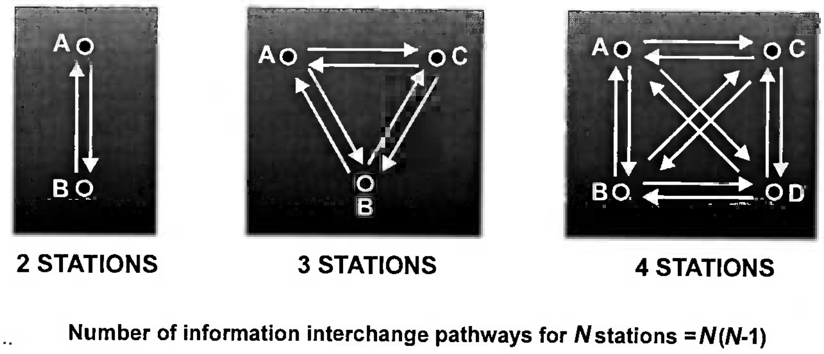

Figure 3 Data interchange paths for increasing numbers of stations. A–D = possible locust stations. Arrows indicate possible migration pathways with different wind directions.

The first section of the model uses a rule-based system, dependent on life-cycle parameters to track locust population changes driven by rainfall and temperature at a given site (Starfield *et al.*, 1994). Adequate rainfall is used as the trigger to stimulate egg development. The model updates all individuals at increments of one day on the basis of the rules set. Much of the update of development through the life cycle is dependent on equations for calculating degree-days.

The migration section of the model is constructed differently. On the basis of other studies, it was decided that the following were important considerations.

- Migrations occur predominantly in a down wind direction.
- They only occur if the temperature is sufficiently high.
- The insect flight speed is irrelevant and the rate of movement is that of the prevailing wind speed.

The model therefore takes into account wind speed, wind direction and air temperature and immigration and emigration are calculated on the basis of probability equations. At present the work has considered migration between two stations but could be enlarged to incorporate more (Figure 3).

The model has been developed in MATHWORKS MATLAB (MATLAB, 1992) and can be run on a personal computer with 16 Mbytes of memory. The model now operates through a standard WINDOWS graphical interface with menus and dialogue boxes, with all data input and output in spreadsheet format with graphical and statistical tools.

RESULTS AND DISCUSSION

Figure 4 shows the outbreaks recorded at the four chosen magisterial districts for the period 1985–92. These are expressed as locust swarms eradicated per month. There is no measure of other swarms that may not have been recorded and no measure of effectiveness of control measures. It can be seen from these graphs that both the timing and the intensity of swarming varied between stations.

Model simulations were compared to real data with the migration activity disabled and while no comparison can be made between locust numbers, the model does yield a reasonable matching in timing of the outbreak events (Figure 5).

The model was then run with the migration activity included and a notable improvement in matching of events occurred (Figure 5).

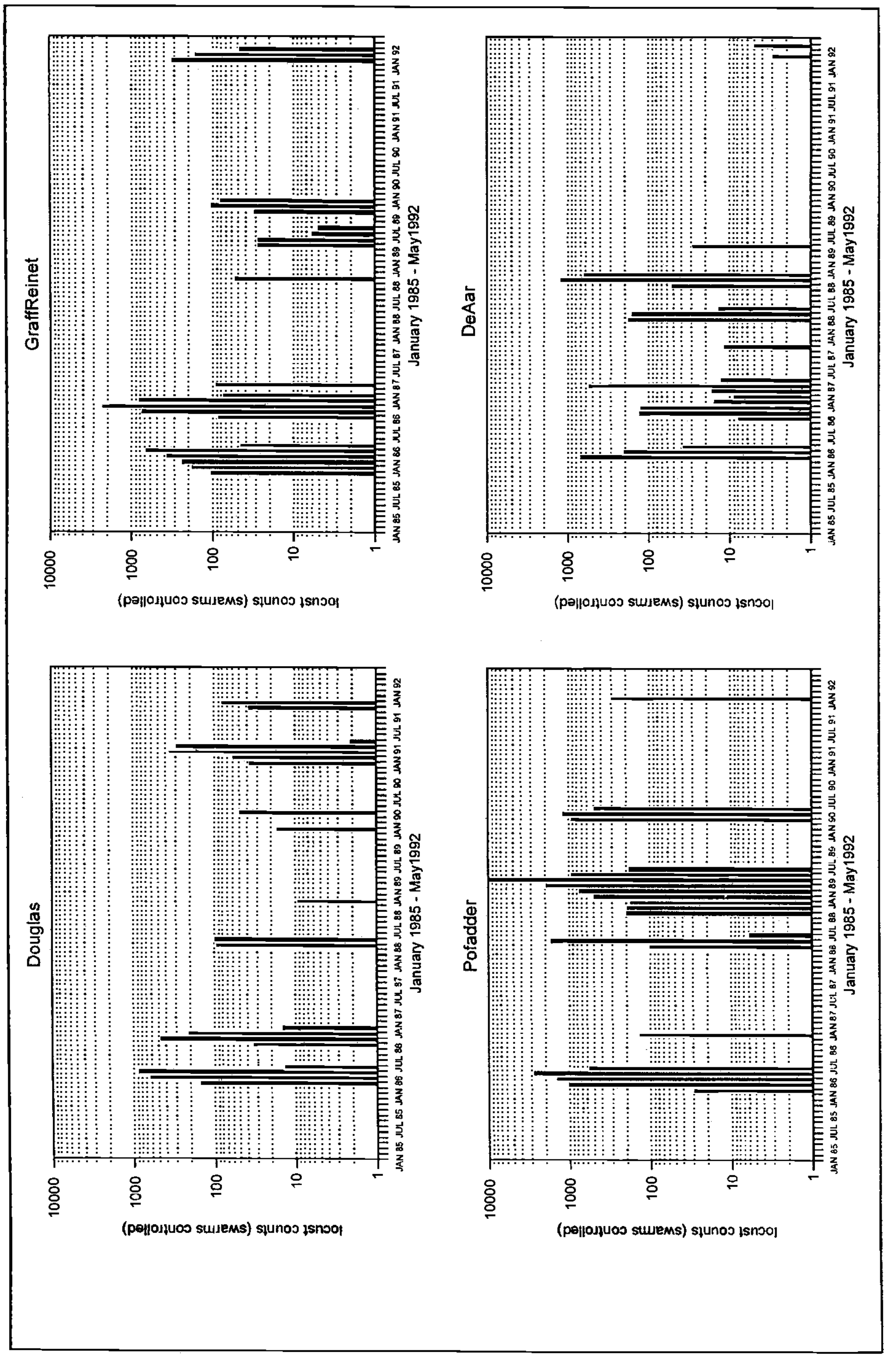

Figure 4 Outbreaks recorded at four magisterial districts for 1985–92, expressed as locust swarms controlled per month.

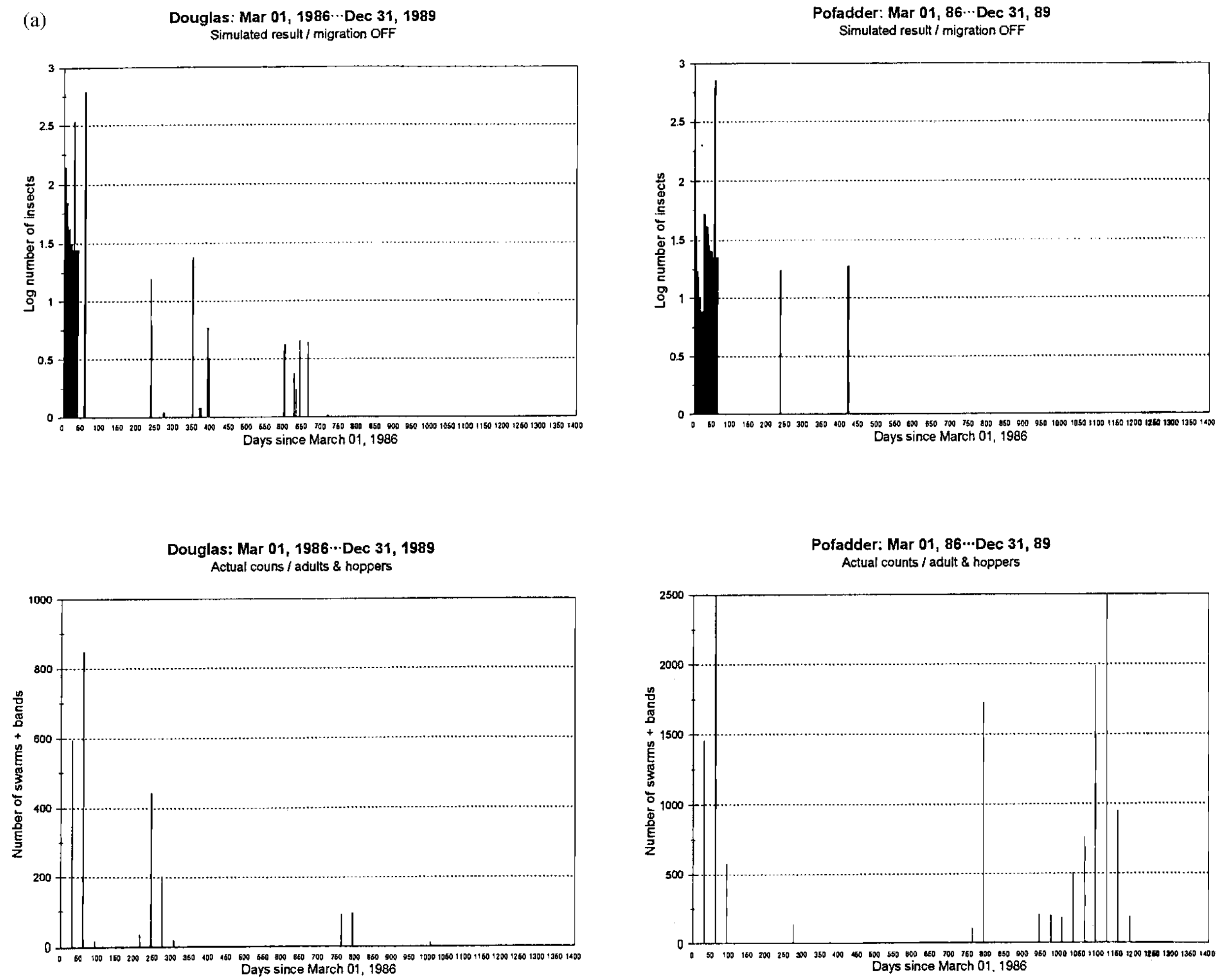

Figure 5 Locust swarms controlled compared to swarms generated by the simulation model. (a) without migration and (b) with migration.

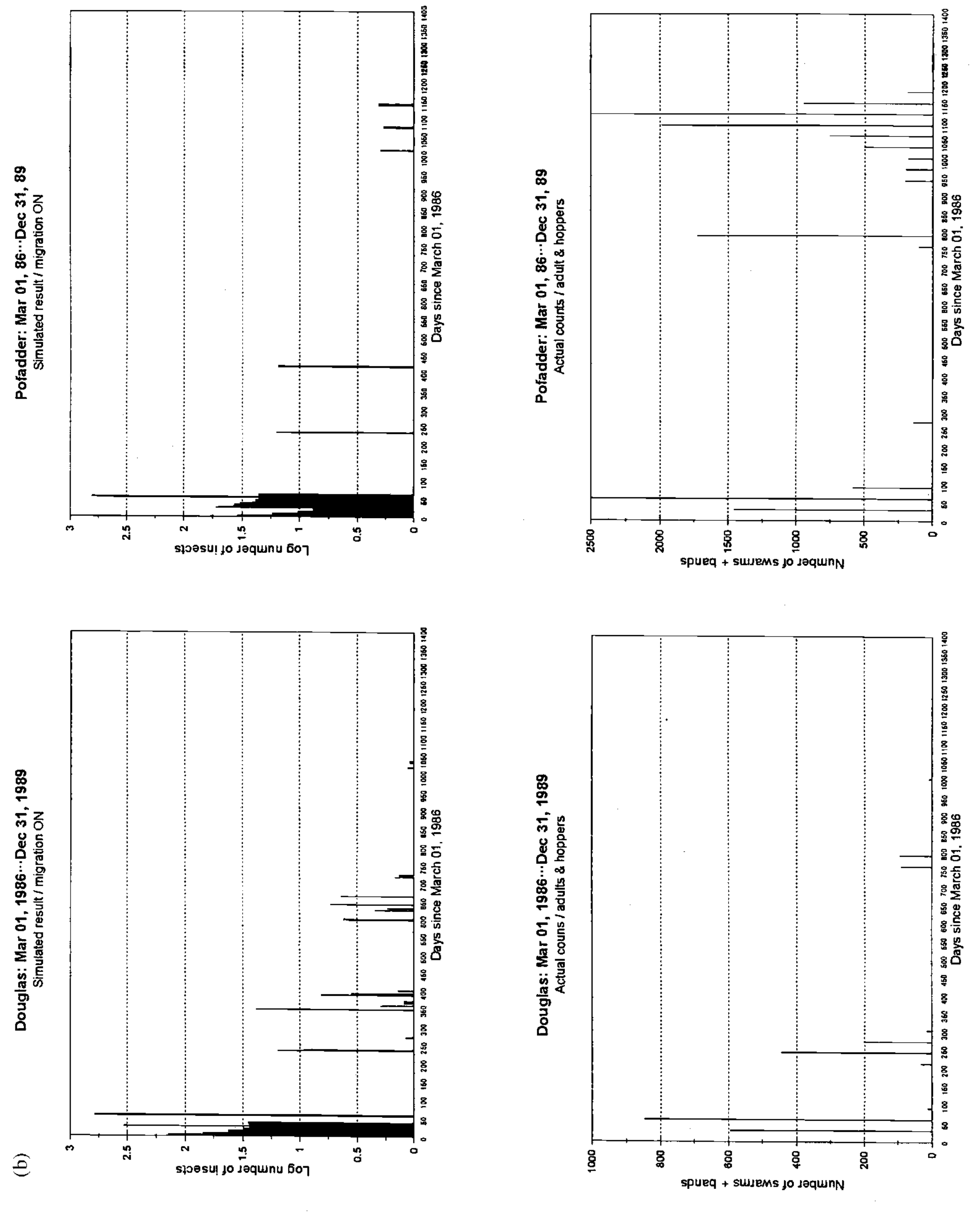

Figure 5 Continued.

We can assume that the model represents a reasonable match to the true driving forces of the Brown Locust population numbers. It obviously needs more testing and refinement and could be used to test the limitations of environmental factors such as high rainfall levels.

ACKNOWLEDGEMENTS

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R. A. Cheke, L. J. Rosenberg and M. E. Kieser (eds) (2000) Natural Resources Institute, Chatham, UK.

8 Locust Control Data Analysis: Environmental, Manpower and Financial Analyses of Locust Control in South Africa

S. M. Peters[1], H. Lindeman[2] and M. C. van der Westhuizen[1,3]

[1] Department of Zoology & Entomology, University OFS, Bloemfontein 9300, South Africa
([3]email: vdwestmc@dre.nw.uovs.ac.za)
[2] Directorate Agricultural Resource Conservation, NDA, Pretoria 0001, South Africa

ABSTRACT

Locust control campaigns are administered in South Africa by the Directorate Land and Resource Management. Improved management, by using control data, can lead to a reduction in control costs and more effective utilisation of tax-payers' money. A data and information management system was developed to help meet the environmental, economic and human impact criteria of sustainable agriculture and, using ArcView, provide an holistic view of the implications of locust control.

Quantities of pesticides sprayed, the area of pesticide deposition, the exposure of people to pesticides, the areas sprayed per day, positioning of managers/supervisors, the utilisation of administration staff, the progress of locust outbreaks and the consequential socio-economic and environmental implications were monitored. A component analysis showed the control input to output, e.g. wages, pesticides, travel and diverse costs, relative to the number of locusts controlled, and the economic efficiency of a campaign was estimated by a cost-benefit analysis. This information system assisted management by facilitating proper planning within and between campaigns.

INTRODUCTION

The National Department of Agriculture is responsible for combating migratory pests in South Africa, where the Brown Locust (*Locustana pardalina*), Red Locust (*Nomadacris septemfasciata*), African Migratory Locust (*Locusta migratoria migratorioides*) and the Southern African Desert Locust (*Schistocerca gregaria flaviventris*) are responsible periodically for damage to crops and pasture. The Brown Locust recurs most often and has the most significant impact on agriculture.

Brown Locust outbreaks usually occur in the Northern Cape Province. The three regional offices of the Directorate Land and Resource Management, situated at De Aar, Upington and Kimberley, co-ordinate locust control activities, which are subdivided into different locust control districts. A District Locust Officer (DLO) is appointed by the National Department of Agriculture and supervises control actions in each district. Individuals from the local community act as supervisors (drivers) and pest control operators (assistants). The

Table 1 Supervisors must record these details for each locust band or swarm controlled in South Africa

Bladsy Nr:
Padge Nr: 00001

Jaar: Maand: Naam van beampte: Identiteitsnommer: Distrik:
Year:............ Month: .... Name of official: .... Identity number: .... Distict: ....

Datum Date	Afstandsmeterlesing Amptelik(km) Odometer reading Official (km)		Afstand Gereis Distances travelled		Vertrek van Departed from	Gereis na (Plaasnaam en Kodestel) Travelled to (Farm name and Codeset)	Nr Ass Nr Ass	Groote van konsentrasie Size of concentration Tree / Paces		Sprinkane Locust		Middels gebruik Formulation used		Spuit Toerusting Spray Equipment	
	Begin Start	Einde End	Amptelik Official	Rrivaat Private				Lengte Length	Breedte Width	Tipe Type	Stdm Stage	Tipe Type	Hoev. Quan	Tipe Type	Hoev. Quan
Totale/Total:															

I certify that above mention information is correct, the official trips were necessary and that the arrangements made were the most economical in each instance.
Ek sertifiseer dat bogenoemde inligting korrek is, die amptelike ritte noodsaaklik was en dat die reëlings getref in elke geval die mees ekonomiese was.

Signature of reporting officer
Handtekening van verslaggewende beampte

I certify that this return has been examined and that all official trips undertaken were necessary and in the public interest.
Ek sertifiseer dat hierdie opgawe nagegaan is en dat alle amptelike ritte wat onderneem was noodsaaklik en in staatsbelang was.

Signature of controlling officer
Handtekening van kontrolerende beampte

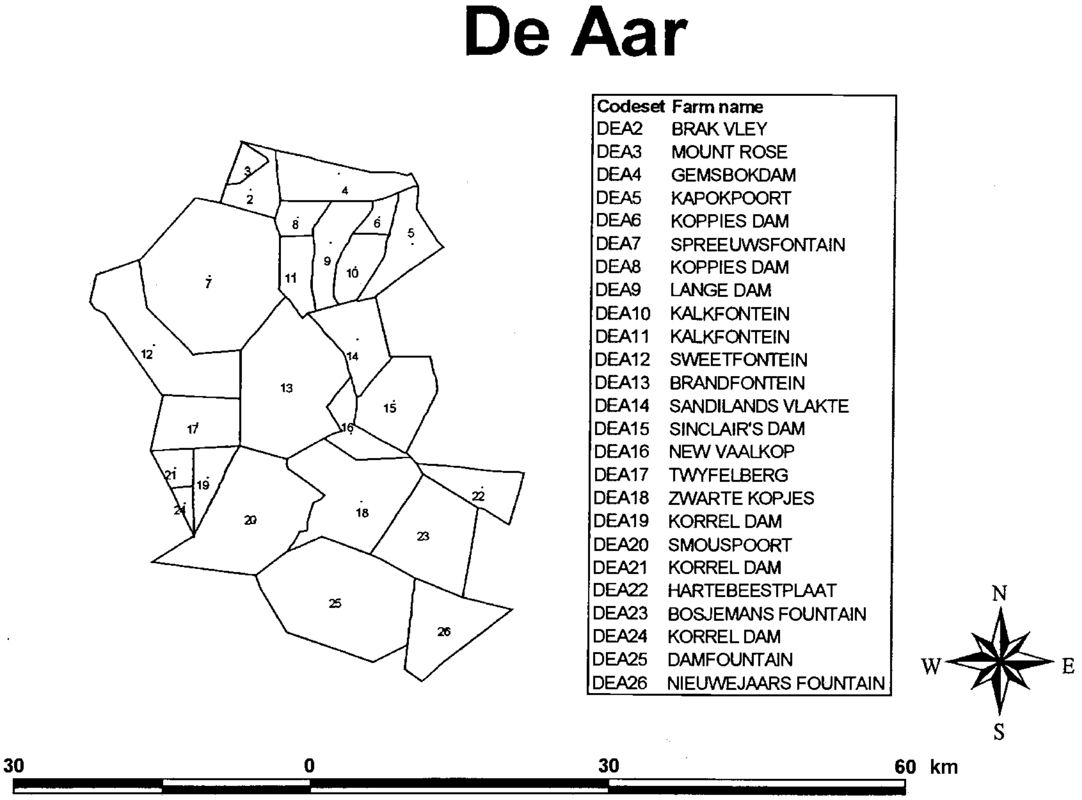


Figure 1 Map of farms in De Aar district.

DLOs, supervisors and assistants claim day-fees (wages) from the National Department of Agriculture. Since private vehicles are commonly used to locate locusts and to transport the control operators and equipment, the DLOs and supervisors are also remunerated for their travel costs.

In South Africa, locusts are mostly controlled using ultra low volume (ULV) spraying equipment and Deltamethrin (Decis© UL6) is the main insecticide used. The formulation Decis (r) UL6 is registered for locust control at 12–18 g ai/ha and should be applied at a volume of 2.5 l/ha (Krause *et al.*, 1996). The spraying equipment consists of Power Solo 'bakkie' pumps and knapsack Solo pumps. According to Heyns *et al.* (1995) the larger locust swarms are mostly controlled with the Power Solo pumps and the smaller swarms and hopper bands with the knapsack Solo pumps. The National Department of Agriculture provides sufficient quantities of acridicides and application equipment to trained locust control officers free of cost. The supervisors are obliged to note the control details: date, number of assistants involved, daily odometer readings before and after control actions, name of the farm where control took place, development stage of locust, dimensions of band or swarm controlled, locust species and type and amount of pesticide applied. The so-called yellow-and-green cards are collected on a monthly basis and serve as hard copy records.

The control of locusts involves temporary employment of control teams, the issue of pesticides and equipment, remuneration of the teams for days involved in control actions and travelling costs, and operational and managerial co-ordination of campaigns. The immediate objective of the project described here was to develop an integrated operational and

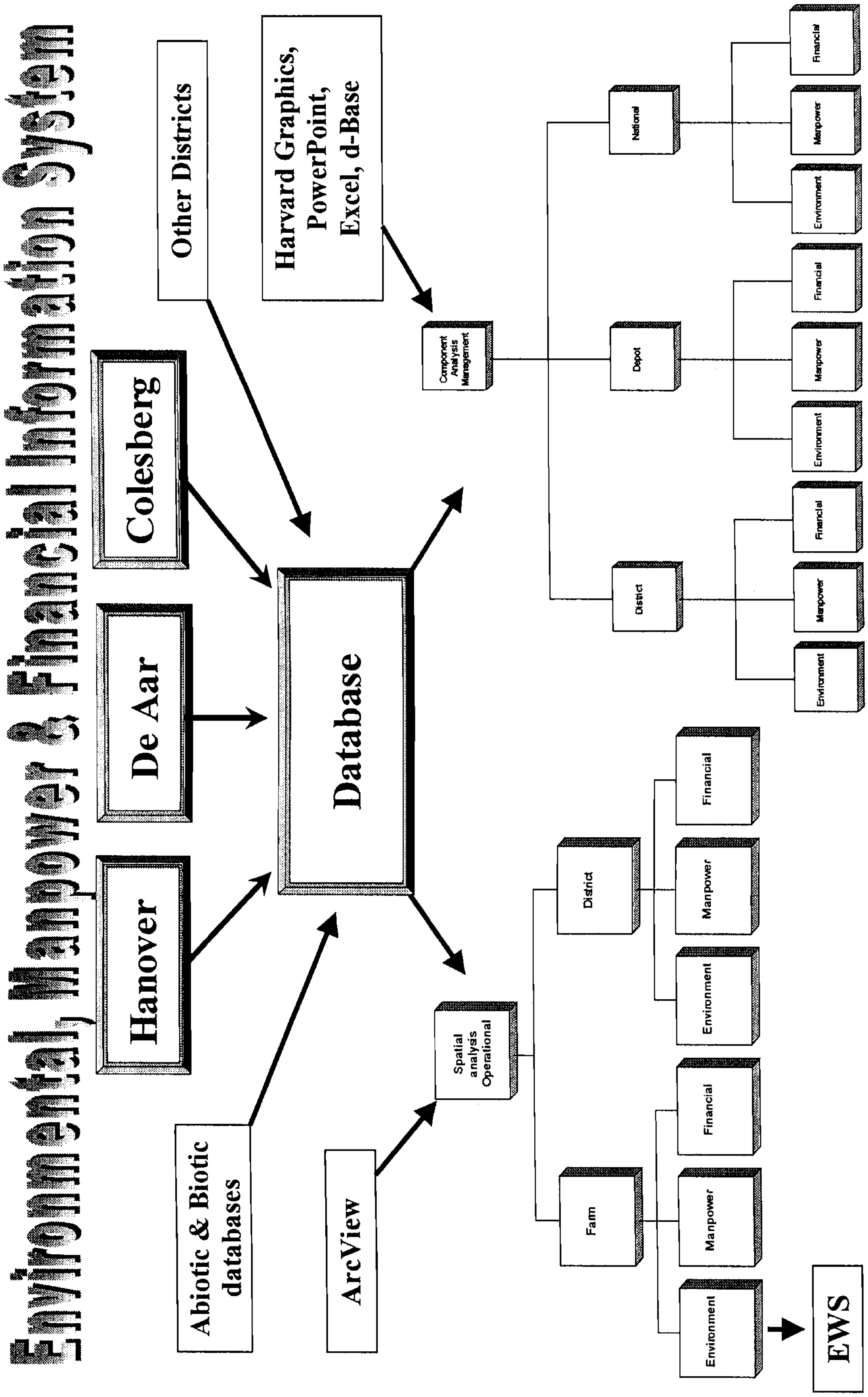


Figure 2 Diagram of integrated information system.

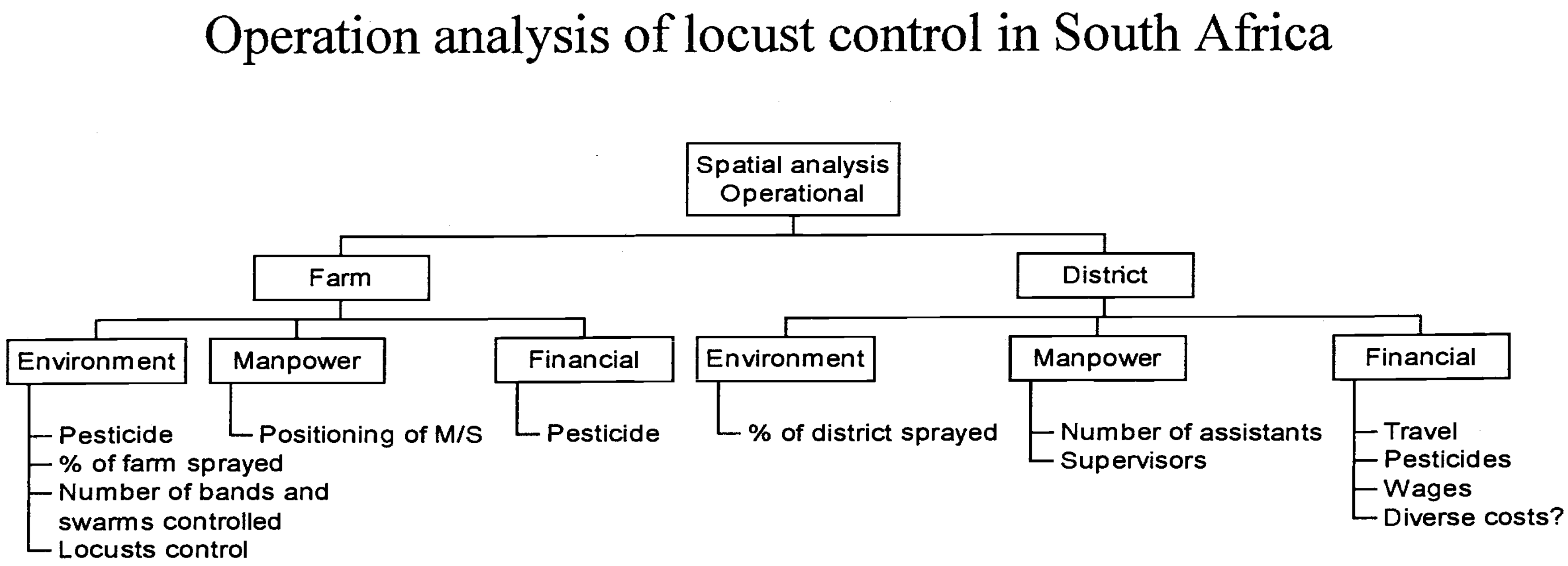


Figure 3 Diagrammatic presentation of spatial analysis of the integrated information system.

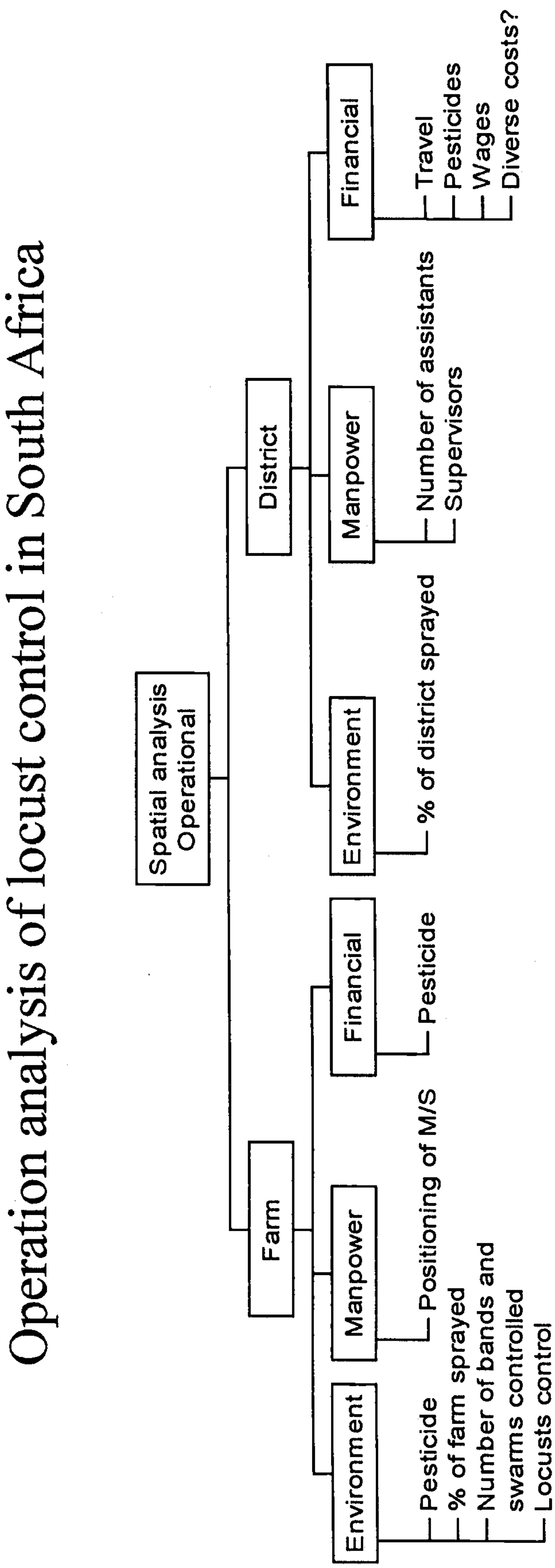


Figure 4 Diagrammatic presentation of component analysis of the integrated information system.

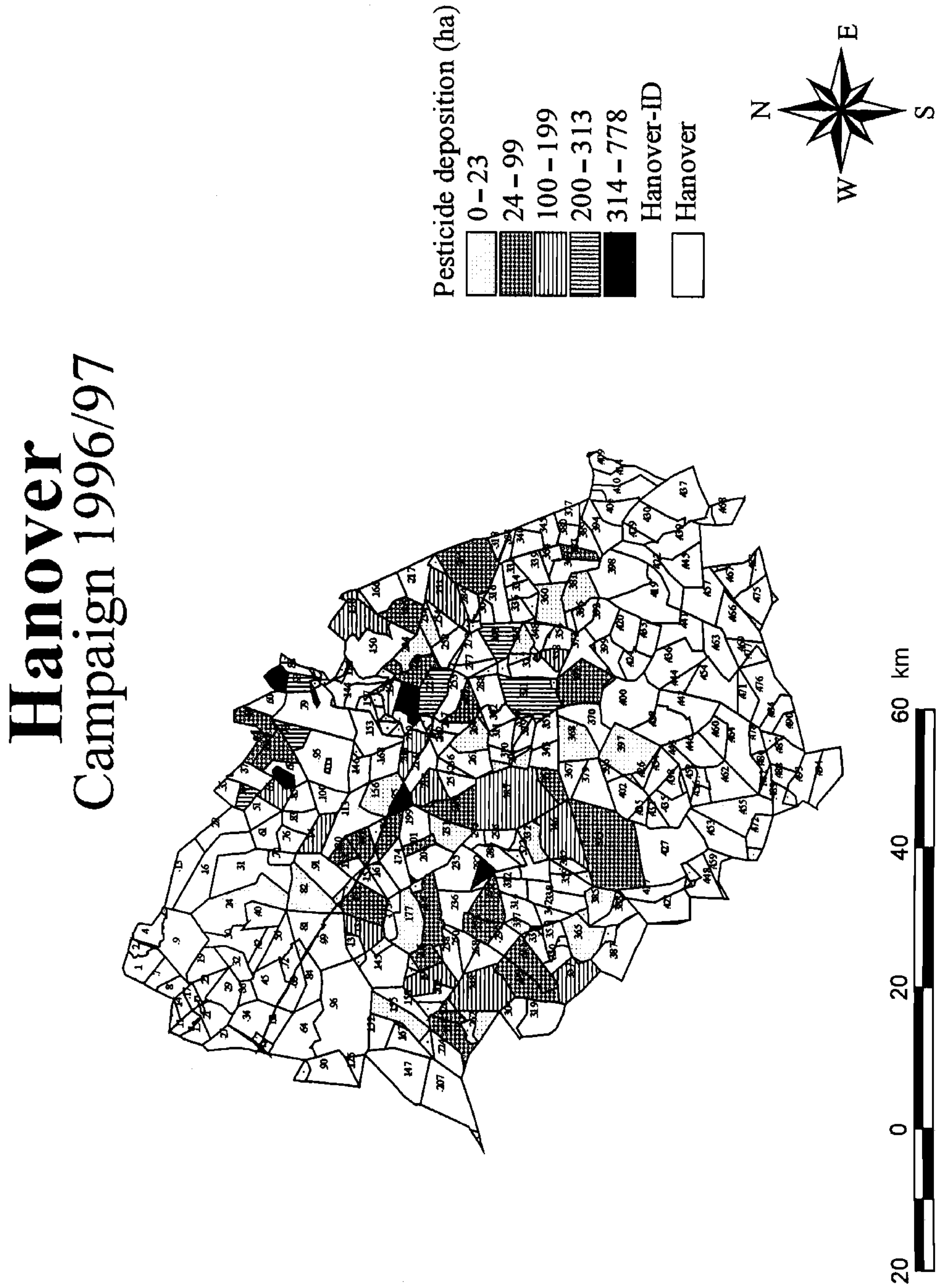


Figure 5 Amount of pesticide sprayed per farm for locust control in Hanover district.

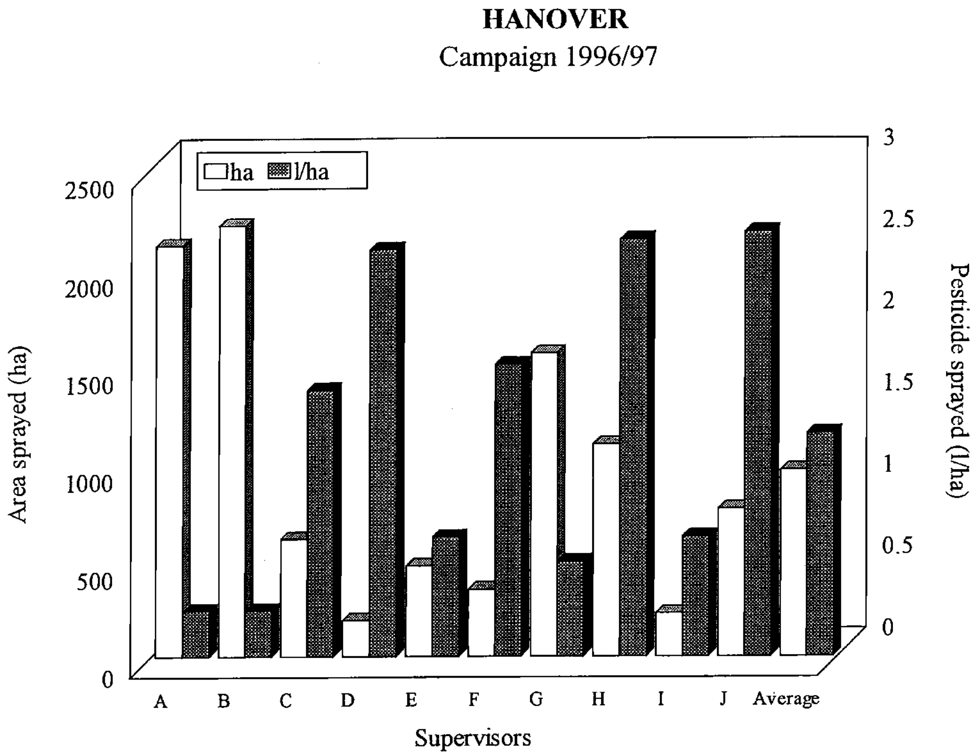


Figure 6 Total area sprayed and average application rate of supervisors (coded A-J) in Hanover district. Average column indicates average values of district.

management information system to incorporate all facets of locust control in South Africa. The research project consists of two parts, the analysis of the campaigns and the presentation of the data in a geographical information system (GIS).

MATERIALS AND METHODS

The information on the yellow-and-green cards, provided by the DLOs and supervisors on a monthly basis, was entered in a Dbase database. The kilometres driven per supervisor were allocated equally between the number of bands or swarms controlled per day and, if no detailed figures are provided, the volume of pesticide sprayed per day was distributed relative to the size of each locust band or swarm controlled on the farm. The information listed in Table 1 was available for each locust band or swarm controlled. The control details of each farm or Codeset were linked to the ArcView attribute tables and thus to farm polygons (see Figure 1). Thereafter, the data were analysed according to the flow diagram shown in Figure 2. Spatial and component analyses of the locust control data, climate and other ArcInfo data can be integrated easily for an operational and managerial information system.

RESULTS AND DISCUSSION

Eventually, data from all districts will be entered into the database, but the emphasis in this paper will be on the Hanover district. The information in the databases was channelled into the two main components of the system, the spatial analysis for operational purposes and the component analysis for management purposes. Within these two components, a distinction was also made between information at farm, district and national level. Each

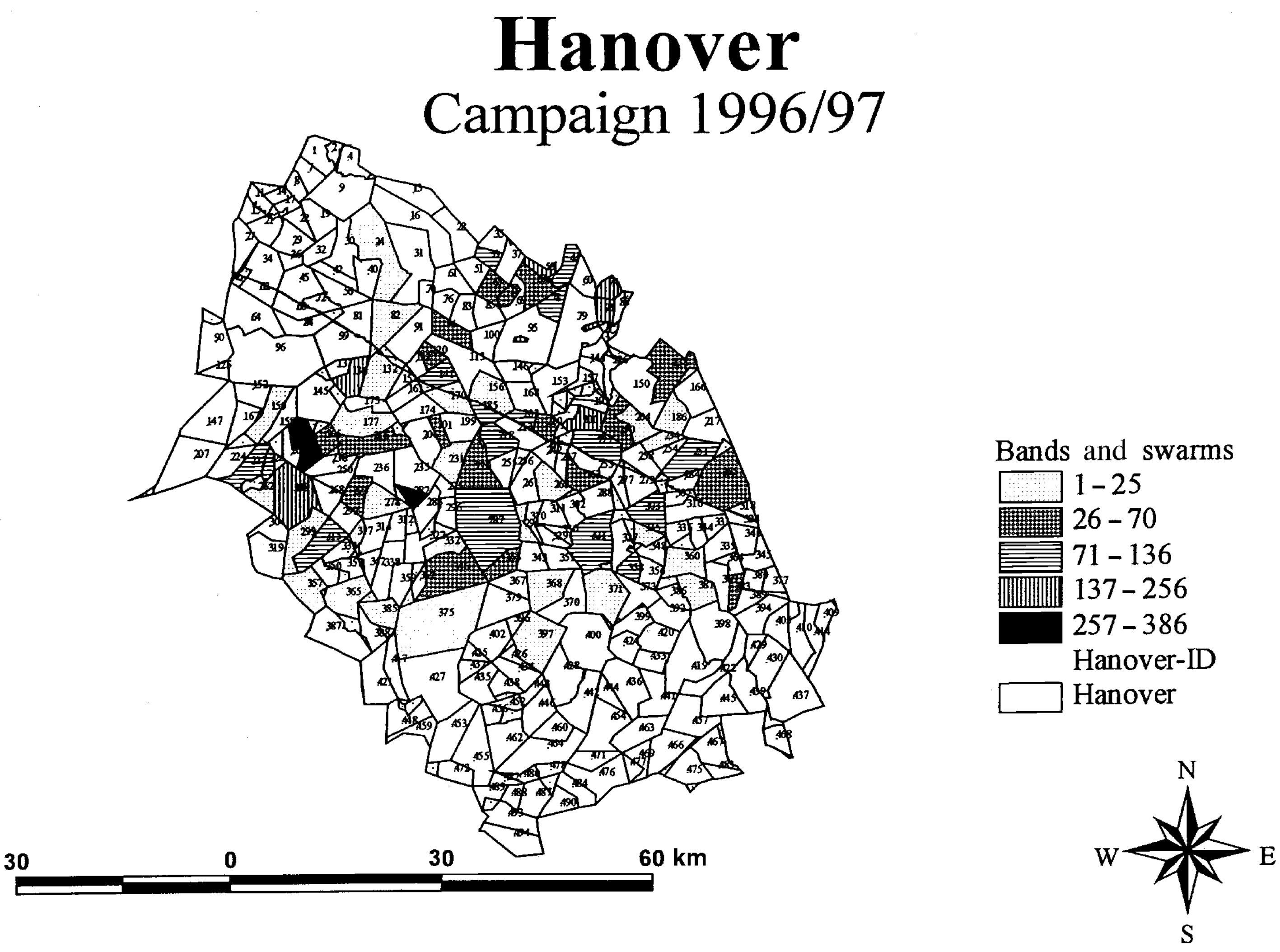
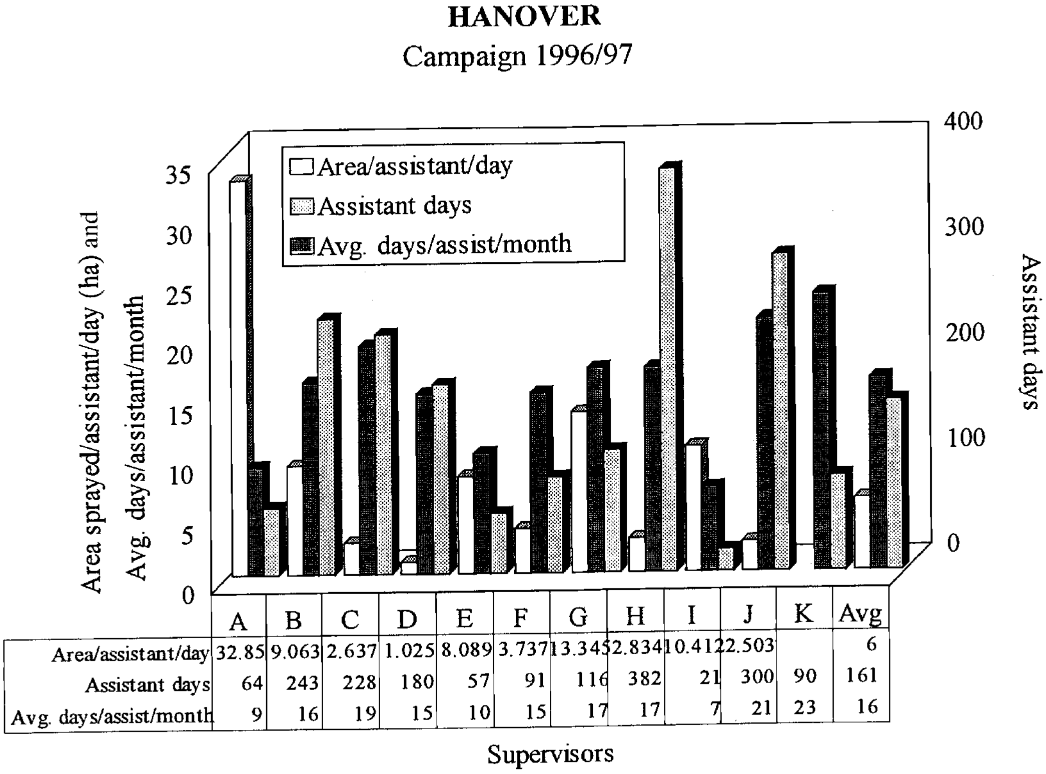


Figure 7 Number of locust bands or swarms controlled per farm in Hanover district.



	A	B	C	D	E	F	G	H	I	J	K	Avg
Area/assistant/day	32.85	9.063	2.637	1.025	8.089	3.737	13.34	2.834	10.41	2.503		6
Assistant days	64	243	228	180	57	91	116	382	21	300	90	161
Avg. days/assist/month	9	16	19	15	10	15	17	17	7	21	23	16

Figure 8 Manpower input in locust control in the Hanover district. Supervisors coded A–K. Avg. indicates average values of district.

of these levels was then sub-divided and analysed in terms of the environmental, manpower and financial criteria (Figures 3 and 4).

Figures 5 and 6 show some examples of the environmental analysis carried out at operational and managerial level respectively. Manpower (control activities and man days) utilised at farm and district level is shown in Figures 7 (control activities) and 8 (man-days) and expenditure on travel to undertake locust control at farm and district level, analysed using spatial and component analyses, is shown in Figures 9 and 10.

The operational and managerial analysis can be extended to district and national level. Another outcome of the spatial analysis was an early warning system for locust control. By monitoring sites of adults with eggs, areas of possible future outbreaks can be predicted.

Figures 5, 7 and 9 show how the spatial analysis can be carried out at farm and district level. Figure 5 is an example of environmental analysis at farm level. The total area (ha) sprayed per farm (Figure 5) was grouped into five classes by default, but any number of classes as well as unique values can be chosen. From this analysis it was apparent which farms received the greatest coverage of pesticide and further analysis should reveal a close correlation between this and the highest concentration of locusts.

Figure 4 illustrates the different levels the component analysis can be broken down to and also explains the different parameters associated with each criterion. Differences among the supervisors in terms of the number of hectares sprayed and average application rate

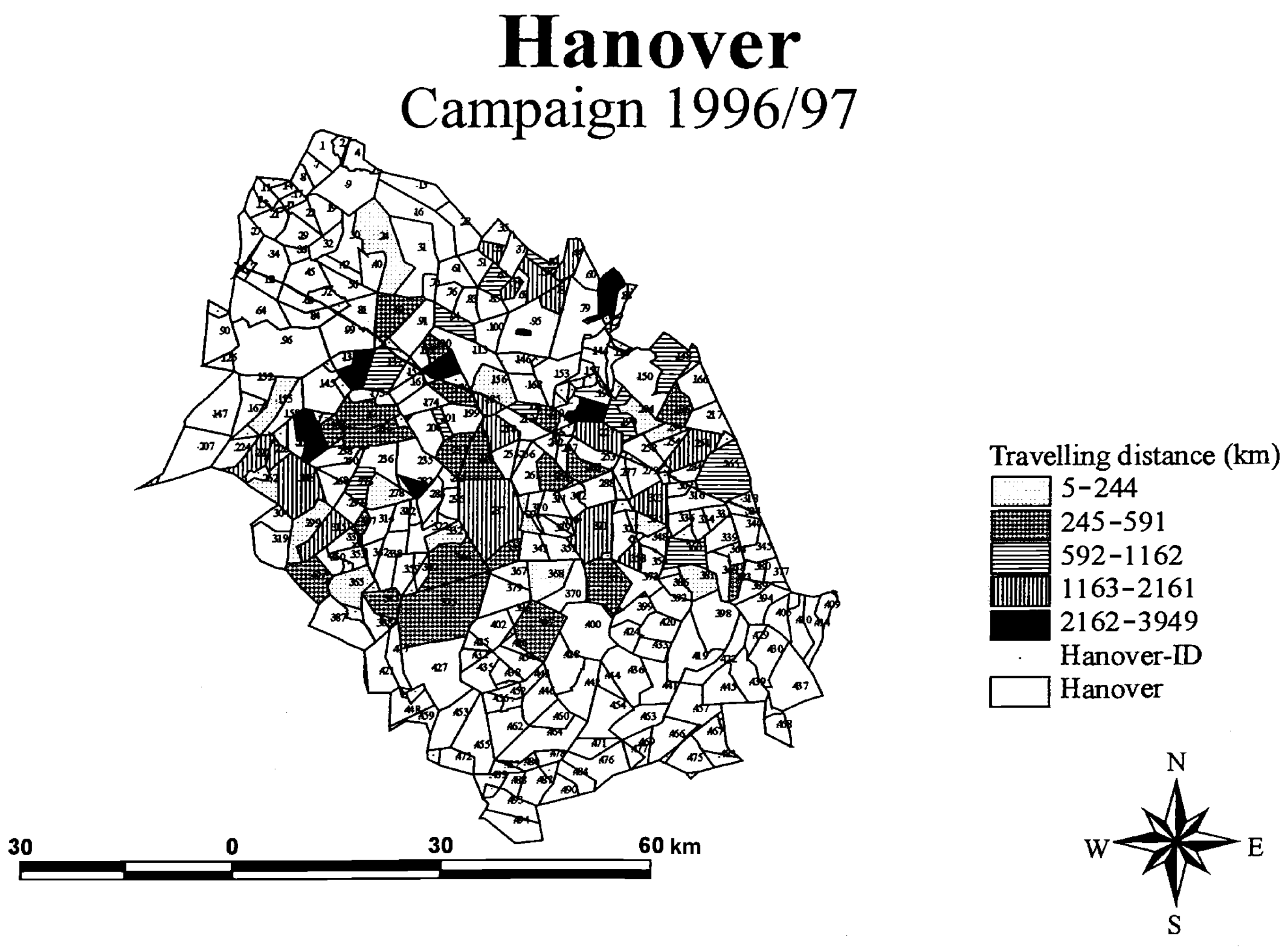
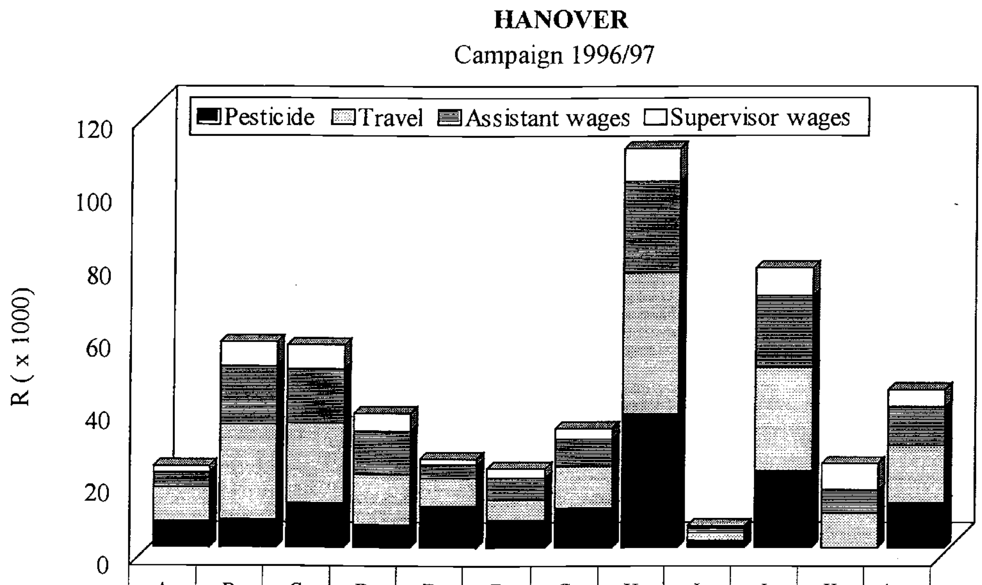


Figure 9 Travelling distance (km) allocated to farms for locust control in Hanover district.



	A	B	C	D	E	F	G	H	I	J	K	Avg.
Supervisor wages	1.836	6.759	6.675	5.006	1.585	2.587	2.92	9.095	0.584	7.76	7.202	4.728
Assistant wages	4.195	15.929	14.945	11.799	3.736	5.965	7.604	25.04	1.377	19.665	6.436	10.608
Travel	9.118	26.187	21.933	13.823	7.682	5.662	11.345	38.962	2.057	28.281	9.501	15.868
Pesticide	7.284	7.724	12.215	6.264	11.386	7.557	10.951	36.639	2.001	21.24		12.326

Supervisors

Figure 10 Financial input in locust control in the Hanover district. Supervisors are coded A–K. Avg. indicates average values of district.

are shown in Figure 6. These parameters as well as others, such as the number of bands and swarms controlled and the impact on grazing are relevant to the analysis of the environmental criteria (Figure 4).

The number of bands or swarms controlled and man-days used during the control campaigns are important parameters in the analysis of the manpower criteria. According to Figures 7 and 8, there was much variation between the different supervisors in the number of bands controlled and the time involved, but there was a positive correlation between number of bands controlled and number of assistant days for each supervisor.

Figures 9 and 10 show some of the parameters used in the analysis of the financial criteria. The pesticides and travel costs were the largest single components of the expenses of each supervisor. The distribution of wages among DLOs, supervisors and assistants can easily be compared with those of other supervisors at the district level. Totals for each district can be compared at depot level. Similarly, the depot totals can be evaluated at national level. It is thus possible to compare supervisors, DLOs or districts and depots.

Hartzer *et al.* (1995), Lindeman *et al.* (1997), Peters *et al.* (1997) and van der Westhuizen and Botha (1997) used this information system for annual reports on the locust control campaigns. Locusts were effectively controlled on less than 0.25% or 92,000 ha of the outbreak area of approximately 40 million ha during the 1996/97 campaign. The system also enables the user to compare different campaigns in order to rule out inaccuracy and facilitate better planning among and within campaigns.

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SESSION 2B CURRENT MIGRANT PEST RESEARCH BASED IN SOUTHERN AFRICA: QUELEA BIRDS

Workshop on Research Priorities for Migrant Pests of Agriculture in Southern Africa, Plant Protection Research Institute, Pretoria, South Africa, 24–26 March 1999. R. A. Cheke, L. J. Rosenberg and M. E. Kieser (eds) (2000) Natural Resources Institute, Chatham, UK.

9 Research at PPRI on Environmental Effects of Quelea Control Operations

Etienne van der Walt

Quelea Research Unit (QRU), Agricultural Research Council-Plant Protection Research Institute, P/Bag X134, Pretoria, South Africa
(e-mail: nipbevdw@plant1.agric.za)

ABSTRACT

The degree of environmental contamination and environmental risk posed by air-to-air control operations with ULV formulations of fenthion against the Red-billed Quelea, *Quelea quelea*, and possible reasons for the apparent lack of efficacy achieved during such control actions were investigated. Air-borne residues were monitored using high volume monitoring and pesticide deposition was studied after deliveries of microscopic pesticide droplets above roosting and breeding sites of quelea, when environmental contamination due to primary and secondary drift is likely.

Fenthion persisted in environmental samples far longer (64 h in air, 46 days in soil) than reported previously and could be detected as far as 3 km from the spray site. Deposition results showed uneven target site coverage, which may explain the lack of efficacy during aerial control actions. Fenthion was also detected in non-target bird species, confirming the risk of primary and secondary poisoning.

Additional observations after fuel-explosion operations against roosts of quelea indicated a high potential risk and mortality of non-target raptor species.

INTRODUCTION

Red-billed Quelea birds, *Quelea quelea*, are pests not only in South Africa but throughout many African countries because of their depredations of small grain crops. Although various methods of controlling them have been utilised, the most successful methods remain (a) chemical control by aerial application of Queletox© 640 UL with fenthion (an organophosphate pesticide) as active ingredient, and (b) ground-based explosion control.

Both types of quelea control operations in South Africa, mostly conducted between 24° and 30° S and 24° and 28° E, may have severe effects on non-target bird species and the environment. The aerial application of small pesticide droplets (± 90 μm) with a concentration of 64% fenthion (m/v), at a registered dosage rate of 3 l/ha as a cloud above roosting sites (> 5 m above ground level), creates a high off-target drift potential which may lead to contamination over a larger area. Chemical control actions are normally performed after dark in order to limit the number of quelea relocating to other areas.

The average volumes used during aerial applications are 7 l/ha of Queletox and 2085 l/ha of petrol for explosion operations. During explosions, 20-l metal drums are used, spaced at intervals of 7–10 m from each other depending on the density of foliage of the roosting site. The petrol is detonated using 120 300-g pentolite boosters and 1-m cordex fuses (10 g/m). Individual drums are connected with approximately 1000 m of cordex detonation cord. The average size of a target controlled by explosion is 1.5 ha, and the average size of targets controlled by chemical application is 5.3 ha (Geertsema, 1998).

Aerial pesticide applications for the control of quelea have resulted in unreliable efficacy rates due to, amongst other reasons, uneven target area coverage and random behaviour of quelea during the spray actions. The unreliable efficacy and the environmental pollution caused by using fenthion has led to the development of the explosion technique, as an alternative to control by avicide. The respective impacts of the two control procedures on the environment were compared, to guide future research efforts into control techniques, which would be compatible with Integrated Pest Management (IPM) strategies.

METHODS AND MATERIALS

Pesticides applied from the air were monitored using wool surface deposition traps (WSAT), with stationary and mobile high-volume aerial monitoring systems. Dead raptorial birds were analysed chemically using gas chromatography (GC) to establish primary and/or secondary poisoning. After explosions, the surrounding areas were surveyed and samples collected for later chemical analysis using GC.

Surface Deposition Traps

The wool traps consisted of 21.3 x 21.3 cm aluminium frames into which 3 mm grooves were drilled at 5 mm intervals, at opposite sides. White wool yarn was spun in between the grooves in a 'zig zag' fashion. The surface areas of the wool traps were 454 cm^2 and used 10 m of woollen yarn per trap.

High-Volume Air Monitoring

The high-volume air sampling system (HVAS) consisted of a 9.3 m telescopic mast containing four sampling heads spaced at 1.5, 4, 6.7 and 9.3 m above ground level. Each head was fitted with a removable cartridge containing two polyurethane plugs. Samples were collected for up to 64 h after application. A stationary mast was positioned in the site. Two other masts were placed 1 and 3 km down-wind from the spray site, in order to determine off-target drift. After sampling, the PUFs were extracted and analysed by GC-Nitrogen Phosphorus Detector (NPD) methods.

RESULTS

Survey of Sprayed Site

Pesticide deposition monitoring (Figure 1) showed that:

- deposition rates were extremely variable and uneven during the 64-h monitoring period;
- deposition rates ranged from 0.01 to > 550% of the expected pesticide deposition rate;
- penetration of pesticide into the canopy of the roosting site was poor;
- fenthion persisted at canopy as well as ground level during the 64-h monitoring period.

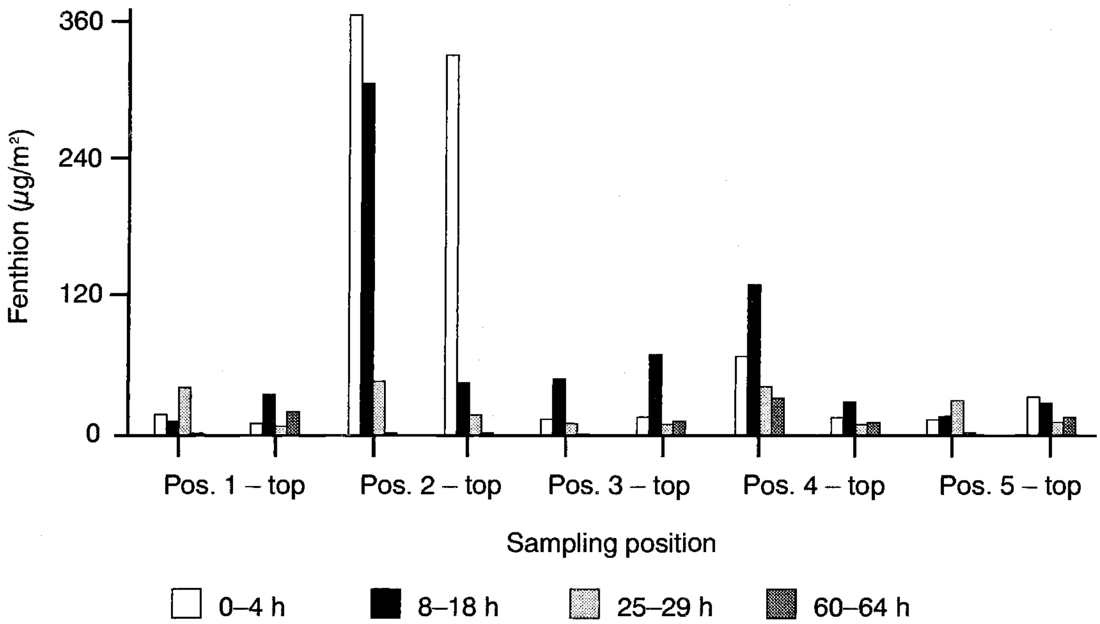

Figure 1 Pesticide deposition results. Sampling positions were at 1.5, 4, 6.7 and 9.3 m above ground level.

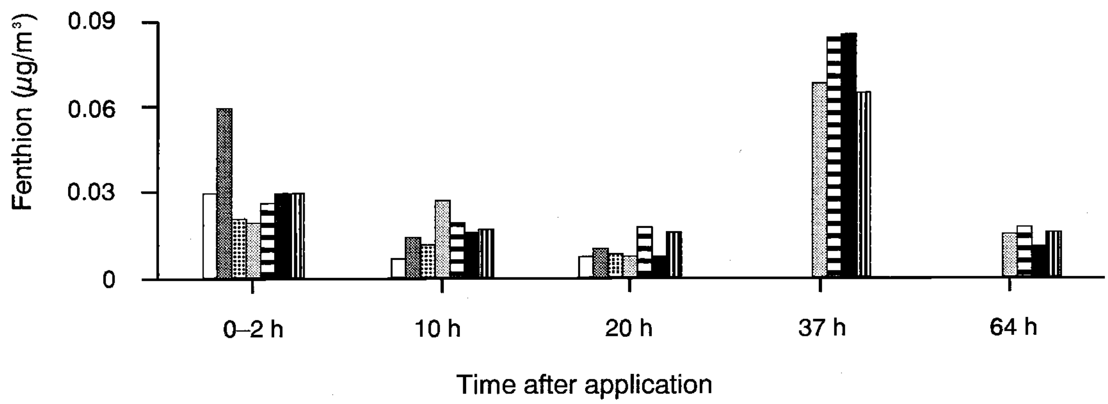

Figure 2 Results of air monitoring. Bars refer, in order, to samples 6.7 m high, 3 km from the site; 6.7 m high, 1 km from the site; 9.3 m high, 1 km from the site; 1.5 m high in the site; 4.1 m high in the site; 6.7 m high in the site and 9.3 m high in the site. Only the latter 4 are shown for results 37 and 64 h after spraying.

Air monitoring (Figure 2) showed that:

- off-target drift occurred up to 3 km down-wind from the spray site during the 24-h monitoring period;
- pesticide persisted in the air within the spray site, for at least 64 h after application.

Residue analysis (Figure 3) showed that:

- fenthion residues were detectable in the soil up to 46 days after application.

Non-target species analysis showed that:

- fenthion was detectable on all non-target samples (Black Kite, *Milvus migrans*, Wahlberg's Eagle, *Aquila wahlbergi*, Black-shouldered Kite, *Elanus caeruleus* and

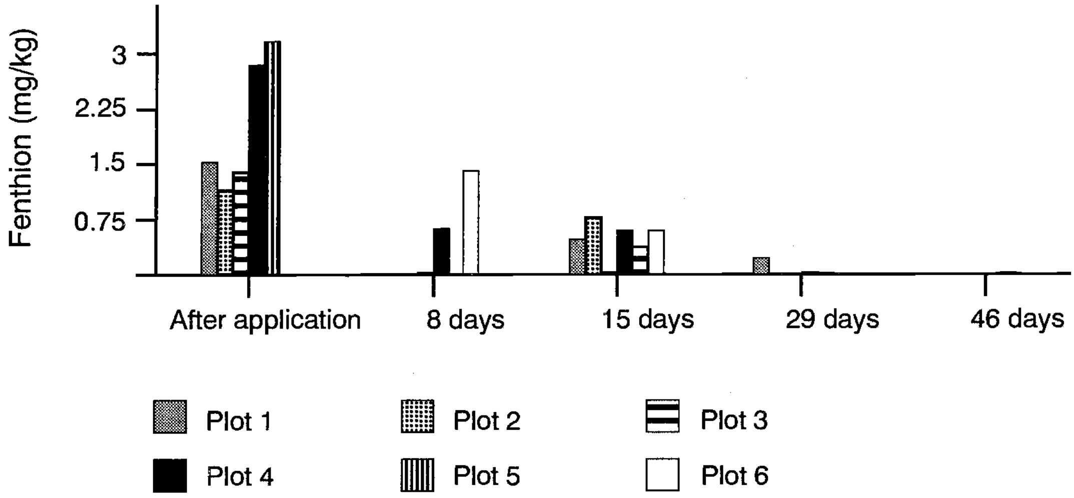

Figure 3 Residues of fenthion in soil at different times after spraying.

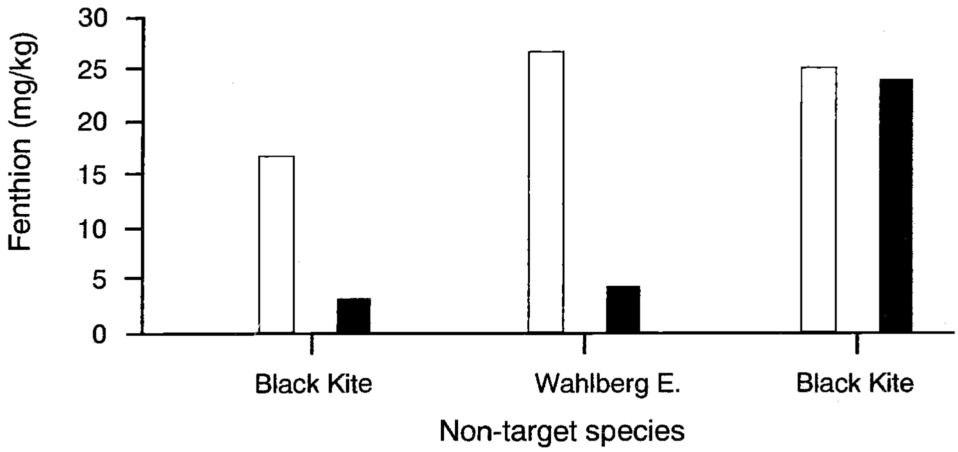

Figure 4 Fenthion residues in crops (open bars) and feathers (dark bars) of non-target raptorial birds.

invertebrates) analysed and indicates primary and secondary poisoning (Figures 4 and 5);

- residues in non-target invertebrate species persisted for up to 42 days after application in samples collected throughout the site (Figure 5).

Survey of the Explosion Site

The survey of the explosion site showed that:

- incompletely incinerated containers remained in explosion site craters;
- no pesticide residues were detectable after chemical analysis of crater sediment samples;
- parts of the explosion site were not incinerated;
- there were >100 incinerated carcasses of Black-shouldered Kites (*E. caeruleus*) at the explosion site.

DISCUSSION

The results showed that both control methods currently used have impacts on the environment and on non-target species. Off-target drift, primary and secondary poisoning and

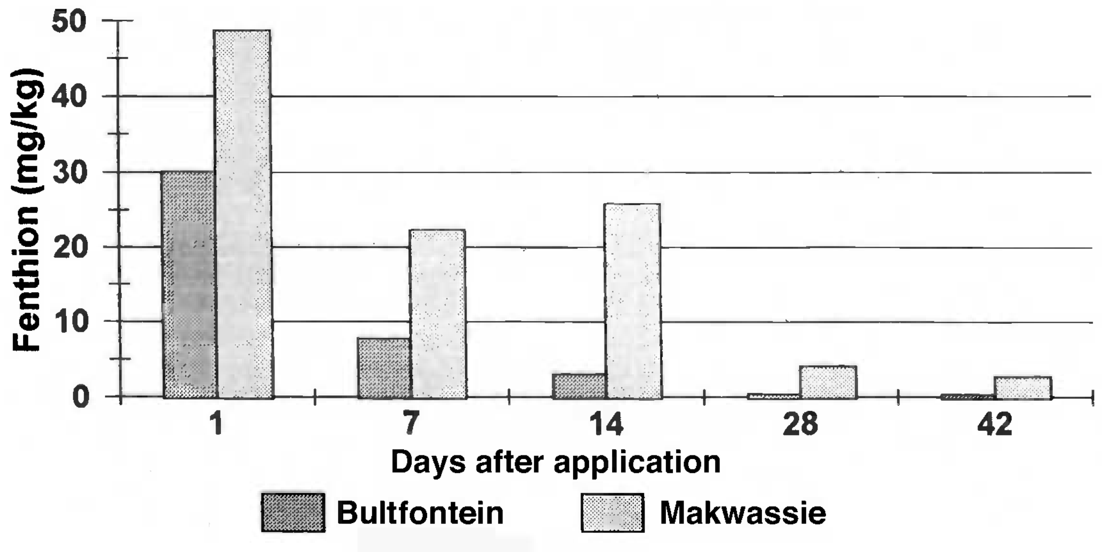

Figure 5 Fenthion residues in non-target soil invertebrates at different times after spraying at Bultfontein and Makwassie.

environmental persistence were detected from pesticides applied aerially. Pollution, non-target mortality and impacts on the habitat were detected after explosion control operations.

As governments are obliged to control quelea in order to maintain food security, continued research should be supported and encouraged in order to establish safer, and more environmentally friendly, control procedures and strategies, which would ensure sustainable production systems in southern Africa.

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10 Red-billed Queleas in Zimbabwe

Peter J. Mundy

Department of National Parks and Wild Life Management, Box 2283, Bulawayo, Zimbabwe
(email: mundy@telconet.co.zw)

ABSTRACT

The Red-billed Quelea, *Quelea quelea*, is a major pest of small grain crops in Zimbabwe, both on irrigated wheat and barley in winter, and on sorghum and millets in summer. Its pest status in summer has caused many subsistence farmers in semi-arid areas to plant maize instead of the better-adapted small grains, with zero harvest potential, forcing the country to need food aid programmes. Spraying with Queletox remains the preferred control measure, despite misgivings about its impact on the environment in general and on non-target species in particular, and its very high cost. Although there is much general information about the Red-billed Quelea in Zimbabwe, from atlas and species surveys, unpublished files, ringing and recovery data, the movements of the species in and through Zimbabwe are unclear. Further research into the Red-billed Quelea, and into the control measures, continues to be necessary to the point of urgency.

INTRODUCTION

For the latter half of this century, research into, and action against, the Red-billed Quelea, *Quelea quelea*, has been a continuing activity in Zimbabwe (Mundy and Jarvis, 1989). The bird was recognised as a crop pest for many years before that, and no doubt even before the country was colonised in 1890, but its impact must have been small then due to the more natural ecology pertaining at that time. It is only since 1950 (Plowes, 1950) to date, that increasing concern has been voiced, in spite of all the lethal control undertaken in most of the years in the interim. The quelea has simply refused to go away, indeed it may even have increased in this half century!

BIOLOGY

At present, queleas are recorded throughout Zimbabwe (Mundy and Herremans, 1997). However, they are apparently absent from just a few areas (communal land) especially in the wet season, but this is probably attributable to a lack of observers. Breeding, however, occurs almost entirely only at altitudes below about 1000 m (Jarvis, 1989), and it starts, on average, in January of each wet season, after there has been substantial rainfall.

The species exhibits two very different 'life-styles' or behaviours in the country.

(1) As mentioned, it breeds later into the southern summer rainfall season, usually in January to April in good years, but hardly at all in drought years such as 1991/92

and 1994/95. Its colonies are found in lowveld and middleveld areas in both the north and the south of the country. In this period it feeds on the ample wild grass seeds, and insects, but sometimes has an impact on 'rain-fed' crops, in particular on sorghum, millet and rice. Most of these crops are grown in communal areas, and on a subsistence basis.

(2) In the winter and dry season, from June/July to October, it gathers into non-breeding roosts, many of which occur in the irrigated croplands of wheat and barley in the commercial sector. Most of these lands are on the highveld (above 1200 m) in the middle of the country, and occupy on average only about 55,000 ha/year. The impact from queleas on wheat and barley can therefore be considerable, exacerbated too by the high cost and capital outlay needed for such crops.

Clearly there are two periods in the year usually May/June and November/December – when the birds change from one style to the other and *vice versa*. These are the times of moulting, and in addition they must be times of movement, probably long-distance movement. During November – December, in particular, quelea do seem to 'disappear' from large areas of the country, and it is assumed that they are moving on their early-rains migration (Jones, 1989). These periods, and the movements of the birds, are being investigated both directly by means of flight cages and indirectly by DNA analysis (M. Dallimer pers. comm.; Dallimer, 1999).

Another intriguing aspect of quelea biology, is the polymorphism in breeding plumage shown by the males. From extended studies in Zimbabwe, Dale (1998) has suggested that polymorphisms facilitate individual recognition among nesting males. Hitherto, the results from 'finger-printing' of hundreds of males at colonies, using their colours (black or white face, yellow or pink general plumage) and the mask index (Mundy, 1992), have rather closely agreed with those produced by Ward (1966) on much smaller samples. At the time of Ward's studies, his purpose was to categorise the *Quelea* subspecies. In southern Africa, the subspecies is recognised as *Q. q. lathamii* (Smith, 1836), but Clancey (1960) had proposed a second subspecies in the region: *spoliator*. The status of this taxon has always been controversial and has recently been shown to lack validity (Jones *et al.*, 2000b).

CONTROL

Because of its potential impact on small grain crops, and its known impact in a few unfortunate (and measured) incidents the quelea bird must be controlled. When it gathers near vulnerable crops, whether in winter or summer, it is now subjected to a planned campaign of lethal control by chemical poisoning with fenthion. For this purpose, a Problem Bird Control Unit (PBCU) within the Department of National Parks and Wild Life Management was set up in 1986, and it is still operating. Some of the early results were published (Mundy and Jarvis, 1989), but since 1985 good documentation was made of each kill. It is hoped that these data can form part of the forecasting model being developed by R. A. Cheke and P. J. Jones (Jones *et al.*, 2000a *or* see page 139).

In 1998, for example, the Unit reacted to 91 of 105 reports of quelea on irrigated crops, received in the winter/dry season, and to 77 of 111 complaints received in the summer season. It was estimated that 13.5 million birds were sprayed with Queletox ®, in operations that were costed at Z$1.44 million (about US$38,000 at the year-end exchange rate). That is, approximately one Zimbabwe dollar (or about 2.5 US cents) was needed to spray ten quelea birds. The value of the winter crop alone was about Z$1.5 billion, or one thousand times as much, being calculated as: 50,000 ha x 6 t/ha (average yield) x Z$5000/t (average price per tonne in 1998). The value of the summer crop cannot be accurately assessed, as we need to know the areas *at risk* from quelea, and therefore the summer distribution of quelea. The latter is unknown in any detail, and the former is difficult to assess especially if one allows that in the summer (rainy) season the quelea are very largely thought to take smaller wild grass seeds. It is acknowledged, however, that the juveniles are more likely to eat cultivated crops.

The quelea are controlled entirely by the use of Queletox ®, in the ULV formulation. Wherever possible, they are sprayed from back-packs carried by walking operators and, sometimes, from a vehicle-mounted sprayer. On rare occasions, an aerial spray is conducted using a crop spraying aircraft from a local commercial company. Unfortunately, the cost of the aeroplane is almost prohibitive (US$700/h by the end of 1998), and certainly so for the crops at hundreds of kilometres from the base at Charles Prince aerodrome. In this regard, one government estate at Chisumbanje, in the south-east of Zimbabwe, preferred to use casual workers for a few weeks to scare the birds off physically, rather than pay for the aeroplane. This method was about one-third as expensive – and no poison was used – but regrettably no follow-up on the effectiveness of the method was made. More alarming, the estate involved has now turned most of its wheat fields into sugar cane, one of the reasons for the change being the high cost of quelea control.

At a wildlife conservancy, also in the south-east, 500 rural people were allowed to harvest quelea chicks from a large colony, where it was estimated that 3.5 t were collected (Pelham, 1998). This is a very sensible control method, and should be included in any policy document (Mundy, 1998).

On the one hand it is necessary to prevent the quelea from being a pest, and undoubtedly the best solution is to kill them – *before* they do any damage at all. Also, quelea are tasty and nutritious, and local people want to eat them. On the other hand, however, our long-standing method of lethal control – by fenthion (Queletox ®) in ULV formulation, and in earlier years in dilution with diesel – is causing anxieties. It is necessary to guard against poisoning of the operators through careless application; concerns are raised by fenthion's impact on children who collect the poisoned quelea in the morning after a spray; numerous non-target birds are killed on site by the spray (Stiles, 1995); a proportion of the sprayed birds leaves the roost on the following day and therefore takes poison out into the wider environment; and break-down products from fenthion are far more poisonous than the fenthion itself (G. Verdoorn, pers. comm.) so that the roost area may in effect be being 'sterilised'. In addition, given the current macro-economic environment in Zimbabwe (high inflation, risk of further currency devaluation, low reserves of foreign exchange), the cost of fenthion is approaching unsustainable levels (Z$700/l at the end of 1998, or about US$18.5/l).

For the present, criteria for effecting a control on a quelea roost are simple and remain as follows.

- Kill the birds just before the crop becomes vulnerable.
- Assume that any crops within 30 km of a roost can be attacked by quelea from that roost.
- It is the responsibility of the land owner to find and report a roost.
- If the roost is in a protected area then control can still be effected, provided that extra measures are taken, in particular to chase away non-target birds and to pick up all dead birds in the morning (e.g. Mundy and Pakenham, 1988).

- Aerial sprays are to be avoided whenever possible, but a wheat/barley farmer can demand the aeroplane provided he pays separately for its operation. Nevertheless, only the PBCU officer-in-charge can actually call in the aeroplane.

During the winter/dry season, quelea are a problem in the commercial sector. Since the Department of National Parks became a cost-recovery institution (now called the Parks and Wild Life Conservation Fund), effectively during 1996, commercial farmers have been invoiced for quelea operations, through their commodity association, the Zimbabwe Cereals Producers' Association.

Operations against colonies have the same set of criteria, except that the protection of non-target birds and the collection of all dead birds must be applied at every site if possible. Quite a few colonies are in communal lands, and it has proved very difficult to pursue cost-recovery with their district councils. This is currently an intractable problem at that level, so instead the higher levels of the Ministries of Finance, and of Lands and Agriculture have been turned to in an effort to set up a national quelea 'fund' to redeem the cost-recovery principle. All stake-holders would be expected to contribute to the fund, on the basis that the Red-billed Quelea is a recognised international migratory pest (along with locusts and the armyworm *Spodoptera exempta*) that can affect any cereal farmer.

SOCIO-ECONOMIC ASPECTS

Many communal lands were (and still are) in lowveld areas where quelea breed. The sorghum and millet crops of the communal people are therefore vulnerable to attack by the birds and especially by the juvenile birds. Late or second breeding would produce juvenile quelea to coincide with the filling-out of the crop – a good rainy season would be likely to exacerbate the situation by leading to more quelea and more crops. Locals know the birds well, and use various scaring methods against them. Over the years the problem of the birds on small grain crops has increasingly been side-stepped, apparently, by a change to maize, which the birds do not eat. Unfortunately the droughts of the last years (the two worst of the century were in 1992 and 1995) have militated against producing much maize in these areas, because maize is a 'thirstier' crop than sorghum and millet. Therefore, food aid is required (called 'drought relief'), which is an obvious cost to the exchequer but passed on through the income tax structure as a 5% drought levy. Thus an article in a national newspaper, *The Herald*, of 30 September 1998, carried the headlines 'Over 3.4 million register for food assistance,' from the Matabeleland South and Masvingo provinces. This phenomenon is an annual event (the country's annual food aid requirement is said to be 77,000 t, ICRISAT 1999), partly caused by the depredations of the quelea bird. Hence the desire to let people harvest the quelea wherever possible.

In the past, the possibility of breeding bird-resistant sorghum and millet was being investigated by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), but this is no longer deemed feasible or necessary. Other aspects such as the use of fertiliser and earlier flowering varieties are more important (ICRISAT, 1999).

Another aspect, which may become important, is a movement away from winter wheat and barley, as already mentioned. Being expensive to produce in terms of capital outlay (e.g. irrigation pipes) and water and electricity costs, any additional impact from the quelea birds – or rather the cost necessitated by having to control them – may erode profits to zero. The country would then have to import these crops at extra expense. It would be so much easier to have an efficient PBCU in place – and cheaper in the long run. At present

Zimbabwe's annual requirements for wheat and barley are about 400,000 t and 30,000 t respectively.

With all these factors in mind, from the individual farmer up to the macro-economic level, it seems clear that an experimental or varied approach is required for controlling quelea, with a concomitant increase in monitoring of the effects of control measures.

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11 The Cyanogenic Glycoside Dhurrin as a possible cause of Bird-resistance in Ark-3048 Sorghum

Thadeo M. C. Tarimo

Plant Protection Department, Ministry of Agriculture and Co-operatives, PO Box 7474, Arusha, Tanzania

ABSTRACT

Sorghum has the potential to reduce grain deficit in Africa, but it is highly vulnerable to the Red-billed Quelea bird, *Quelea quelea*. Bird-resistant crop varieties, when incorporated into current control methods, may reduce quelea damage. Farmers have selected brown sorghum containing tannin as a means of reducing damage. However, it is not only less preferred by birds but also by humans. The purpose of this study was to develop a laboratory bioassay method for screening sorghum varieties for bird repellency, to determine if Ark-3048 sorghum is bird-resistant, and, if so, whether any compounds that induce repellency are extractable and can be identified. Caged quelea preferred the white, whole-grain, low-tannin Segaolene to yellow Ark-3048. They avoided brown, low-tannin P-8333 in preference to cracked Ark-3048. House Sparrows, *Passer domesticus*, preferred P-8333 to Ark-3048. However, they preferred Ark granules to P-8333 and BR-64 high-tannin sorghum. Both species avoided neutral material treated with Ark-3048 extract. Of the birds fed exclusively on Ark-3048, 85% died within 21 days. The repellent was extractable with polar solvent and repelled both species but the residue did not. Both species preferred water-soaked grain of Ark-3048. The extract did not bind to XAD-4 resin. Extract from Ark-3048 seedlings and immature grain showed significant levels of dhurrin while that from mature grain showed insignificant levels. Results of the bioassay confirmed that Ark-3048 is bird-resistant but has no phenol, suggesting the presence of toxic dhurrin. A method of detoxifying it is suggested. Field observations that Ark-3048 is bird-resistant during its immature stages and contains the cyanogenic glycoside dhurrin were supported by these experiments. The toxic effect can be detoxified by soaking or boiling the grains in water and/or grinding them to flour, followed by mixing with water.

INTRODUCTION

Sorghum (*Sorghum bicolor* (L) Moech) has the potential to reduce grain deficit in sub-Saharan Africa. However, it is vulnerable to the Red-billed Quelea bird, *Quelea quelea*. The present quelea control methods involve traditional scaring, and lethal night-spraying of toxic chemicals. This is difficult to sustain because it is costly, labour-intensive and can affect non-target species or cause environmental pollution, so there is a need to conduct research into environment-friendly techniques of protecting crops from quelea. Non-lethal methods such as scaring, cultural practices and bird-resistant crop varieties, when incorporated into the current traditional quelea control methods may reduce quelea damage more economically because they have no added cost.

Bird-resistant sorghum can reduce quelea depredations but they have been associated with anti-nutritional effects. However, there is evidence that this is not always the case (Tarimo, 1994). Tannin-free bird-resistant sorghum such as the Ark-3048 and Brazil hybrids, have shown promise in reducing damage in field trials in the USA, Brazil and Puerto Rico (L. G. Butler, pers. comm.) and in Zimbabwe (K. Leuschner, pers. comm) (Tables 1, 2, and 3).

Table 1 A comparison of bird damage scores (1 = 0–10%, 10 = 90–100% damage; 1991 and 1992 combined data) in quelea bird evaluation trials at Jotsholo, Zimbabwe

		Damage	
Variety	Sorghum group	Milk and soft dough stage	Harvest
ARK-3048	I	1	1
HAGEEN DURRA -1	I	3	2
IIS 2827	I	8	9
IS 2319	II	1	4
IS 8768	II	3	4
BLACK SEEDED SUDAN	II	1	1
IS 1109	III	3	6
ScB0167	III	1	1
IS 8260	III	1	1

Source: Data supplied by K. Leuschner (pers. comm.), Matopos, SADC ICRISAT Research Centre

Table 2 A comparison of bird % damage means from 1988 bird evaluation trials in Southern Indiana, USA

Variety	Group	Aug. 6	Aug. 19	Sept. 3	Sept. 17	Sept. 30	Oct. 15
Ark-3048	I	0	0	0	0	0	0
Brazil		0	0	0	0	1	1
HD -1		0	0	15	40	35	25
IS2827		0	30	100	100	100	100
IS3171	II	0	0	0	0	1	2
IS8260	III	0	0	0	0	22	24
SCO714E		0	0	0	0	49	70
*IS1109		0	25	30	23	35	35

Table 3 A comparison of bird % damage means from 1987 and 1988 bird evaluation trials in Fayetteville, Arkansas, USA

		Damage	
Variety	Group	Milk and soft dough stage	Harvest
ARK-3048	I	2	30
OROG × TRA	I	51	75
TX 399 × Tx 430[1]	I	48	62
TX 2790 × AR3048[1]	I	86	94
TAM2566DW3	II	4	8

[1]1988 Data only (J. York, pers. comm.)

However, no laboratory evaluations or replicated experiments have evaluated the performance and optimal use of tannin-free sorghum. In addition, no studies have been conducted to determine the tannin-free factors in sorghum that are responsible for bird resistance. It is possible that the resistance factors will have some deleterious nutritional effects on humans and livestock, as in the case of high-tannin sorghum. Therefore, there is a need to know and characterise tannin-free, bird-resistant sorghums before putting them into commercial production.

Determination of these characteristics may lead to easier screening, evaluating and classifying of other tannin-free, bird-resistant varieties in sorghum such as the Brazil varieties. Identification of the grain component that contributes to bird repellency, but which has no anti-nutritional effects on humans and livestock would be an important contribution to sorghum production and improved nutritional quality for the people in many countries. Similarly if the repellent compounds have toxic qualities, ways of detoxifying them must be developed.

Ark-3048 plants average 35 cm in height with 5 cm head insertion and reach mid-flower 85 days after emergence. The plant has an oval and compact head. The grain has a yellow pericarp, no mesocarp, no testa and has mahogany glumes. It was selected from IS1140S at the Texas Agriculture Station and the United States Department of Agriculture released the bulk population in their sorghum conversion programme. This line has been self-pollinated for 13 generations. It has shown bird resistance each year in the breeding nursery and was observed to be extremely bird-resistant under Arkansas conditions. Its great resistance to Red-winged Blackbirds (*Agelaius phoeniceus*) and cowbirds (*Molothrus ater*) occurs at the milk and soft dough stages (approximately 21 days after mid-flowering).

The objectives of this study were to: (1) confirm if mature Ark-3048 is bird-resistant; (2) develop a laboratory method for screening bird resistant sorghums; (3) determine if Ark-3048 has some extractable bird-resistant compounds; and (4) identify and quantify any such compound(s).

MATERIAL AND METHODS

Trials with House Sparrows, *Passer domesticus*, were undertaken at the Animal Care Laboratory, Agriculture Research Building, Purdue University, West Lafayette, Indiana, USA from September 1991 to March 1994. Trials with quelea were conducted at the International Crop Research Institute for Semi-Arid Tropics (ICRISAT) at Matopos Research Centre, Bulawayo, Zimbabwe from November to December 1992. Adult and sub-adult birds were used in this study because there was 93% juvenile mortality in captivity, but only 7% adult mortality (Tarimo, 1994).

Bird Capture

House Sparrows were trapped around Purdue campus and brought directly to the laboratory. Each bird was individually caged (41 x 25 x 25 cm) in a room with a 12:12 light:dark cycle, at approximately 50% relative humidity and 23 °C. The birds were provided with two cups of maintenance diet (MD) which consisted of a mixture of sorghum grain, millet grain, Purina bird chow, sunflower and grit. Water was provided *ad libitum* from a cup located in between the food cups. Protein was provided by pup chow, fried ground meat and ground boiled eggs. Positions of the cups were alternated daily to prevent birds from becoming accustomed to a particular position and cup.

Quelea were trapped at Jotsholo and Nyamandlovu roosting areas in Zimbabwe. They were placed in plastic cages (60 x 35 x 35 cm) and transported to Matopos Research Centre the following morning; and held in captivity for almost 2 years prior to feeding preference trials. The captive birds were housed outdoors, in groups of 30 to 50 birds, in 3.0 x 2.0 x 2.5 m aviaries. During captivity, they were fed on cracked maize, various types of sorghum and millet. Apart from test days, during which food was restricted, food was provided *ad libitum* from 2 of 16 hoppers. These hoppers were made of 2-l plastic containers, were spillage free and presented from two sides. Water was also provided *ad libitum* and a tray of sand provided grit. No additional source of protein or vegetative matter was provided. The three aviaries had two shaded perches on one side and two unshaded perches in the centre part. The aviaries were away from buildings to minimise human disturbance.

Test Materials

Mature Ark-3048 grain was used as a model tannin-free, bird-resistant sorghum variety because of its availability and knowledge of its resistant qualities in the field. P-8333 (brown) and Segaolene (white) were used as controls because both are tannin-free but very susceptible to birds. DC-75 and BR-64 represented high tannin, bird-resistant controls. cracked corn, cracked Segaolene, cracked P-8333 and P-8333 granules were used as inert material on which Ark-3048 extract was deposited. All grains used were standardised for size to ensure equivalent coatings with the bran or extract.

Quelea

Quelea were kept together in each of two outdoor aviaries with 25 birds apiece, as feeding rates decrease when birds are caged individually. Each aviary had 16 spill-free, 2 l plastic hoppers from which the test sorghums were presented to the birds in a free-choice test. The birds were presented with 500 g daily from 09.00 to 16.30 h and from 16.30 to 08.00 h, or for 23 h, starting from 09.00 h one day and ending at 08.00 h the next day. Each treatment was assigned to one hopper the first day and alternated daily. The amounts consumed from the hoppers were compared. A few trials with individually caged quelea were conducted separately. The study took almost 2 months, during which the birds were exclusively fed on test sorghum. Although bird-repellent experiments require at least 2 weeks and the recommended period is 4 weeks (Bullard 1989), time only permitted tests of 4–7 days.

House Sparrow

Forty birds were caught, of which 24 birds were randomly picked and kept in individual cages for conducting three different trials concurrently, with eight cages in each. The remaining birds were used to replace dead birds. However, dead birds were only replaced between trials and not within trials. Both free-choice and non-choice preference tests were conducted because the former is more sensitive in detecting avoidance, while the non-choice test is a better measure of absolute repellency (Bullard *et al.*, 1991; R. W. Bullard, pers. comm.). Preference trials were conducted daily for 7–12 days. For the free-choice test, one cup containing the test material and a second containing the control were simultaneously placed in eight cages containing one bird each. Position of the cups was randomly determined on the first day and alternated daily. The test sorghum, 4 g/cup was placed in each cage between 08.00 h and 09.00 h and any remaining food was removed between 12.00 h and 13.00 h. At the end of a 4-h test period, the remaining food, including spillage, was weighed. The amount of test sorghum consumed was determined by subtraction from the original weight.

For the no-choice tests, each bird was presented with only one cup containing 8 g of either control or test sorghum. The cages were divided into two groups of four. One group was given control and the second test diet for 4 days and then feeds were switched on the fifth day for the next 4 days. Moisture gain or loss from test foods was determined and considered insignificant. This test was stopped because of the high mortality (75%) of the birds which were initially fed on Ark-3048.

Extraction

In each extraction 500 g of Ark or P-8333 was extracted with 4000 ml of methanol. The extract was concentrated to 100–200 ml and coated on 500 g of cracked corn or P-8333 granules or cracked P-8333. To determine the location of repellent within the seed, the susceptible grains were decorticated and the pericarp from Ark was coated onto susceptible grain. Both the bran and inner part of Ark were extracted for repellent material and compared in feeding preference tests. To determine if the bird-repellent compound(s) from Ark-3048 can be bound to a resin column which usually binds all hydrophobic and/or aromatic compounds, especially phenols, the extract of Ark-3048 was prepared by first using petroleum ether, then the residue was extracted with methanol. The methanol extract was put over a small column (18–38 cm high and from l3–25 mm in diameter) of XAD-4 resin. The column was washed twice with fresh methanol and maintained wet. The elute was dried onto cracked P-8333 and fed to the birds, in various different concentrations and mixtures of water and methanol.

Dhurrin Determination

Analysis of Ark-3048 and P-8333 seedlings, immature and mature grains for presence of dhurrin was performed on extracts with both pictrate and Feigl-Anger papers. Strips of the papers were suspended in vials containing Ark-3048 without touching the extract. Presence of hygrogen cyanide gas changed pictrate paper from yellow to orange or red and Feigl-Anger paper from pale blue green to bright blue or purple.

RESULTS

Sparrows showed no difference in consumption during the no-choice test. However, more than 62% of the test birds that were initially fed on Ark-3048 died before the end of the second week. No mortality occurred in the birds that were initially fed P-8888 or Segaolene. In the free choice, the birds ate more than twice as much P-8333 (72.9%) as Ark-3048 (27.1%) even when the grains were presented in the same cup (Table 4). They also ate more than 20 times as much cracked mature Ark-3048 as dried and cracked immature Ark-3048.

In contrast to the sparrow results, there was no significant difference ($P = 0.3384$) in the amount of Ark-3048 and P-8333 eaten by quelea. However, quelea showed a significant preference shift with time, consuming more P-8333 after the third day. They also avoided whole Ark-3048 compared to whole Segaolene ($P = 0.0003$) but preferred Ark-3048 to DC-75 ($P = 0.000l$). When all four grains were presented simultaneously, quelea fed more on Segaolene (46%) ($P = 0.05$) than P-8333 (19.4%), Ark-3048 (18.8%) and DC-75 (15.7%). When the grains were decorticated, grains were eaten; quelea preferred both whole and cracked Ark-3048 to its endosperm suggesting some residual repellency in de-hulled Ark-3048. Sparrows on the other hand significantly ($P = 0.0001$) avoided Ark-3048 whole grain when compared to its endosperm (Table 5). These results are similar to the responses of quelea when different proportions (0, 5, 10, and 20%) bran were added to dry cracked Segaolene, which caused the birds to decrease feeding with increasing amount of bran (Table 6), suggesting the presence of a repellency factor in the bran.

Table 4 Mean daily consumption by house sparrow of different forms of sorghum in a two-choice test; sparrows were caged individually and offered the test food for 4 h

	% Feed consumed				
Feed condition	**Ark-3048(m)**	**Ark-3048(i)**	**P-8333(m)**	**BR-6**	***P* value**
Same cup	27.1	—	72.9	—	0.0001
Separate cups	32.9	—	67.1	—	0.0001
Cracked grain	97.8	2.2	—	—	0.0001
Water-soaked					
5 min	53.0	—	47.0	—	0.2385
20 min	47.3	—	52.7	—	0.7199
2 h	66.4	—	33.6	—	0.0001
Water extract (l)					
Flour	48.4	—	51.6	—	0.2350
Whole grain	46.8	—	53.2	—	0.0006
Granules	87.8	—	16.2	—	0.0001
Boiled					
0 min	32.9(u)	62.14	—	—	0.0001
1 min	52.0(b)	48.14	—	—	0.0432
30 min	26.0(b)	73.0(u)	—	—	0.0001
1 min	49.8(b)	50.2(b)	—	—	0.9398
30 min	57.0(b)	43.0(b)	—	—	0.0001
Roasted					
30 min	28.2(r)	71.8(r)	—	—	0.0001

b = boiled, u = untreated, r = roasted, m = mature, i = immature, l = liquid

Table 5 Mean daily consumption by House Sparrow and quelea of endosperm and whole grain Ark-3048 and P-8333 in a two-choice test

		% Feed consumed		
	Feed	**Endosperm**	**Whole**	***P* value**
Sparrows	AE/WGA	75.8	24.2	0.0001
	AE/WGP	36.5	63.5	0.0001
	AE/PE	26.3	73.7	0.0001
Quelea	AEC/AWC	30.3	69.1	0.0001
	AE/AW	10.6	89.1	0.0001

AE = Ark-3048 endosperm, PE = P-83333 endosperm, WGA = Whole grain Ark-3048, WGP = Whole grain P-8333, and C = Cracked

Table 6 Mean daily amount of cracked Segaolene treated with different proportions of Ark-3048 bran consumed by quelea

	% Bran added to Segaolene				
	0	**5**	**10**	**20**	***P* value**
% Consumed	37.5	24.0	21.5	17.2	< .05

Both species strongly preferred Ark-3048, water-soaked for 2 h, and then dried, to either soaked P-8333 or soaked Segaolene. The acceptability of Ark was greatly improved by the soaking and the effects of moisture increased with increasing temperature. Birds preferred Ark boiled for 1 min to untreated P-8333 ($P = 0.0432$). They also preferred Ark boiled for

Table 7 Mean daily consumption of cracked corn, cracked P-8333, cracked Segaolene, P-8333 granules, treated with either Ark-3048 or P-8333 extract and their residue

		% Feed consumption			
Species	**Grain/solvent**	**Ark-3048 extract**	**P-8333 extract**	**Segoalene untreated**	***P* value**
Sparrow	Cracked corn	41.6	58.4	—	0.0001
	Cracked P-8333	12.0	88.0	—	0.0001
	Cracked corn	46.0	54.0	—	0.0149
	P-8333 granule	40.4	59.6	—	0.0034
	P-8333 residue	93	7.0	—	0.0001
Quelea	Cracked	—	28.1	71.8	0.0001
	Cracked	46.0	54.0	—	0.0001
	Cracked	37.6	—	62.3	0.0001

30 min to boiled P-8333 ($P = 0.0001$). However, they avoided Ark-3048 boiled for more than 30 min compared to untreated P-8333. There was no difference in response to untreated and 30 min-boiled Ark-3048; but there was a difference between untreated and 30 min-boiled P-8333. There was also no significant difference ($P = 0.6817$) between the amounts of water drunk from 30-min boiled grain. They drank 2.12 ml of P-8333 'extract' and 2.18 ml of Ark-3048 'extract'. However, the birds significantly preferred the water extract of 30-min boiled grains of Ark-3048 to that of P-8333. Boiling for as little 1 min eliminated the repellency of Ark-3048, but roasting to temperatures between 90 and 97 °C did not affect the repellent qualities of Ark-3048. It appears that both heat and moisture are required to eliminate the repellency.

The repellent compound was extractable with polar solvents such as methanol and acidic methanol. The repellent showed higher repellent activity when lipids and other materials attractive to birds were removed. The repellent was not bound to a slurry of XAD-resin. Both species significantly avoided neutral material or cracked or granules of susceptible sorghum treated with Ark-3048 (Table 7). Extraction of the repellent material from Ark-3048 left a residue that the birds strongly preferred to the P-8333 residue by a factor of 13:1.

The toxicity of Ark was clearly indicated during no-choice tests because more than 62% of birds that were fed exclusively on Ark died before the end of 2 weeks and no mortality was observed in birds feed initially on P-8333. Birds that were fed initially on Ark-3048, ate less after the first 10 days, losing weight at the beginning of the second week. Over 70% of the birds died before the end of the third week, death shown by necropsies to be associated with emaciation, starvation and unconfirmed infections, possibly *Salmonella*. Birds that were fed initially on P-8333 maintained their feeding rate until the end of the experiment. However, 25% of the birds died after the third week.

DISCUSSION

The results of the laboratory study confirmed the resistance of Ark-3048 to birds, a resistance in a tannin-free sorghum, which is remarkable and important. The avoidance of mature Ark-3048 compared to P-8333 and Segaolene is consistent with the field results in Arkansas, southern Indiana and Zimbabwe. Ark-3048 did not have the same repellency when compared to larger and lighter Hageen Durra-1 (HD-1). This is consistent with other studies that showed larger grain tends to be less preferred to smaller grains. Whole grain

Ark-3048 was preferred to whole grain HD-1 possibly because HD-1 is almost as twice as big as Ark-3048, so that birds had difficulty breaking and swallowing it compared to the smaller Ark-3048. Studies have shown quelea is not able to eat large and hard grain. Researchers are encouraged to breed for cereal with larger grain hoping that quelea will prefer to feed on nearby small wild grasses.

The non-preference of P-8333 and Segaolene to Ark-3048 in a no-choice test agrees with the definition of bird resistance: that resistance is effective only in the presence of an alternative food source. In this study birds fed on Ark-3048 despite its demonstrated repellency and toxicity. The toxicity of Ark was clearly indicated during no-choice tests because more than 62% of birds that were fed exclusively on Ark died within 2 weeks, from emaciation, starvation and unconfirmed infections, possibly of *Salmonella*. On this basis it is logical to assume that the birds were subjected to stress, predisposing them to diseases and causing the mortality. Because of the decreased weight, emaciation and high mortality in the birds fed exclusively on Ark-3048, it is likely that stress or food deprivation or food refusal increased the birds' susceptibilities to systemic infections.

Soaking Ark-3048 grain in water for more than 2 h, draining and drying it can eliminate the repellency. This suggests that water may: (1) diminish the resistant qualities or toxicity of Ark-3048; (2) remove or react with the repellent; (3) affect physical barriers such as hardness; (4) activate enzymes that act on the repellent; (5) the combination of the repellent material with other components in the grain, or the product may not be repellent or volatile after drying. Boiling in water for as little as 1 min destroys the repellency of Ark-3048, but boiling for more than 30 min or dry heating did not. This suggests that moisture is necessary for loss of repellency. Over-boiling tends to destroy the integrity of the grain, so either soaking and/or boiling Ark-3048 in water for a few minutes or grinding it into flour or mixing it with water are simple methods of eliminating Ark-3048 repellency or its toxicity.

It is reasonable to assume that the repellent or toxic compounds would be stored in the bran or parts of the seed which the birds encounter first. However, the birds preferred the whole grain Ark to its endosperm. This may be due to differences in nutritional quality. Endosperm is rich in starch and proteins while the bran is rich in fibre, lipids, minerals and amino acids that are readily available to the birds and easily digestible. The decorticating results are contradictory, not clearly defining the location of the repellent material. Water used in the coating process may have affected the repellent.

The bird-repellency of Ark-3048 grains was due to hardness and presence of compounds extractable with polar solvents. The higher preference for Ark residue to P-8333 residue after methanol acid extraction confirmed that Ark-3048 contains extractable compounds. The repellent material has some characteristics similar to churn because it was destroyed by water. Ark-3048 also has no phenol because the compound was not bound to a XAD-resin column. The production of hydrogen cyanide from both Ark-3048 immature seedlings and its absence in mature grains shows that the sorghum contains compounds during immature stages that diminish with maturity. This is in contrast to high-tannin sorghum that usually has high concentrations of tannin during its immature stages with low amounts at mature stages. Absence of HCN in the mature grains does not confirm the absence of active compounds, because studies have shown both pictrate and Fiegl-Anger papers sometimes give inaccurate results, particularly when the amount of dhurrin is very low (Nahrstedt, 1982).

The resistance factors need to be incorporated into other sorghums, as tannin-free bird-resistant sorghum could be incorporated into integrated quelea control programmes and thus reduce the bird problem in Africa.

CONCLUSION

Ark-3048 has some extractable compounds with bird-resistant properties. It is likely that one compound is the toxic cyanogenic glycoside dhurrin. The grain can be de-toxified simply by soaking in water, boiling for a few minutes, draining and re-boiling. Other non-phenolic compounds may also be involved in the resistance mechanisms. Additional studies are needed to: (1) quantify the amount of dhurrin in Ark-3048 relative to other sorghums; (2) conduct nutritional feed trials to demonstrate anti-nutritional effects; (3) screen and identify other tannin-free sorghums with similar properties; (4) find ways to detoxify it chemically; (5) combine the morphological and chemical bird resistance factors; and (6) breed plants to incorporate the resistance factors into higher-yielding varieties.

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12 The Pest Status and Biology of the Red-billed Quelea in the Bergville-Winterton Area of South Africa

A. Berruti

BirdLife South Africa, PO Box 515, Randburg 2125, South Africa
(email: info@birdlife.org.za)

ABSTRACT

The seasonal abundance, diet and habitat use of Red-billed Quelea, *Quelea quelea*, in the Bergville-Winterton area was studied from August 1994 to June 1995. Breeding colonies were located in the same areas as in previous years, and birds were present throughout the year except for a few weeks after substantial rains. Local recruitment from the two main breeding colonies in 1994–95 appeared to be sufficient to sustain the populations. Crushed maize obtained from cattle feedlots was the main diet in winter and wild grass seed during the breeding season, much of it obtained in or on the edges of agricultural lands. Quelea occurred ten times more abundantly in agricultural lands than in natural grasslands. Natural grasslands were used commonly only after burning had removed nearly all growth. Records show that quelea have become far more abundant in the Bergville-Winterton region in the last 20 years. It is suggested that agricultural changes have resulted in quelea becoming (1) far more abundant (10–100 times since the 1970s) and (2) more sedentary because of the use of crushed maize in winter and wheat for a few weeks in spring. Harvesting chicks is seen as a viable control measure.

INTRODUCTION

The Red-billed Quelea, *Quelea quelea*, was reported to be a pest on wheat crops in the Bergville-Winterton area of KwaZulu-Natal, South Africa. The Directorate of Resource Conservation (now the Directorate Land and Resource Management) of the Department of Agriculture of South Africa provided funding to investigate the problem.

METHODS

Monthly trips to the Bergville-Winterton district were undertaken between August 1994 and June 1995. During these monthly trips, the seasonal abundance, diet, and habitat use of quelea were investigated. Aspects of the impact of quelea on wheat crops in this region are under investigation by P. B. Taylor and S. E. Piper (pers. comm.).

Diet was investigated by examination of crop and stomach contents of shot birds. The crop and stomach contents were removed and separated. Stomach contents were divided into food categories, the number of items weighed and then a total mass obtained.

Table 1 Numbers of quelea collected monthly in the Bergville-Winterton district, KwaZulu-Natal, South Africa

Sampling period 1994–95	No. of quelea collected
8–9 August 1994	84
13–16 September	114
20–22 October	158
No trip in November*	40
12–15 December	122
11–13 January 1995	52
22–24 February	85
27–29 March	76
25–26 April	87
23–25 May	41
26–28 June	87

*Birds collected during the month on request

Habitat usage was determined along four permanent road transects in the Bergville-Winterton district. These were designed to show differences between the use of natural and agricultural landscapes by quelea. One transect was placed entirely within the Spioenkop Nature Reserve (28° 41′S, 29° 25′E) whilst the other three were designed to include both natural and agricultural habitats. Habitats were classified at the beginning of each month, and each side of the road was treated as a separate sample. Transects were sampled within 3 h of sunrise during the birds' early morning peak of feeding activity. Birds were observed and counted or their numbers were estimated from a vehicle travelling at about 30 km/h, and their activity was recorded. More detailed observations (species identification, confirmation of numbers, activity) were made with the vehicle halted as required.

The total number of breeding birds was estimated by pacing the area of the two main colonies with a known-length stride at Spioenkop and Driel Dam (28° 47′S, 29° 17′E) on 23 February and 28 March 1995 respectively. The area of the Spioenkop colony was checked on a 1:10,000 aerial photograph. The density of nests within the colony was estimated by counting the number of nests in quadrats within the colony. At the Spioenkop colony in February 1995, two areas (sparse and dense reedbeds) were selected as representing the extremes of nest density within the colony.

RESULTS

Birds were collected in all months from August 1994 to June 1995 (Table 1). The diet of the quelea (% mass) and sample size is shown in Table 2. Crushed maize, *Zea mays*, made up between 77% and 94% of the diet between August and January. Maize then made up 0–9% of the diet until May, increasing to 33% of the diet in June. Wild grass seed (species unidentified) made up nearly all of the diet (66–99%) between February and June. Invertebrates made up a small part of the diet during February and May, whilst wheat made up 20–22% of the diet in November and December.

Each transect of 7.7–10.1 km was repeated in all months except November (Table 3). The lengths of transect in natural and agricultural habitats were almost the same at 36.9 and 38.7 km monthly. The numbers of quelea/km and number of flocks/km in natural and agricultural habitats are shown in Table 3. On average, the number of quelea/km and number of flocks/km were ten times and five times higher respectively in agricultural lands than natural habitats. There were virtually no birds recorded in January and February.

Table 2 Diet of Red-billed Quelea (% mass) in the Bergville-Winterton district, August 1994–June 1995

Month	% maize	% grass	% wheat	% invertebrates	*n*
Aug	86	14	0	0	51
Sept	89	10	0	0	52
Oct	94	6	0	0	48
Nov	80	0	20	0	40
Dec	77	1	22	0	59
Jan	89	11	0	0	25
Feb	9	88	0	3	43
Mar	0	99	0	< 1	25
Apr	0	99	0	1	25
May	3	96	0	1	25
June	33	66	0	< 1	25

Table 3 Habitat usage by Red-billed Quelea in the Bergville-Winterton district in 1994–95

	Natural habitats (36.9 km/month)		Agricultural habitats (38.7 km/month)	
Date	**No/km**	**Flocks/km**	**No/km**	**Flocks/km**
Aug	—	—	—	—
Sept	1.5	0.7	37.4	3.4
Oct	1.7	0.4	13.3	1.4
Nov	—	—	—	—
Dec	0.5	0.5	2.1	2.2
Jan	0	0	0.01	0.1
Feb	1.8	1.2	0.4	0.3
Mar	1.5	0.9	9.9	3.1
Apr	1.4	0.3	24.0	3.4
May	0	0	12.9	1.9
Jun	2.8	0.3	16.8	1.8
Mean	1.2	0.4	11.5	1.9

The areas of the Spioenkop and Driel Dam colonies were estimated as 7950 m^2 and 9730 m^2, respectively. Selection of nest density figures was based on nest densities in sample quadrats (Table 4). The extremes were 2.7 and 15.7 nests/m^2, with an average of 11.1 nests/m^2. The figure of 11 nests/m^2 was used. This gave an estimate of 87,450 and 107,300 nests at Spioenkop and Driel Dam respectively, giving a total of 389,500 breeding adults. Other smaller breeding colonies in the district are estimated to comprise another 50,000–

Table 4 Densities of Red-billed Quelea nests at Spioenkop and Driel Dam

Area	Habitat	Area (m^2)	Density (nests/m^2)
Spioenkop	Sparse reedbed	10.5	2.7
	Dense reedbed	1	11.0
	Sparse reedbed	6	6.5
	Dense reedbed	9	15.7
Driel Dam	Dense reedbed	4	15.0

100,000 breeding adults. The number of breeding birds in the Bergville-Winterton district in February 1995 was estimated as 450,000.

Using Jones' (1989a) estimate of 2.2 chicks as the average number of fledglings per nest, the numbers of fledglings from the two main colonies were estimated as 192,390 and 235,856, rounded to 190,000 and 235,000 respectively.

DISCUSSION

The primary item of diet of quelea in winter was crushed maize obtained in cattle feedlots. This was also the case in quelea collected at roosts in Spioenkop Nature Reserve, showing that the sampling was not biased by the collection of birds on farms. In summer, the quelea ate large amounts of wild seeds, much obtained whilst feeding in agricultural lands.

Red-billed Quelea occurred throughout the Bergville-Winterton area, although numbers had declined in December and birds were almost absent in January, after the late heavy summer rains. In January, the only large (> 100 individuals) flocks of quelea were seen at a single cattle feedlot whilst most other farmers had stopped feeding cattle by January. Once the two major breeding colonies at Spioenkop and Driel Dam had formed in February, the quelea were localised around them. Birds were not detected on transects during this time, because none was located sufficiently close to the breeding colonies, from which birds seemed not to venture more than 10 km.

Maize fields were the most favoured habitats for feeding, with quelea feeding on ripening grass seeds on the edges of the fields, and on grasses and maize seeds within them. It was also apparent that the quelea breeding at Driel Dam fed in large numbers on wild grasses on the fringes of maize lands. Quelea are thought to prefer agricultural lands because the ground vegetation is less dense, allowing the birds ready access to seed on the ground. Typically, when quelea feed on the ground and in natural grasslands, where grass cover is dense, they are able to look for seeds efficiently only once the grass has been burnt.

Jarvis and Vernon (1989) noted that quelea were often seen in old maize fields, where they fed on weed seeds and shattered fragments of maize seeds and the present study has now shown that they are sometimes reliant on such agricultural lands for feeding.

The decline in quelea numbers during the summer rains is in accordance with the general model of quelea migration described by Jones (1989b,c) although occurring later in the year than he suggested for southern Africa. This may be attributed to the fact that the rains were late in summer of 1994–95. Thereafter quelea were restricted to the immediate vicinity of the breeding colonies.

Provided that the adult birds did not depart after breeding, and assuming that there was no additional recruitment from itinerant breeding elsewhere, then it is possible to make the following calculations. Given a population of 500,000–1 million and assuming an annual mortality of 50% (Jones 1989d), 250,000–500,000 new recruits would be required to maintain the Bergville-Winterton population. Juvenile mortality is also likely to be about 50%, suggesting that 500,000–1 million chicks are required annually to maintain the population. There was only one breeding attempt in the summer of 1994–95, suggesting a total recruitment of about 495,000. It seems likely that the 1994–95 recruitment was poor because there were no repeat breeding attempts, presumably because of late rains. It appears that under more usual conditions, the productivity of the local colonies would be sufficient to maintain a breeding population of half a million birds.

T. B. Oatley (Berruti, 1970) reported that the population in the Winterton area in 1970 was between 7000 and 45,000, with lower figures being more realistic. It is clear that the Red-billed Quelea have increased in abundance by one or two orders of magnitude since 1970.

Harvesting of chicks by hand from the two major colonies at Driel Dam and Spioenkop is an alternative means of species-specific harvesting. Because the colonies are apparently predictably present annually at the same localities, it is practical to organise harvesting, although the locations of the colonies, in reeds in water, may present problems.

This study has shown that Red-billed Quelea have adapted well to modern agricultural practices, feeding mainly in farmlands and in cattle feedlots. Previously regarded as a highly migratory species relying mainly on wild grass seed, this population appears to be more sedentary and dependent on agricultural practices for most of its food. It would be instructive to know when cattle feedlots and centre-pivot irrigation became common farming practice in the area. The building of large dams, which support large reedbeds, also provide secure breeding sites. Thus, agricultural changes and water impoundments have created highly favourable ecological conditions, which have supported the increase in quelea numbers.

ACKNOWLEDGMENTS

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13 Alternative Strategies for Red-billed Quelea Population Management

Maria Garanito[1], M. J. Botha[2] and L. van der Westhuizen[1,3]

[1]Department Zoology and Entomology, University OFS, Bloemfontein 9300, South Africa
[2]Directorate Land and Resource Management, NDA, Pretoria 0001, South Africa
[3]Author for correspondence, email: VDWestMC@dre.nw.uovs.ac.za

ABSTRACT

Alternative methods for the control and management of Red-billed Quelea birds, *Quelea quelea*, were investigated to devise a strategy with lower environmental and economic costs than conventional methods. Both lethal control, by chemicals and explosives, and habitat manipulation were addressed. Manipulation of the birds' habitats was achieved with environment-friendly methods, such as repelling them from breeding and roosting habitats with bird X-pellers, physical means and canons or by the destruction of their habitat by mechanical, physical or chemical methods. Of the methods examined, it was concluded that mechanical destruction of roosting and breeding habitat was the most cost-effective and chemical control the least cost-effective.

INTRODUCTION

The Red-billed Quelea, *Quelea quelea*, is a major pest of agriculture in Africa. Although quelea prefer the seeds of wild grasses, they will eat agricultural crops when their preferred food is scarce and so cause extensive losses to cultivated cereals such as millet, sorghum, rice and wheat (Jarvis and Vernon, 1989).

Various traditional scaring methods have been used to keep birds out of crops, such as cracking plastic flags, shouting and clapping, scarecrows, moveable rattles and even magic and superstition. Although such methods have little impact on the quelea populations, they do reduce crop damage to a limited extent. However, they have not been practised extensively, as they are time-consuming and unproductive (Bashir, 1989).

In this study, various alternative control methods were evaluated. These methods included (a) lethal control methods (chemical and explosives) and (b) displacing the birds with repellents or by destroying their habitats.

MATERIALS AND METHODS

Most of the habitat manipulation experiments and surveys were conducted at or close to the Krugersdrift Dam in the Soetdoring Nature Reserve, in the Bloemfontein district of South Africa (chemical control of quelea is not permitted within the Soetdoring Nature

Reserve itself; Anonymous, 1994). For roosting and breeding, quelea preferred to use areas of the common reed *Phragmites australis*. Potential breeding sites were destroyed by cutting the reeds using hand implements only, or mechanically by using tractors and brushing equipment. For the manual cutting, trials of both single-handed cutting and working in groups were conducted. The mechanical control was repeated at four different farms. In all cases, the time taken, manpower needed and type of equipment used, were recorded. The running cost and labour costs of the four different farmers were compared using local financial norms. The methods used for repelling birds included canons, physical and mechanical means, and bird X-pellers. Data on lethal control methods (date of control, farm name, crop threatened, habitat, vegetation type, control method, cost of control, number of target and non-target birds killed) were mostly obtained from the National Department of Agriculture in Pretoria. The influence and impact of the different control methods on the numbers and behaviour of quelea and other species were recorded after each control action, and the various control methods were evaluated in relation to environmental, human and financial considerations. The averted impact of the quelea finches on the different crops, the duration, amount and output of manpower involved and the economical input and benefit of the different methods refer respectively to the environmental, human and financial considerations.

RESULTS AND DISCUSSION

Explosives and chemical control are the most frequently used methods of control in South Africa. The average number of quelea controlled annually during the last three campaigns (1995–98) together with the control costs, and estimates of benefits in terms of R9260 million worth of crop losses prevented and an associated added value of R27,652 million

Table 1 The average number of quelea killed, total costs of control (*R*) and losses prevented (*R*) with chemical and explosive control actions in South Africa from 1995–98

			Losses prevented (*R*)	
	Quelea killed	**Total cost (*R*)**	**Crop**	**Added value**
Chemical control	27 964 000	987 572.90	3 640 727.56	10 601 269.79
Explosives	52 186 000	1 673 990.44	5 619 372.44	17 051 113.20
Total	80 150 000	2 661 563.34	9 260 100.00	27 652 382.99

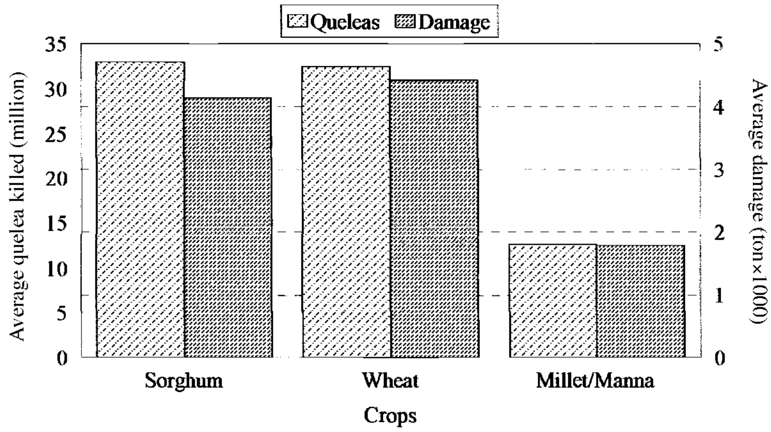

Figure 1 Average numbers of quelea killed (million) and average damage (ton × 1000) prevented to different crops during three seasons (1995–98).

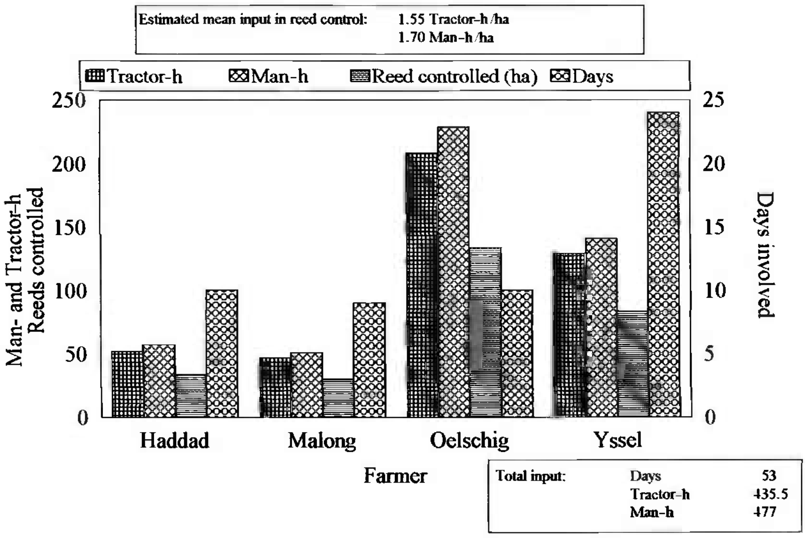

Figure 2 Input of farmers in mechanical destruction of common reeds in the Soetdoring Nature Reserve.

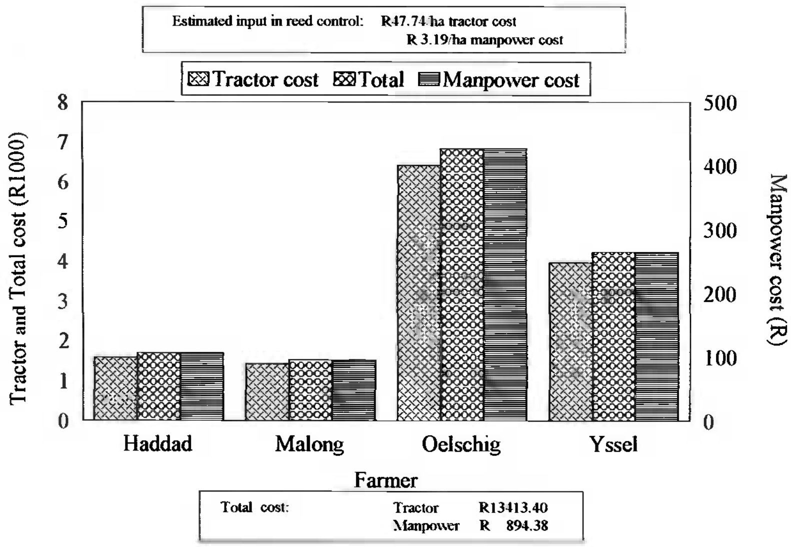

Figure 3 Financial impact of mechanical destruction: tractor and manpower costs/ha.

are given in Table 1. The averted damage to the crops and added value products (bread, meal, bird seed, etc.) were calculated according Jarvis and Vernon (1989) and Geertsema (1996). Division of the latter figure by the control costs suggests that the South African economy experienced a control benefit ratio of 10:4.

Of all quelea killed from 1995 to 1998, 42% were a threat to sorghum, 40% to wheat and 16% threatened the millet and manna productions in South Africa (Figure 1). The averages of damage prevented to the relevant crops were 4137 tons of sorghum, 4413 tons of wheat and 1787 tons of millet and manna.

Results of the trials are presented in Figures 2–4. To destroy 127,363 m^2/day with mechanical means needed an average of 1.70 man-h/ha and 1.55 tractor-h/ha (Figure 2), costing R51/ha (Figure 3). The destruction by hand of 58 m^2/day of common reeds along riverbanks took an average of 1565.76 man-h/ha costing R2595 (Figure 4). The group labour

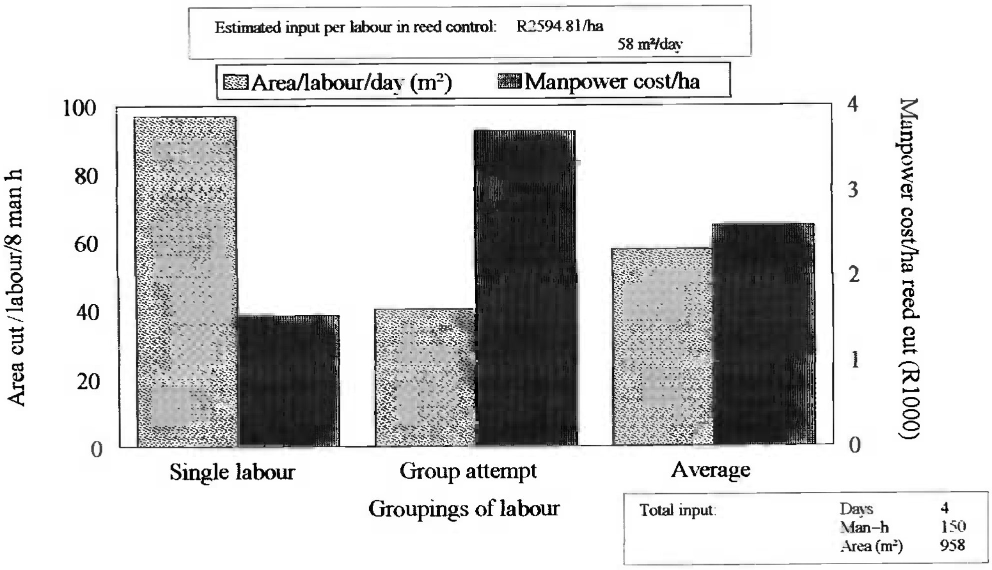

Figure 4 Performance and cost of physical removal of reeds in the Soetdoring Nature Reserve.

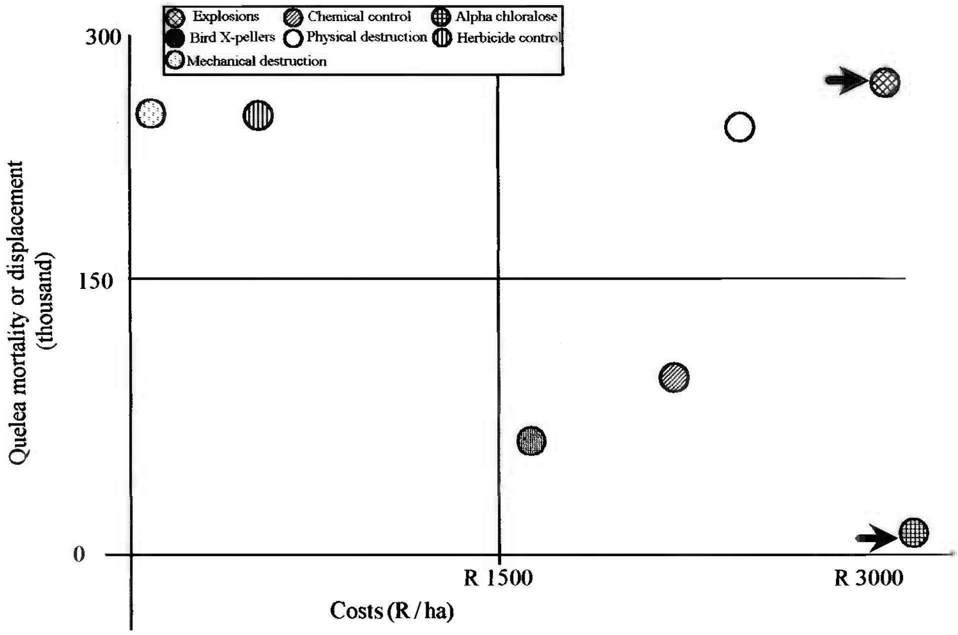

Figure 5 Quadrant illustration of the costs versus efficiency of various control methods.

activity was less effective than single-handed cutting, because of its higher costs and the smaller areas being cut (Figure 4).

The various strategies are compared in Figure 5 using the control impact and financial expenditure as vectors. Ratings for the bird X-peller, alpha-chloralose (lethal control by baiting) and herbicidal control of roosting and breeding sites are also given in Figure 5, although no other analyses for these methods are presented here. Mechanical destruction, and thus displacement of roosting and breeding quelea, was rated as the most cost-effective method of those considered. Chemical control by baiting with alpha-chloralose on the other hand was rated as the least cost-effective.

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14 Red-billed Quelea Movements in Southern Africa shown by Ringing Recoveries in the SAFRING Database

H. D. Oschadleus

SAFRING, Avian Demography Unit, University of Cape Town, Rondebosch, 7701, South Africa
(email: dieter@maths.uct.ac.za)

ABSTRACT

Summaries of quelea movements, based on recoveries in the database of the South African bird-ringing scheme (SAFRING) are presented. By 1999, the database included details of 510 recoveries of Red-billed Quelea, with recovery rates for quelea ringed as adults or juveniles unchanged since the 1960s (0.24% in 1966; 0.29% in 1980; 0.25% in 1995). Inclusion of 'non-significant' recoveries (birds caught again within a few days of ringing) increased the overall rate to 0.38%. Short-term movements were examined by analysing the average and median distances, for each month, of recoveries with elapsed times of less than 6 months. Data on movements according to the month of recovery are presented in maps. The longest movement (2545 km) for a quelea in SAFRING's database was by a bird recovered in the Democratic Republic of Congo in November 1998. Four other birds (adults and immatures) were ringed in South Africa and recovered in foreign countries more than 1000 km distant. The results are discussed in relation to prevailing meteorological conditions in southern Africa and the short-comings inherent in analyses of ringing recovery data.

INTRODUCTION

The Red-billed Quelea, *Quelea quelea*, is a pest of small grain crops. The quelea is mobile, flying long distances on a daily and seasonal basis (Mundy and Herremans, 1997). Understanding its movements could help to predict when the birds are likely to arrive in an area. Ward (1971) proposed that throughout Africa quelea have two main migrations in their annual cycle. The 'early rains' migration involves quelea being forced out of areas where grass seed germination has occurred following the first rains, and flying over the approaching rain-front to areas where fresh grass seed has been produced. The subsequent 'breeding' migration follows the rains in successive breeding attempts. This report brings previous summaries of quelea movements, based on the recoveries in the database of the South African bird ringing scheme (SAFRING) (McLachlan, 1966; Jarvis, 1989; Jones, 1989; Tree, 1989), up-to-date.

METHODS

All recovery reports of quelea were checked, or entered into the database of SAFRING, including 'non-significant' recoveries, i.e. those caught again after ringing (controlled)

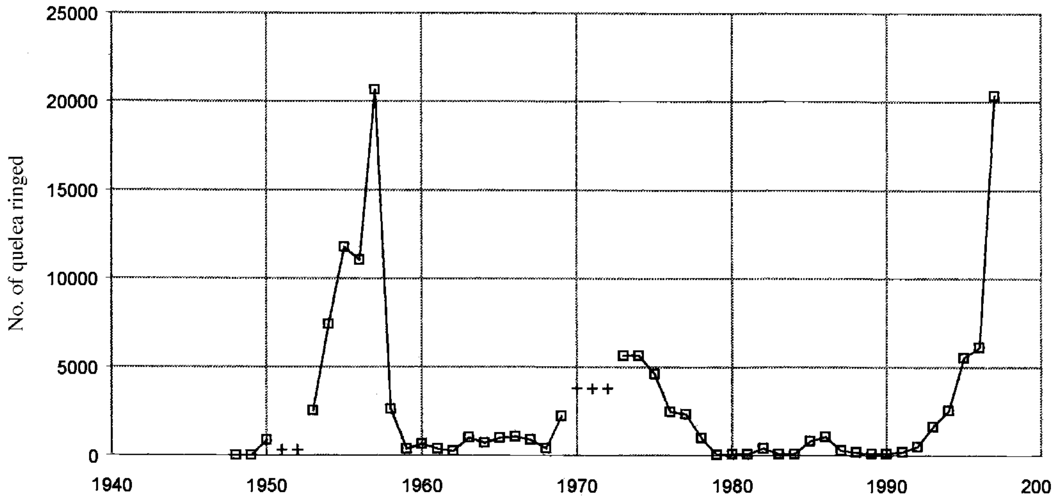


Figure 1 The number of Red-billed Quelea ringed in southern Africa from 1948 to 1998. The squares represent the number of quelea ringed in a particular year. The crosses represent the average number of quelea ringed in years when annual totals are not available.

within a few days of ringing. To study short-term movements, only recoveries with elapsed times of less than 6 months were analysed.

RESULTS

The total number of quelea ringed in southern Africa between 1948 and July 1998 was 133,574 (SAFRING database; Figure 1). The peaks in ringing in the late 1950s and late 1990s indicate periods of involvement by the South African Department of Agriculture (by

Table 1 Distribution of Red-billed Quelea recoveries by country and month of recovery; data are for all recoveries, including non-significant ones

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum	%
Democratic Republic of Congo											2		2	0
Malawi					1		1	2	1	2	3	1	11	2
Zambia								1	1				2	0
Namibia					1				1		1		3	1
Botswana										1		1	2	0
Zimbabwe	1	3	2	2	2	3	10	14	16	10	6	3	72	14
South Africa:														
Northern Province	22	4			1	3	2			1			44	9
North West Province	3	2	2	2		1	3	1	6	13	193	13	239	47
Gauteng	5	2	1					3	2	13	17	23	66	13
Mpumulanga	1						1	2	1		2	4	11	2
Northern Cape									1		1		2	0
Free State		2		1	1	3	2	2	2	10	12	13	48	9
KwaZulu Natal												1	1	0
Eastern Cape						3			2	1		1	7	1
Sum	32	13	5	5	6	13	19	25	33	51	237	71	510	
%	6	3	1	1	1	3	4	5	6	10	46	14		

ringing and sponsoring ringing, respectively). By 1999 SAFRING's database included details of 510 recoveries of Red-billed Quelea, ringed with SAFRING rings over the previous five decades (16 of these records were recaptures of living birds by ringers). The recovery rates for quelea ringed as adults or juveniles did not change between the 1960s (0.24% McLachlan, 1966; 0.29% Jones, 1980, who also reported a recovery rate of only 0.05% for birds ringed as nestlings) and 1995 (0.25% Oatley, 1995a), although including 'non-significant' recoveries increases the overall rate to 0.38%. Of these recoveries, 46% occurred in November and 47% were in the North West Province (Table 1), due largely to a control operation at Barberspan on 19 November 1975 during which 181 recoveries were made. Such events and the variable search efforts associated with ringing recovery data introduce biases to be borne in mind when making interpretations from them.

The maps (Figure 2a-l) show the recoveries by month of recovery. Points of interest, summarised for convenience according to the arbitrary criterion of month of recovery, include:

- *January* (Figure 2a). Recoveries appear to converge on the highveld. The maximum number of recoveries during January in any one year was 7. Except for six birds, all movements were greater than 100 km but 25 recoveries occurred within 6 months of ringing, so birds recovered in January had made relatively long movements in a short time.
- *February* (Figure 2b). (From February until June, the number of recoveries is small.) The majority of long-distance recoveries (85% between 100 and 800 km) and mostly within short periods (69% within 6 months).
- *March* (Figure 2c). Two long-distance recoveries (846 and 1162 km) from South Africa to Zimbabwe, both within 5 months of ringing.

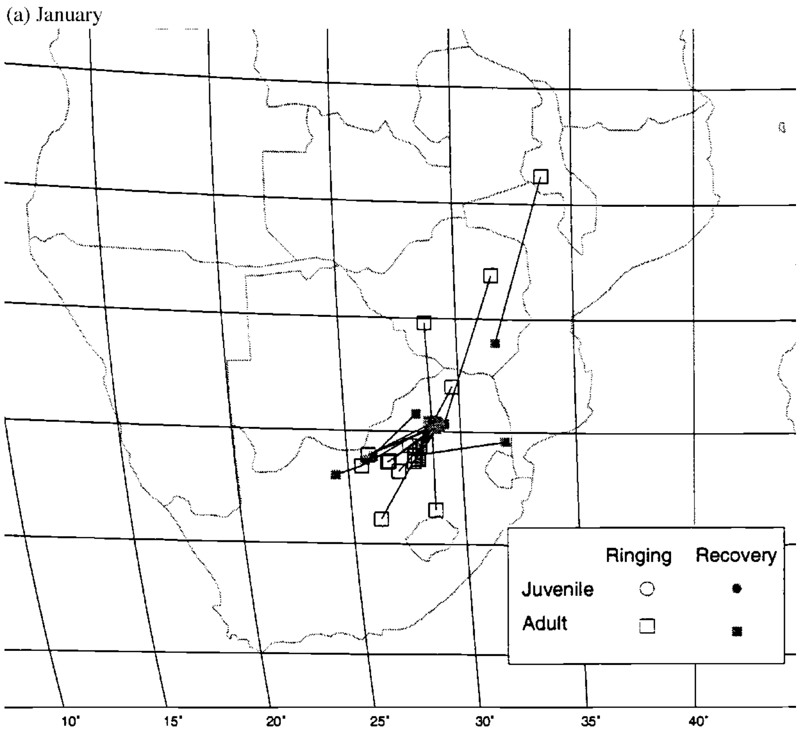
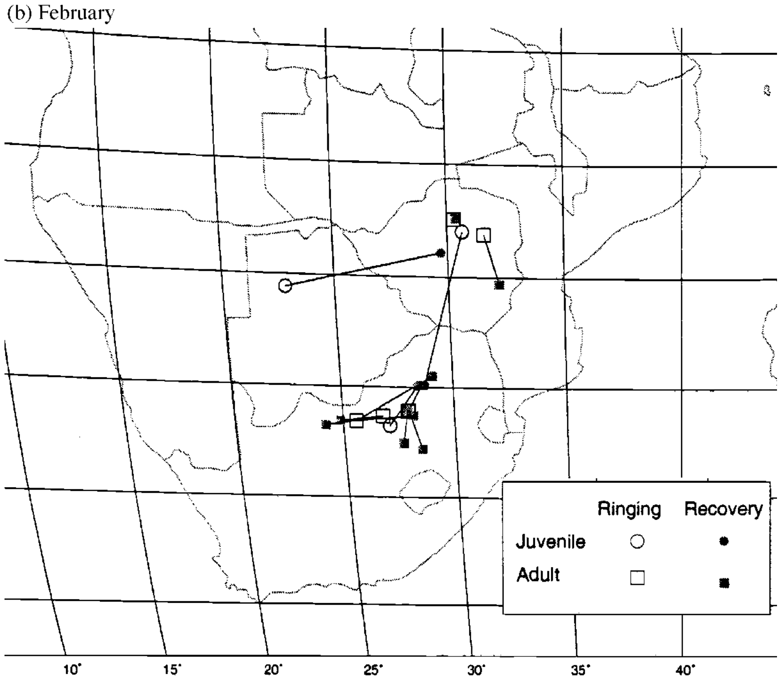
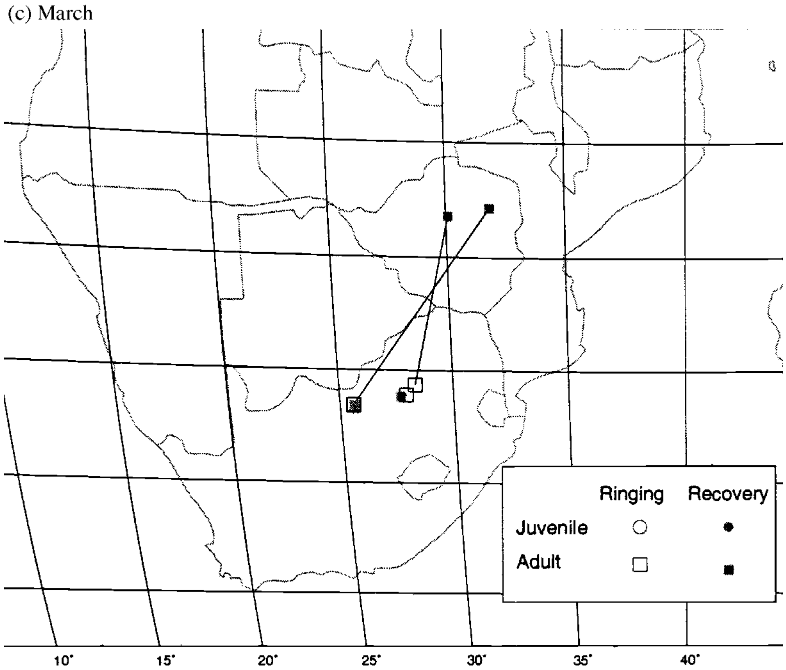


Figure 2 Maps showing recoveries of quelea, with lines linking ringing site (open circles or squares) and locations of recoveries (dark circles or squares). a January; b February; c March; d April; e May; f June; g July; h August; i September; j October; k November; l December.

(b) February



(c) March



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- *April* (Figure 2d). One long distance movement of 778 km, within 6 months of ringing.
- *May* (Figure 2e). All the recoveries in May occurred more than 6 months after ringing, most having covered medium distances (> 100 km).
- *June* (Figure 2f). Eight recoveries were more than 100 km, and only three within 6 months of ringing.
- *July* (Figure 2g). Most of the movements occurred within the country of ringing. There was one long-distance migration between KwaZulu-Natal and Malawi: a nestling (AC00815) ringed in January was recovered 6.5 months later (Oatley, 1995b).

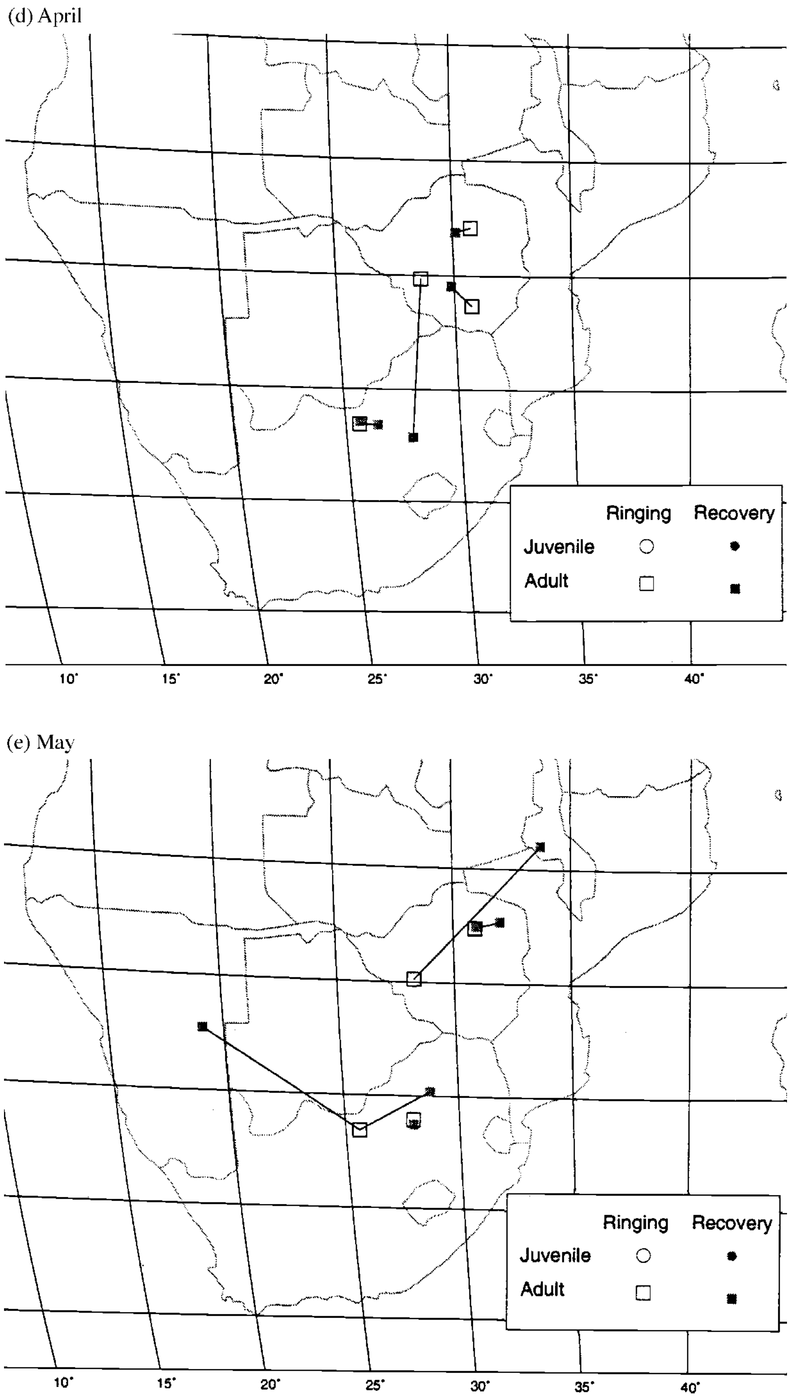
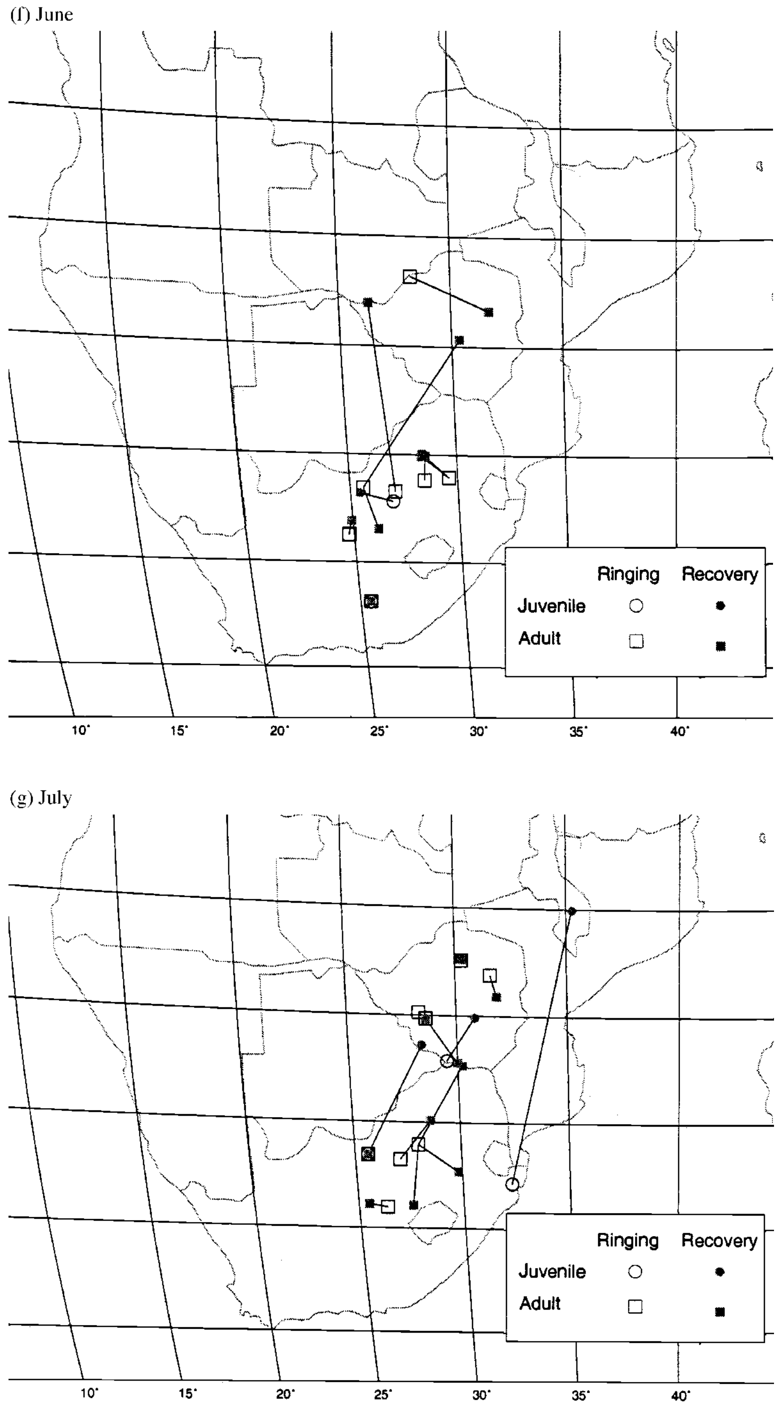


Figure 2 Continued

- *August* (Figure 2h). A juvenile (AA26591) was recovered in Malawi in August, 11 months after being ringed in Namibia. Five quelea ringed at Barberspan in the 1970s were recovered in Zimbabwe, all more than 12 months later.
- *September* (Figure 2i). The six longest distances moved were by adults ringed in North West or Gauteng Provinces during August to December. One was recovered in Malawi 9 months later, the rest in Zimbabwe more than 12 months later.
- *October* (Figure 2j). The longest migration was by bird AD49898, ringed in North-West Province and recovered 2 years later in Malawi (Oatley, 1996). The next three



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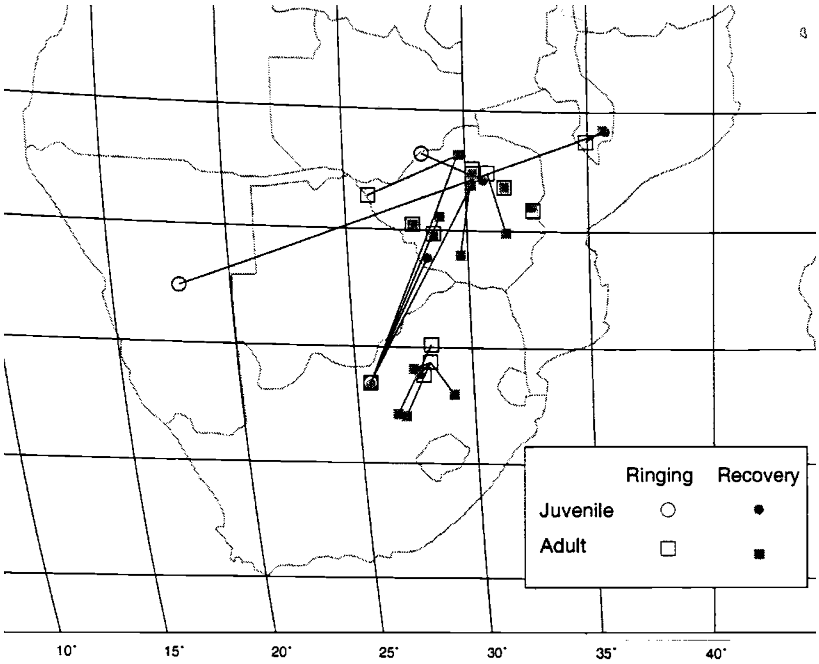
longest movements were from Gauteng to Botswana, and from Zimbabwe to Malawi and Gauteng respectively, all having elapsed times of 11 to 14 months. Sixteen recoveries occurred in South Africa within 6 months and within 40 km of ringing.

- *November* (Figure 2k). The longest movement for a quelea in SAFRING's database is by bird AE10821, recovered in the Democratic Republic of Congo in November 1998 (Oschadleus, 1999). Four other birds (adults and immatures) were ringed in South Africa and recovered in foreign countries more than 1000 km distant (in different directions; Figure 2k). The elapsed times were between 12 and 18 months. One bird flew

(h) August



(h) August

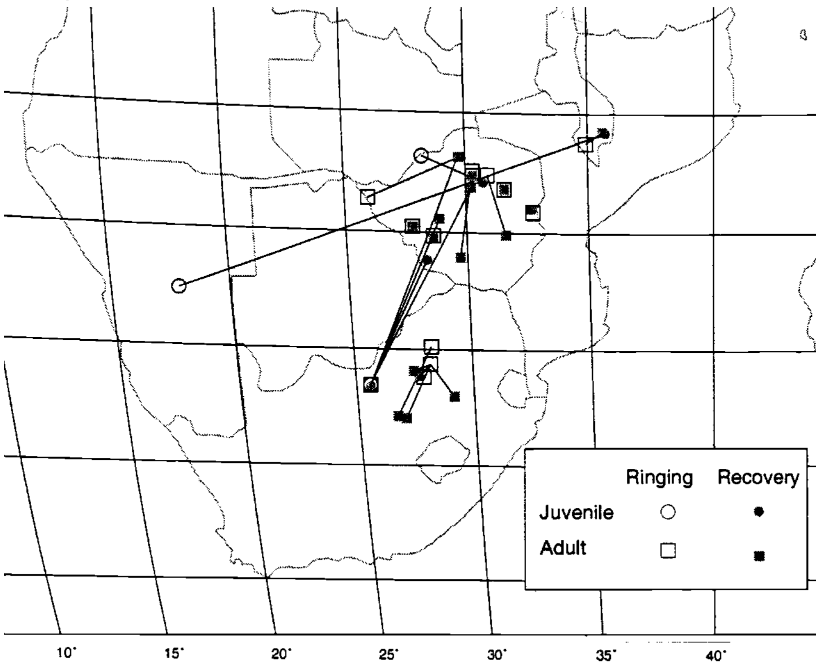
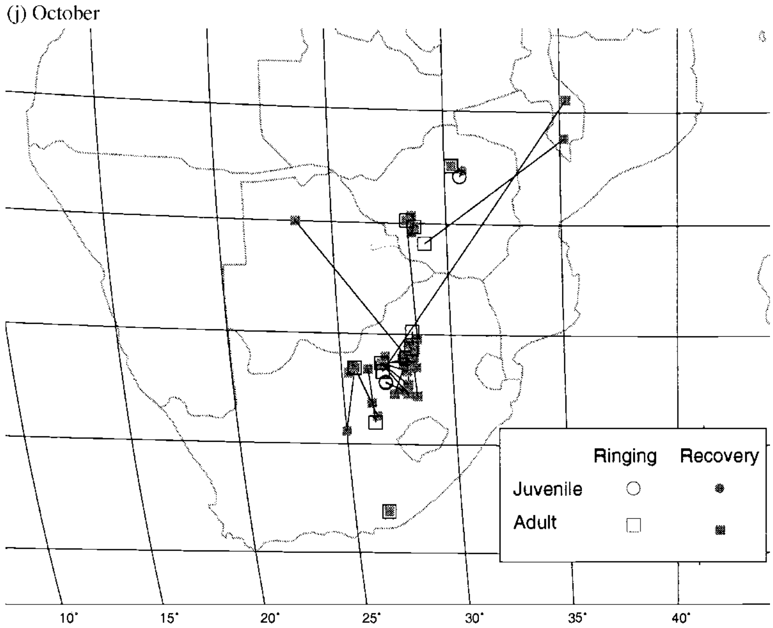
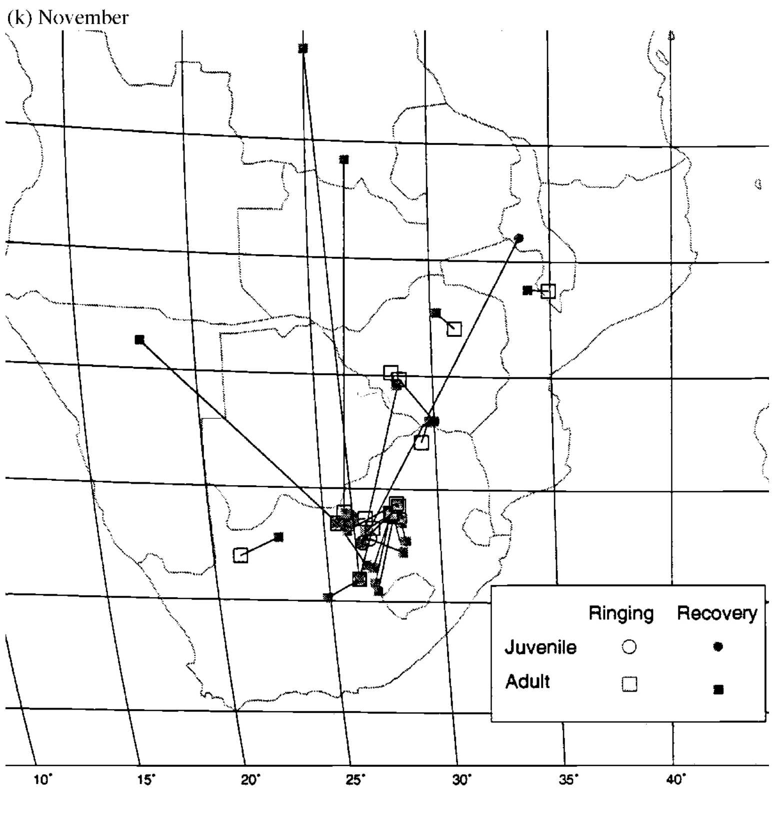


Figure 2 Continued

from Zimbabwe to South Africa, the elapsed time being 2 years. After a control operation on 19 November 1975 at Barberspan, the largest number of recoveries (181) for one site was obtained. All the birds had been ringed at Barberspan within 4 km of the control operation, from the preceding day to over 3 years previously, indicating some site fidelity. Seventy-eight recoveries were of birds ringed less than 1 month previously, and 82 prior to that. Although the 1975/76 ringing report gave a total of 203 quelea recoveries (Vernon, 1977), this does not include the recoveries made 1 or 2 days after ringing.





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- *December* (Figure 2l). An adult (5504721) was recovered in Malawi (1957), having been ringed 2 years previously in Johannesburg (McLachlan, 1962). One adult moved from Barberspan to KwaZulu-Natal during 1.3 years. Of the rest, 47 birds (68%) were recovered within 6 months. In Zimbabwe two adults moved 309 and 229 km south in 10 days and 7.5 months, respectively. The greatest elapsed time was of a quelea (60174461), ringed on 28 December 1963 in Zimbabwe as a first-year male and recovered 244 km away, 7 years 1 month later (Tree, 1989).

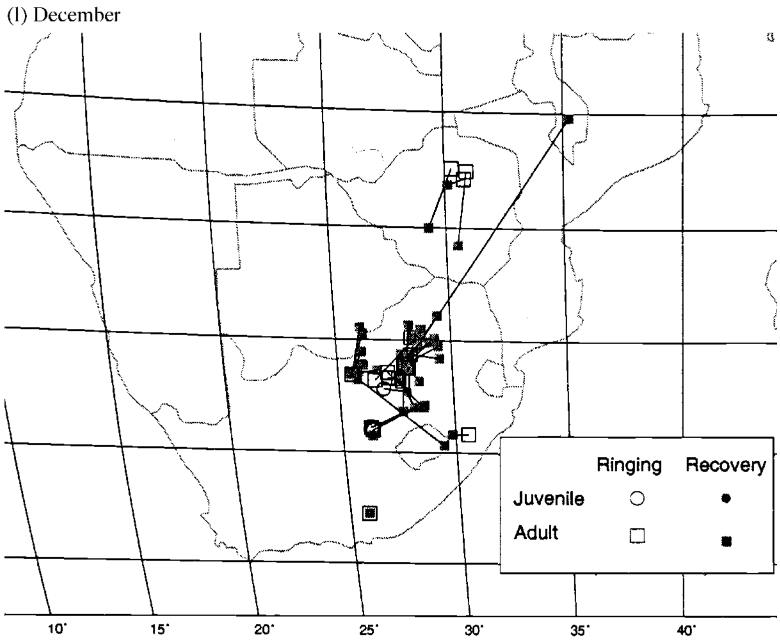

Figure 2 Continued

Table 2 Distance moved by Red-billed Quelea ringed in southern Africa, and recovered within 6 months (184 days) of ringing, classified by month of recovery

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	215	185	671	248		52	83	28	37	15	10	71
Median	206	196	846	101		0	13	13	12	13	4	35
Standard Error	36	43	346	178		52	38	13	24	3	2	12
Minimum	6	7	4	12		0	0	0	0	0	0	0
Maximum	838	417	1162	778		157	272	89	220	40	263	309
n	25	9	3	4	0	3	9	8	9	23	192	47

To look at movements over a relatively short time, the recoveries with elapsed times of less than 6 months were analysed by the average and median distances for each month (Table 2). Although the sample sizes are small in many months, and the different sample sizes may introduce a bias, the maximum distance travelled within 6 months was less than 300 km for birds recovered between June and November, and the median distances were all 13 km or less. From January to April the maximum distances exceed 300 km and the median exceed 100 km.

DISCUSSION

From April to July there were few short or long distance recoveries (Table 2, Figure 2d–2g). Most long-distance recoveries were of birds found during September, perhaps reflecting direct movements between South Africa and Zimbabwe, following the start of the rains in KwaZulu-Natal. From October to December there was a high proportion of short-distance recoveries in the crop-growing Free State and North-West Provinces. During these months the rain front passes from east to west across southern Africa. The scale is too coarse to determine whether quelea are flying over the rain front. Also they probably congregate in the crop-growing areas where irrigated crops provide a reliable source of food, reducing the need to travel. The recoveries in January to March decrease in number but increase in distance, probably as a result of the breeding migration.

Analyses of the data on recoveries are limited in several respects. Using the recovery data from five decades is insufficient to determine patterns of quelea movements relative to rainfall since the start, intensity and duration of the rains is variable from year to year. Many recoveries are made within days of ringing due to control operations and coverage of both ringing and control operations during the year varies widely. There were no recoveries from Angola or Mozambique, where quelea do occur, probably due to lack of both ringing and control operations, and only two from Botswana, although there are probably extensive movements of quelea between South Africa and these countries. The recovery rate of quelea is low (0.38%), requiring a large number of birds ringed. The cheapest way to ring the large numbers of quelea needed to generate sufficient recoveries to discern patterns of movements is to involve amateur bird ringers, who are prepared to volunteer their time and expertise. Provided the costs of rings, transport and accommodation are covered, they are willing to go to great lengths and endure considerable hardship in undertaking the ringing (Scott, 1996). Most ringing and controlling of quelea have been in South Africa and Zimbabwe, so that the most useful areas for concentration of quelea ringing efforts in surrounding countries in future would be in Botswana.

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SESSION 3 CURRENT UK-BASED MIGRANT PEST RESEARCH

Workshop on Research Priorities for Migrant Pests of Agriculture in Southern Africa, Plant Protection Research Institute, Pretoria, South Africa, 24–26 March 1999.
R. A. Cheke, L. J. Rosenberg and M. E. Kieser (eds) (2000) Natural Resources Institute, Chatham, UK.

15 Quelea Populations and Forecasting in Southern Africa

P. J. Jones[1], R. A. Cheke[2], P. J. Mundy[3], M. Dallimer[1] and J. F. Venn[2]

[1] Institute of Cell, Animal & Population Biology, University of Edinburgh, Edinburgh EH9 3JT, Scotland, UK (email: Peter.Jones@ed.ac.uk)
[2] Natural Resources Institute, University of Greenwich, Central Avenue, Chatham Maritime, Kent, ME4 4TB, UK
[3] Department of National Parks & Wild Life Management, PO Box 2283, Bulawayo, Zimbabwe

ABSTRACT

Different subspecies of Red-billed Quelea, *Quelea quelea*, occur in different parts of Africa and each has its own migration pathways determined by local rainfall patterns and the availability of grass seed. The migration patterns of *Q. q. lathamii*, the subspecies present in southern Africa, began to be understood in the 1970s. Only now, however, are sufficient remote-sensed data on rainfall distribution and vegetation growth available over southern Africa as a whole to make the accurate prediction of quelea movements in any one year a realistic possibility. The DFID-funded project 'Models of quelea movements and improved control strategies' has assembled a computerised database of 3543 historical records of quelea occurrences throughout southern Africa, from which a forecasting model has been developed to assist pest managers in predicting control needs and targeting them effectively.

In parallel with this project, a DNA microsatellite study is being conducted to try to identify possible sub-populations of quelea within southern Africa and thereby assist in tracking their movements. Orientation studies on caged birds have also been carried out in Zimbabwe to establish the intended direction of movement during the 'early-rains migration', in order to detect whether a 'migratory divide' might separate birds heading towards two possible alternative destinations – Angola or South Africa – and hence lead to genetic differentiation. Preliminary results are discussed.

INTRODUCTION

The overall strategy for the management of the Red-billed Quelea, *Quelea quelea*, now accepted Africa-wide, is to control only those birds likely to pose a threat to vulnerable local crops (Ward, 1979). The pattern of quelea occurrences, however, is very variable from year to year, depending on regional variations in rainfall and grass seed production. In addition, the reporting of quelea occurrences, whether as roosts or breeding colonies, is often haphazard and slow, such that national control teams may find it difficult to mobilise in time or to operate with full efficiency and effectiveness. What is required is a forecasting system for quelea similar to that already existing for African Armyworm, *Spodoptera* *exempta*, which can almost instantaneously incorporate remotely-sensed data on relevant environmental parameters into a simple predictive model that can be used in the field (Holt *et al.*, 2000 *or* see page 151).

This paper reports on the project 'Models of Quelea Movements and Improved Control Strategies', funded by the UK Department for International Development (DFID) and being carried out on the southern African race of the Red-billed Quelea, *Q. q. lathamii*. It also reports on work, collaborative with this project, on molecular genetic variation in Red-billed Quelea, as part of a CASE studentship to Edinburgh University and the Natural Resources Institute (NRI) funded by the UK Natural Environment Research Council. The DFID project is centred on Zimbabwe, where the target institutions are the Ornithological Research Unit and the Problem Bird Control Unit of the Department of National Parks and Wild Life Management. It also involves the collection of additional data from the surrounding countries of the Southern African Development Community (SADC) that share the same quelea populations.

In order to achieve the prime objective of building a practical quelea forecasting model, these two parallel projects have involved three main areas of work.

(1) The compilation of an electronic database of historical quelea records in SADC countries (but excluding Tanzania, which harbours only the separate East African subspecies, *Q. q. intermedia*).

(2) A re-assessment of the conjectured migration patterns of Red-billed Quelea in southern Africa, as originally proposed by Ward (1971) and Jones (1989b). This is based on new information from plumage polymorphisms and patterns of molecular genetic variation using microsatellite DNA to identify and track discrete sub-populations during their annual migrations, and from an investigation of the preferred migratory orientation of birds preparing for the 'early-rains migration'. This work is also attempting to resolve the '*spoliator* problem' – the uncertainty surrounding the possible existence of a genetically discrete second population of quelea in southern Africa (Jones *et al.*, 1998, 2000), which would have implications for quelea management.

(3) The construction of the computer model itself.

THE NRI QUELEA DATABASE

An electronic database has been re-compiled from the Quelea Archives originally assembled by Joyce Magor (Magor and Ward, 1972; COPR, unpubl.) in the early 1970s at the former Centre for Overseas Pest Research (COPR, now NRI). The original electronic database on magnetic tape was lost but one hard copy of the print-out was preserved. It was from this that 3543 separate entries concerning SADC countries have been re-keyed by Nicola Buss into an Access database at NRI (Venn *et al.*, 1999).

In its current state, the database extends from 1836 (South Africa) to 1974 but subsequent years up to the present (with inevitable gaps for some countries) are being added from Botswana, Namibia, South Africa and Zimbabwe, including raw data from the Southern African Bird Atlas Project (Harrison *et al.*, 1997). The most useful information is available only from the early 1950s, detailing precisely located colonies where the dates of egg-laying are known (these form the basis of the predictive model – see below) but the database also contains details of dry-season roosts, control operations, and reported crop damage.

A RE-ASSESSMENT OF QUELEA MIGRATION STRATEGIES IN SOUTHERN AFRICA

The migration patterns and the timing of the annual cycle (breeding, moult, etc.) of Red-billed Quelea are all determined by seasonal changes in food availability (annual grass seeds, insects) and hence, ultimately, by the movements of local rain-fronts (Ward, 1971; Jones, 1989a). A general model of quelea migrations in southern Africa was first described in detail by Jones (1989b) and it is this that forms the basis of the predictive model being developed by the NRI project (see below). However, two aspects of quelea biology that were highlighted by Jones's (1989b) review remain unresolved – flock cohesion and the '*spoliator* problem'. Their resolution will greatly improve our understanding of how quelea population structure relates to their migration patterns, thereby providing a stronger theoretical framework to support the assumptions of the forecasting model.

Flock Cohesion and Genetic Variation at the Sub-Population Level

Several lines of evidence indicate that quelea aggregations may be remarkably cohesive over long distances and prolonged periods, which may include the breeding season (Jaeger *et al.*, 1986, 1989; Jones, 1989b). M. Jaeger (*in litt.*) has suggested theoretical reasons why such cohesion might be adaptive in the context of the Red-billed Quelea's wide-ranging migration and nomadism. We suspect that such cohesion within aggregations, which rarely mix, might account for differences occasionally observed between the plumage characters of males in adjacent breeding colonies (P. J. Jones, unpubl.). The extensive DNA sampling being carried out by M. Dallimer will provide molecular genetic data to establish whether the Red-billed Quelea forms a homogeneous and freely-interbreeding population across southern Africa, or whether it is subdivided into genetically distinct sub-populations maintained by differences in geographical range, migration patterns or seasonality of breeding.

Seventy-three avian microsatellite primers from 16 species in eight families have been tested for cross-species amplification using Red-billed Quelea DNA as a template, obtained from blood samples collected in Bulawayo, Zimbabwe in 1997. Twenty-one markers from nine species successfully amplified an homologous product, with some loci proving to be highly polymorphic (Dallimer, 1999). Six out of eight markers from the most closely-related species, the White-browed Sparrow-weaver *Plocepasser mahali*, worked. The extensive sampling programme is still in progress and has involved obtaining series of blood samples from many hundreds of birds collected in Botswana, Namibia, South Africa and Zimbabwe. In most cases these derive from breeding colonies at each of which 50–80 males and *c.* 20 females were sampled and full plumage data recorded for each bird. The data are currently being analysed.

The Validity of *Q. q. spoliator*

The other unresolved issue raised by Jones's (1989b) review was the taxonomic validity of a second putative subspecies of Red-billed Quelea, *Q. q. spoliator*, within southern Africa, where previously *Q. q. lathamii* had been the only subspecies recognised from the region. *Q. q. spoliator* was described from KwaZulu-Natal by Clancey (1960), and was claimed to be typical of quelea breeding in the wetter areas of the central highveld and eastern coastal zone of South Africa, Swaziland and southern Moambique (Figure 1), i.e. the south-eastern part of the formerly-accepted range of *Q. q. lathamii*. Subsequent work by Clancey (1968, 1973) suggested that *spoliator* occurs during the non-breeding season (May to November) throughout the interior of southern Africa, including Namibia, within the breeding range of *Q. q. lathamii* (Figure 1). A clear resolution of the taxonomic distinctness of these two

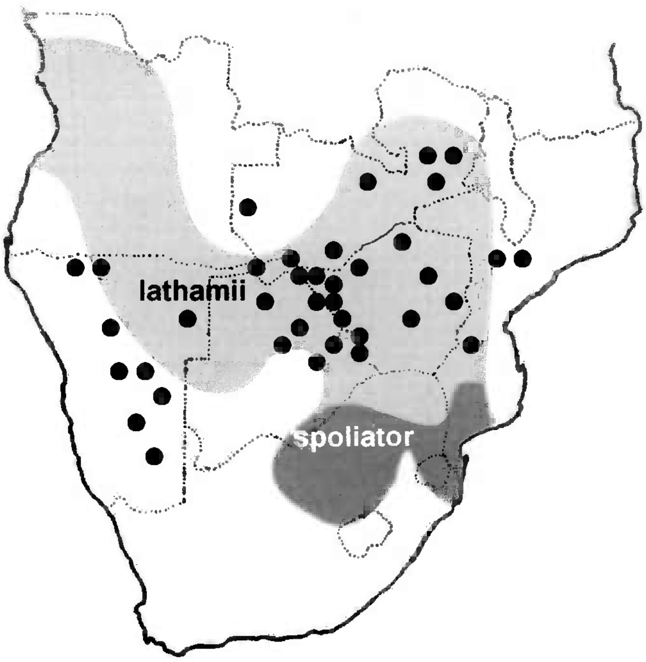

Figure 1 Conjectured breeding distributions of *Q. q. lathamii* (light grey shading) and *Q. q. spoliator* (dark grey shading). Filled circles indicate occurrences during the non-breeding season (May to November) of *spoliator*-type individuals within the breeding range of *lathamii* (after Clancey, 1973).

subspecies is required if the migratory behaviour of southern African quelea is to be properly understood and lead to a more effective control strategy.

The validity of *Q. q. spoliator* is particularly difficult to assess, because it was described on the basis of differences in the colour of the upper-parts in non-breeding plumage (grey-brown in the case of *Q. q. spoliator*, compared to the warm buff-brown of 'true' *Q. q. lathamii*). In contrast, all other subspecies of the Red-billed Quelea had been characterised by the different plumage morphs of males in breeding dress (Ward, 1966). These differences can be reliably quantified only in large, randomly-sampled collections of breeding males (Ward, 1966, 1973; Jaeger *et al.*, 1989), which has still not been done for birds within the *Q. q. spoliator* breeding range.

The taxonomic status of *Q. q. spoliator* has remained controversial for two further reasons: (a) intermediates between *Q. q. spoliator* and *Q. q. lathamii* occur throughout southern Africa (Lourens, 1961), and even museum specimens designated as *Q. q. spoliator* by Clancey himself show wide variation in dorsal coloration (Jones *et al.*, 1998, 2000); and (b) both *Q. q. lathamii* and *Q. q. spoliator* must respond in similar ways to the timing and distribution of rainfall, such that they remain sympatric for much of the year and, most crucially, when they are breeding (Jones, 1989b).

We therefore collected new plumage data to distinguish *spoliator* from *lathamii*, and data on the timing of prenuptial moult and gonadal growth to establish whether possible differences in the timing of breeding, resulting from differing migration patterns, could maintain genetic isolation between them (Jones *et al.*, 1998).

Based on comparison with the dorsal coloration of museum specimens, males from breeding colonies in Zimbabwe in March 1998 were scored as *spoliator*, *lathamii*, or intermediate,

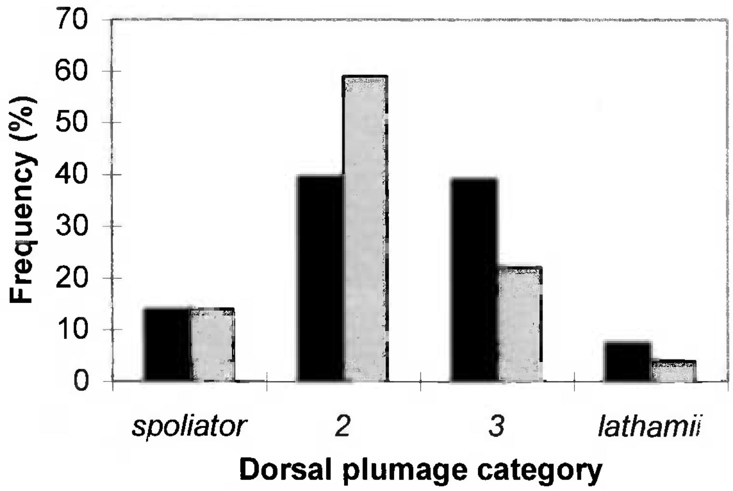

Figure 2 Frequency distributions of *spoliator*-type, *lathamii*-type, and intermediate Red-billed Quelea, based on dorsal plumage coloration. Black bars: birds in non-breeding plumage (no difference between males and females, sexes therefore combined, $n = 230$); grey bars: breeding males only ($n = 99$).

and their breeding plumage morphs were recorded. These data showed that the whole range of dorsal coloration, from *spoliator* to *lathamii*, was represented among males in the same breeding colonies well within the supposed breeding range of *Q. q. lathamii* (Figure 2). These same males were also scored for the polymorphisms in their breeding plumage to see whether there was any association between morph frequencies and dorsal coloration. A Principal Components Analysis of these data showed no discrete clusters of individuals associated with the prior classification into *spoliator*- or *lathamii*-type and that the category means are indistinguishable from each other in the centre of the distribution (Figure 3).

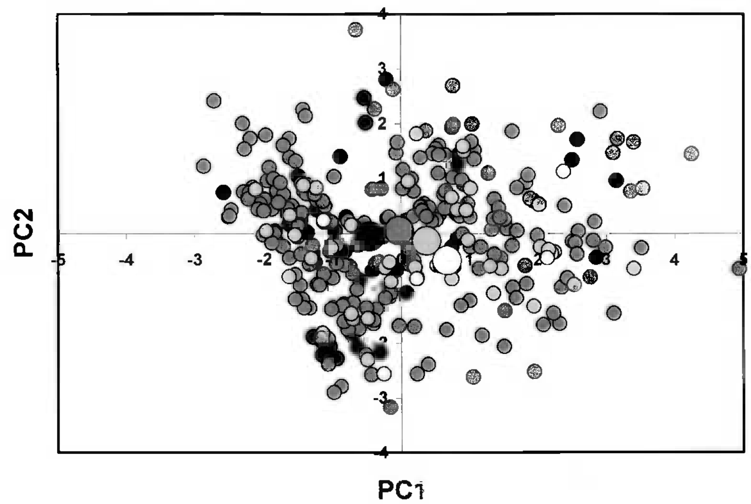

Figure 3 A Principal Component scatter-plot of plumage variation among breeding male Red-billed Quelea that had been independently scored as 1 (black circles) = *spoliator*-type, 2 and 3 (dark grey and light grey) intermediate, 4 (open circles) = *lathamii*-type on the basis of their dorsal plumage coloration. PC1 + PC2 represents nearly 50% of variation in male plumage pattern. A positive PC1 indicates a pinker, more deeply coloured belly and lesser extent of grey, scaly feathers on the chest. A higher PC2 score indicates a greater width of the black facial mask above and below the beak. Large symbols indicate the means of each distribution.

Although further extensive data on plumage polymorphisms from across southern Africa are still being analysed, in conjunction with the DNA microsatellite study (M. Dallimer, unpubl.), on the basis of present evidence we have come to the preliminary conclusion that, because '*spoliator*' individuals cannot be separated from *lathamii* on morphological criteria in either breeding or non-breeding plumage, and because all colour variants breed in the same places at the same time, the subspecies *Q. q. spoliator* does not reflect any significant phylogenetic division.

The 'Early-Rains Migration' and a possible 'Migratory Divide'

One further mechanism remains unexplored, however, by which two genetically distinct populations might co-exist within southern Africa. Jones (1989b) did not consider in this context Ward's (1971) suggestion that quelea might migrate in different directions at the start of the rains and so become separated into two sub-populations. As described in greater detail below, virtually all Red-billed Quelea leave the interior of southern Africa each year by late November, when the remaining dry grass seed germinates. They must then perform an 'early-rains migration' to parts of southern Africa where the rains had begun earlier and where fresh grass seed is by now available. There are two possible destinations offering such conditions: Clancey's suggested *spoliator* breeding range in South Africa and Mozambique or, alternatively, Angola to the north-west, where the rains also begin in September-October (Ward, 1971; Jones, 1989b). There is no information on the relative proportions of the population that might fly in either direction. It is possible that were such a separation then to persist during the first breeding attempt of the wet season, some degree of genetic isolation between the sub-populations might be established. A migratory divide of this sort could therefore separate *spoliator*, flying to early-rains quarters in the south-east, from *lathamii* flying north-west.

Such a possibility had not previously been considered but is now being investigated further. The preferred migratory directions of quelea have been measured in orientation cages using birds caught during the period of rapid pre-migratory fattening in Zimbabwe in November 1998. All birds were blood-sampled and their plumage morphs recorded; these data are still being analysed (M. Dallimer, unpubl.).

THE NRI FORECASTING MODEL

Biological Background

In southern Africa much of the loss to subsistence agriculture caused by quelea involves damage to rain-fed sorghum and millet at the milky-doughy stage shortly before harvest. The damage is almost always caused by newly-independent juveniles from nearby breeding colonies, usually within a 10–30 km radius. In contrast, the adults at breeding colonies tend not to be a major problem, because during colony establishment, egg-laying, incubation, and the nestling period, their diet consists almost exclusively of insects and wild grass seeds (Ward, 1965; Jones, 1989c). Furthermore, they abandon their young at fledging and seek new breeding sites elsewhere, often hundreds of kilometres away.

After breeding has finished, the former colony may then serve as a roost for a further 1–2 months for these juveniles, which may be joined by others born earlier in distant colonies whose local food supplies have become exhausted. Such roosts in favourable areas may continue to attract increasing numbers of young birds and, eventually, post-breeding adult quelea, and may persist well into the ensuing dry season, though by then all local subsistence crops have long been harvested. It is only in areas where irrigated wheat is grown commercially in the dry season that such aggregations may be problematic.

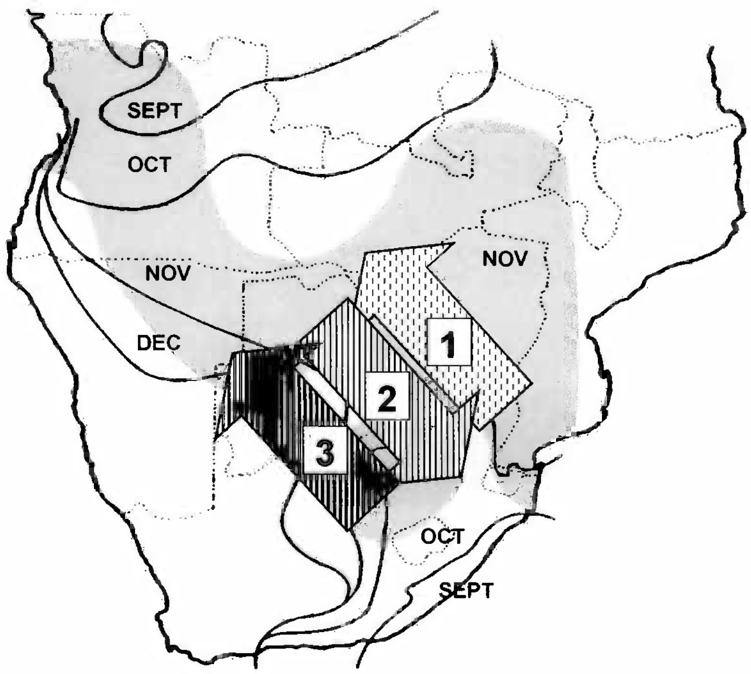

Figure 4 Schematic representation of Red-billed Quelea migration patterns in southern Africa. Arrow 1: birds forced ahead of the rain-front as rains begin in the areas of earliest rainfall; arrow 2: all birds perform an 'early-rains migration' over the advancing rain-front; arrow 3: birds return to areas of successively later rainfall on 'breeding migration'. For simplicity, this scenario does not illustrate any 'migratory divide' (see text). The grey shaded area indicates the approximate breeding range of both *lathamii* and '*spoliator*' combined. Isohyets indicate the start of the wet season.

Because this project is concerned only with alleviating damage to rain-fed subsistence crops, our model is intended to forecast the timing and locations of quelea breeding colonies that would require control to prevent successful fledging of juveniles. We are not concerned here with the forecasting of damage to commercially grown irrigated cereals.

The forecasting model developed by the NRI project is, therefore, designed to predict where and when breeding colonies will be established. Then pre-emptive control can protect local cereal crops that will mature some 5 weeks later, when the newly-fledged and inexperienced juveniles are abandoned by their parents and left to fend for themselves.

The basis of the NRI model is the conjectured migration pattern of quelea in southern Africa first proposed by Ward (1971) and developed by Jones (1989b), in which the timing and distribution of rainfall and the growth of annual grasses are the main determinants of the birds' movements. As shown schematically in Figure 4, when the rains begin in the first areas to receive rainfall and grass seed germinates, quelea are forced ahead of the rain-front to the remaining dry areas where un-germinated seed remains. By November, grass seed germinates everywhere across the birds' range in the interior of southern Africa. This sudden lack of food forces quelea to move once more, and they perform an 'early-rains migration' back across the rain-front to the first areas to have received rain. Here, by now, fresh seed and the insect prey required for breeding (mainly caterpillars and nymphal grasshoppers) are available in large quantities, providing conditions suitable for the first breeding attempt of the season. Although it is still unresolved whether a 'migratory divide' splits the southern African quelea population into two sub-populations, one heading for areas of early rain in north-west Angola and the other to Mozambique and South Africa (not shown in Figure 4; see above), this does not fundamentally affect the structure of the model. Its resolution, however, will improve the model's predictions.

On arrival in the early-rainfall areas, some birds breed immediately, while others come into condition more slowly and begin breeding somewhat later. As soon as the young from these first broods fledge, the adults continue with what now becomes their 'breeding migration', returning in the reverse direction towards areas of later rain in the southern African interior, where fresh grass seed (and insects) are also now becoming available. Somewhere along the route of this breeding migration, birds will breed wherever suitable conditions of rainfall and grass growth have occurred, and avoiding areas of drought. Because some places may reliably provide good breeding conditions for quelea in most years, even under a variable rainfall regime, these may represent traditional breeding sites to which birds return year after year. Other areas may be occupied only if the traditional sites prove unsuitable, or otherwise only in years of above-average rainfall. Even then, they may remain unoccupied if the birds have settled elsewhere first.

Structure of the Model

Like the armyworm model described in these proceedings (Holt *et al.*, 2000; see page 151), the quelea forecasting model is rule-based, allowing qualitative data to be used and incorporating state changes by logical 'if-then' type rules. Areas (grid-squares) become suitable for breeding after a gap of at least 6–8 weeks following grass seed germination and after a minimum amount of rain has fallen to produce new seed (and insects) in sufficient quantity. Quelea may then breed in the grid-square provided there are not equally suitable areas already fulfilling these conditions available in the direction of the early-rains migration, i.e. in the early-rains quarters. If there are, then breeding birds will be occupied there for the duration of a breeding attempt (5 weeks + 1 further week to regain breeding condition) before they can move elsewhere, though this period may be shorter if the breeding attempt is already partly completed. Only after earlier breeding attempts are completed can birds occupy grid-squares of later rainfall but, even then, because breeding conditions are ephemeral and the opportune time in any one place is very short, they will do so only if the area has only recently become suitable. If the grass seed has already matured and fallen from the seed heads, it becomes much less readily available to quelea and, by this time, caterpillars and nymphal grasshoppers have become adults and are unavailable as prey. Quelea seeking new nesting areas will by-pass such places and move on further along the line of the breeding migration to areas of even later rainfall. Such a leap-frogging process will continue until no more areas are suitable to receive birds that are ready to make a further breeding attempt, and the breeding season comes to an end.

To construct the quelea forecasting model, the timing and amount of rainfall necessary to initiate breeding have been established from correlations between past rainfall records and the dates of breeding attempts in the quelea database. For breeding records since 1981 it has also been possible to establish how the growth condition of local vegetation correlates with quelea breeding attempts, using the NOAA-AVHRR Normalised Difference Vegetation Index (NDVI) data as a measure of vegetative productivity (FAO, 1991).

The model's resolution is specified by one-degree grid-squares (*c.* 11,500 km^2 at these latitudes) and 10-day periods. It may be possible (and much more useful) to improve the spatial resolution to $30' \times 30'$ squares (*c.* 2860 km^2), since the distribution of suitable quelea breeding sites is patchy and generally confined to distinctive vegetation types (*Dichrostachys-Acacia* bush, mainly *A. mellifera*, and occasionally reedbeds). The relevant data are being obtained from detailed vegetation maps where available. The temporal resolution is currently constrained by imprecision in the recording of laying dates in the historical database but, in any case, it may be conveniently taken to correspond with the 10-day resolution of the NDVI data.

To run the model, all that is required is to enter rainfall estimates obtained from Meteosat Cold Cloud Duration (CCD) data and the corresponding NDVI values. Confirmation of the presence or absence of quelea is not initially needed and, indeed, the model can run for the entire breeding period without such input, though its predictions become less useful. Of course, the precision of the model is greatly improved as the rainy season progresses by including updated information about quelea breeding activity from areas where their presence has already been confirmed (e.g. breeding still in progress or completed, colonies abandoned, or control has taken place). These data may often be lacking, however, because in some countries field reporting systems are inefficient or non-existent, and information is inaccurate, slow to arrive, or entirely absent.

The prototype model is still being developed and its predictions tested against field observations.

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16 Modelling African Armyworm Population Dynamics to Forecast Outbreaks

J. Holt[1], W. L. Mushobozi[2], M. R. Tucker[1] and J. F. Venn[1]

[1]Natural Resources Institute, University of Greenwich, Central Avenue, Chatham Maritime, Kent, ME4 4TB, UK
(email: J.Holt@gre.ac.uk)
[2]Pest Control Services, PO Box 7473, Arusha, Tanzania

ABSTRACT

Moths of the African Armyworm, *Spodoptera exempta*, displace downwind and are concentrated by convergent wind flows associated with rainstorms. The moths land and breed, sometimes resulting in outbreaks of larvae at high densities which cause considerable damage to crops and grassland. Moths emigrating from an outbreak site can initiate further outbreaks in other locations and a model was developed to forecast their fate. The model simulates population change from one week to the next and movement over a grid of one degree-square units. The model predicts the direction, distance and dispersion of moths based on prevailing winds. Rainfall is central to *S. exempta* biology and is estimated from rain-gauges or Meteosat cold-cloud data. Rainfall determines emigration from the source outbreak, and aggregation, fecundity, mortality and food quality at the potential destinations of the displaced moths. To forecast one armyworm generation (*c.* 5 weeks) ahead, historical frequencies of rainfall patterns are used. Repeated sampling of this rainfall frequency distribution in an ensemble forecast allows a spatial probability footprint of outbreak risk to be calculated. The forecast comprises a prediction of the probabilities of low, medium and high outbreak risk in each degree square of the grid.

INTRODUCTION

The African Armyworm (*Spodoptera exempta*) is an important but sporadic pest. The polyphagous larvae can occur in large high-density aggregations, and rapidly consume crops and grasses in localised areas. After emergence, armyworm moths fly downwind and can be concentrated by convergent winds associated with rainstorms (Pedgley *et al.*, 1982; Riley *et al.*, 1983; Rose *et al.*, 1985). Trajectory analysis, based on daily wind-fields, has been used to estimate downwind migration of African Armyworm (Tucker *et al.*, 1982; Tucker, 1994). When armyworm moths land they are likely to breed. The hatching larvae benefit from the flush of green vegetation resulting from the rain and can then give rise to high-density outbreaks. Severe African Armyworm outbreaks have long been reported to occur when rainstorms follow droughts (Brown, 1962; Tucker, 1984; Harvey and Mallya, 1995; Haggis, 1996; Tucker, 1997), and the timing and distribution of rainstorms is of fundamental importance in governing armyworm population processes. Armyworm moths that leave one outbreak site may be re-concentrated and deposited to cause further outbreaks. Control of outbreaks early in the season may have economic benefit in preventing future outbreaks (Cheke and Tucker, 1995). The objective of this modelling work is to provide a probability distribution of future outbreaks from a known source outbreak.

THE POPULATION MODEL

Holt and Day (1993) developed a rule-based simulation model of armyworm population dynamics which was elaborated by Kirenga (1994). The model described by Holt and Day was expanded to incorporate moth migration and satellite-derived rainfall information. The simulation model is rule-based allowing qualitative data to be used. A rule-based model is a qualitative equivalent of a conventional quantitative simulation model. It represents components by a small set of distinct states, and changes by logical 'if-then' rules (Starfield and Bleloch, 1986). The approach has been applied in pest population dynamics (Holt and Cheke, 1997) and here enables qualitative knowledge about armyworm population processes to be used to build a model.

The resolution of the model is specified by degree squares and weeks. This keeps the data required to run the model to manageable proportions whilst providing a model with useful predictive power. Armyworm life history can be divided conveniently into 5 stages, each of 1 week's duration: adults, small larvae, large larvae, pre-pupae, and pupae. Note that the 'adult' stage includes the period from pupal emergence to egg hatch. A life cycle of 5 weeks is appropriate for a large area of central and western Tanzania in the altitude range 750–1200 m. At lower altitudes, nearer the coast, the life cycle is shorter (Persson, 1981).

The dynamics of the armyworm population from one week (t) to the next ($t+1$) in each degree square proceeds according to the sequence shown in Table 1. Although population size is described on a relative scale, because it was frequently possible to say that the

Table 1 Algorithm sequence of the armyworm model within each degree square in each week

Life stage (end)	End of week	Action	Action determined by
Pupae	t-1	disperse emigrants	degree of aggregation of last generation (determined in week t-5) and weather during week t,
		add immigrants	driving variable
		determine level of aggregation of the new generation	weather during week t
		action fecundity	weather during week t
Adults/eggs	t	impose mortality on young larvae	food quality during week $t+1$, itself a function of weather history
		impose mortality on young larvae	drowning and disease due to weather during week $t+1$
Young larvae	$t+1$		
Older larvae	$t+2$		
Pre-pupae	$t+3$		
Next generation of pupae	$t+4$		

Table 2 Categorisation of rainfall in a degree square from weekly (a) rainfall and (b) CCD summaries

Total for the week of (a) rain or (b) CCD	Number of days in which (a) > 10 mm rain falls, or (b) with > 4 h CCD	Rainfall category for the week
0	0	1. Dry
> 0	0	2. Light rain
> 0	1–2	3. Isolated storms
> 0	3–4	4. Occasional widespread storms
> 0	5–7	5. Frequent widespread rain

population would be expected to become smaller or larger but not by how much, mathematical consistency is nonetheless maintained. Population growth is an inherently exponential process so steps on a logarithmic rather than a linear scale were employed throughout to specify population change. The population model can be formulated very simply since the number in each life stage and the rates of fecundity, mortality and emigration are steps on a logarithmic scale. Thus, the fecundity state indicates the number of points the population moves up the scale and the mortality and emigration states, the number of points the population moves down the scale.

Rainfall is the driving variable and five categories of mutually exclusive rainfall pattern are defined for each degree square and each week (Table 2). These were chosen as the minimum necessary to describe the major effects on armyworm populations. Either rain-gauges or cold cloud durations can be used to estimate rainfall category. For real-time forecasting, rain-gauge data are generally only available for synoptic meteorological stations, of which there are for example 28 covering the whole of Tanzania. Meteosat data are, however, available on a daily basis for a resolution of about 7 km over eastern Africa. Each of the response variables in the model: moth fecundity, quality of food available for the larvae, larval mortality due to drowning and pathogens, aggregation of airborne moths and emigration rate of emerged moths, are defined as having three to six alternative states, depending on the variable concerned (Table 3). Annex 1 (p. 162) is a formal statement of the model and the relationship between rainfall and the response variables is specified in Equations 1–6 (Annex 1).

Rainfall is the major limiting factor in determining armyworm fecundity, though only a small amount is required (Page, 1988). Fecundity is assumed to increase from drier to wetter rainfall categories (Equation 1). Very young larvae are susceptible to drowning (Rose *et al.*, 1995) but mortality from this cause is only likely to occur when heavy rain is widespread. Heavy rain and overcast conditions also increase mortality due to pathogens (Persson, 1981). Mortality is assumed to be high when it is wet (Equation 2).

Armyworm outbreaks usually occur when sufficient individuals have become aggregated and breed synchronously. The extent of aggregation of moths, and subsequently of larvae, is assumed to be greatest when the moths are deposited by discrete but substantial storms (Pedgley *et al.*, 1982) (Equation 3). Grass quality as food for larvae is highest in the new growth following heavy rains. As the rainy season proceeds and the grass ages, food quality declines (Equation 4).

Moth emigration is linked to rainfall in a more complicated way. High levels of aggregation of larvae are assumed to lead to a greater propensity for subsequent emigration (Parker and

Table 3 Variables and their alternative states used in the armyworm model

Variable	Alternative state and symbol		Log. scale point (and meaning)	Numeric equivalent
Rainfall *W*	Dry	*d*		No rain
	Light rain	*lr*		No rainstorms
	Isolated rainstorms	*ir*		1–2 rainstorms
	Occasional widespread rainstorms	*ow*		3–4 rainstorms
	Frequent widespread rainstorms	*fw*		5–7 rainstorms
Fecundity *F*	Very low	*vl*	1 ($2e^1$)	5 eggs / female
	Medium	*m*	4 ($2e^4$)	110
	High	*h*	5 ($2e^5$)	297
	Very high	*vh*	6 ($2e^6$)	807
Food quality *Q*	Very low	*vl*		
	Low	*l*		
	Medium	*m*		
	High	*h*		
	Very high	*vh*		
Larval mortality (*M*1 and *M*2)	Very high	*vh*	4 ($100(1-e^{-4})$)	98%
	High	*h*	3 ($100(1-e^{-3})$)	95%
	Medium	*m*	2 ($100(1-e^{-2})$)	86%
	Low	*l*	1 ($100(1-e^{-1})$)	63%
	Negligible	*n*	0 ($100(1-e^{-0})$)	0
Aggregation of airborne moths *A*	Low	*l*		
	Medium	*m*		
	High	*h*		
Emigration rate *E*	Extremely high	*eh*	5 ($100(1-e^{-5})$)	99.3%
	Very high	*vh*	4 ($100(1-e^{-4})$)	98%
	High	*h*	3 ($100(1-e^{-3})$)	95%
	Medium	*m*	2 ($100(1-e^{-2})$)	86%
	Low	*l*	1 ($100(1-e^{-1})$)	63%
	Negligible	*n*	0 ($100(1-e^{-0})$)	0

Gatehouse, 1985). Rainfall at moth emergence, however, reduces emigration: the moisture required for maturation can be obtained locally and wind-flow in the vicinity of storms is likely to prevent long-distance migration (Equation 5). Also, low food quality is thought to reduce the survival of early-instar larvae (Equation 6).

To provide a spatial model of armyworm population processes, the model for a single-degree square was replicated over a grid of squares linked by migration of moths between squares. As discussed above, the numbers of moths emerging at an outbreak site which migrate away from the site depend both on the aggregation of the emerging moth population and on the weather conditions at the time of their potential dispersal. The direction and distance of migrations of armyworm moths between breeding sites depends primarily on speed and direction of the wind during the migration period. To model migration, the mean direction and distance travelled are estimated; this allows the degree squares, which are most likely to be destinations of the migrating moths, to be calculated. Whether moths arriving at a new destination concentrate to form a new outbreak or remain as a low-density scattered population depends on the weather conditions at the destination.

The distance and direction of migration can be estimated in a variety of ways. Real-time synoptic wind-flow information could be used if available on a regular basis. In the absence of real-time information, the prevailing wind, specific for each month and each degree square was used to estimate the probable displacement of moths for a particular time and place. The prevailing wind-flow patterns in Tanzania are reasonably stable and usually veer from NE to SE over the course of the armyworm season (Tucker *et al.*, 1982). Moths emerging from a degree square are likely to be distributed over several squares depending on the variability in the wind-field during the week of moth emergence. The extent of this dispersal is represented by the standard deviation around the mean destination. An appropriate value of σ can be estimated by model testing.

COMPARISON OF MODEL PREDICTIONS WITH OUTBREAK DATA

The population dynamic component of the model, but not the movement component, has been tested. The probability of occurrence of armyworm outbreaks following particular sequences of rainfall category was examined. Rain-gauges in the same degree square as the reported outbreak were used for a comparison which involved 164 outbreaks spanning 11 years and 25 locations in Tanzania (Tucker and Holt, 1999).

Expressing the results as conditional probabilities allowed comparisons to be made with model predictions. In the absence of any information, there was a 6% chance of an outbreak, i.e. the prior probability of an outbreak in any week in any district was 0.06. The conditional probability was greatest (0.24) when widespread rains were followed by dry weather (sequence 4,1; Figure 1). The probability was higher than the prior probability when isolated storms in the week of moth arrival were followed by any weather category (3, followed by any category) and when widespread storms were followed by dry weather or light rain (4, followed by 1 or 2). Other weather patterns gave conditional outbreak probabilities similar to, or less than, 0.06.

The outbreak risk predicted by the model is also shown in Figure 1. This is the product of log population size and aggregation level. Thus, the larger and more aggregated the population of late instar larvae the greater the outbreak risk. The data and model appear to be in reasonable agreement with '4,1' having the highest outbreak probability and '1,4' the second lowest in the data set examined (Figure 1).

Two particular discrepancies were noted. First, when isolated storms (at *t*-2) were followed by widespread storms (at *t*-1) the model gave a lower risk rating than isolated storms followed by drier weather. The historical records showed the reverse. The underlying assumption of the model was that moths concentrated at potential outbreak sites by isolated storms in week *t*-2 would be likely to suffer some mortality if hit by any of the widespread storms occurring in week *t*-1. Second, in the model, it was assumed that widespread storms followed by isolated storms resulted in just as high a risk rating as did widespread storms followed by drier weather. This was not the case with the historical data when the outbreak probability associated with '4,3' was about one third of that associated with '4,2'. The rationale of the model is that, following the concentration of the armyworm population by widespread storms in week *t*-2, a relatively small proportion would be likely to be hit by isolated storms in week *t*-1 (Equation 2).

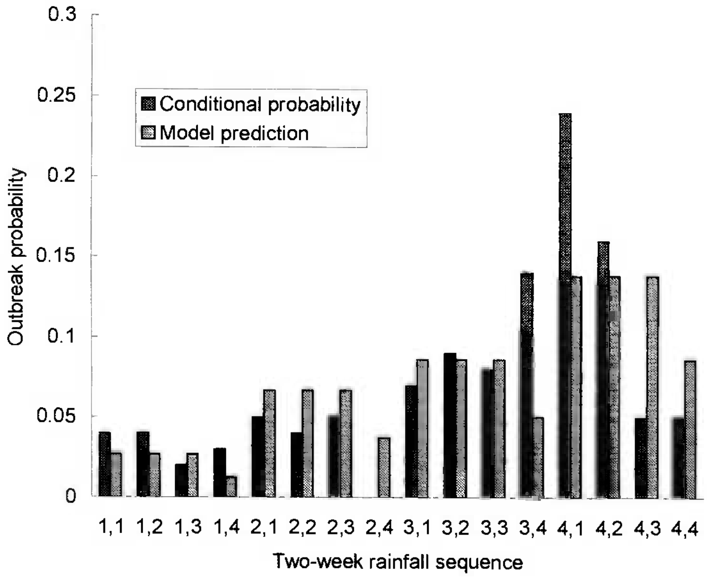

Figure 1 Comparison between the conditional probability of outbreaks following particular rainfall sequences determined from historical records of rain-gauge data, spanning 11 years and 25 locations in Tanzania, and the outbreak probability predicted by the model following such sequences. Rainfall category codes: dry (1), light rain (2), isolated storms (3), occasional widespread storms (4).

USING THE MODEL

In each degree square, armyworm population dynamics are simulated. A wide range of outbreak outcomes can occur depending on the pattern of moth arrival and its interaction with rainfall events. The spatial model predicts outbreak risk in the next armyworm generation across a grid of 20 degree-squares following an outbreak in a source square. The parameter input screen of the model (Figure 2) allows the distance, direction and dispersion of moths leaving the source square, and the frequency of each weather category to be specified. Moths from the source are distributed across the possible destination squares and occurrence of subsequent outbreaks depends upon the weather patterns encountered in each square. When projecting forward to the next armyworm generation, historical probability distributions of rainfall category for different places and times will be used.

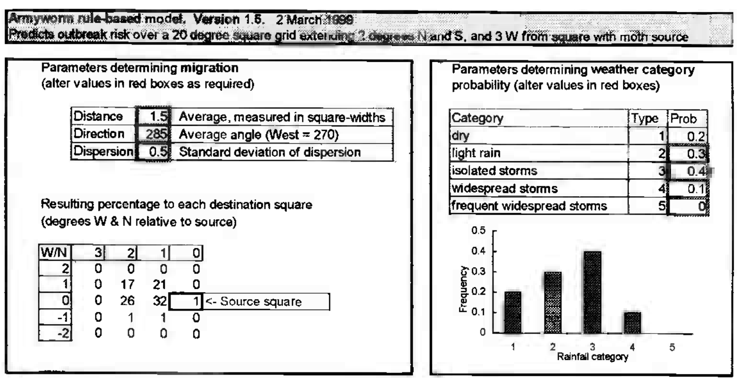

Figure 2 Parameter input screen of the model where the user can specify both the armyworm dispersal parameters (mean distance, direction and dispersion) and the rainfall frequencies (probabilities of each of the five rainfall categories for the coming week).

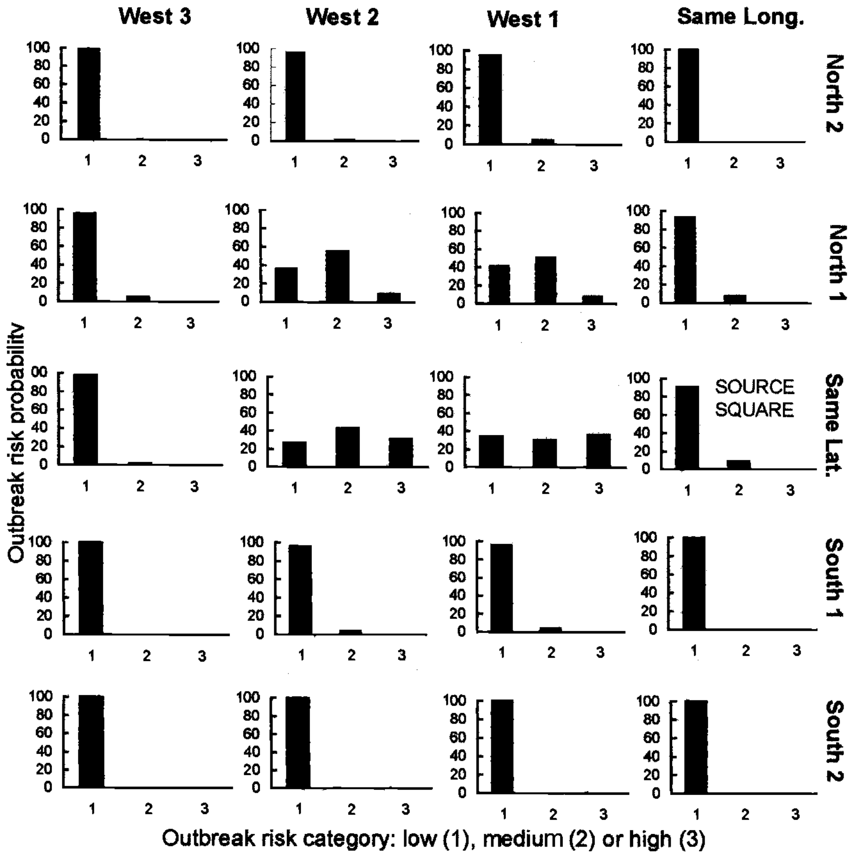

Figure 3 The probability of low, medium, and high armyworm outbreak risk in each degree square based on a 100-run ensemble forecast, e.g. in square W1, N1, the probability of high outbreak risk is about 10%, medium 50%, and low 40%. The forecast for each square thus gives not only the most likely outcome but also a measure of the degree of certainty associated with this prediction.

The potential impact of different scenarios, e.g. 'drier than usual', 'wetter than usual', and average, can be examined.

In the example shown in Figure 3, a general weather forecast of rainstorm probability for a large area of Tanzania was used. Therefore, the same rainfall frequency distribution for all squares was adopted, and an ensemble forecasting technique (Zhang and Krishnamurti, 1997) was used to estimate outbreak risk. In ensemble forecasting, repeated runs of the model are made, each time taking different values of the driving variables sampled from the known distributions of the variables. The proportions of different outcomes (e.g. of armyworm outbreak risk) in the set of repeated runs forms the basis of the forecast. Forecasters at the Tanzanian Pest Control Services (PCS) describe armyworm risk as low, medium or high and the index of outbreak risk obtained from the model (abundance x aggregation) was categorised similarly. Repeated runs of the model (usually 100) were made for different realisations of the rainfall category distribution and the number of occurrences of low, medium and high outbreak risk in each square were recorded to estimate the probability of these events (Figure 3). Model output such as that in Figure 3 can be used to help judge not only the most likely outbreak risk level in a square, but also to assess the variability associated with this estimate. A major benefit provided is to allow a sensitivity analysis of the outbreak prediction to different armyworm dispersal and rainfall patterns.

Table 4 Summary of decision criteria leading to an outbreak risk assessment for armyworm in Tanzania

	Possible situations					
Decision criterion	**1**	**2**	**3**	**4**	**5**	**6**
High moth catch or emergence of moths from previous outbreak	√	√	?	√	√	?
Rainstorms or ground already wet	√	?	†	?	√	†
Outbreak historically likely in the month and the district	†	√	√	×	†	×
Outbreak risk prognosis:	H	H	M	M/L	L	L

√	Yes
×	No
?	Unknown
†	Yes, no or unknown
H, M, M/L, L	Forecast of outbreak risk high, medium, medium to low and low, respectively

THE MODEL IN THE CONTEXT OF EXISTING FORECASTING METHODS

Since 1969, the forecasting of armyworm outbreaks by national forecasting units and by the regional Desert Locust Control Organisation for Eastern Africa (DLCO-EA) (Brown *et al.*, 1969; Odiyo, 1990) has been based on plotting the changing distribution of outbreaks and trap catches in relation to winds and rainfall. In 1991 a computer database, WORMBASE, was developed to incorporate both historical and current armyworm data, in the form of outbreak reports, light and pheromone trap catches and rainfall data (Knight and Day, 1993; Day *et al.*, 1996). It facilitates forecasting by enabling distribution maps to be printed out and plots of trap catches to be compared between stations and between armyworm seasons. WORMBASE is being used routinely by the Armyworm Forecasting Unit in Arusha, Tanzania.

The decision process in current use by forecasters at PCS in Tanzania is summarised in Table 4. To simplify the decision process to its essential features, the factors have been presented as having yes/no options but a continuum of responses is possible. 'High moth catch' has a site-specific definition and the historical (WORMBASE) records for a particular trap are used to indicate whether a given catch is high for that trap. The existences of current storms or of already wet ground are considered as being of equivalent significance. Although current storms are clearly important for moth convergence, the existence of a high trap catch is itself taken as evidence of a sufficient concentration of moths to produce an outbreak. A high moth catch and local emergence of moths from a previous outbreak site are also given equal significance. For example, it may be known from information gained earlier in the season that an emergence is due even when trap information is unavailable.

The six situations presented in Table 4 encompass all possible scenarios. In situation 1, historical records play no part because conditions are known to favour outbreaks. In the absence of current or previous rainfall information, the prognosis depends on historical records. The outbreak risk is considered high if outbreaks are common historically in that district and month (situation 2) but medium to low if outbreaks are not common historically (situation 4). Where it is known that rain has not fallen recently, then the outbreak risk is low even if the moth catch is high and irrespective of historical data (situation 5). Where no moth catch data or emergence data are available, then the prognosis depends on historical records not rainfall information, and outbreak risk is considered either medium (situation 3) or low (situation 6).

The two central data requirements are therefore moth reports of some sort (outbreaks or trap catches) and rainfall (meteorological station reports, rain-gauge or Meteosat data). Cold Cloud Duration (CCD) data which can be used to run the population model are also being used directly in current forecasting procedures. Meteosat has been used to locate night-time rainstorms from infra-red images. Rainstorms are identified by the temperature of the cloud tops as measured by the Meteosat infrared channel. The software calculates a CCD image by adding the number of hours that a cloud-top temperature lower than a fixed threshold of -50 °C is present for each pixel (data point). Daily (or nightly) values of CCD are calculated to identify the presence of individual rainstorms. Results are summarised for a grid of degree squares (1° latitude x 1° longitude) for each day and this information is sent weekly by electronic mail from the Natural Resources Institute to the Tanzania Armyworm Forecasting Unit at Pest Control Services, Arusha.

Trap catches for the current week are compared with rainstorm information for the current week to produce a forecast of where moths are likely to have been deposited, and eggs laid. Following a period for the hatching and development of larvae, outbreaks are predicted for these places. The population model attempts to go a step further. Instead of simply predicting the outbreak risk in the current generation it projects one generation ahead (about 5 weeks). As future rainfall over the next 5 weeks is not known, historical data are used, appropriate for different places and periods of the year. From the historical data, a probability of rainfall category can be obtained. By simulating multiple realisations of this probability distribution in an ensemble forecasting approach, a probability footprint of outbreaks can be projected forward for the moths departing an existing outbreak site. Thus the model is designed to produce a medium-term forecast to complement a short-term forecast. The accuracy of this medium-term forecast can be improved during the 5-week interval from the current armyworm generation to the next, and actual rainfall data become available. If real-time data are available, they are substituted for the historical probability distribution. This forecast is designed to provide farmers, extension services and control services with a probability distribution of outbreaks one generation hence.

CONCLUSIONS

The model described here allows information from a variety of sources to be summarised, processed and analysed in a short time. It combines knowledge of armyworm population processes with historical and real-time rainfall data. The model can be used alongside the current forecasting system. It attempts to address the difficult area of medium-term forecasting to complement the short-term weekly prognosis.

It is envisaged that the model be run over the course of an armyworm season, to test the accuracy of its predictions. After such testing, and any modification that is required, it is intended to use the model routinely each week to project one armyworm generation ahead to predict the pattern of outbreaks at that time.

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Annex 1. Statement of the Model (see Table 3 for symbol definitions)

Fecundity (F), a component of mortality of early instar larvae ($M1$) and the aggregation of airborne moths (A) are determined by rainfall category (W):

$$W\{d, lr, ir, ow, fw\}_t \Rightarrow F\{vl, m, h, vh, vh\}_t \qquad \text{eqn. 1}$$

$$W\{d, lr, ir, ow, fw\}_t \Rightarrow M\{l, l, l, h, vh\}_t \qquad \text{eqn. 2}$$

$$W\{d, lr, ir, ow, fw\}_t \Rightarrow A\{l, l, m, h, l\}_t \qquad \text{eqn. 3}$$

Food quality (Q) is determined by rainfall category and by the period of weeks elapsed since the first heavy rains occurred:

$$W\{d, lr\}_t \Rightarrow Q\{vl, vl\}_{t+1} \text{ where } W\{ir, ow, fw\} \text{ has not already occurred,}$$

$$W\{ir, ow, fw\}_t \Rightarrow Q\{h, vh, vh\}_{t+1} \text{ where } W\{ow, fw\} \text{ has not already occurred,}$$

$$\text{otherwise,} \quad \begin{array}{l} \mathrm{Q}_{t+1} = \mathrm{Q}_t \text{ where } (t \text{ modulo } 3) \neq 0 \text{ or } Q_t = vl, \\ Q_{t+1} = Q_t\text{-}1 \text{ where } (t \text{ modulo } 3) = 0 \end{array} \qquad \text{eqns. 4}$$

Emigration (E) is determined by both the aggregation of the larval population giving rise to the emigrants and by rainfall during the period of emigration:

$$W\begin{Bmatrix} d \\ lr \\ ir \\ ow \\ fw \end{Bmatrix}_t \& \ A\{l\}_{t\text{-}5} \Rightarrow E\begin{Bmatrix} m \\ l \\ l \\ n \\ n \end{Bmatrix}_t \quad W\begin{Bmatrix} d \\ lr \\ ir \\ ow \\ fw \end{Bmatrix}_t \& \ A\{m\}_{t\text{-}5} \Rightarrow E\begin{Bmatrix} vh \\ h \\ h \\ l \\ l \end{Bmatrix}_t,$$

$$W\begin{Bmatrix} d \\ lr \\ ir \\ ow \\ fw \end{Bmatrix}_t \& \ A\{h\}_{t\text{-}5} \Rightarrow E\begin{Bmatrix} eh \\ vh \\ vh \\ h \\ h \end{Bmatrix} \qquad \text{eqns. 5}$$

Food quality (Q) determines a second component of mortality ($M2$) of early instar larvae:

$$Q\{vl, l, m, h, vh\}_t \Rightarrow M2\{vh, h, m, l, n\}_t \qquad \text{eqn. 6}$$

To combine immigrants with a population already present in a degree square, the resulting population is rounded to the nearest point on the logarithmic scale (note also that, by convention, the variables refer to the number present at the *end* of each stage):

$$\begin{array}{ll} N_{t+1} = P_t - E_{t+1} + F_{t+1} & \text{where } I_{t+1} < p_t\text{-}E_{t+1}, \\ N_{t+1} = I_{t+1} + F_{t+1} & \text{where } I_{t+1} > p_t\text{-}E_{t+1}, \\ N_{t+1} = P_t - E_{t+1} + 1 + F_{t+1} & \text{where } I_{t+1} = p_t\text{-}E_{t+1}, \end{array} \qquad \text{eqns. 7}$$

where N, P, I = abundances of adults, pupae and immigrants, respectively. The dynamics of the other life stages are specified as:

$$\begin{array}{c} LS_{t+1} = N - M1_{t+1} - M2_{t+1} \\ LL_{t+1} = LS_t \\ PP_{t+1} = LL_t \\ P_{t+1} = PP_t \end{array} \qquad \text{eqns. 8}$$

The number of emigrants (G) from a degree square is determined by the number of pupae, and by the emigration rate, and is rounded to the nearest point on the logarithmic scale:

$$G_{t+1} = P_t \quad \text{where } E_{t+1} > 1,$$
$$G_{t+1} = P_t - 1 \quad \text{where } E_{t+1} = 1, \qquad \text{eqns. 9}$$
$$G_{t+1} = 0 \quad \text{where } E_{t+1} = 0$$

The co-ordinates of mean destination of migrating moths emerging from a degree square are given by:

$$\bar{x} = r \cos \alpha \text{ and } \bar{y} = r \sin \alpha \qquad \text{eqn. 10}$$

where r = mean distance and α the mean direction. The distance from the mean destination to the centre of each degree square (x,y) is:

$$s = \sqrt{(\bar{x} - x)^2 + (\bar{y} - y)^2} \qquad \text{eqn. 11}$$

and the relative fraction (R) of emigrants going to each square (x,y) is determined by the proximity of the square to the mean destination. Using discrete realisations of the normal distribution with standard deviation σ:

$$R_{x,y} = \exp\left(\frac{s}{2\sigma^2}\right) \Big/ \sigma\sqrt{2\pi} \qquad \text{eqn. 12}$$

Normalising the discrete values across all squares gives the proportion of immigrants going to each destination square:

$$\omega_{x,y} = R_{x,y} \Big/ \sum_{x=\min,\, y=\min}^{x=\max,\, y=\max} R_{x,y} \qquad \text{eqn. 13}$$

The number (in logarithms) of emigrants from a source square going to square (x,y) as immigrants I, is $\ln(\omega_{x,y} \exp(E))$ and these are combined with the local population of moths in square (x,y) according to Equation 7.

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17 Information Systems for Locust Forecasting

L. J. Rosenberg

Natural Resources Institute, University of Greenwich, Central Avenue, Chatham Maritime, Kent, ME4 4TB, UK
(email: l.j.rosenberg@greenwich.ac.uk)

ABSTRACT

Information about migrant pests is collected principally to develop forecasting systems to predict when and where pests will cause damage in time for preventative action to be taken. Different types of information have to be integrated according to whether the forecasts are for long-, medium- or short-term purposes. Most forecasting systems for agricultural pests rely on integrating data relating to interactions between the pest, its habitat and the weather. For migrant pests, seasonal migration patterns and the geographical extent of the pest's invasion area are additional components in the forecasting system.

Control strategies for most major species of locusts involve locating breeding or outbreak areas and preventing the populations in them from forming swarms and escaping to damage crops and pastures. Uvarov's early work in the 1930s, including mapping field reports on locust life-cycle stages, established the importance of examining both spatial and temporal aspects of migrant pest population developments, particularly in the case of the Desert Locust, *Schistocerca gregaria*, which has no permanent outbreak area (Uvarov, 1951). While much of the early work to enhance Desert Locust forecasts was carried out to predict population developments and the movements of swarms during plagues, the emphasis has now changed to identifying the sequences of rain and vegetation change that could lead to population growth and the initiation of upsurges and plagues.

This paper will discuss the ways different types of data can be used to examine interactions between locusts, their habitats and environmental factors.

INTRODUCTION

Information systems about migrant pests are developed mainly to assist in forecasting when and where the pests will cause damage in time for preventative action to be taken (Magor, 1995). For the Desert Locust, *Schistocerca gregaria*, as for many other locust species, the forecasts are part of a strategic preventative control strategy that encompasses:

- control of populations during upsurges to prevent their spread to agricultural areas; and
- control of gregarising populations to reduce the amount of pesticides used and the extent of the area sprayed.

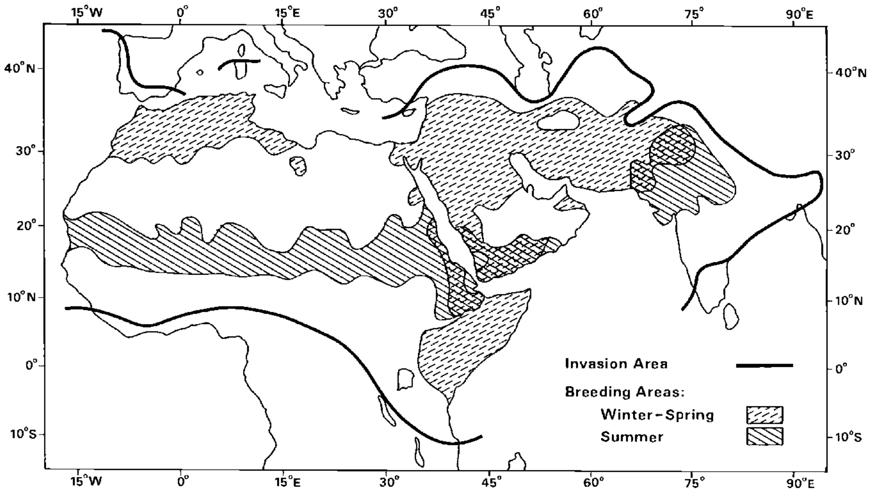

Figure 1 Main seasonal breeding areas of the Desert Locust and limits of swarm invasions during plagues (after Waloff, 1966).

The implementation of such a strategy is dependent on:

- ground surveillance of pest populations and breeding conditions by survey teams;
- monitoring of environmental conditions, particularly rainfall, by weather stations and satellite derived information; and
- co-ordinated intervention by all involved parties (governments, local communities, surveillance and control teams, farmers and pastoralists).

LOCUST FORECASTS

The Desert Locust differs from most other species of locust in that it has no permanent outbreak or breeding area, but lives instead in scattered populations in an arid recession area, which covers some 16 million km^2. In order to breed, populations move downwind between areas of seasonal rainfall (Figure 1). When plagues develop as a result of successful breeding over a number of seasons in a succession of breeding areas, Desert Locust swarms can migrate over a vast invasion area, stretching over 28 million km^2 in 65 countries (Figure 1). Thus, a high level of intra- and inter-national co-ordination is required to both confine the populations to the recession area and to combat mobile swarms, if they form and escape the seasonal breeding areas.

Operational forecasts for Desert Locusts as with other locust species, are prepared for a variety of involved parties (e.g. government departments, regional agricultural organisations, plant protection services, pesticide and equipment suppliers, control teams, farmers and pastoralists) that require the forecasts for different purposes and for different lead-in times (Magor, 1995). Three types of forecast are usually issued:

- long-term predictions (<12 months ahead) to help donors, administrators and officials allocate central budgets for staff and equipment;
- medium-term predictions (1–2 months ahead) to enable campaign managers and pesticide companies to deploy survey and properly equipped control teams; and
- short-term predictions (1–2 days ahead) to give day-to-day guidance to local field teams and farmers.

Forecasters use different types of information according to the time-scale of the forecast (Magor, 1995). Long-term forecasts are prepared up to a year in advance and consequently, have to rely on climate normals and long-term estimates of pest frequency. Since pests such as locusts are highly adapted to respond quickly to the very variable environmental conditions that exist in their breeding areas (e.g. Roffey and Popov, 1968), the accuracy of long-term forecasts is generally low. Similarly, medium-term forecasts combine the likely effects of the preceding few weeks' weather with the current locust population situation to offer only a range of possibilities for breeding and migrations based on historical analogues (Pedgley, 1981). Only short-term forecasts narrow down the area to be surveyed and controlled, since the latest synoptic weather information issued regularly throughout the day, can be used reliably to indicate the suitability of conditions for the onset of breeding or the direction of swarm migration (e.g. Rainey, 1963).

The spatial resolution of the forecast improves as the forecast period shortens (Magor, 1995) and the area to be considered by the forecaster declines as the forecast period shortens. For example, a forecaster asked early in the year, to predict the probability of Desert Locusts invading the Red Sea coastal plains before the next winter breeding season, would have to use climate means and locust frequency data from the whole Desert Locust distribution area. This is because seasonal displacements of populations from as far away as North-West Africa and the Indo-Pakistan border region could, over successive generations, reach the Red Sea area. A medium-term forecast, issued during the summer or autumn, 1 to 2 months ahead, will mainly consider the movements of populations from summer breeding areas in countries bordering the west coast of the Red Sea, the Gulf of Aden-Horn of Africa region and the Arabian Peninsula. Finally, a short-term warning or forecast would be issued when, for example, locusts were reported by ships on the Red Sea or a cyclone was forecast to cross the southern Arabian coast where locusts had been reported previously (Pedgley, 1981).

LOCUST INFORMATION SYSTEMS

Since the last major Desert Locust plague in the late 1980s, most research and development work on information systems for Desert Locust forecasting has focused on the use of Geographical Information Systems (GIS) as aids in the management and integration of the diverse data used to prepare forecasts. Computer-based GIS assist in the management and analysis of the large spatially referenced data-sets used to interpret and forecast the changing relationships between environmental processes and pest population dynamics. The two main GIS-based Desert Locust management systems are:

- SWARMS (*Schistocerca* WArning Management System) – a work station-based GIS to support the administration, mapping and analysis of data for operational forecasting of Desert Locusts across the whole distribution area at FAO's centralised Desert Locust Information Service in Rome (Healey *et al.*, 1996); and
- RAMSES (Reconnaissance And Management System for the Environment of *Schistocerca*) – a PC-based system designed to assist national locust units in storing, analysing and disseminating Desert Locust and related environmental information derived mainly from their own data capturing network (see http://www.nri.org).

Both systems contain current information on the pest, weather, rainfall and vegetation status that can be compared to previous locust and environmental data (Figure 2). The resulting analysis and interpretation form the basis of the forecast. However, the systems differ in scale both spatially and temporally. SWARMS covers the whole Desert Locust

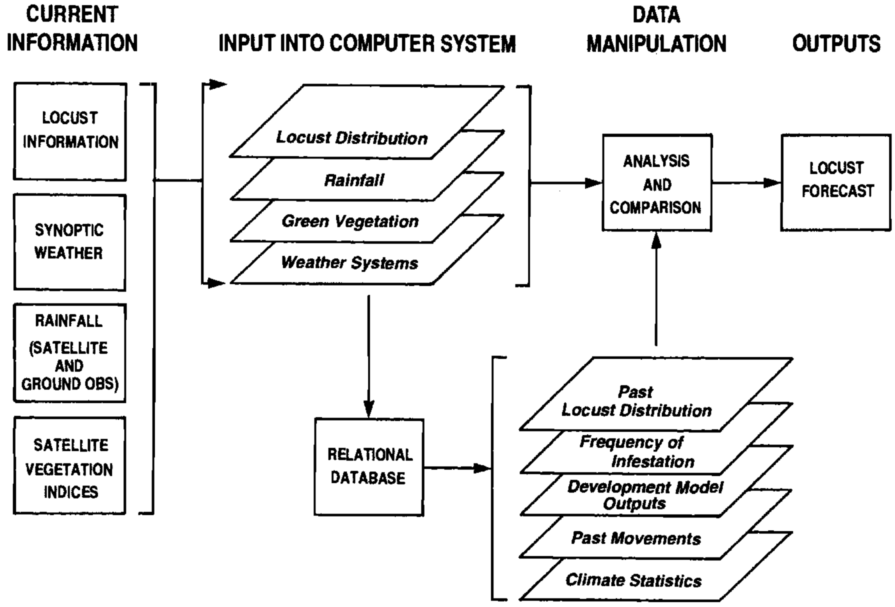

Figure 2 Schematic representation of data input, management and output organisation in a Geographic Information System for Desert Locust forecasting (after Magor, 1995).

distribution area and contains climate statistics and an archive of locust frequency data going back to 1930, thereby enabling long-term forecasts to be developed as well as the routine medium-term forecasts issued by FAO every month (http://www.fao.org/news/global/locusts/Locuhome.htm) (Cressman, 1997). At the national scale, RAMSES is designed to focus more on medium-and short-term forecasts for the immediate region. It allows the current locust and environmental situation to be compared visually to the previous month's situation (Figure 3), or to comparable months in former years and to historical analogues that show how and why previous locust events developed (Pedgley, 1981). In the past, much of a forecaster's time was spent manually re-plotting all the data at different scales to produce an overview of the pest and environmental situation for a defined period. The advantage of GIS-based technology is that it is designed to enable the different data layers to be displayed simultaneously, thereby releasing the forecaster from routine re-plotting tasks to focus on interpretation and assessment and the building-up of databases for historical analogues (Cressman, 1997).

IMPROVEMENTS IN INTEGRATED INFORMATION

While most early research on Desert Locust population dynamics was carried out to predict the development and movement of swarms during plagues (e.g. Rainey, 1963; Waloff, 1966), the emphasis has now changed to identifying the sequences of rainfall and vegetation change that lead to the growth of existing locust populations and the possible initiation of upsurges and plagues. Although technological advances have provided improved means of integrating data for forecasting purposes, locust forecasters are very aware of the inadequacies in the data they are handling (Magor, 1995). Information used as early warning for outbreaks and plagues of the Desert Locust varies in source, format and quality (Cressman, 1997). There is no substitute for the field surveys that provide data on locust numbers and distribution, but during recession periods scattered, low-density, locust populations are often missed by ground survey teams (Roffey, 1994). It is likely that less than half of the hopper population in a breeding area would be surveyed during the early phases of an outbreak, leading to under-estimates of the locust population in a breeding area.

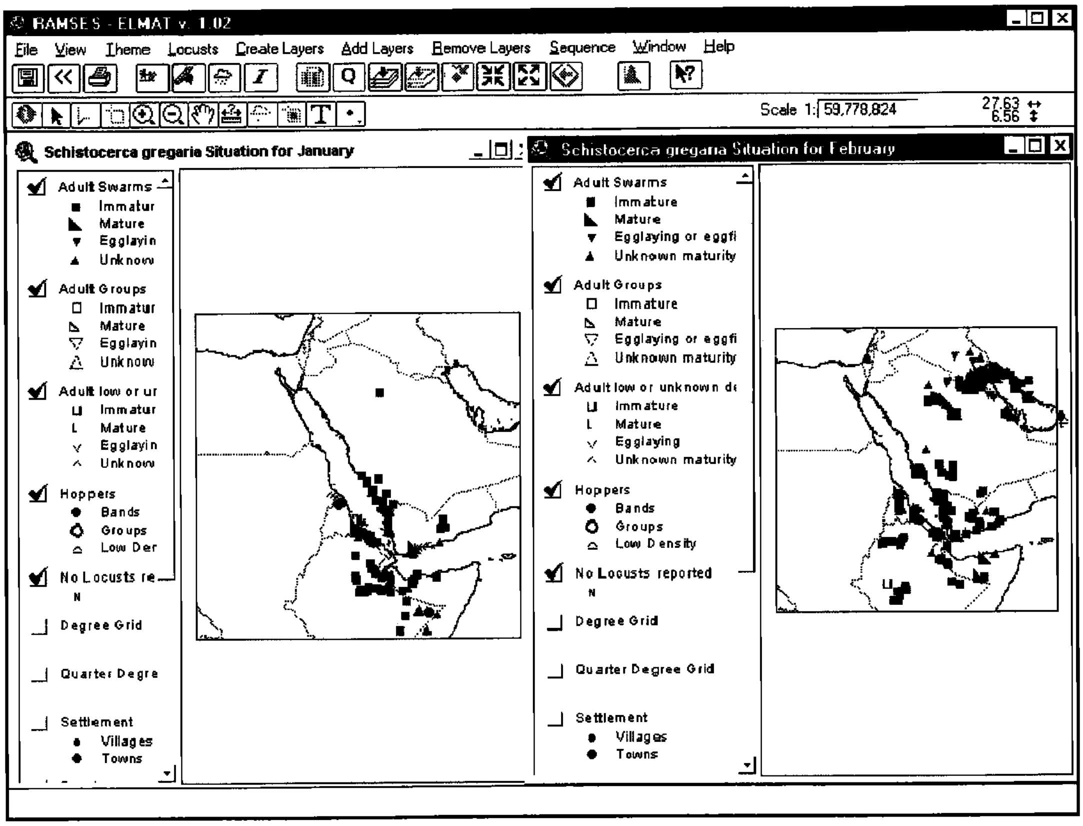

Figure 3 RAMSES screen for visually comparing two Desert Locust situations in January and February around the Red Sea, Horn of Africa and Persian Gulf.

Since Desert Locusts have no permanent outbreak area, time-series of these sequences have to be traced over geographically distinct seasonal breeding areas, usually over one or more years. Because of the vastness of the distribution area, satellite derived data are increasingly used to obtain estimates of rainfall and vegetation growth in the seasonal breeding areas. Within a GIS environment, these data can be integrated with other background information, such as vegetation and soil types to improve estimates of breeding potential for locusts (Cherlet and Di Gregorio, 1991). NDVI's (Normalised Difference Vegetation Index) derived from the NOAA series of satellites are the most widely used data for the operational monitoring of vegetation health, mainly because of the frequency of their temporal resolution. However, it has not been possible yet to use NDVI's to identify operationally changes in the very low (<5%) vegetation cover typical of Desert Locust breeding habitats, particularly in the early stages of greening, and forecasters tend to rely on point rainfall reports and field observations by survey teams.

Forecasters also need to know where and when rains have fallen since rainfall directly or indirectly provides the ecological requirements for breeding and maturation. Larger rainfall events that are of particular interest because they can start or maintain upsurges, are often associated with certain synoptic situations and their possible occurrence can be estimated from daily weather maps (Pedgley, 1981). Other rainfall events in the semi-arid breeding areas are often too short-lived to appear on 6-hourly synoptic weather charts used for operational forecasting, although hourly imagery from geostationary satellites such as Meteosat can provide some evidence of the spatial extent of such individual rainfall events, particularly at the start of the rainy season (Burt *et al.*, 1995).

CONCLUSIONS

The geographical extent of pest populations and the ease of monitoring them are of prime importance when organising and implementing a control strategy. Preventative control depends on the presence of experienced survey teams, effective monitoring of environmental conditions and timely interventions by control teams. Desert Locusts are an intermittent problem and the ability to reduce survey, monitoring and control resources during recessions and enhance them when upsurges seem likely, are crucial in convincing policy makers and budget holders that preventative control is a sustainable management strategy. Timely increases and decreases in resources depend on reliable forecasts, which in turn rely on improvements in methods of monitoring locusts and their environment and in enhanced knowledge about the relationship between changes in pest distribution and numbers and related changes in the environment.

ACKNOWLEDGEMENTS

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18 Development of a Myco-insecticide for Biological Control of Locusts in Southern Africa

M. B. Thomas

Leverhulme Unit for Population Biology and Biological Control, NERC Centre for Population Biology and CABI Bioscience, Imperial College, Silwood Park, Ascot, Berks., SL5 7PY, UK
(email: m.thomas@cabi.org)

ABSTRACT

The LUBILOSA (Lutte Biologique contre les Locusts et les Sauteriaux) Programme has been working on the development of a myco-insecticide for the control of locusts and grasshoppers for the past 9 years. The resulting myco-insecticide product (trade name Green Muscle™) is based on an oil formulation of aerial conidia of the fungal entomopathogen, *Metarhizium anisopliae* var. *acridum*. Field testing of this myco-insecticide in southern Africa has been conducted in close collaboration with the Locust and Termite Research Division of the Plant Protection Research Institute, South Africa. Trials have been conducted against Brown Locust, *Locustana pardalina*, in the Karoo region of South Africa and the Red Locust, *Nomadacris septemfasciata*, in the Buzi outbreak area of Mozambique. High (>90%) insect mortalities have been demonstrated following field applications with standard ultra low volume (ULV) spraying equipment normally used in acridid control. Moreover, extensive eco-toxicological work has shown that Green Muscle™ has minimal impact on other non-target species, including other insects, reptiles, birds and mammals. Accordingly, *Metarhizium* has been recommended by the Food and Agriculture Organisation (FAO) Pesticide Referee Group for locust control in environmentally sensitive areas. Most significantly, Green Muscle™ has recently undergone successful registration for locust control in South Africa. This represents a fundamental breakthrough in locust control and creates, for the first time, real opportunities to move away from the use of chemicals towards more integrated control strategies incorporating biological control techniques. This paper presents an overview of the progress of the LUBILOSA Programme and examines some of the research challenges that remain to fully implement this new technology in the future.

INTRODUCTION

Locusts and grasshoppers are amongst the most serious and dramatic of the insect pests. The Desert Locust, *Schistocerca gregaria*, with its potential to cause damage from the Atlantic coast of West Africa to India in plague years (Steedman, 1990), is the key pest species, but there are other locust species that are controlled in Africa every year. In the Karoo district of South Africa, the Brown Locust, *Locustana pardalina*, has required control measures nearly every year for the last 50 years, with 400,000 l of insecticide sprayed in the last 5 years alone (PPRI, South Africa, unpublished report). In other parts of southern Africa, the Red Locust, *Nomadacris septemfasciata*, and the African Migratory Locust, *Locusta migratoria migratoriodes*, require regular control measures. Indeed, Madagascar is currently under attack from the worst locust plague in many years.

CURRENT CONTROL METHODS

Existing strategies for locust and grasshopper control usually rely on knowledge of breeding areas, monitoring of populations and ultimately spraying with chemical insecticides. Such strategies can be highly effective. However, many of the chemicals currently in use are indiscriminate and can have significant impacts on the environment. Murphy *et al.* (1994) reviewed the toxicity of chlorpyrifos, fenitrothion, malathion and deltamethrin to non-target invertebrates and found that these chemicals fell within toxicity rating 5 (mortality >90%) in 45–55% of the available records, and within rating 4 (mortality 30–90%) in another 25–35% of cases. Moreover, Peveling *et al.* (1997) showed that single field applications of even short-persistent fenitrothion against African Migratory Locusts in Madagascar caused long-lasting (up to 1 year) population declines of >90% in epigeal collembolans. Most recently, the phenylpyrazole, fipronil, has been promoted as a significant breakthrough in locust control and has been used widely in the recent outbreak in Madagascar. The pesticide is highly effective even at very low doses and has a long half-life in the field allowing a possible return to effective barrier spraying. However, studies have shown fipronil to be highly toxic to certain birds, fish, terrestrial and freshwater invertebrates (information taken from US Environmental Protection Agency Fact Sheet EPA-737-F-96-005 May, 1996), so it is clear that its wide-scale use is not without risks.

In the light of these data, there is now considerable concern about the use of chemical pesticides for locust control. This is particularly so in ecologically sensitive areas such as the Karoo where land owners, game farmers and conservation bodies have all expressed a desire to reduce the use of chemicals for locust control (Price *et al.*, 1997).

THE MOVE TOWARDS BIOLOGICAL CONTROL

From the above, it can be seen that the traditional and new chemicals currently in widespread use for locust and grasshopper control can all be classified as harmful either to key non-target insects, crustaceans and other invertebrates, indicator vertebrate fauna, or to combinations thereof. This does not mean that they cannot be used for effective locust control but, given the need for more environmentally benign and sustainable strategies for locust and grasshopper control, the integrated strategies of control that do not rely solely on the use of such chemicals are called for.

In response, a number of research programmes around the world have been developing biological pesticides, based on entomopathogenic fungi, as environmentally benign alternatives to chemicals for locust and grasshopper control. One programme in particular (the LUBILOSA programme) has made considerable progress in the development of an effective and reliable myco-insecticide. LUBILOSA is an international, multi-institutional, multi-disciplinary programme executed by CABI Bioscience in collaboration with IITA (International Institute of Tropical Agriculture, Benin), CILSS (Comité Inter-Etats pour la Lutte contre la Secheresse dans le Sahel, Mali) and GTZ (Deutsch Gesellschaft für Technische Zusammenarbeit, Germany).

The LUBILOSA myco-insecticide comprises an oil-based formulation of a naturally occurring African strain of the entomopathogenic fungus, *Metarhizium anisopliae* var. *acridum*

(IMI 330189). This pathogen has good storage, production and formulation characteristics and many field tests have been conducted against different locust and grasshopper species throughout Africa. Testing of the myco-insecticide has taken a 'step by step' approach. Trials have increased in scale from controlled droplet applications in field arenas, through small- to intermediate-scale field applications with hand-held spinning disc sprayers, to larger field trials involving vehicle-mounted and aerial ultra low volume sprayers (Lomer and Prior, 1992; Bateman, 1997; Lomer *et al*., 1997). Tests carried out to date against the important acridid pests in southern Africa are described in brief below.

Brown Locust

Several successful trials were carried out between 1994 and 1998 in the Karoo district of South Africa in collaboration with the Locust and Termite Research Division of the Plant Protection Research Institute (Bateman *et al*., 1994; Price *et al*., 1997; LUBILOSA, unpublished report). Brown Locusts are highly mobile and so much of the assessment of the pathogen has taken place using field enclosures called bomas (this method of enclosing treated bands in the field is also used for assessing the impact of conventional chemical insecticides). Application methods have included hand-held spinning disk sprayers, motorised 'Solo' knapsack sprayers and aerial treatments using Micronair AU 7000 atomisers. In the majority of trials, mortality of treated hoppers exceeded 90% demonstrating that the myco-insecticide can provide effective control of this species. However, apart from this basic message, two further points emerge from these trials. First, although mortality is generally high, speed of kill is quite slow and variable, with the first mortality rarely occurring before day 7 and maximum mortality occurring some 10–30 days after treatment. Second, pick-up of spores via the spray residue from vegetation and the soil surface is a key route of infection which influences both overall mortality and speed of kill. This slow and variable speed of kill and the effect of secondary pick-up have important consequences for practical use of the product and are discussed in more detail below.

Red Locust

Only laboratory and 'semi-field' experiments have been conducted against Red Locust to date, but results indicate that the myco-insecticide is highly effective (PPRI, South Africa, unpublished report). In brief, initial tests using the standard LUBILOSA bioassay technique indicated that Red Locust is highly susceptible to the pathogen with $>90\%$ mortality within 6–9 days. These data compare very favourably with similar tests on many other locust and grasshopper species. During January 1997, field-based tests comprising treatment of hopper bands with motorised knapsack sprayers were conducted in the Buzi outbreak area in Sofala Province, Mozambique, by PPRI. First mortality from infection in caged samples taken from the field after 24 h, occurred 3 days after treatment. Third instar hoppers succumbed rapidly with a median lethal time of just under 4 days and 98–100% kill within 8–9 days. Fourth instar hoppers took longer to die with a median lethal time of approximately 6 days and $>90\%$ mortality after 21 days. These high levels of mortality greatly exceeded those of control samples, which showed only 13–23% mortality after 21 days. In addition, limited observations in the field indicated that cohesion of some of the treated bands broke down after 6 days while controls still behaved as cohesive units. Unfortunately, full assessment of populations in the field was not possible due to severe flooding of the habitat.

The results of these and many other tests against a range of locust and grasshopper species in Africa (and also Europe and Australia) appear consistently good. Operational scale trials in West Africa have demonstrated better overall control than chemical standards such as fenitrothion. Part of the reason for this is that unlike broad spectrum chemicals, the myco-insecticide conserves important natural enemies which help to maintain the locust or grasshopper populations at low levels once they have been reduced. Indeed, extensive research into the environmental effects of the myco-insecticide has indicated that it has minimal impact on non-target species and is harmless to humans, other mammals, reptiles and birds. Moreover, although the myco-insecticide itself is not as persistent as products like fipronil or diflubenzuron, it does typically have a half life of between 4–8 days which, as mentioned above, does enhance the effect of a single spray application. Furthermore, under certain conditions, insects that die from contact with the myco-insecticide can produce more spores and infect other individuals (secondary cycling). This route of infection provides a mechanism whereby the original spray application can have an effect throughout the season and even between seasons (the role of persistence and potential for horizontal transmission are discussed further below).

In 1996 the Desert Locust Pesticide Referee Group of FAO approved the LUBILOSA myco-insecticide (trade name Green Muscle™) for operational locust control in environmentally sensitive areas. Most recently, at the end of 1998, Green Muscle™ was successfully registered for use in South Africa, where a commercial production facility is being developed to provide limited amounts of the product for use in control programmes by the end of 1999. Thus, for the first time, there is now a real possibility for using biological control as a substitute for chemical control in certain strategic control situations. This does not mean that chemical control is unimportant nor suggest that the myco-insecticide doesn't have limitations: it takes time to kill insects and there is a significant and variable interval between its application and insect mortality. This is not necessarily a problem nor a unique property of the pathogen. Insect growth regulators and low doses of fipronil are other examples of proposed novel control techniques with similar operating characteristics; interestingly, the banned product dieldrin also had a slow speed of kill. However, it does create some practical problems. First, operators are accustomed to organophosphates and pyrethroids, which kill very quickly and act as their own marker. Thus, there is a need for control operators to know whether their application will be effective or not and when significant mortality will occur. Secondly, there may be situations where a quick kill is essential, such as when insects are posing an immediate threat to crops. To deal with these issues effectively will require use strategies appropriate to the operating characteristics of the product. A constraint lies in being assured that slower kill can be accepted (and, if not, then to supplement its use with chemicals), and positive attributes include low mammalian toxicity, conservation of natural enemies and potential for re-cycling.

FUTURE RESEARCH PRIORITIES

Determining the Role of Horizontal Transmission

Studies in the LUBILOSA programme have demonstrated that contact with spores from the spray residue and from infected cadavers can provide important sources of infection by both prolonging the effects and increasing the overall impact of single spray applications (Thomas and Wood, 1997). Simple modelling studies have been conducted to examine which of these secondary routes of infection is most important and to identify what relative effects they have when combined (Thomas and Wood, 1997). The overall conclusion from these studies is that pick-up of spores from the residue appears to kill more hoppers, because it acts first while numbers are still high, but horizontal transmission from infected cadavers clears up those remaining. Thus, although residual pick-up produces the more immediate results, it does so in a simple density independent manner and it is the density dependent horizontal transmission that can help to reduce the pest population to very low levels. This, in turn, can contribute to better overall control by restricting population peaks and allowing for a potential reduction in spray frequencies. Furthermore, these studies reveal that under realistic conditions when direct hit and residual pick-up have a high initial impact, the effect of horizontal transmission, although important, is very subtle and is not likely to be apparent until late in the season. Thus, to fully evaluate the efficacy of a bio-pesticide, it is necessary to understand that, like any living control agent, the effectiveness of a pathogen depends not just on its capacity to kill pests but also its capacity to reproduce on pests and thereby continue and compound its killing action. The interaction between these functional and numerical components of bio-pesticide activity can be subtle and may not be apparent from short-term field studies. This highlights the need for an increased appreciation of both the similarities and the differences between bio-pesticides and chemical pesticides and cautions against considering all bio-pesticides simply as analogues of chemical pesticides with slow-acting active ingredients.

These studies clearly suggest that cycling of the pathogen after spraying via horizontal transmission can have a profound effect on control. Evidence suggests that this may be of particular relevance to Red Locust since the humid wetland habitats occupied by this species during the breeding season are likely to provide optimum conditions for pathogen spread and persistence. Thus, it is anticipated that the potential for secondary cycling will be greater for Red Locust than most other locust and grasshopper species in Africa (and particularly Brown Locust in the Karoo, where experiments indicate that the hot dry conditions are likely to prohibit disease cycling after spraying). If this proves to be the case, then not only will the pathogen be extremely effective but it may create opportunities for the development of novel spray strategies based on smaller-scale inoculative pathogen releases rather than large-scale inundative releases. This could have significant consequences for the economics of control and development of sustainable Red Locust Integrated Pest Management (IPM) programmes.

Further field trials against Red Locust are needed to evaluate the myco-insecticide fully and to optimise both its short- and long-term impacts. Ecological research is also required to explore the role of secondary cycling and to understand how Red Locust and the pathogen interact with each other and with the environment. Central to this will be investigations to determine the fate of infected individuals. These studies will need to determine what proportion of individuals survive to become new sources of infection (interactions with other mortality factors such as predation or cannibalism will be critical), how environmental conditions affect spore production and persistence, and how behaviour and spatial dynamics influence risk of infection.

Understanding Speed of Kill

As described above, the myco-insecticide has a relatively slow and variable speed of kill. This is clearly most important in the context of crop protection when rapid action is required to prevent direct damage, or to prevent immediate invasion of a key cropping area. Under these circumstances, it may be inappropriate to use a slow-acting product like a myco-insecticide. However, the majority of locust control (and this applies to both Brown and Red Locust) is preventive and relies on spraying in largely un-cropped outbreak areas in order to restrict population build up and prevent dispersal of swarms to areas of cultivation. Here, speed of kill is not necessarily a key issue; it makes relatively little difference with respect to ultimate protection if locusts die within days or weeks, as long as they are prevented from leaving the outbreak areas. Slow speed of kill might still create operational difficulties, particularly with respect to targeting mobile hopper bands and identifying which ones have been treated already.

There is a need to understand what factors influence speed of kill to determine how quickly the pathogen will act at different times and/or places, and to develop use strategies that account for the slow and variable activity. In this respect, key studies in LUBILOSA have identified that environmental temperature and host thermal biology are central to interpreting patterns of mortality observed following spray applications. The reason for this is that many grasshoppers and locusts actively maintain their body temperatures around a preferred set point during the day. This set point can be significantly different from ambient temperature and can be maintained for a number of hours given the right environmental conditions. For example, studies in the Karoo reveal that the preferred body temperature of Brown Locust is approximately 39 °C (Blanford and Thomas, 2000). This temperature represents the upper limit for growth of *Metarhizium anisopliae* var. *acridum* (Thomas and Jenkins, 1997) and means that under conditions of optimal thermoregulation, the pathogen is unable to develop inside infected insects. However, optimum regulation is only possible during the day, and then only under certain environmental conditions. This is revealed in Figure 1 which shows the daily body temperature of Brown Locust nymphs measured at three different times in the Karoo (Blanford and Thomas, 2000). The upper line shows mean hourly body temperatures taken from a band of hoppers under clear and dry conditions during mid-season in late February 1998. Here conditions are optimal for regulation and body temperatures are maintained in the range 37–40 °C from 10:00 h to about 17:00 h. Consequently, pathogen growth would be minimal for a large part of the day, with speed of kill prolonged accordingly. Interestingly, however, the other daily profiles in the figure show rather different patterns and indicate that conditions can be quite variable and far more suitable for pathogen growth. The lowest profile, for example, was taken from the same hopper band as above, but one week earlier during a period of cooler, cloudy weather. This provided a constraint to thermoregulation and

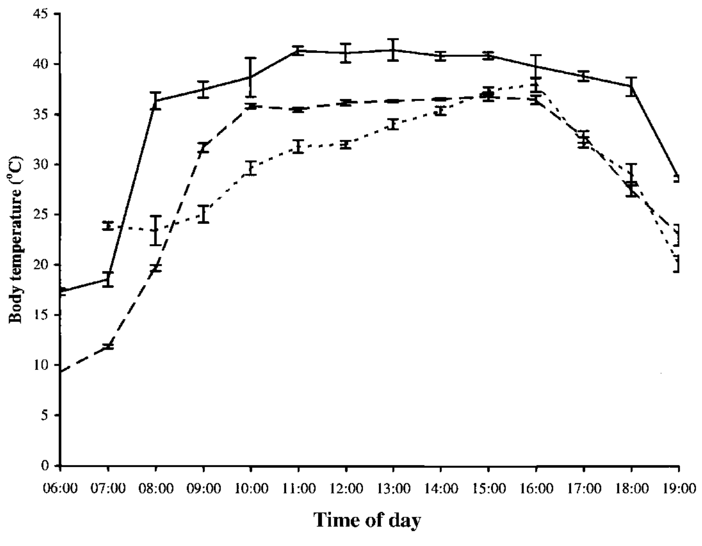

Figure 1 Daily profiles of Brown Locust body temperatures measured on three different occasions in the Karoo during 1998. The solid line shows body temperatures under optimum environmental conditions for thermoregulation during the middle of the season. Under these conditions locusts are able to maintain body temperatures close to 40 °C for many hours during the day. The dotted line shows body temperatures from the same population but under cool, cloudy conditions. These conditions inhibit thermoregulatory ability and severely restrict increases in body temperature above ambient temperature. The intermediate profile (the dashed line) shows body temperatures measured during a period at the end of the season. Here, although locusts are actively thermoregulating they are prevented from reaching their preferred body temperature because of reduced solar intensity at this time of year. Full details of methodologies are provided in Blanford and Thomas (2000).

resulted in body temperatures being maintained in a range, which would be optimum for pathogen growth (i.e. 25–30 °C) for large parts of the day. Under these conditions, speed of kill would be expected to be much reduced. Similarly, the third (the middle) profile, shows body temperature also to be constrained below optimum with a maximum of 35 °C. Interestingly, this was not due to cloud cover but represents data collected at the end of the season and, although locusts were actively thermoregulating (indicated by the stable body temperature throughout the mid-part of the day), the intensity of the sun was not sufficient to allow optimum body temperature to be achieved. Accordingly, pathogen growth would not be severely limited at this time.

The example above indicates the importance of host thermal behaviour in the performance of the myco-insecticide. For all these examples, speed of kill was not only determined by conditions during the day, but also by the extent of pathogen growth during the evening, night and morning, when active thermoregulation is not possible, and the body temperature of the locusts was close to ambient temperature. If, for example, night-time temperatures ranged around 15–25 °C, this would provide good conditions for pathogen growth and would compensate, to some extent, for minimal growth during the day. If, however, temperature fell to 5–10 °C (which is not unusual for the Karoo at certain times), then this again would be restrictive as the minimum temperature for growth for the pathogen is 5 °C (Thomas and Jenkins, 1997). This could result in a relatively short time for pathogen growth during a 24-h period and a long survival time, especially if these cool night-time conditions coincided with optimal thermoregulatory conditions in the day.

An understanding of thermal ecology of the host-pathogen interaction is central to determining the likely performance of the myco-insecticide. What is important is that performance will vary in time and space. Thus, effects and patterns observed with Brown Locust may be very different to those for Red Locust, not only because the species are likely to differ in their thermal biology, but also because the Karoo represents a very different thermal environment to the flooded, grassland areas characteristic of Red Locust habitats. Accordingly, studies on thermal ecology are essential so that use strategies can be developed that take pathogen performance under different environmental conditions into account.

Development of Use Strategies

A myco-insecticide can provide highly effective control, but understanding and predicting its performance is complex and there is a need to develop appropriate use strategies. These strategies should optimise myco-insecticide use in terms of its operating characteristics within an IPM framework. This means that if conditions indicate that the pathogen will work too slowly, either because fast knock-down is required for economic reasons or because speed of kill is too slow to be managed in practical terms (but see below), then alternative control methods should be used. If, on the other hand, conditions indicate that the pathogen will perform satisfactorily (i.e. where it acts relatively rapidly or where speed of kill is not an issue and also considering its benefits in terms of environmental impact), then it should be used. Where the challenge lies is determining where and when these different conditions apply. One potentially powerful tool to assist in this would be the development of a ‘pathogen performance’ forecasting model. Based on an understanding of locust thermal biology, a model could be developed using relatively simple driving variables such as angle of the sun, number of sunshine hours per day and minimum night-time temperature to predict speed of kill of the pathogen. Using historical data and a GIS platform, it might then be possible to derive maps, which describe likely pathogen performance across the season at different locations. Real-time data could then be added to modify these average predictions and explore the effects of, for example, weather fronts and novel spray tactics (such as those described below). Such efficacy maps could be overlaid with data on environmental sensitivity to chemical pesticides (e.g. designated conservation areas, wetland habitats or other areas with important biodiversity, organic farms, etc.) and with predictions of locust populations (PPRI are already developing a GIS forecasting model for Brown Locust), to identify key areas and times for deploying stocks of the myco-insecticide.

Development of strategic guidelines for use of the myco-insecticide will clearly require additional research effort. However, given that bio-pesticides are notorious for their patchy and variable performance and, as a consequence, the majority has failed (either before or in the market place), then this type of approach is essential if the LUBILOSA myco-insecticide is to become an established technology. A product that is used, for example, only 20% of the time, but which works, is far more likely to succeed than a product which is used everywhere but which is only 20% reliable.

In addition to the strategic approach outlined above, further research is also required to optimise control tactics in the field. Current control procedures for Brown Locust, for example, rely on spot treatment of individual hopper bands as and when they are identified. For a fast-acting chemical, this approach works even though hoppers leave the sprayed area quickly because survival time is short and the chances of the band being re-encountered are remote. For the myco-insecticide, however, this rather unsystematic approach may not be the best method of target location since the slower activity makes re-encounter

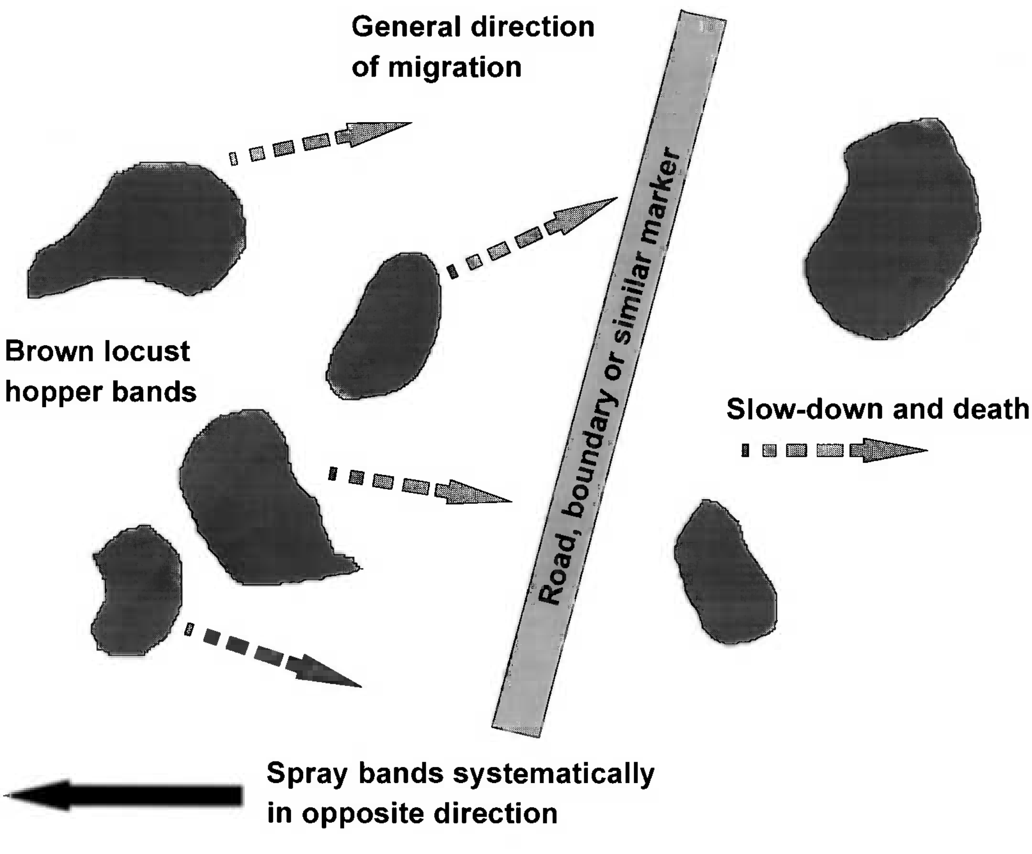

Figure 2 Diagrammatic representation of tactics for systematic spraying of hopper bands with the myco-insecticide to minimise the risk of repeated application and thus, 'manage' the problem of slow speed of kill.

more likely, creating the practical problem of identifying whether a band has been treated already. A potential solution to this is illustrated in Figure 2, which shows a more systematic approach to locating and treating bands. This utilises the knowledge that hoppers tend to march in the same direction in a given area and creates a situation where bands are targeted in a sequential manner, moving into the population of untreated bands and away from those sprayed already. An alternative approach, perhaps particularly suitable for high-density situations, is to use blanket applications when all bands are treated in a given area, thus reducing the relative risk of repeated application of individual bands. Blanket spraying is rare for Brown Locust at present but is an established technique for other species such as Desert Locust. Such an approach also has the added benefit of increasing exposure to the spray residue, which could have important consequences for both increasing overall mortality and reducing speed of kill.

Finally, a key step in implementing this new technology will be to train locust control operators to understand and appreciate the qualities of the myco-insecticide and its mode of action. In this way, user expectation can be matched with product specification, rather than trying to achieve the reverse; the myco-insecticide is not a chemical and trying to force it into the existing pesticide model, with its associated techniques and perceptions, could result in failure.

CONCLUSIONS

Locusts are important pests in southern Africa that present a considerable challenge for effective control. The need to move towards sustainable, environmentally friendly control strategies has increased this challenge further. The development of a myco-insecticide by the LUBILOSA programme represents a fundamental breakthrough in locust control and creates, for the first time, real opportunities to move away from the use of chemicals towards more sustainable control strategies incorporating biological control techniques. However, development of the product alone is not sufficient and further ecological research is required to develop strategies to ensure its effective use within an IPM framework.

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19 Addressing the Poverty Focus in Migrant Pests Research

Helen J. Altshul

Natural Resources International Limited, Central Avenue, Chatham Maritime, Kent, ME4 4TB, UK
(email: h.j.altshul@greenwich.ac.uk)

ABSTRACT

The Crop Protection Programme (CPP) of the UK Department for International Development began in 1995 and to date has funded six projects concerned with migrant pest problems: two on the African Armyworm (*Spodoptera exempta*), three on locusts and one on the Red-billed Quelea bird (*Quelea quelea*). There is increasing donor pressure to demonstrate the impacts of natural resources research on the livelihoods of poor people. Since none of the CPP migrant pest projects are classed as Type III (downstream applied or adaptive) research, it is difficult to demonstrate any direct impacts at the community level. However, the projects address problems with clear impacts on poverty and, in the longer term, may develop practical applications that can have impacts directly on the small-scale farming community. This paper identifies and discusses some of the generic issues that (a) need to be addressed in order to ensure that research results are taken up, and acted upon, by institutions (macro-level interactions) and that (b) are relevant to resource-poor farmers (micro-level interactions).

INTRODUCTION

The Crop Protection Programme (CPP) is one of twelve research programmes funded by the UK Government's Department for International Development (DFID) under their strategy for renewable natural resources research. The broad objective of the CPP is to enhance sustainable productive capacity in selected natural resources production systems through the development, application and promotion of results of research on socially and environmentally acceptable crop protection technologies (Natural Resources International Ltd, 1999). In the light of the UK Government's White Paper on International Development (HMSO, 1997), the CPP is also increasingly being required to demonstrate that the research projects in its portfolio have a clear poverty focus. The UK government has funded research on migrant pests since colonial times, but the CPP only started in 1995, building on the knowledge, networks and linkages established under the previous 5 years' operation of the Integrated Pest Management Strategy Area.

TYPES OF CPP MIGRANT PESTS RESEARCH

CPP research on migrant pests falls under Purpose 4 of the Semi-Arid Production System, which reads: benefits for poor people generated by application of new knowledge to control

Table 1 List of CPP migrant pest projects to date

Project No.	Project Title	DATES	Type of Research (Annex 2)
R6746	Entomopathogenic baculoviruses for the control of the African armyworm, *Spodoptera exempta*, in Tanzania	10/96–03/97	I
R6762	Decision tools to aid armyworm surveillance and outbreak prediction	04/97–03/99	I
R6809	Statistical analyses of locust movements and their determinants	10/96–03/98	I
R6822	Identification of factors which lead to changes in desert locust populations at the beginning and end of recession periods	12/96–11/99	I
R6823	Models of Quelea movements and improved control strategies	04/97–03/99	I
R7065	Optimising the IGR barrier technique for locust control	01/98–03/00	II

of migrant pests in semi-arid systems. The full logical framework is given in Annex 1. Since programme inception, there have been two projects on the African armyworm (*Spodoptera exempta*), three projects on locusts and one project on the Red-billed Quelea bird (*Quelea quelea*). These projects are listed in Table 1.

It can be seen from Table 1 that five out of the six projects are classed as Type I (strategic) research and the other is classed as Type II (upstream applied/adaptive research). None of the projects are classed as Type III (downstream applied/adaptive research) (Annex 2). Since only Type III research projects are carried out closely with the intended beneficiaries, it is difficult for the CPP migrant pest projects to demonstrate any direct impacts on poverty alleviation at the micro (community) level yet. However, they address problems with very clear impacts on poverty in terms of food security and, in the longer term, project outputs may develop practical applications that can have impacts directly on target beneficiaries, namely the small-scale farming community.

UPTAKE BY INTERMEDIARIES AND BENEFICIARIES

There is increasing donor pressure to demonstrate the links between natural resources research and improving the livelihoods of poor people. A number of generic issues can be identified that need to be addressed in order to ensure that research results are taken up and acted upon by institutions (macro-level interactions) and relevant to resource-poor farmers (micro-level interactions). Some of these issues are more applicable to strategic research and others to applied research, as illustrated in Figure 1.

At the strategic end of the research continuum *synchronisation of efforts* is important, especially in the case of migrant pests, which are an international problem and thus do not fall neatly within national boundaries. There is a need for concerted actions between countries and care should be taken to ensure that new research projects fit in with existing

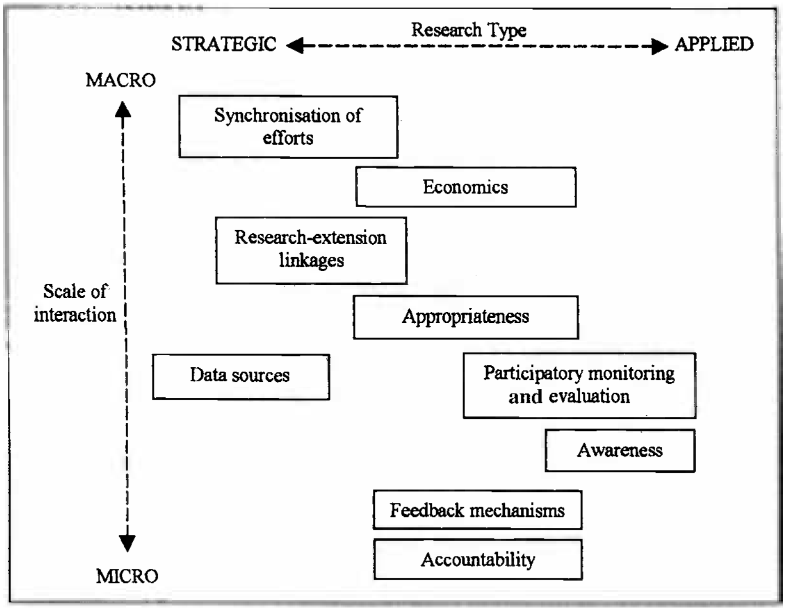

Figure 1 Generic issues for strategic and applied research.

activities and priorities. However, the issue of sovereignty can be problematic, i.e. do certain organisations have the authority to impose control strategies on others? Political and economic barriers to co-operation may also exist.

An enabling infrastructure and procedures for *research-extension linkages* are needed in order to maximise co-ordination and co-operation between farmers. Dissemination mechanisms should be developed at all levels, e.g. research to research, research to extension and extension to farmer. In the majority of cases, it is easier to work with groups of farmers than with isolated individuals.

Much migrant pest research concentrates on providing more efficient forecasting of pest population dynamics. The results should translate into direct impact at the micro-level by forewarning farmers of impending pest outbreaks and enabling them to take the necessary action, but this impact may be reduced by institutional and resource constraints. There is scope to increase the involvement of farmers in strategic and upstream applied research by providing them with sufficient information on research objectives and results to encourage them to participate in data gathering. They could then become valuable *data sources* for population forecasting, providing researchers with farm-level qualitative and quantitative data. Consideration should also be given to who needs to use the data and whether they are given to the right people at the right time, e.g. do strong enough links exist between researchers and policy makers?

Economics is important in both strategic and applied research. On a national scale, migrant pest control measures may not be economic, as explained in the following extract (Joffe, 1998).

“The damage caused by desert locust attack shows great variation. Economic impacts depend on the locusts’ behaviour and the nature of the affected economy. Serious impacts are rare on a national scale but a desert locust population that causes severe damage in marginal subsistence areas may pose a significant threat to food security. Control and surveillance campaigns are capable of reducing the risks substantially, but will only be an economic proposition if they successfully prevent severe economic or food security impacts. Countries with substantial production in areas subject to desert locust infestation, particularly high-value export crops (e.g. Algeria, India, Morocco and Pakistan) have a major economic interest in regionally effective preventive control. However, for many other affected countries that have low values of production at risk, the net benefits in economic terms will rarely justify expensive control efforts."

Nevertheless, there may be substantial benefits in social terms due to a reduced incidence and severity of migrant pest damage and this must be weighed against the economic costs. At the local level, there is the question of whether farmers or governments should pay for migrant pest control, since dependency on government interventions often leads to inaction by farmers. The issue of off-site effects of control measures, particularly on bio-diversity, is also important and should be included in economic analyses.

The *appropriateness* of research results is also of paramount importance. In the past, there may have been an overemphasis on high technology methods of pest control and researchers need to work with farmers to find appropriate field solutions to prevent damage to crops. An appropriate technology is one that is affordable and readily available in terms of markets and distribution systems, as well as being within the capability of farmers to implement.

The *accountability* of research is important at the micro-level, e.g. research must be accountable to farmers with respect to the health risks of pesticide application and the quality of pest-resistant crops for human consumption. However, it applies at the macro-level too in terms of the relationship between research and national governments, particularly in relation to their endorsement of international conservation agreements. In order to ensure the maximum utility and applicability of research results, *feedback mechanisms* are also necessary at all levels, from farmers, extension workers and governments to researchers and to each other.

In applied research projects, 'farmer friendly' monitoring and evaluation systems can be developed by incorporating farmer-determined indicators, e.g. of well-being. This *participatory monitoring and evaluation* (PM&E) increases the level of involvement of farmers in research and thus fosters an increased sense of ownership. As with research-extension linkages, PM&E is much easier to implement with farmer groups than with individuals.

The final issue is farmer *awareness*. Farmers need to be well informed about research results and trained in the new methods developed. This can be achieved through farmer field schools or farmer exchange visits to see the pest damage (or lack of it) on other peoples' farms. Awareness also includes appreciating that migrant pest problems can be worsened by farmers' own actions, e.g. in the Bergille-Winterton Area of South Africa, the Red-billed Quelea bird population has increased between 10 and 100 times over the last 20 years due to changes in farming practices (Berruti, 2000 *or* see page 113).

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Annex 1 Logical framework for the CPP Semi-Arid Production System Purpose 4

Narrative Summary	Achievement Indicators	Means of Verification	Risks and Assumptions
Goal			
Livelihoods of poor people improved through sustainably enhanced production and productivity of renewable natural resources systems.			

Narrative Summary	Achievement Indicators	Means of Verification	Risks and Assumptions
Purpose			
Benefits for poor people generated by application of new knowledge to control of migrant pests in semi-arid systems.	1. By 2005, technology available to improve the success rate of forecasting for locust, armyworm and quelea by 10% over 1995 baseline. 2. By 2000, the value to end-users (FAO, etc.) of inputs to forecasting models for the control of locusts is objectively confirmed. 3. By 2002, ground moisture measurements incorporated into forecasting models for locusts.	Reports of national, bilateral and multilateral surveys of indicators of improved benefits (productive capacity, food security, wealth, nutrition and environment).	Poor people invest in benefits to improve livelihoods.
Outputs			
SA4 (A) Strategies developed to improve forecasting and reduce the impact of migrant pests in semi-arid cropping systems, for benefit of poor people.	A. Technologies developed and validated targeting improved forecasting and environmentally safer management of: • (SA401) locust, grasshopper and armyworm outbreaks (four technologies by 2000) • (SA402) avian pests, notably quelea (one technology by 1999)	Project technical reports, publications, etc.	Enabling environment exists through regional and national plans and programmes of target institutions. Resources of target institutions for technology development are adequate and sustained.
SA4 (B) Promotion and adoption of strategies to improve forecasting and reduce the impact of migrant pests in semi-arid cropping systems, for benefit of poor people.	B. Technologies developed (under SA401 & 402): • disseminated and promoted at a South African regional workshop (in 1999) • incorporated in national and regional programmes for control of target pests (by 2005).	Reports of workshops. Reports of target institutions. Endorsement of outputs by development fora. Adoption by development programmes or community organisations.	Resources of technology transfer partners are adequate and sustained. Target beneficiaries adopt strategies and practices.

Annex 2 Definitions of types of research

Type	**DFID Definition (Natural Resources Research Department, 1998)**	**CPP Definition (Eden-Green, 1998)**	**Position on uptake pathway**[1]
I	Strategic research	Problems/mechanisms defined/understood	A
II	Upstream applied/adaptive research (for uptake by intermediate beneficiaries such as institutions or research organisations)	Technologies developed/ adapted and field tested	A–E
III	Downstream applied/adaptive research (carried out closely with the intended beneficiaries, e.g. farmers)	Practical IPM/pest control strategies demonstrated and promoted with farmers	E–H

[1]A = generation of relevant research results (output delivered);
B = formal/informal agreement with target institutions;
C = development of appropriate research-based products through adaptation/packaging;
D = promotion of products into target institutions;
E = adoption of products by target institutions;
F = application and replication of results in target institution programmes;
G = promotion of technology or behavioural change among end-users by target institutions;
H = adoption of technology by end-users and generation of economic benefits, i.e. development impact (purpose delivered).

Workshop on Research Priorities for Migrant Pests of Agriculture in Southern Africa, Plant Protection Research Institute, Pretoria, South Africa, 24–26 March 1999.
R. A. Cheke, L. J. Rosenberg and M. E. Kieser (eds) (2000) Natural Resources Institute, Chatham, UK.

20 Biodegradation of Fenthion by *Phanerochaete chrysosporium*

L. Zacchi[1], J. R. Cox[2], R. A. Cheke[2], E. van der Walt[3] and P. J. Harvey[1,4]

[1]Department of Chemical and Life Sciences, University of Greenwich, Wellington Street, London, SE18 6PF, UK
[2]Natural Resources Institute, University of Greenwich, Central Avenue, Chatham Maritime, Kent, ME4 4TB,UK
[3]Plant Protection Research Institute, Agricultural Research Council, Private Bag X134, Pretoria 00001, South Africa
[4]Corresponding author (email: P.J.Harvey@greenwich.ac.uk)

ABSTRACT

Fenthion was metabolised by the white-rot fungus *Phanerochaete chrysosporium* in liquid culture when applied to the limit of its solubility in aqueous media (7.2 μM). Using GC-NPD, no evidence for either adsorption to or accumulation in intra-cellular compartments was obtained and after 5 days culture, less than 1% of fenthion remained in the extra-cellular medium. Fenthion did not inhibit spore germination at the concentrations supplied, but appeared to inhibit the rate of spread of the fungus on solid media. Fenthion was oxidised by lignin peroxidase (LiP), but enzyme turnover was dependent on the concentration of H_2O_2 supplied, with inhibition accompanying the formation of the inactive intermediate Compound III at an H_2O_2 concentration equal to the k_m of LiP for H_2O_2 (*c.* 0.4 mM). Available evidence suggests that fenthion was metabolised via the fungal ligninolytic system and it represented the reducing substrate for LiP Compound I to return to the native state.

INTRODUCTION

Fenthion is an organophosphorus pesticide (Figure 1) used to control bird pests in agricultural systems. In particular, it is used against the Red-billed Quelea, *Quelea quelea*, a major pest of cereal crops in semi-arid areas of sub-Saharan Africa. For instance, during the 1997/98 season more than 5000 l of a commercial formulation (Queletox R) were sprayed at 7 l/ha to protect wheat, sorghum, millet and sunflower crops in South Africa (Geertsema, 1998). After application, fenthion and toxic degradation products, particularly the sulphone and sulphoxide derivatives for example, can be persistent, depending on environmental conditions (Minelli *et al.*, 1996; Rotunno *et al.*, 1997; Lacorte *et al.*, 1997). In addition, off-target drift for 3 km was detected in samples taken at a height of 6 m 20 h after application and at 9 m after 64 h (van der Walt *et al.*, 1998; van der Walt, 2000 *or* see page 91). Also, birds that have collected a lethal dose of fenthion may be able to disperse and contaminate other sites up to 30 km distant, resulting in secondary contamination. Both primary and secondary contamination have been detected in non-target birds such as raptors (van der Walt *et al.*, 1998) and recent reports suggest that fenthion persists

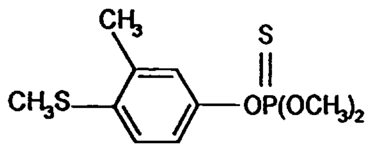

Figure 1 Chemical structure of fenthion, the active ingredient of numerous organophosphorus pesticides, including Tiguvon and Queletox.

in the soil for at least 54 days after spraying (van der Walt, 1999). So, control methods which are less damaging to the environment are urgently sought, with remediation of contaminated sites being a priority.

White-rot fungi are micro-organisms which colonise wood and are capable of mineralising polymeric lignins (for a review see Kirk and Farrell, 1987). *Phanerochaete chrysosporium* is the best characterised wood-rotter (for reviews, see Gold and Alic, 1993; Reddy and D'Souza, 1994), but there are other efficient lignin-degrading fungi including *Pleurotus* spp. (Orth *et al.*, 1993), *Trametes* spp. (Vares and Hatakka, 1997), *Panaeolus* spp. (Heinzkill *et al.*, 1998) and *Phlebia radiata* (Niku-Paavola *et al.*, 1988). *P. chrysosporium* can attack lignins as well as numerous xenobiotics (see for instance Haemmerli *et al.*, 1986; Bumpus, 1989; Lin *et al.*, 1990; Paszcznski and Crawford, 1991; Stahl and Aust, 1993; Yadav and Reddy, 1993; Yadav *et al.*, 1995), using an extra-cellular ligninolytic system, which lacks specificity with respect to the nature of the aromatic substrate and enables the fungus to modify recalcitrant organic polymers oxidatively. Initial extra-cellular oxidation of lignin sub-structures can be carried out by two microbial peroxidases, lignin peroxidase (LiP) and manganese-dependent peroxidase (MnP). Both enzymes use H_2O_2 as the oxidant to catalyse one-electron oxidation reactions of aromatic substrates, but require distinct redox mediators for completion of the catalytic cycle (for LiP, see Harvey *et al.*, 1986; Hammel and Moen, 1991; Goodwin *et al.*, 1995; Candeias and Harvey, 1995; for MnP, see Glenn *et al.*, 1986; Paszczynski *et al.*, 1986). With respect to MnPs, the oxidation of non-phenolic substrates is mediated by lipid peroxyl radicals (Jensen *et al.*, 1996). Also extra-cellular laccases, produced by many white-rot fungi including *P. chrysosporium* (Srinivasan *et al.*, 1995), may be indirectly involved in the oxidation of non-phenolic lignin sub-structures by a mechanism of redox mediation by oxidisable substrates such as ABTS (Bourbonnais and Paice, 1990). Low-molecular weight compounds produced by the initial extra-cellular oxidation of polymeric aromatic substrates can then be intra-cellularly metabolised and mineralised. In the case of xenobiotics such as 2,4-dinitrotoluene and 2,4,5-trichlorophenol, the multi-step catabolic pathways were shown to involve cycles of intra-cellular reductions and extra-cellular oxidations (Valli *et al.*, 1992; Joshi and Gold, 1993), terminating in intra-cellular oxidative ring cleavage prior to complete mineralisation (Rieble *et al.*, 1994). Because of their catabolic versatility, white-rot fungi including *P. chrysosporium* hold potential in practical applications as bio-remediation agents (see for instance Aust, 1990; Lamar *et al.*, 1990; Lamar and Dietrich, 1990; Morgan *et al.*, 1993; Holroyd and Caunt, 1997).

In the case of *P. chrysosporium*, LiPs can represent the only extra-cellular oxidative enzymes involved in ligninolysis (Leisola *et al.*, 1985). The catalytic cycle of LiP, which is typical for the family of peroxidase enzymes (Banci, 1997), involves an initial two-electron oxidation with H_2O_2 to yield Compound I, which is reduced back to the native state in two steps of single-electron reduction via the intermediate Compound II.

In this paper we report on the metabolism of fenthion by liquid cultures of *P. chrysosporium* maintained on cellulose, under conditions that favour the production of LiP as the only detectable ligninolytic extra-cellular oxidative enzyme (Zacchi *et al.*, 2000) and on the oxidation of fenthion by LiP.

MATERIALS AND METHODS

Tiguvon, a commercial formulation containing fenthion as the active ingredient, was utilised for initial tests, incorporated as an emulsion into agar plates. For analytical determinations, pure fenthion (98% min.) was purchased from the Institute of Organic Industrial Chemistry, Poland.

Phanerochaete chrysosporium, strain BKM-F-1767 (ATCC 24725), was maintained in 300 ml medical flat bottles, containing 50 ml of 2% (w/v) malt extract agar, that were incubated for 2 weeks at 37 °C. Both liquid and solid-phase cultures were grown as follows.

Liquid cultures: 600 ml growth medium in 2-l Erlenmeyer flasks closed with foam stoppers was inoculated with a spore inoculum of $2x10^7$ spores and incubated under a continuous agitation regime (130 rpm, 2.5 cm cycle) at 37 °C. A non-limiting nutrient N regime (24 mM) was used according to Tien and Kirk (1988), with the following modifications: microcrystalline cellulose (Avicel PH-101, from Fluka Chemika) was used as the C-source; veratryl alcohol (VA) was included in the medium composition, to a final concentration of 1.5 mM. The pH was adjusted to 4.5 with 10 M NaOH. All chemicals were purchased from Sigma, unless otherwise stated. A purified LiP preparation (48 μM; 39.6 U/mg protein; Rz = 2) was obtained from a 5 day-old culture's broth of *P. chrysosporium*, after concentration of the medium and purification of the enzyme according to Tien and Kirk (1988). One unit of LiP was defined as that amount of enzyme able to form 1 μmole/min of veratraldehyde using $\varepsilon = 9.3$/mM/cm (Tien and Kirk, 1984).

Solid phase cultures: The solid medium (2% w/v agar) contained per litre: 0.5 g $MgSO_4{\bullet}7H_2O$, 0.6 g KH_2PO_4, 0.4 g K_2HPO_4, 0.5 g $(NH_4)_2SO_4$, 0.1 g sodium deoxycholate, 1 mg thiamine hydrochloride and 1.5 mM VA, 0.4% (w/v) cellulose with or without 0.02% (w/v) Poly R-478. Petri dishes were inoculated by a loop of spores placed in the centre of the plates.

Analytical Methods

Extra-cellular LiP activity was measured using veratryl alcohol as substrate according to Tien and Kirk (1984). Fungal growth in liquid cultures was estimated by measuring mycelium dry weights after thorough washing with distilled water to remove extra-cellular-attached polysaccharides, and dried at 90 °C for 24 h.

HPLC analyses were performed using a C8 12 cm column (Merck) connected to a Kauner ERC pump 64 with a Varian 9050 UV-Vis. detector. The mobile phase was methanol: H_2O (8:2). Potassium phosphate buffer (20 mM, pH 2.75) was used for incubating LiP (0.1 nmol) with veratryl alcohol and H_2O_2 (both 250 nmol), and fenthion (7.2 nmol-maximum solubility in water). Spectroscopic analyses of the reaction between LiP and fenthion were carried out using a HP8452A Diode Array spectrometer. Gas chromatography was performed using a Perkin Elmer 8310 gas chromatograph, with a DB5 capillary column (30 mm x 0.25 mm, 0.25 μm film thickness) and nitrogen and phosphorus detection (GC-NPD); oven temperature was programmed between 200–250 °C, at a ramp rate of 10 °C/min; injection temperature 230 °C; detector temperature 300 °C; column flow rate 50 ml/min of N_2. For analysis of fenthion in the extra-cellular medium, 20–300 ml samples were extracted 4–5 times with dichloromethane, clarified with anhydrous Na_2SO_4 then evaporated to dryness and taken up in 3 ml of methanol. Pellets of mycelia (3–4 g) were suspended in 100 ml dichloromethane and homogenised with an Ultra-Turrax T25 homogeniser 3 times for 20-s periods. The resultant homogenate was filtered through a column of anhydrous Na_2SO_4 to remove water and then evaporated to dryness. Samples were taken up in 5 ml acetone for analysis.

RESULTS

Tiguvon, a commercial preparation of fenthion in an oil base, was investigated for its inhibitory effects on the growth of *P. chrysosporium* and expression of LiP. Agar plates containing cellulose as the C-source and increasing concentration of Tiguvon (Figure 2) were inoculated in the centre with a spore suspension of *P. chrysosporium*, using a sterile point. Tiguvon inhibited the rate of spread of the fungus across the plate surface, with a linear dose response curve up to 50 ppm (Figure 2).

Tiguvon had no effect on the fungal ability to degrade and bleach the polymeric dye Poly R when this was simultaneously incorporated into the agar matrix. This dye is degraded by the ligninolytic system of *P. chrysosporium*, via a mechanism involving LiP and the fungal secondary metabolite VA acting as a redox mediator (Candeias and Harvey, 1995).

When pure fenthion was supplied at a final concentration of *c.* 7.2 μM to liquid cultures of *P. chrysosporium*, the biomass yield (Figure 3) was comparable to that obtained from control cultures where no fenthion had been added (data not shown). Furthermore, fenthion did

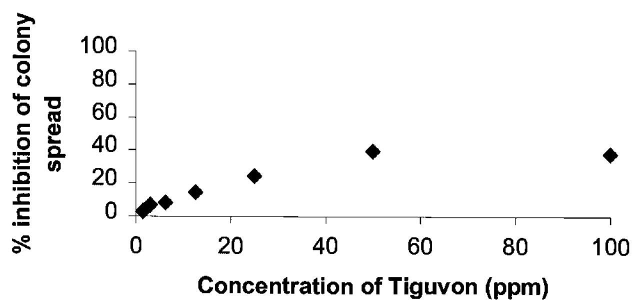

Figure 2 Dose-response curve of fenthion assayed with *P. chrysosporium* maintained on 2% agar plates to which Tiguvon was incorporated over the concentration range shown. The diameter of colonies relative to control plates without Tiguvon gave a measure of percentage inhibition.

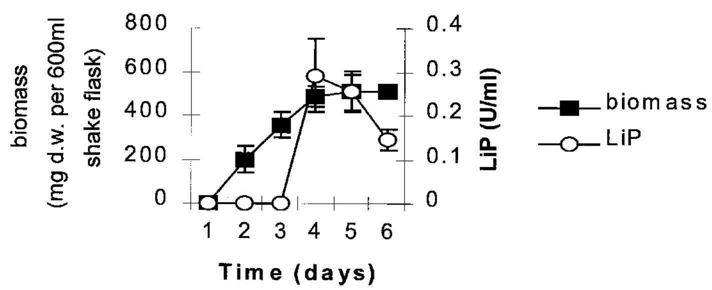

Figure 3 Growth of *P. chrysosporium* in liquid culture in the presence of 7.2 μM fenthion added at the time of inoculation. Data points are means of three replicates, error bars indicate standard deviations.

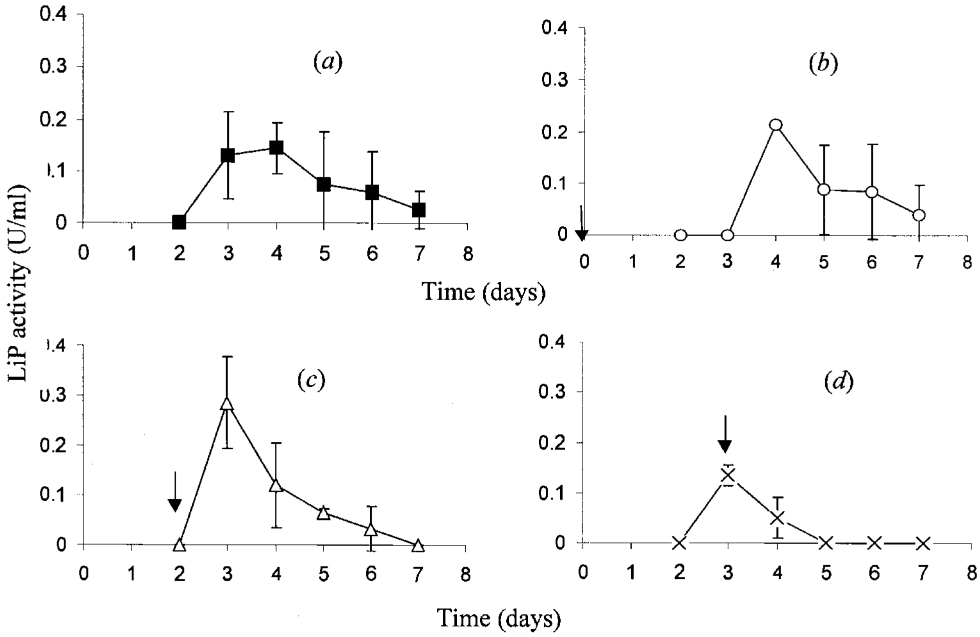

Figure 4 Production of LiP by liquid cultures of *P. chrysosporium* (a) without fenthion; (b) to which fenthion (7.2 μM final concentration in the culture broth) was added at the time of inoculation; (c) on the second day of growth; and (d) on the third day of growth.

not inhibit the production of LiP detected in the extra-cellular medium (Figure 4).By contrast, the addition of fenthion stimulated the synthesis of higher titres of LiP than measured in its absence (Figure 4).

In order to assess whether fenthion was degraded by *P. chrysosporium* in liquid cultures, samples were analysed by GC-NPD. When fenthion (elution time 5.92 min, see Figure 5a) was added to cultures at the time of inoculation, two fenthion-derived metabolites were detectable on the third day of growth, prior to the appearance of LiP. Based on their elution times (6.43 and 6.59; Figure 5c) and by comparison with data on known substances, they were tentatively identified as fenthion sulphoxide and fenthion sulphone. (The organism was exposed to fenthion and material with phosphorus was observed, presumably derived from the parent fenthion.) However, by the fourth day of growth when LiP was detected in the culture medium, no peaks with elution times of 6.43 and 6.59 could be detected and only a residual amount of the original sample was evident (Figure 5d). After 5 days the amount of fenthion detectable represented less than 1% of the original sample (data not shown). Furthermore, neither fenthion nor its degradation products could be detected in fungal pellets of mycelia that were extracted with dichloromethane after 5 days of growth.

To explore whether LiP itself was capable of oxidising fenthion, the enzyme was purified from culture media and its ability to oxidise fenthion investigated. Figure 6a shows the UV-visible spectrum of LiP (absorbance maximum at 408 nm; Renganathan and Gold, 1986) in the presence of 5 equivalents of fenthion (7.2 nmol; absorbance maximum at 250 nm).

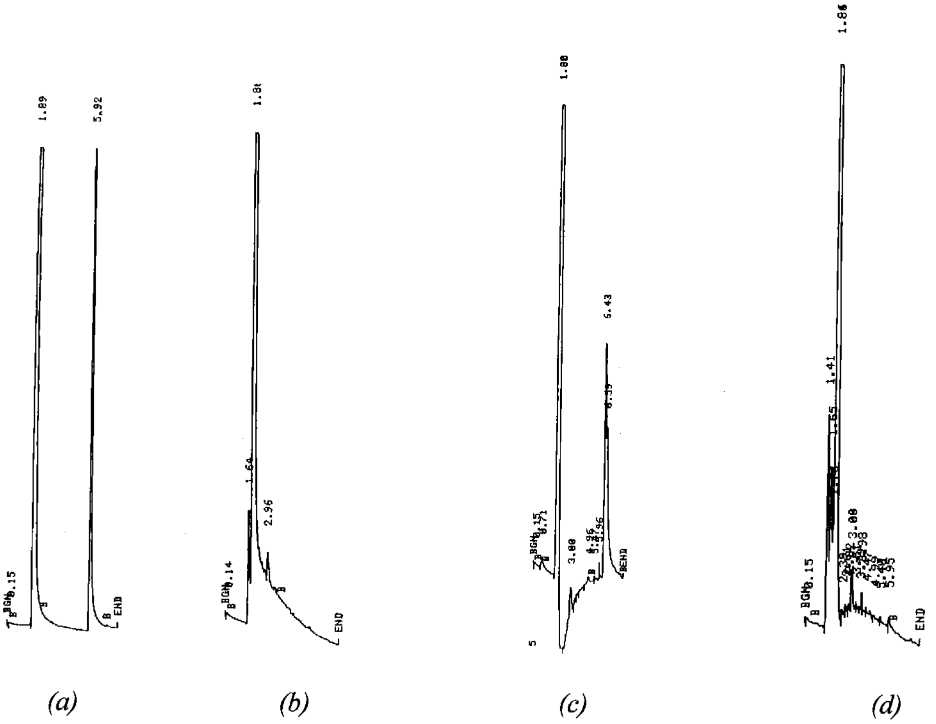

Figure 5 GC-NPD analysis of (a) fenthion and extracts concentrated from the culture broth of liquid cultures of *P. chrysosporium*. 20-ml samples were extracted with dichloromethane and taken up in 3 ml methanol for analysis. Culture broth was extracted after 3 days growth of *P. chrysosporium* in (b) the absence and (c) presence of 7.2 μM fenthion; in (d), samples were extracted after 5 days growth.

On addition of 7 equivalents of H_2O_2, the absorbance maximum at 408 nm (native state of LiP) shifted to 412 nm (native state and oxidised intermediate compound II; Renganathan and Gold, 1986) and then returned to 408 nm, indicating turnover of LiP with fenthion as reductant. Fenthion was oxidised in the course of the reaction as judged by the decrease in absorbance at 250 nm, as well as by HPLC analysis (data not shown). However, when H_2O_2 was supplied in an amount equal to the k_m of LiP for H_2O_2 (*c.* 0.4 mM), the formation of oxidised fenthion was not stoichiometric to the amount of H_2O_2 supplied, as judged by HPLC analysis of the products of the reaction. Analysis by UV-visible spectrometry showed a shift in the absorbance maximum for LiP to 420 nm followed by a decrease in value, indicative of the formation of the inactive enzyme intermediate, Compound III (Renganathan and Gold, 1986). To obviate this problem, VA was included in the reaction mixture. However, whilst able to prevent the formation of the inactive intermediate compound III by supplying an increased level of reducing equivalents, VA did not serve as a redox mediator in these reactions, rather, it inhibited the oxidation of fenthion. Figure 5b shows that when veratryl alcohol was supplied in an amount equimolar to fenthion (7.2 nmol) the absorbance at 250 nm did not decrease, rather, the absorbance at 310 nm increased corresponding to the formation of veratraldehyde from the oxidation of veratryl alcohol.

DISCUSSION

In the presence of fenthion, liquid cultures of *P. chrysosporium* not only produced higher titres of LiP but also transformed the pesticide, possibly into fenthion sulphoxide and

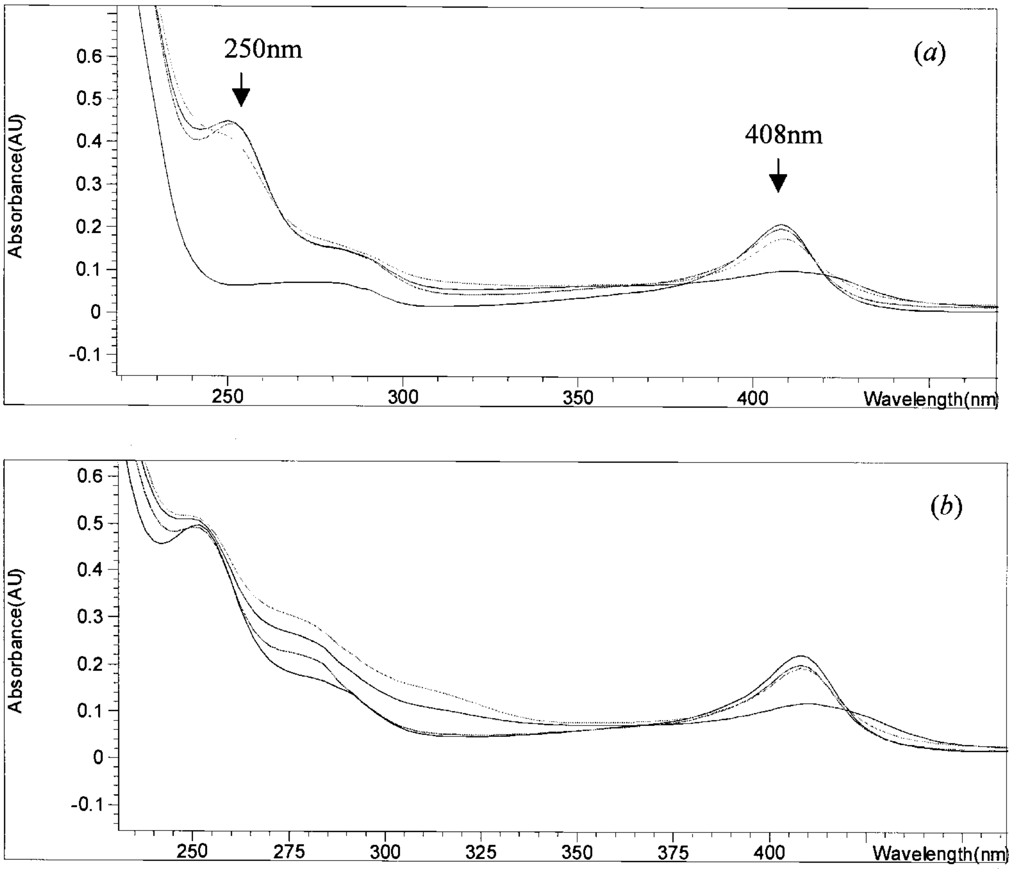

Figure 6 Absorbance spectra for the reaction of LiP (1.5 nmol) with 7.2 nmol fenthion and 20 nmol H_2O_2 in 20 mM potassium phosphate buffer pH 2.75 in (a) the absence and (b) presence of 50 nmol veratryl alcohol.

sulphone derivatives prior to complete mineralisation. These latter fenthion derivatives were identified in the extra-cellular medium during the primary growth phase of the fungus, consequently the possibility that fenthion, when added at the outset of growth, was initially degraded by abiotic means cannot be ruled out. However, the rapid disappearance of both fenthion and derivatives at the time of LiP appearance supports the view that fenthion was metabolised during fungal secondary metabolism via the ligninolytic system centred on LiP expression. This is further supported by the fact that purified LiP was able to accept fenthion as a reductant, but only at low levels of H_2O_2. At high levels of H_2O_2, evidence for enzyme inactivation was found. LiP is known amongst peroxidases to be sensitive to H_2O_2 (Wariishi and Gold, 1990). It readily forms the catalytic dead-end enzyme intermediate Compound III by reaction of the active intermediate Compound II with H_2O_2, when substrates other than dimethoxylated aromatics are supplied as reductants (phenols or mono-methoxylated aromatics of high redox potential, for example). It can also be driven into Compound III when the concentration of reductant relative to H_2O_2 supplied is low. In the case of fenthion, the low solubility of this compound in an aqueous medium may have contributed to enzyme inactivation at the higher H_2O_2 levels. The problem of enzyme inactivation during catalysis can be circumvented by addition of veratryl alcohol, which both stabilises Compound II against reaction with H_2O_2 as well as serving as a redox mediator. Surprisingly, no evidence for redox mediation with fenthion by veratryl alcohol was obtained at the concentrations of the reactants used. This may simply reflect the low solubility of fenthion in aqueous medium, but the possibility of fenthion having a high redox potential relative to veratryl alcohol radical cations cannot be ruled out. Alternatively, there may be no kinetic pathway between reactants.

Some evidence for growth inhibition by Tiguvon incorporated in agar plates was obtained, but it is unclear whether this was due to fenthion itself, given that in liquid cultures fungal growth, measured in terms of biomass yield, was not affected by the presence of the pesticide. Fenthion was not inhibitory to the germination of spores, differently from, for example, crystal violet, which inhibited the germination of spores of *P. chrysosporium* grown under similar conditions (Bumpus and Brock, 1988). The capacity of fungal spores to germinate in the presence of the xenobiotic may be exploited in practical applications using direct spore inocula, rather than growing the fungus on wood chips or other material prior to incorporation into contaminated soil (see, for example, Holroyd and Caunt, 1997). Furthermore, *P. chrysosporium* appeared to metabolise, rather than adsorb or accumulate, fenthion into intra-cellular compartments, paving the way for optimising degradation methods with this fungus.

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SESSION 4 POSITION STATEMENTS BY REPRESENTATIVES OF COUNTRIES, INSTITUTIONS, NGOS AND OTHER STAKEHOLDERS

BIRDLIFE INTERNATIONAL

Aldo Berruti remarked that BirdLife South Africa had published a book on the Important Bird Areas (IBAs) of Southern Africa (Barnes, 1998) and that they were drafting a position paper on quelea control, probably involving recommendations for a total ban on control measures in areas of conservation interest.

BOTSWANA

Ms Rebecca Kolare (Ministry of Agriculture, Botswana) reported that the problem of migrant pests became significant in Botswana in 1986 when the country experienced an outbreak of Brown Locust, *Locustana pardalina*. Since then the problem of migrant pests had continued, though at varying levels from year to year, and included damage by Red Locust, *Nomadacris septemfasciata*, African Armyworm, *Spodoptera exempta* and Red-billed Quelea birds, *Quelea quelea*. The Botswana Government launched a policy on the control of these migrant pests, stating that the Government will provide manpower and equipment necessary for control actions, but that farmers are expected to assist with surveys and reporting of such pests.

Quelea caused problems every year and were controlled from the air and the ground, usually with a 64% ULV formulation of fenthion. Although scaring birds is a widely used method, its application is hampered by limited labour resources. Also because they harvested the chicks for their own use, farmers often did not report quelea colonies. A multilateral agreement exists between Botswana, South Africa and Zimbabwe to provide liaison and co-operation during control campaigns near these countries' borders.

Low populations of flying adult Red Locusts were seen during the current season (1998/99) in Parakarungu near the Chobe/Caprivi border, a zone where Botswana and Namibia have an agreement on the management of locusts.

African Armyworm were seen in the north-western part of the country during 1998/99, with only 32 ha affected. The moths were monitored using a network of 45 pheromone trap stations.

Botswana is divided into six agricultural regions, each with one or two plant protection officers who are responsible for surveys, monitoring and control of pests, supported by 52 field assistants. Hand-held and vehicle-mounted ULV sprayers and one aircraft were available for control.

MALAWI

Dr Thindwa (Ministry of Agriculture and Irrigation, Malawi) reported that migrant pests frequently affecting Malawi were the Red Locust, African Migratory Locust, *Locusta migratoria migratorioides*, African Armyworm and mixed species of grain-eating birds. Not much research has been conducted on migratory pests and the focus has been mainly on evaluating the efficacy of pesticides in the control of the Red Locust. The main control method used against migrant pests has always been chemical. However, the threat of environmental contamination (especially in the sensitive Lake Chilwa area), and the health risk posed from continuous use of pesticides, has forced Malawi to look at research into more environmentally acceptable means of control, e.g. biological control methods. Outbreaks of migrant pests occurred every year with African Migratory Locust affecting 15,000 ha of crops and African Armyworm 10,000 ha in 1993.

Malawi has one designated outbreak area for the Red Locust – the flood-plains of Lake Chilwa, which are part of a protected wetland area. Other known Red Locust breeding areas are the marshes of the River Shire, Vwaza marsh, Mpatsanjoka dambo and some fallow lands in Ntcheu and Mchinji. The Red Locust had infested 30,000 ha during 1996, followed by very severe infestations over a much bigger area in 1997. A co-ordinated effort to disseminate information on migrant pests and to provide an early warning system was called for.

The African Migratory Locust was establishing itself as a pest in sugar plantations along the edges of the marshes of the Shire River in the Lower Shire Valley.

African Armyworm infestations occur sporadically in Malawi, with the Lower Shire Valley more prone to outbreaks than the rest of the country. Moths were monitored throughout the country by a network of pheromone traps. Outbreaks are controlled by ground chemical control methods. The last major outbreak was in 1993, when 10,000 ha of mostly cereal crops were infested.

Not much information has been documented regarding grain-eating birds, although these are very common in the Lower Shire Valley and in Karonga, close to the River Songwe. During discussion, it was pointed out that quelea are also a problem in the south and north of Malawi, with a breeding colony reported in 1994 in a National Park in the south of the country.

NAMIBIA

Mr Sibolile (Ministry of Agriculture, Water and Rural Development, Namibia) reported that Namibia had a monitoring system for Red Locust, a pheromone trap network for detecting African Armyworm and that breeding areas for Red Locust and Brown Locust in southern Africa were known. Red Locust and African Migratory Locust caused problems in the Caprivi strip. A pesticide store was to be built in Okahandja and 10,000 l of deltamethrin ULV (Decis 15, for aerial control) and 5000 l of deltamethrin ULV (Decis 7.5, for ground control) were currently in stock. Insecticides were usually dispensed with knapsack sprayers, but a pilot and helicopter were available. However, the micronair spraying equipment and the aircraft were currently inoperative.

Early rain in November 1998 in the Caprivi region led to an outbreak of African Armyworm in the Linyanti farming area. Control was successfully undertaken although some fields had to be re-planted.

Red Locust and African Migratory Locust populations increased from January 1999 onwards in the Livu-Livu and Liambezi areas, but were controlled by ground control teams. Damage in the Sangwali area reached 30%. A helicopter survey was planned for April 1999 to assess the current situation.

Problems currently experienced with migrant pest control in Namibia are the limited manpower capacity, limited cross-border communication and co-ordination, financial constraints, and maintenance of equipment.

SOUTH AFRICA

Mr Thys Botha (National Department of Agriculture, South Africa) emphasised the vulnerability of the environment in South Africa to migrant pest control measures. South Africa was sensitive to environmental concerns and the Department of Agriculture was the first signatory to the Convention on Biodiversity in 1995. South Africa was also a signatory to the RAMSAR Convention, the Bonn Convention and Agenda 21.

He reported that in South Africa the Brown Locust is the main problem, with averages of 40,000 hopper bands (at densities of 0-4 ha/band) and 10,000 swarms (8 ha/swarm) occurring each year in the Northern Cape Province. The African Migratory Locust caused problems every 3 years or so.

In 1999, the quelea population was one-third of its usual size, with 80 roosts and 10 colonies reported. Control involving 20 explosions and 60 aerial operations had killed 30,000,000 birds.

Man-biting and cattle-biting Blackflies, *Simulium* spp., mostly members of the *S. damnosum* species complex, were also considered as migrant pests in South Africa with major problems along the main rivers such as the Orange and Vaal river systems. Larvae in the rivers are treated with Temephos (= Abate) and *Bacillus thuringiensis* H-14. *Editors' note*: The geographical distribution of the *Simulium damnosum* complex in South Africa is now known to be much more extensive than hitherto realised (Palmer and de Moor, 1998; 1999), and there have even been cases of man-biting flies in Johannesburg (Jupp and Palmer, 1999).

SWAZILAND

Mr Mbuli (Plant Protection, Swaziland) reported that the Red Locust and the African Migratory Locust were occasional pests in Swaziland where they arrived from surrounding countries, e.g. Mozambique, and quelea invaded from South Africa. However, they bred in the Basuto river basin and at Kwei during December and January. African Armyworm were monitored with a network of pheromone traps. Primary outbreaks occurred during October-December but major outbreaks also occurred in January-February.

TANZANIA

Mr G. Kirenga (Ministry of Agriculture, Tanzania) reported that the most serious pests were the Red Locust, African Armyworm and quelea. The main Red Locust outbreak area is at Lake Rukwa, but there are more than three breeding areas in Tanzania. Most of the locust outbreak areas were currently flooded and no serious outbreaks of locusts were expected.

During 1999, there had been a major outbreak of the African Armyworm in the central part of the country.

There are serious invasions of quelea every year in the central and north-eastern parts of Tanzania and control was now also taking place in the north-west.

The Ministry of Agriculture was reducing its numbers of employees from 19,000 to 6000 but the Plant Protection Department was as yet unaffected by these measures. A new agricultural policy is being drafted to promote sustainable measures including Integrated Pest Management (IPM) techniques.

ZIMBABWE

Dr Simon Sithole (SADC Food Security Unit, Harare, Zimbabwe) reported that the major migrant pest problems in Zimbabwe were African Migratory Locust, Red Locust, African Armyworm, Larger Grain Borer *Prostephanus truncatus*, and Red-billed Quelea birds. Zimbabwe did not have any outbreak areas but there was a resident population of African Migratory Locusts in sugar plantations near the border with South Africa.

Zimbabwe has allocated a ‘standby budget’ for operational costs of migrant pest control. Control is mainly undertaken with pesticides (96% technical fenitrothion) by ground and aerial methods. The goal is to use ‘softer insecticides’ or bio-pesticides. No figures are available about the financial losses due to migrant pests.

Farms growing winter wheat are monitored for the appearance of Red Locust populations. African Armyworm are monitored through a network of pheromone traps.

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SESSION 5 LOGICAL FRAMEWORK WORKSHOPS ON LOCUST, ARMYWORM, QUELEA AND CROSS-CUTTING ISSUES

LOCUST LOGICAL FRAMEWORK (includes Brown Locust, Red Locust, African Migratory Locust and Southern African Desert Locust)

Narrative Summary	Objectively Verifiable Indicators	Means of Verification	Indicative Partnerships (Alphabetical order)	Assumptions	Constraints
Goal					
Impact of migrant locust pests on food producing areas of resource-poor people in southern Africa minimised					
Purpose					
Improved methods for forecasting and control of migrant locusts in southern Africa	Early Warning System (EWS) and effective control strategies developed	Forecasting Bulletins Technical Reports Scientific Publications	ARC; IRLCO-CSA; Ministries of Agriculture; NRI; SADC; Universities	Uptake and implementation of findings by Locust Control Organisations/ Ministries of Agriculture	Funding Manpower Availability of locust targets
Outputs					
1. Improved forecasting of locust outbreaks	Effective survey and forecasting systems developed	EWS Bulletins Forecasts	ARC; IRLCO-CSA; Ministries of Agriculture; NRI; Universities	Uptake and application of forecast findings	Funding for research Manpower
2. Improved understanding of population biologies of different locust species	Research data obtained on population biology	Scientific Publications Technical Reports	ARC-PPRI; IRLCO-CSA; NRI; Universities	Research findings have a valid input into operational control	Funding Manpower
3. Improved control methods	Efficacy trial data obtained	Scientific Publications Technical Reports	ARC-PPRI; IRLCO-CSA; Ministries of Agriculture; NRI; Universities	Uptake and implementation of alternative locust control methods by Locust Control Organisations	Funding Manpower
Activities					
1.1 Survey and forecasting of upsurges from key outbreak areas improved	Regular surveys undertaken and information disseminated	EWS Bulletins Technical Reports	ARC-ISCW; ARC-PPRI; IRLCO-CSA; Ministries of Agriculture; NGOs[1]; NRI; SADC; Universities	Forecasts are of benefit to resource-poor farmers	Funding Manpower
1.2 Development of Geographical Information System (GIS) for EWS	Maps of locust distribution, climatological and environmental parameters	Maps GIS	ARC-ISCW; ARC-PPRI; IRLCO-CSA; Ministries of Agriculture; NRI; Universities	Maps verify field data	Funding Availability of locust targets
1.3 Target detection technology	Microlight aircraft Satellite detection	Reports of efficiency of alternative detection methods	ARC-PPRI; IRLCO-CSA; Locust Control Organisations; Ministries of Agriculture; NRI	Improved detection techniques and cost-effective benefits	Funding Availability of targets

[1] NGOs = Non-Governmental Organisations

Narrative Summary	Objectively Verifiable Indicators	Means of Verification	Indicative Partnerships	Assumptions	Constraints
Activities					
2.1 Field and laboratory research on basic locust biology undertaken (e.g. diapause, gregarisation, hatching, mortality factors)	Field and laboratory research data obtained	Scientific Publications Technical Reports	ARC-PPRI; CABI-BioScience; IRLCO-CSA; NRI; Universities	Improved understanding of locust biology	Funding Manpower
2.2 Development of population models	Data on basic research components obtained	Scientific Publications Operational model	ARC-PPRI; IRLCO-CSA; NRI; WITS[2]	Sufficient data available for development of model	Funding Manpower
2.3 Environmental Impact (EI) of locust control operations evaluated	Impact of locust control determined	Scientific Publications Technical Reports	ARC-PPRI; CABI-BioScience; Conservation Organisations; IRLCO-CSA; Museums; NRI; Private Consultants; Universities	Environmental Impact can be determined	Funding Manpower
2.4 Areas sensitive to pesticide contamination delineated and identified	Ecologically sensitive areas identified	Scientific Publications Technical Reports	ARC-PPRI; CABI-BioScience; Conservation Organisations; FAO; IRLCO-CSA; Museums; NRI; Private Consultants	Findings implemented in locust control policies	Funding Manpower
3.1 Application techniques and strategies evaluated (myco-insecticides/barrier/baiting treatments)	Application under operational conditions effective	Scientific Publications	ARC-PPRI; CABI-BioScience; IRLCO-CSA; NRI; Universities	New application strategies implemented	Funding Manpower Availability of targets
3.2 Current control efficacy evaluated (including cost-benefit analysis)	Field evaluation data obtained	Technical Reports Scientific Publications	ARC-PPRI; IRLCO-CSA; Ministries of Agriculture; NRI; Universities	Training of locust control officers undertaken	Funding Availability of locust targets Manpower
3.3 Development of new and promising acridicides (including pathogens)	Field efficacy data obtained	Technical Reports Scientific Publications	ARC-PPRI; CABI-BioScience; Commercial Companies; IRLCO-CSA; NRI; Universities	Results implemented	Funding Manpower Availability of targets
3.4 Development of an alternative Integrated Pest Management (IPM) strategy	Field efficacy trials undertaken	Technical Reports Scientific Publications	ARC-PPRI; CABI-BioScience; IRLCO-CSA; Ministries of Agriculture; NRI; Universities	Results implemented	Funding Manpower
3.5 Feasibility of harvesting locusts investigated	Harvesting data obtained	Technical Reports Cost-benefit analysis	ARC-PPRI; Business Partners; Farmers; IRLCO-CSA; NRI; UOFS	Alternative methods implemented Economic viability proven	Funding Availability of locust targets Manpower

[2] WITS = University of the Witwatersrand

ARMYWORM LOGICAL FRAMEWORK

Narrative Summary	Objectively Verifiable Indicators	Means of Verification	Indicative Partnerships (Alphabetical order)	Assumptions	Constraints
Goal					
Impact of armyworm on food production by resource-poor people in southern Africa minimised					
Purpose					
Improved methods for forecasting and control of armyworm in southern Africa	Improved forecasting system Models improved Alternative control strategies developed	Technical Reports Scientific Publications	FAO; FOs[3]; Extension Services; IRLCO-CSA; National Forecasters; NRI	Uptake and implementation of research findings by control organisations and communities	Funding Control inputs
Outputs					
1. Improved forecasting developed and promoted	Effective forecasting system	Scientific Publications Refined models	National Forecasters; SADC; NRI	Uptake and promotion of findings by armyworm control organisations	Funding Farmer resources
2. Alternative, more acceptable control technologies developed and promoted	More environmentally acceptable technologies	Technical Reports Scientific Publications	Commercial Companies; IRLCO-CSA; NARS[4]; NRI	Uptake and implementation of more acceptable control technologies	Funding Availability of pesticides Unpredictable outbreaks
3. Prediction and control strategies linked	Field control efforts assisted by forecasting	Operations reports	IRLCO-CSA, NARS; NGOs	Activities 1.1 to 2.3 completed successfully and institutional links improved	
Activities					
1.1 Refining and testing of medium-term (1 month) and short-term (1 week) models to improve understanding of how outbreaks are triggered	Rainfall and moth displacement data obtained Model predictions compared with outbreak events	Technical Reports Scientific Publications	CBOs[5]; FOs; National Forecasters; NGOs; Programmes	Uptake and implementation of model findings by control organisations	Funding Sporadic nature of outbreaks
1.2 Development of local data collection capability to enhance existing network	Existing trap network maintained and enhanced	Technical Reports Database	CBOs; FOs; National Forecasters; NGOs; Programmes	Co-operation of farmers and stakeholders	Funding Co-operation at all levels

[3] FOs = Farmers Organisations
[4] NARS = National Agricultural Research Systems
[5] CBOs = Community-Based Organisations

Narrative Summary	Objectively Verifiable Indicators	Means of Verification	Indicative Partnerships (Alphabetical order)	Assumptions	Constraints
Activities					
2.1 Development of Nuclear Polyhedrosis Virus (NPV) for farm use	Field trial data Virus strains from field identified Local production developed	Technical Reports	IRLCO-CSA; NARS	Uptake and implementation of research results by control organisations/communities	Funding
2.2 Testing of low-dose insecticides	Field trial data obtained	Scientific Publications Technical Reports	IRLCO-CSA; NARS Commercial Companies; International Research Organisations; NARS	Uptake and implementation of research results by control organisations/ communities	Funding Outbreaks occur only in environmentally sensitive areas
2.3 Testing of potential botanical pesticides	Efficacy data obtained	Technical Reports	IRLCO-CSA; NARS Commercial Companies; International Research Organisations; NARS	Uptake and implementation of research results by control organisations/communities	Funding Availability of botanicals
3. Prediction and control strategies linked	Field control efforts assisted by forecasting	Operations reports	IRLCO-CSA, NARS; NGOs	Activities 1.1 to 2.3 completed successfully and institutional links improved	

QUELEA LOGICAL FRAMEWORK

Narrative Summary	Objectively Verifiable Indicators	Means of Verification	Indicative Partnerships (Alphabetical order)	Assumptions	Constraints
Goal					
Impact of quelea on small grain producing areas of resource-poor people in southern Africa minimised					
Purpose					
Improved methods of forecasting and control of quelea in southern Africa	Forecasting techniques and alternative control strategies developed	Technical Reports Scientific Publications	ARC-PPRI; Ministries of Agriculture; NRI; Universities; Zimbabwe Parks	Uptake and promotion of findings by Quelea Control Organisations	Funding Manpower
Outputs					
1. Current control techniques improved (adopted and promoted)	Efficacy trial data obtained	Technical Reports Scientific Publications	ARC-PPRI; Ministries of Agriculture; Zimbabwe Parks	Uptake and implementation of improved quelea control methods by Quelea Control agencies	Funding Manpower
2. Alternative, more beneficial control measures to kill and knock down quelea (developed and promoted)	Field trial data obtained	Technical Reports Scientific Publications	ARC-PPRI; Ministries of Agriculture; NRI; Zimbabwe Parks	Uptake and implementation of improved quelea control methods by Quelea Control agencies	Funding Manpower
3. IPM strategies (developed and promoted)	Field trial data obtained	Technical Reports Scientific Publications	ARC-PPRI; Ministries of Agriculture; NRI; Zimbabwe Parks	Uptake and implementation of improved quelea control methods by Quelea Control agencies	Funding Manpower
4. Monitoring and forecasting of quelea improved	Population data obtained	Scientific Publications Operational model	Existing project; Avian Demography Unit Cape Town; Edinburgh University; SADC	Access to remote sensing Resources for monitoring available	Weak infrastructure Funding Manpower
5. Utilisation of quelea as a food source investigated	Harvesting data Cost analysis data	Technical Reports Cost-benefit analysis	ARC-PPRI; Communities; Ministries of Agriculture; NGOs, NRI; Private Sector	Harvesting is economically viable	Funding Manpower Market-related issues

Narrative Summary	Objectively Verifiable Indicators	Means of Verification	Indicative Partnerships	Assumptions	Constraints
Activities					
1.1 Application techniques and strategies, and efficacy of current control measures evaluated	Field evaluation data obtained	Technical Reports Scientific Publications	ARC-PPRI; Ministries of Agriculture; NRI; Private Sector; Zimbabwe Parks	Resources for uptake	Unpredictability Infrastructure Resources for uptake Green Lobbies
1.2 Strengthening and co-ordination of recording, and analysis of current control methods	Workshops and meetings on reporting systems held	Standardisation of reporting	Ministries of Agriculture (whole region); SADC; Zimbabwe Parks	Uniform reporting methods adopted	Lack of consistency Weak infrastructure and training
1.3 Environmental Impact Assessment of current and improved techniques (pesticide behaviour etc.)	Impact of quelea control determined	Technical Reports Scientific Publications	Whole Region; BirdLife SA	Environmental impact can be determined	Funding Manpower
1.4 Repair and contamination minimisation of environmental damage (e.g. bio-remediation) resulting from current and/or improved control methods/actions evaluated	Environmental damage minimised	Technical Reports Scientific Publications	Whole Region	Environmental damage can be repaired	Funding Manpower
2.1 Application techniques, strategies and efficacy of alternative control measures evaluated (soft pesticides, biocontrol, non-toxic methods)	Field trial data obtained	Technical Reports Scientific Publications	ARC-PPRI; NRI; Other groups concerned with bird control; BirdLife SA	Research feasibility	Funding Manpower Green Lobbies
2.2 Impact (environmental and sociological) of alternative control measures	Impact of control determined	Technical Reports Scientific Publications	ARC-PPRI; NRI; Other bird control groups/organisations; BirdLife SA	Research feasibility	Funding Manpower

Narrative Summary	Objectively Verifiable Indicators	Means of Verification	Indicative Partnerships	Assumptions	Constraints
Activities					
3.1 Field and lab research on basic bird biology undertaken (eg. behaviour, physiology)	Field research data obtained	Technical Reports Scientific Publications	ARC-PPRI; Ministries of Agriculture; NRI; Zimbabwe Parks; Universities	Improved understanding of quelea biology	Funding Manpower
3.2 Component technologies evaluated to identify optimum techniques	Field trials undertaken	Technical Reports Scientific Publications	ARC-PPRI; Ministries of Agriculture; NRI; Zimbabwe Parks; Universities	Results implemented	Funding Manpower
3.3 Appropriate component technologies integrated	Field trials undertaken	Technical Reports Scientific Publications	ARC-PPRI; Ministries of Agriculture; NRI; Zimbabwe Parks; Universities	Alternative methods implemented	Funding Manpower
4.1 Improved effective monitoring and forecasting	Data on identification of strategic populations obtained Regular surveys undertaken and information timely disseminated	Scientific Publications Operational models	Existing project Avian Demography Unit Cape Town; Edinburgh University; SADC	Access to remote sensing and resources for monitoring	Weak infrastructure Funding Manpower
4.2 Development of population models	Data on basic components obtained	Scientific Publications Operational models	Existing project Avian Demography Unit Cape Town; Edinburgh University; SADC	Sufficient data inputs for development of model	Funding Manpower
5.1 Evaluate demand and market potential, cost benefits and sociological conflicts	Market research data obtained	Technical Report Cost benefit analysis	ARC-PPRI; Communities; NGOs; NRI; Private Sector; Zimbabwe Parks	Economic viability proven	Conflict with other control measures Unpredictability Green Lobbies
5.2 Evaluate methods of capture, processing and distribution	Harvesting, processing and distribution data obtained	Technical Report	ARC-PPRI; NRI; Private Sector; Zimbabwe Parks	A market for processed quelea exists	Funding Manpower
5.3 Evaluate impact of control measures on consumers	Data on effects of control on consumers obtained	Technical Report	ARC-PPRI; Communities; NGOs; NRI; Zimbabwe Parks	Toxic residues are acceptable	Funding Manpower
5.4 Evaluate non-target effects	Field data obtained	Technical Report	ARC-PPRI; NRI; Zimbabwe Parks; BirdLife SA	Evaluation methods are available	Funding Manpower

CROSS-CUTTING LOGICAL FRAMEWORK (includes armyworm, locust and quelea)

Narrative Summary	Objectively Verifiable Indicators	Means of Verification	Indicative Partnerships (Alphabetical order)	Assumptions	Constraints
Goal					
Impact of migrant pests on resource-poor farmers in semi-arid farming systems in southern Africa minimised					
Purpose					
Development and promotion of strategies to improve forecasting and control of migrant pests in semi-arid farming systems in southern Africa for the benefit of poor people	Uptake of outputs by relevant Organisations and Ministries	Proceedings of Meetings Technical/Annual Reports	ARC; CABI; Community and Farmers Groups; IRLCO-CSA; Ministries of Agriculture; National Forecasters; NRI; SADC; Universities	Uptake and implementation of findings by relevant Organisations and Ministries of Agriculture Economically and environmentally sound control policies remain a priority	Funding Manpower Availability of field data
Outputs					
1. Strengthened institutional and communication structures to sustain cost-effective forecasting and control	Requests for emergency outbreak assistance reduced Populations confined to outbreak areas Communication channels improved	Proceedings of Meetings Technical/Annual Reports Links developed and maintained Websites established	ARC; CABI; Community and Farmer Groups; Extension Services; IRLCO-CSA; Ministries of Agriculture; NARS; NRI; SADC; Universities	Migrant pests continue to threaten livelihoods of poor farmers Control remains a priority for governments in affected countries	Active participation is fostered Funding for training and workshops Suitably qualified manpower available
2. Improved environmental information to sustain environmentally sound forecasting and control	Pesticide usage reduced Biodiversity levels maintained in outbreak/invasion areas	Maps Technical Reports Published regulations	ARC-PPRI; CABI; Community and Farmer Groups; Extension Services; IRLCO-CSA; Ministries of Agriculture; NGOs; NRI; Public Sector; SADC	Environmental impact and operator safety remain priorities	Funding Suitably qualified manpower

Narrative Summary	Objectively Verifiable Indicators	Means of Verification	Indicative Partnerships (Alphabetical order)	Assumptions	Constraints
Activities					
1.1 Institutional links from local to international levels re-established and developed	Improved interaction with community Workshops and meetings on reporting systems	Reports	ARC-PPRI; IRLCO-CSA; Ministries of Agriculture; SADC; NGOs; NRI; Public Sector; CABI; Extension Services; Community and Farmer Groups	Institutional framework in place and suitable for collaborative development	Funding Key personnel maintained
1.2 Reporting protocols refined and dissemination mechanisms established	Standardised reporting procedures adopted	Reports Standardisation of reporting and documentation	ARC-PPRI; IRLCO-CSA; Ministries of Agriculture; SADC; NGOs; NRI; Public Sector; CABI; Extension Services; Community and Farmer Groups	Uniform reporting methods accepted and adopted by national bodies	Funding Key personnel maintained
1.3 Communication/ dissemination mechanisms established	Communication channels developed and operating	Internet website Schools and Farmers' Days TV/Radio talks Brochures/Leaflets GPPIS[6]	ARC-PPRI; IRLCO-CSA; Ministries of Agriculture; SADC; NGOs; NRI; Public Sector; CABI; Extension Services; Community and Farmer Groups	Communications network functioning	Funding Key personnel maintained
2.1 Environmentally sensitive areas defined and delimited	Surveys completed and databases established	Maps GIS Technical Reports and papers	ARC-PPRI; IRLCO-CSA; Ministries of Agriculture; SADC; NGOs; NRI; Public Sector; CABI; Extension Services; Community and Farmer Groups	Field observations carried out to required standard	Funding Manpower
2.2 EIA procedures established for control campaigns	Guidelines adopted	Reports Campaign Reports	ARC-PPRI; IRLCO-CSA; Ministries of Agriculture; SADC; NGOs; NRI; Public Sector; CABI; Extension Services; Community and Farmer Groups	New EIA methods developed	Funding Manpower
2.3 National regulations for pesticides, application methods and health and safety measures developed	Legislation/registration procedures in place	Published Regulations	ARC-PPRI; IRLCO-CSA; Ministries of Agriculture; SADC; NGOs; NRI; Public Sector; CABI; Extension Services; Community and Farmer Groups	Co-ordinated actions between participating countries	Funding Manpower

[6] GPPIS = Global Plant and Pest Information System

Workshop Steering Committee

A Steering Committee consisting of Dr Bahana, Mr Botha, Prof. Cheke, Dr Eden-Green, Dr Elliott, Mrs Kieser, Mr Kirenga, Dr Rosenberg, Dr Tarimo, Mr Terry and Dr van Dyk, convened during the meeting to assess progress and make plans for the future.

The Steering Group made the following recommendations.

- The ARC-PPRI Website (http://www.arc.agric.za/lnr/institutes/ppri/migrant/main.htm) should be maintained as an information point for follow-up actions, e.g. the Summary Report of the Workshop (Rosenberg and Kieser, 1999) could be made available there and information about any work relevant to the content of the Workshop.
- The Summary Report should be disseminated to all participants and other relevant stakeholders, e.g. country Ministries, NGOs, private industries.
- The full Proceedings of the Workshop should be published as a comprehensive technical record of research progress to date, and as guidance for future research strategies.
- ARC-PPRI, IRLCO-CSA and NRI should be the dissemination points for the full Proceedings of the Workshop.

REFERENCE

ROSENBERG, J. and KIESER, M. (eds) (1999) *Summary Report on Workshop on Migrant Pests of Agriculture in Southern Africa. Research Priorities, Plant Protection Research Institute, Pretoria, South Africa, 24–26 March 1999.*