CROP PROTECTION PROGRAMME

Forecasting movements and breeding of the Red-billed Quelea bird in southern Africa and improved control strategies

R7967 (ZA0467)

FINAL TECHNICAL REPORT

1 January 2001 – 31 March 2003

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July 2003

This publication is an output from a research project funded by the United Kingdom Department for International Development for the benefit of developing countries. The views expressed are not necessarily those of DFID (R7967 Crop Protection Programme).
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Executive Summary

The project sought to improve the livelihoods of small-scale farmers in semi-arid areas of southern Africa, where their cereal crops are threatened by the Red-billed Quelea bird, and thus contribute to reductions in poverty. Means to improve the efficiency of control measures against his pest and to reduce environmental damage during control activities were achieved as follows. (1) A quelea short-term forecasting system, the first of its kind, was created for use by target organisations involved in quelea control and improved during a validation process. (2) For the 2002/2003 season (September 2002 – May 2003), the system’s forecasts were displayed on a dedicated internet web-site every week. Eight-nine of 91 colonies reported were at sites where the model predicted that conditions would be suitable for the birds to breed when they did. (3) No simple method for medium-term forecasts was established but promising lines for future research were identified. For instance, (a) significant autocorrelations, with lags of up to three years and a significant partial autocorrelation with a lag of one year, were found within a quelea time series of reports of quelea colonies, implying that very high populations will only occur if there have been high populations in the preceding season; (b) there was a significant positive correlation between numbers of quelea colonies reported from 1979-2001 and December rainfall; and (c) the three years with the highest numbers of colonies in the Springbok Flats area in South Africa were years of above average rainfall in January-March and the three lowest years all had below average rainfall. (4) A desk study of the environmental effects of quelea control showed them to be substantial, but means to minimise them were identified. (5) Protocols for future environmental impact assessment (EIA) work were proposed that need to be tested in the field. (6) The forecasting system has been disseminated widely to control planners, through the linked CPP-funded ICOSAMP project and other routes, and may lead to substantial improvements in quelea control success rates and hence reduce the impact of pest damage to the crops of the rural poor throughout southern Africa. (7) Target institutions have requested assistance with training and field-work for EIAs and increasing the area covered by the quelea forecasts. (8) Uptake of the project’s outputs has included a handing-over of the running of the forecasting model to the Southern Africa Development Community (SADC).

Background

The developmental potential of small-scale farmers growing small-grain cereal crops in southern Africa is constrained by the reductions in their yields caused by the Red-billed Quelea bird (Quelea quelea). Annual losses to this pest in Africa have been estimated as USS$45 million (Elliott 1989), equivalent to USS$65 Million at 2002 prices. Populations of quelea threatening subsistence crops are killed with avicides applied either from the ground or from the air or by explosions set off at the bases of roosts or colonies, if they are located soon enough. In some countries, such as Botswana and South Africa, control takes place in most years but there has been no system to warn where the birds are likely to occur in a particular season. Even when breeding colonies are located, the speed of the birds’ development often means that the control teams reach the areas too late i.e. after the birds which cause most damage, the juveniles, have left their nests. During the non-breeding season quelea also occur in very large concentrations and spend the nights in communal roosts, which are also important targets for control. The demand for the project arose from the requirements of target institutions responsible for quelea control to have a system for forecasting where their activities would be needed and the need for the environmental effects of their control measures to be minimised.

Since quelea regularly perform long distance migrations from one affected area or country to another, movements that have been shown to exceed 2500 km, prediction of where and when they will occur relies on knowledge of their migratory habits in response to the seasonal movements of rain-fronts. Rain causes their main food, grass seeds, to germinate at the start of the wet season forcing birds to perform an “early rains migration” away from their dry season quarters. Over the following 3-4 months the birds then undertake further “breeding migrations” to areas where adequate rainfall will permit them to breed. Thus, the patterns of quelea occurrences vary from year to year. For instance in 1968-69 breeding did not begin until January when the highest concentrations of colonies were in northern South Africa, southern Zimbabwe and eastern Botswana. By February they had spread further north and birds later occurred in yet different locations in March and April. These positions and timings were quite different from the sequence in 1994-95 and examples of such seasonal variations were illustrated in the Final Technical Report of the predecessor CPP Project (R6823). The main objective of this project was to devise a model to forecast where and when the birds would be able to breed during a season. In order to do this, existing quelea data, compiled during the earlier
project (R6823), were analysed in relation to environmental variables to seek medium-term predictors and to see if existing models could be improved.

Control of quelea birds by spraying their colonies or roosts with avicide, usually the organophosphate fenthion, or by blowing up concentrations of the birds with explosives is not environmentally benign but its effects have not been assessed systematically. Another objective of the project was to conduct a desk-based review of the environmental impacts of quelea control. Whilst the forecasting was restricted to the movements of the subspecies restricted to southern Africa, *Quelea quelea lathamii*, the environmental impact assessment encompassed literature on quelea control throughout Africa.

The project was closely linked to another CPP project, the Information Core for Southern African Migrant Pests (ICOSAMP) which has created a web-based system for information exchange. Outputs from the quelea project were disseminated at the first two ICOSAMP workshops and the ICOSAMP web-site route will be used in future disseminations. Representatives of the main target institutions attended the ICOSAMP meeting and those in Botswana, Mozambique, South Africa and Swaziland were visited for discussions and data exchanges during 2001, as part of this project. As with most migrant pests, the responsibility for their management falls not only on national agricultural organisations but also on international bodies. In the case of quelea control, the International Red Locust Control Organisation for Central and Southern Africa (IRLCO-CSA), the Desert Locust Control Organisation for East Africa (DLCO-EA) and the FAO are the international organisations involved, together with the Southern Africa Development Community (SADC). The Plant Protection Sub-Committee of SADC has endorsed ICOSAMP and it is has been arranged that they will take on the operation of the quelea model as from September 2003.

**Reference**


**Project Purpose**

*Purpose:*

Strategies developed to improve forecasting and reduce the impact of migrant pests in semi-arid cropping systems, for the benefit of poor people.

*Objectives:*

1. A desk-based assessment of the environmental impacts of quelea control operations.

2. A preliminary analysis of the potential for developing a statistical medium term quelea seasonal forecasting model based on sea surface temperature (SST) data and atmospheric indicators.

3. Increased knowledge of the key relationships between environmental factors and quelea migrations and breeding activities.

4. An initial computer-based model for forecasting the timing and geographical distribution of quelea breeding activity in southern Africa developed in relation to control strategies of stakeholders.
Research Activities

Activities for Output 1: A desk-based assessment of the environmental impacts of quelea control operations.

Activities consisted of an extensive review of published and unpublished literature, conducted by A. N. McWilliam and R. A. Cheke. A desk-based assessment of the environmental impacts of quelea control operations was conducted to identify the known effects on non-target organisms of the two principal methods used by government agencies for quelea control:
1. Chemical control by air or ground application of the avicide Fenthion to breeding colonies and roosts.
2. The detonation of explosives in roosts.

The main sources for this information were the library and quelea archives held at the Natural Resources Institute (NRI) of the University of Greenwich and libraries at the Natural History Museum, Tring, Hertfordshire, the Edward Grey Institute of Field Ornithology, University of Oxford and the Percy Fitzpatrick Institute of Ornithology at the University of Cape Town (visited by R. A. Cheke during 2002). Extensive unpublished data were supplied by the Dept of National Parks and Wild Life Management of Zimbabwe and by the Plant Protection Research Institute (PPRI) of South Africa.

The assessment considered (a) control in ecologically sensitive areas and (b) implications for use of quelea as a food source for the rural poor. A detailed bibliography of the environmental impact of quelea control was compiled.

Activities for Output 2: A preliminary analysis of the potential for developing a statistical medium term quelea seasonal forecasting model based on sea surface temperature (SST) data and atmospheric indicators.

Activities involved the collation and up-dating of data on quelea breeding colonies by J. F. Venn and R. A. Cheke. These were then analysed using time series analysis and composite analysis in relation to different rainfall data-sets and data on sea surface temperatures by M. Todd, D. Kniveton and R. Washington. The potential for the development of a statistically-based medium term seasonal forecasting scheme for quelea activity was investigated involving:

(a) Statistical analysis of the historical record of quelea observations at a number of locations in Southern Africa to correlate quelea observations with climatic variability to determine the nature of the climatic controls on quelea activity in the region.

(b) Identification of candidate predictors of quelea activity from composite analysis of global oceanic and atmospheric fields (including sea surface temperatures, sea level pressure and atmospheric winds) in the months preceding the quelea breeding season in Southern Africa. The sampling basis for these composites was derived by identification of years of high and low quelea activity from the historical record.

The work assessed the degree to which quelea activity (as represented by the historical observations) is predictable in the medium term from climate parameters.
Activities for Output 3: Increased knowledge of the key relationships between environmental factors and quelea migrations and breeding activities.

Published and unpublished data on the threshold values of rainfall to (a) elicit quelea movements and (b) permit successful breeding in different areas were re-examined and reviewed by P. J. Jones and R. A. Cheke.

Activities for Output 4: An initial computer-based model for forecasting the timing and geographical distribution of quelea breeding activity in southern Africa developed in relation to control strategies of stakeholders.

Activities for this output relied on running the system installed at NRI for the continuous recording of CCD data from the Meteosat satellite. This and the programming of the model and associated web-site (http://www-web.gre.ac.uk/directory/NRI/que) were achieved by J. F. Venn with inputs from R. A. Cheke and P. J. Jones. The Meteosat recording system is also used for another CPP project on armyworm forecasting (R7966, ZA0449). The model outputs were placed on the web-site at weekly intervals during the 2002/2003 system. A link was set up so that users of the ICOSAMP web-site (http://icosamp.ecoport.org/) produced by a related CPP project could go directly to the quelea forecasts as well. In order to calibrate and validate the model, data on quelea breeding were collated, mostly from data supplied through the ICOSAMP project but also directly during visits to plant protection offices in Botswana, Mozambique, South Africa and Swaziland. After model development a meeting was held with in Gaborone, Botswana, with SADC personnel to arrange for transfer of the operation of the model to them.
2.2. Report on Output 1: A desk-based assessment of the environmental impacts of quelea control operations

2.2.1. Introduction

The most common form of quelea control currently involves ground or aerial application of Queletox ® (60% fenthion, usually at 4 l/ha in ULV formulation) to breeding colonies and night roosts (Elliott and Allan 1989). However, the use of fire-bombs and explosives has long been an alternative methodology, particularly in West Africa (Meinzingen et al. 1989). Although neither method is without environmental impact and mortality to non-target species, there has been particular concern for avian conservation over use of chemical sprays (Verdoorn 1999) in South Africa and greater use of explosives has been adopted (Elliott 2000). As the toxicological properties of fenthion have been well documented (US EPA 2001), this report will concentrate on collating records of non-target casualties from quelea control to emphasise the need for alternative strategies and methodologies. Recommendations to adopt agronomic and control strategies that reduce the environmental impact of quelea control operations on the environment have been made by Jones (1972), Ward (1972, 1973, 1979), Elliott and Allan (1989) and Elliott and Craig (1999).

Non-target mortality, resulting from direct poisoning in sprayed roosts or colonies and secondary poisoning through consumption of contaminated prey items, can be much reduced by restricting control only to those sites where economic damage to crops actually occurs. In this context, it is generally agreed that large breeding colonies or roosts are unlikely to threaten vulnerable crops further than 10 and 40km away, respectively (Elliott and Allan 1989, L. Geertsema, pers.comm.). In addition, where control cannot be avoided by earlier planting of crops it has to be timed to occur before young birds fledge and increase the population size. Currently, in view of the increasing realisation that chemical control of quelea causes significant mortality to other wildlife, there is a move to focus on a more integrated approach (IPM) (Elliott and Craig 1999). However, it is recognised that research is urgently required to develop safer technologies and limit the environmental impact of quelea control (Elliott 2000).

A comprehensive bibliography of Quelea has been prepared with sponsorship by FAO (Oschadleus 2001), which also has a keyword listing for some reports of quelea control that cite impacts on non-target species. Useful references are also to be found in the previous bibliography of Magor and Ward (1972), as well as in the reference lists of the two major books on quelea edited by Bruggers and Elliott (1989) and Mundy and Jarvis (1989). The potential impact of quelea control operations on non-target birds in South Africa is well illustrated by an analysis of quelea distribution in relationship to bird diversity, with emphasis on wetland and predator / scavenger species (Allan et al. 1995). These authors stress the need to avoid spraying in wetland sites, which support a wide variety of waterfowl and other species, and at breeding colonies to which large numbers of predators have been attracted.

The remainder of this section of the report is divided into two main sections. The first considers effects of control of quelea on non-target organisms and the second discusses effects of control in ecologically sensitive areas.

2.2.2. Effects on Non-target organisms

2.2.2.1. Chemical control

This section will be limited to the non-target impact of fenthion, the chemical of choice for many years.

2.2.2.1.1. Non-target exposure

Concentrations of quelea can number millions in very dense breeding colonies or roosts. A night roost may contain as many as 25 million quelea on 10 ha and breeding colonies incorporate up to 100 ha of acacia bush (Manikowski 1988). Such sites, apart from harbouring resident wildlife, frequently attract many predators, of which the most visible are birds of prey. Thus, Thiollay (1989) has recorded 80 species of predatory birds at breeding colonies in western and central Africa. Some 93 raptor species are resident or seasonal migrants in sub-Saharan Africa (Keith and Bruggers 1998). In addition, it is
known that quelea are eaten by a wide variety of mammals - ranging from genets and baboons to hyenas and even lions. Snakes and monitor lizards also frequently prey on eggs and nestlings (Pienaar 1969, Thiollay 1989).

At one quelea colony in South Africa’s Kruger National Park, observers estimated that over 1000 birds of four large eagle species were present (Biggs 2001) and Pienaar (1969) judged that up to 1,200 eagles and about 300 Marabou Storks attended another colony in the park. Scores of vultures and many smaller birds of prey were also observed in both studies (some 19 species of predatory birds between both sites). Even predation rates on nests can be significant and at one of the Kruger colonies 60% of nests had been torn open (Pienaar 1969).

As densities of adults and fledglings at the end of the breeding season can amount to over 100,000 per ha, an efficient spray can result in about 1500 kg/ha of poisoned birds on site (Manikowski 1988). This provides an irresistible and abundant food source to scavengers and predators, which themselves become prone to debilitation and death from secondary poisoning.

2.2.2.1.2. Extent of application

In South Africa, an average of 52,658,000 quelea were controlled per year between 1988 and 2000, over a mean treated area annually of 1243ha (Willemsen 2000). The number of control operations averaged 173 per year and by 1999/2000 the average quelea kill per colony (mean size 7ha) was 385,000 birds. In Zimbabwe, an estimated 13,500,000 birds were sprayed with fenthion (Queletox) in 1988 (Mundy 2000); in Ethiopia and Sudan, yearly control averaged 37 and 145 sites respectively, of 41 and 205 ha in mean size (Elliott 2000).

The few systematic field studies of the impact of control on non-target wildlife at quelea colonies that have been carried out (Bruggers et al. 1989, Keith et al. 1994, Mullié et al. 1999) confirm that fenthion, also being an insecticide, is highly toxic to terrestrial invertebrates. In Kenya, Bruggers et al. (1989) recorded extensive mortality in 14 families of insects and spiders - with particularly high residues found on Carabidae, Acridae, Gryllidae, Tettigonidae and Mantidae. In Senegal, ants, carabid and tenebrionid beetles were most notably affected (Mullié et al. 1999). Thus, these are also a source of fenthion toxicity to other insectivorous predators, particularly birds, in sprayed areas. As fenthion is not highly toxic to mammals (US EPA 2000), these studies have principally concentrated on the impact of both direct and secondary poisoning on birds - which was indeed extensive.

Numbers of poisoned birds found in the above studies, together with other records from the literature are summarised in Table 1. This demonstrates that, although unlikely to be of concern to non-target birds on an Africa-wide scale, resident populations of susceptible species (especially predators that bio-accumulate fenthion) can become locally scarce after years of repeat spraying (Thomsett 1987).

2.2.2.1.3. Technical considerations

Recent technical monitoring of aerial spraying at a quelea roost site, with ULV fenthion at 3 l/ha (concentration of 64% (m/v) and droplet size volume median diameter (VMD) of 90 microns), found off-target drift as far as 3km (van der Walt et al 1998, van der Walt 2000). There was very uneven coverage of target sites (deposition rates varying from 0.01 to >550% of expected) and further lack of efficacy was caused by poor canopy penetration. In addition, persistence was longer than previously reported at 64 hours in air and 46 days in soil.

Aerial drift of small droplets has long been regarded as a problem of ULV application (Manikowski 1988), since more non-target animals are expose over a wider area, leading in turn to a greater incidence of secondary poisoning when these are eaten by predators. Thus, Thiollay (1989) found more carcasses within a 2km radius of a fenthion sprayed colony in Chad than inside the colony.

R. Allan observed (pers. comm., Elliott 2000) that larger droplets were produced when fenthion was first used in a 50:50 diesel mixture and this resulted in a much greater kill efficacy. Indeed, Willemse (2000) reported recently that greater efficacy was achieved by increasing the droplet size from a VMD of 90 to 180 microns (and a volume rate increased to 8.7 l/ha). This also means that debilitated quelea do not fly off and increase the area in which secondary poisoning of predators can occur.

2.2.2.1.4. Recommendations

As fenthion is very toxic to most bird species and other wildlife, an alternative avicide needs to be developed that is more specific for quelea. In addition, research is needed into methods that increase
the efficiency of knock down (perhaps the application of surfactants) so that secondary poisoning is reduced at least outside the sprayed area.

Non-target animals, particularly raptors, should be scared from colonies before control and kept away for two days following treatment while residue levels decline. In Zimbabwe, beaters were used to disturb reed beds containing many water birds and other species during the late afternoon before aerial spraying began. After spraying, no non-target birds were found in a search that yielded 26,400 dead quelea (Mundy and Packenham 1988).

Dead quelea should be removed from sprayed sites to prevent secondary poisoning. Protective garments would be needed for such operations and the carcasses should be buried or burnt in areas that are not environmentally sensitive.
Table 1  Non-target birds killed or debilitated after quelea control with fenthion. N.ind = number of individual birds, N.sp = number of species. * From database records of incidents reported during 1993-1999. ♣ From database records of incidents reported since the 1980s.

<table>
<thead>
<tr>
<th>Location</th>
<th>Birds of Prey poisoned</th>
<th>Other birds poisoned</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N.ind</td>
<td>N.sp</td>
<td>N.ind</td>
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<tr>
<td>Botswana</td>
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<tr>
<td>Kgatleng</td>
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<tr>
<td>Maun (7)</td>
<td>155</td>
<td>2</td>
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<tr>
<td>Tuli Block (1)</td>
<td>28</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Tuli Block (1)</td>
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<td>2</td>
<td>7</td>
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<tr>
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<td>Orange Free (2)</td>
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<tr>
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2.2.2.2. Explosives

Unfortunately, published data on the impact of controlling quelea with explosions or fire-bombs is as yet inadequate to make an informed judgement on the relative environmental costs compared with those attributable to fenthion. However, an unpublished evaluation has been made by the Directorate of Agricultural Land Resources Management in South Africa of 3,509 non-target kills recorded from 150 out of a total of 799 control operations and although non-target mortality is generally under-reported, its extent is similar at explosions and sprayings (L. Lötter, pers.comm.). In excess of 100 Black-shouldered Kites (*Elanus caeruleus*) were incinerated after one fuel-explosion in South Africa, which also polluted and destroyed the habitat (van der Walt 2000).

Meinzingen *et al.* (1989) considered that fire-bombing may be the least environmentally damaging control technique. Thus, only one bird (a Black-shouldered Kite) was found after 10 fire-bomb operations in Kenya (citing C. C. H. Elliott, pers.obs.) where eucalyptus trees were not permanently damaged, recovering within two months (citing F. Kitonyo, pers. comm.). In contrast, many birds of prey were sometimes killed in Nigeria at control explosions in acacia bush (W. Meinzingen, pers.obs.). Nevertheless, because incidents of wildlife poisoning have been frequently reported after chemical spraying, sometimes involving the death of hundreds of non-target birds (see bibliography), the South African authorities made a policy decision to use explosives where possible (L. Geertsma, pers.comm. in Elliott 2000). Half of all control operations currently use fire-bombs which, although more expensive than chemical control, kill more quelea and are thus more cost effective. The applicability of this method, though, is limited practically to smaller roosts of about 4 ha in eucalyptus and 2 ha in reed beds.

After a comparative cost analysis of control at roosts or breeding colonies with fenthion, explosives, repellency or mechanical destruction (by tractor), Garanito *et al.* (2000) concluded that mechanical control was by far the most cost-effective method at about 50 Rand/ha compared to some 3000 Rand/ha for explosives. But mechanical clearance will only displace quelea to neighbouring areas and, by destroying the habitat and undoubtedly contributing to the mortality of resident non-target species, it should only be used selectively in agricultural areas.

2.2.3. Control in ecologically sensitive areas

2.2.3.1 Aquatic Habitats

Although not intentionally sprayed on water, there is considerable evidence both from studies of the non-target impact of mosquito control in America and quelea control in Africa that some faunal assemblages in aquatic habitats are highly susceptible to fenthion. In particular, marked chronic effects have been noted on Crustacea. A study of sand fiddler crabs in simulated aerial spraying of ULV-grade fenthion (at 50% of the field rate application for mosquito control), found that larvae were no longer produced at the end of the third hatching cycle and the mortality of adult crabs at the surface had reached 20%. Three weeks after the final application, survival of adult crabs was only 3% (Schoor *et al.* 2000).

Acute effects have been found in smaller aquatic invertebrates; water fleas and shrimps have been identified as the most sensitive taxa, with reproductive impairment recorded at concentrations as low as 1 ng/l in the cladoceran *Daphnia pulex* (Roux *et al.* 1995). This study, investigating concentrations of fenthion in the aquatic environment after aerial spraying of quelea in South Africa, found marked effects on the survival and reproduction of *D. pulex* for long periods after spraying. Indeed, a protocol had previously been developed in relation to aerial control of quelea on the Orange River in South Africa (van Dyk *et al.* 1975). This protocol used declines in the total population density of crustacea and aquatic insects (Odonata, Ephemeroptera, Hemiptera, Coleoptera and Diptera) as a sensitive indicator of fenthion pollution. In effect, water sampling of population density acted as a proxy for residue analysis of the chemical. Detrimental effects of fenthion have also been reported on rheophilic benthic macroinvertebrates in the Orange River after quelea control (Palmer 1994).

Although fenthion is not highly toxic to amphibians, the brain cholinesterases of which are about 100 times more resistant to inhibitors than those of mammals, it has been shown experimentally that wild caught tadpoles can bio-concentrate sufficient fenthion (averaging 62x) to poison mallard ducks *Anas platyrhynchos* (Hall and Kolbe 1980). A summary of aquatic toxicity data, and a risk assessment for fenthion (JMPR WHO/FAO 1996), concluded that there was no direct risk to fish at the dose rate of 5 l/ha recommended for quelea control.

Assessing the environmental impact of controlling quelea with fenthion at wetland roosts, Keith *et al.* (1994) found that although amphibians and fish were not affected, populations of a variety of aquatic invertebrates (particularly dytiscid and notonectid beetles) were largely eliminated in an adjacent dam. However, some
recovery was observed within six days and eventual re-population would be expected. Unsurprisingly, given the large numbers of reports of non-target bird casualties already cited, the rich non-target bird life in these wetland roosts was damaged. Although the general abundance of waterfowl, waders and other birds appeared to be unaffected, in Kenya 61 birds of 14 species at Njoro dam and a further 22 birds of eight species at Gcheha were dead or severely debilitated. As is commonly the case, fenthion residues on dead birds were sufficient to cause secondary poisoning to scavengers and predators (Keith et al. 1994).

Fenthion used in mosquito control has been implicated in several avian kills in America (Smith et al. 1986). Zinkl et al. (1981) reported fenthion poisoning of wading birds where wind and wave action was thought to have concentrated poisoned food items. Severe mortality of birds following mosquito control of wet meadows with fenthion was linked to depressed brain cholinesterase activity from organophosphate poisoning among individuals, and subsequent declines in population numbers (DeWeese et al 1983). Even dead mammals (marmosets, rabbits and squirrels) were found despite their lower sensitivity to fenthion.

It is clear that quelea control with fenthion should not be carried out near water bodies. Indeed wetland habitats are not sprayed now in South Africa, owing to the established toxicity of fenthion to aquatic organisms (Bouwman and Lotter 1998), and at aquatic sites (mainly reed beds) control of quelea is now effected by fire-bombs.

2.2.3.2. Honey bee colonies

As it is an insecticide, fenthion should never be sprayed within the vicinity of bee colonies, particularly if they are managed for honey collection. Nine colonies of honeybees exposed to relatively low levels of fenthion (0.05 lb/acre) after a single aerial application lost their queens (Nunamaker et al. 1984).

2.2.4. Implications for use of quelea as a food source for the rural poor

Food shortages are prevalent in Africa and many arid areas prone to famine are occupied seasonally by concentrations of quelea in their millions that potentially provide a good source of food. Thus, colonies and roosts in the middle Awash River Valley of Ethiopia were estimated to contain some eight million quelea (Jaeger and Erickson 1980), providing about 37 tons of dried carcasses (Jaeger and Elliott 1989).

The nutritional content of quelea is high, with a greater calorific value than dried mammalian meat and around five times the protein found in staple cereals (Jaeger and Jaeger 1977). The most widespread and easiest method of harvesting quelea is the collection of nestlings from breeding colonies, which is most productive just before they fledge (as carried out in Zimbabwe, Jarvis and Vernon 1989). Some 3.5 tons of quelea chicks were harvested from a large colony in a wildlife conservancy by some 500 rural people (Pelham 1988) - a control method that can be cost effective locally as it is no burden on the exchequer and provides an important food supplement in drought areas.

Although rural people traditionally collect and eat quelea throughout Africa, even after spraying operations, commercial markets are only well developed in Cameroon and Chad where flying birds are intensively trapped by teams with hand-held, cast and large stationary nets (Mullié 2000). Trapping and selling quelea for food is an important economic activity in rural Chad and it was estimated that in one area around N’Djamena the income from some 7 million quelea sold per year comes to within 40% of the maximum capitalised crop loss experienced by farmers (Mullié 2000).

As a control method, however, even this substantial offtake of between 5-10 million birds will have no impact on a natural population of roughly 200 million quelea in the Chad basin, which in any case have a natural annual mortality of about 50% (Mullié 2000). Nevertheless, if trapping activities could be targeted at roosts responsible for depredations of crops then Mullié (2000) anticipates that the value of quelea as a natural bush product could at least match grain losses.

Collection of dead quelea for food after fire bombing is normally safe and, following such control in dense roosts in Kenya, local people were able to collect birds by the sackful (F. Kitonyo, pers. comm., in Meinzingen et al. 1989). This method could be further exploited for local provision of food if decoy or trap roosts, established by planting stands of Napier grass (Jarvis and La Grange 1989), could be fire-bombed instead of sprayed, as normally practised in Zimbabwe. However, combustion needs to be efficient as otherwise pollution occurs from unburnt fuel (van der Walt 2000).

Consumption of birds killed by fenthion is not recommended, as the Acceptable Daily Intake (ADI) is only 0.001 mg/kg of body weight (FAO/WHO 1980). Although allowing for a 100 fold margin of error, this would only permit consumption by an adult of 1 treated bird (Jaeger and Elliott 1989). Apart from being potentially
more dangerous to children and pregnant or nursing women, metabolites of fenthion appear to be more toxic than the active ingredient itself. Practically, to be eaten fresh, quelea would need to be collected soon after control and the risk of poisoning for people that gather the sprayed quelea is clearly higher than for consumers, but this remains unassessed (Manikowski 1988). Thus, to limit exposure to people, re-entry into colonies is not recommended for several days after spraying.

2.2.5. Recommendation

Development of EIA protocols

Objective: Given the lack of any systematic methodology for monitoring the environmental impact of quelea control on non-target wildlife, it is recommended that a follow-on project should develop and test suitable protocols in the field.

Methodology: In order to distinguish the effect of the pesticide application from other site and environmental variables, it will be necessary to develop survey methodologies that facilitate pre-spray and post-spray comparisons of the population abundance of non-target species. In addition, mortality rates arising from direct contact or secondary poisoning will need to be determined. Carcass searches and standard transect-survey techniques for assessing bird and reptile numbers could be adapted for statistical validity under operational conditions, as could sweep-netting, malaise, pitfall, and canopy traps for estimating the relative abundance of invertebrates following pesticide knockdown. In order to confirm that any vertebrate mortality can be attributed to organophosphate poisoning, exposure will need to be confirmed through the selective use of cholinesterase assays and residue analysis.

2.2.5. Bibliography

All references referring to fenthion recorded in the ENVIRON database at NRI are presented with a note of any particular non-target subject in Table 2.
Table 2. All references to fenthion from the ENVIRON database.

<table>
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<th>Author(s)</th>
<th>Year</th>
<th>Reference</th>
<th>Notes</th>
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</thead>
<tbody>
<tr>
<td>Anon</td>
<td>1984</td>
<td>Pesticides in the third world: not yet ready for the 'banned wagon'. The International Council for Bird Preservation Newsletter 6(3):5-7. (Rep)</td>
<td>birdgr, birdpr, birdin, birdom</td>
</tr>
<tr>
<td>Clark JR, Borthwick PW, Goodman LR, Patrick JM, Lores EM &amp; Moore JC</td>
<td>1987</td>
<td>Comparison of laboratory test results with responses of estuarine animals exposed to fenthion in the field. Environ.Toxicol.Chem. 6(2): 151-160. (Abs)</td>
<td>crustacea fish Mysisopsis shrimp Palaemonetes Penaeus minnow</td>
</tr>
<tr>
<td>Author(s)</td>
<td>Year</td>
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<tr>
<td>de Buijn J &amp; Hermens J</td>
<td>1993</td>
<td>Inhibition of acetylcholinesterase and acute toxicity of organophosphorous compounds to fish: a preliminary structure-activity analysis.</td>
<td>Aquat.Toxicol. 24(3,4): 257-274.</td>
</tr>
<tr>
<td>Hanazato T</td>
<td>1991</td>
<td>Pesticides as chemical agents inducing helmet formation in Daphnia ambigua.</td>
<td>Freshwater Biol. 26(3): 419-424.</td>
</tr>
<tr>
<td>Hart ADM</td>
<td>1990</td>
<td>The assessment of pesticide hazards to birds: the problem of variable effects.</td>
<td>Ibis 132(2): 192-204.</td>
</tr>
</tbody>
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**Abbreviations:**
- Lib: Library
- Abs: Abstract
- Rep: Report
- En: English
- Apic.: Apiculture
- Mammal: Mammal
- Human: Human
- Sediment: Sediment
- Water: Water
- Fish: Fish
- Guppy: Poecilia
- Rabbit: Rabbit
- Mollusca: Mollusca
- Crassostrea: Crassostrea
- Cyprinodon: Cyprinodon
- Insecta: Insecta
- Ischnura: Ischnura
- Damselfly: Ischnura
- Verticalis: Verticalis
- Cyprinidae: Cyprinidae
- Crustacea: Crustacea
- Daphnia: Daphnia
- Phalarope: Phalarope
- Sparrow: Sparrow
- Blackbird: Blackbird
- Passer: Passer
- Montanus: Montanus
- Branta: Branta
- Bernicla: Bernicla
- Daphnia: Daphnia
- Moina: Moina
- Paratya: Paratya
- Shrimp: Shrimp
- Polychaeta: Polychaeta
- Cyprinodon: Cyprinodon
- Variegatus: Variegatus
- Cyprinodontidae: Cyprinodontidae
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<th>Journal/Source</th>
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<tr>
<td>Kazanovskii, E.S.</td>
<td>1987</td>
<td>[Residues of organophosphorus insecticides in tissues of deer and their significance in meat inspection].</td>
<td>Veterinar'ya, 2: 86-69. (Russian) (Ab)</td>
<td></td>
</tr>
<tr>
<td>Jahnke, H.E.</td>
<td>1976</td>
<td>Tsetse flies and livestock development in East Africa.</td>
<td>Weltforum Verlag, Munchen, West Germany.</td>
<td>(Lib)</td>
</tr>
<tr>
<td>Kazanovskii, E.S.</td>
<td>1987</td>
<td>[Residues of organophosphorus insecticides in tissues of deer and their significance in meat inspection].</td>
<td>Veterinar'ya, 2: 86-69. (Russian) (Ab)</td>
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</tr>
<tr>
<td>1988</td>
<td>Mane U H &amp; Akarte S R</td>
<td>Toxicity of lebaycid to 3 freshwater lamellibranch molluscs in different seasons. Pesticides (Bombay) 22:51-56.</td>
<td>(Rep)</td>
<td>mollusc Indonai a_caraeuleus Lamellidens_corrianus</td>
</tr>
<tr>
<td>1985</td>
<td>McKenney, C.L., Matthews E, Lawrence DA &amp; Shirley MA</td>
<td>Effects of ground ULV applications of fenthion on estuarine biota. IV. Lethal and sublethal responses of an estuarine mysid.</td>
<td>J.Florida Ant-Mosquito Assoc. 56(2): 72-75. (Abs)</td>
<td>crustacea Mysidopsis</td>
</tr>
<tr>
<td>Author(s)</td>
<td>Year</td>
<td>Title</td>
<td>Journal/Book</td>
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<td>----------------------------------</td>
<td>--------------------</td>
</tr>
<tr>
<td>Shim, J.C. &amp; Self, L.S.</td>
<td>1973</td>
<td>Toxicity of agricultural chemicals to larvivorous fish in Korean rice fields.</td>
<td>Tropical Medicine, 15:123-130. (Rep)</td>
<td>fish</td>
</tr>
<tr>
<td>Tabaru, Y.</td>
<td>1985</td>
<td>Effects of ground UV applications of fenthion on estuarine biota. V. Responses of field and laboratory estuarine benthic communities.</td>
<td>J.Florida Anti-Mosquito Assoc. 56(2):76-81. (Abs)</td>
<td>aquatic-biota crustacea annelid chironomid</td>
</tr>
<tr>
<td>Tagatz ME &amp; Plaia GR</td>
<td>1985</td>
<td>Effects of ground UV applications of fenthion on estuarine biota. V. Responses of field and laboratory estuarine benthic communities.</td>
<td>J.Florida Anti-Mosquito Assoc. 56(2):76-81. (Abs)</td>
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<td>---------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Wiemeyer SN &amp; Sparling DW</td>
<td>1991</td>
<td>Acute toxicity of four anticholinesterase insecticides to American kestrels, eastern screech-owls and northern bobwhites. Environ.Toxicol.Chem. 10(9): 1139-1148. (Lib)</td>
<td>birdpr owl Otus-asio kestrel Falco birdom Colinus bobwhite</td>
<td></td>
</tr>
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</table>
2.2.5.1. References


2.3. Report on Output 2: A preliminary analysis of the potential for developing a statistical medium term quelea seasonal forecasting model based on sea surface temperature (SST) data and atmospheric indicators.

2.3.1. Introduction

Patterns of climate variability, notably the El Niño-Southern Oscillation (ENSO), have a measurable effect on the spatio-temporal distribution of animal and plant species (Glantz, 1996, Todd et al., 2002). Moreover, aspects of the climate system, including ENSO, may be predictable at seasonal time scales (Goddard et al., 2001): the coupling of the ocean and atmosphere provides the physical basis for seasonal forecasting of climate anomalies up to several months in advance (for reviews see Goddard et al. 2001, Murphy et al. 2001).

Seasonal forecasting is based on the notions that (a) the lower boundary forcing of the atmosphere, most notably the state of the ocean, commonly represented by sea surface temperatures (SST), evolves relatively slowly and as such is predictable (SSTs have a significant degree of persistence from one month to the next); and (b) that the atmosphere responds in a predictable manner to this component of forcing. Therefore, SSTs in one season can have impact on the atmosphere in following seasons, thereby providing the basis for probabilistic seasonal predictions of the behaviour of the atmosphere (often rainfall and/or temperature). Previous work has shown some success in seasonal forecasts of southern African climate (Goddard et al., 2001, Murphy et al., 2001).

That some animal species are sensitive to climate, and that in some regions climate is predictable at seasonal time scales, suggests that it might be possible to predict the population dynamics of these species. Todd et al. (2002) demonstrated how a relationship between populations of the Brown Locust Locustana pardalina, a major agricultural pest in Southern Africa and the subject of other CPP projects (e.g. ZA0407), and regional climate provides the basis for seasonal forecasts. An aim of this study, therefore, was to assess the potential for the development of a similar scheme for southern African Red-billed Quelea Quelea quelea lathamii. Specifically, the following questions are addressed: (a) what is the dominant periodicity of quelea populations? (b) To what extent is variability in quelea populations related to exogenous climatic factors? (c) To what extent is variability in quelea populations in southern Africa predictable from climatic indicators?

2.3.2. Methodology

2.3.2.1 Data on quelea populations

The data set, a long-term record of the spatio-temporal distribution of Quelea populations, was derived from the database developed at the Natural Resources Institute (NRI) under a previous CPP Project (R6823) from available archives. These included all reports of Quelea breeding colonies in Botswana, Malawi, Mozambique, Namibia, South Africa, Swaziland, Zambia and Zimbabwe. These data extend from the end of the nineteenth century to the present, but only those with complete data on dates and places of the observations from 1940 to the present were used in the following analysis. Whilst observations of quelea colonies are not quantitative measures of actual populations, they represent a qualitative index of populations and are the best available data source. The quelea data were transformed into the total number of counts of breeding colonies averaged over space (on a 1 degree grid) and time (monthly periods). These quantities were further averaged over time to produce long-term mean quantities, and over time and space to produce an annual index of quelea colonies averaged over southern Africa as a whole ($Q$) for each (hydrological) year (July-June). Most quelea colonies occur in the summer wet season months (December-March) and peak in January / February. Hereafter, the year cited refers to the year of the peak months (e.g. 2001 refers to the 2000/2001 year).

Although the quelea data represent the most comprehensive archive of actual quelea observations available, the observations were conducted on an ad hoc basis. There is no standardised, systematic reporting programme over the whole of southern Africa. It is likely therefore that the data are heterogeneous in space and time and contain errors and biases. It is important that these influences are removed from the data such that any influence of climate on inter-annual variability of quelea may be quantified. Two methods were employed to this end: (a) linear de-trending in which a linear trend is
removed leaving the residuals ($Q_{(t)}$); (b) the first difference of quelea colony numbers ($Q_{FD}$) at time $t$ (in years) is derived from:

$$Q_{FD(t)} = Q_{(t)} - Q_{(t-1)}$$

This is based on the assumption that the reporting methods should not vary greatly from one year to the next and thus $Q_{(t)}$ (Figure 2b; figures for this section are presented together at the end of the section) represents the departure in $Q$ from the previous year, and may be considered to be sensitive to exogenous factors including climate.

2.3.2.2 Climate data

The key climate variable selected for this study is rainfall, for a number of reasons: (a) high quality, long terms records of surface rainfall are available from a variety of independent sources; (b) rainfall is the major climatic determinant of vegetation distribution, determining the availability of food (grass seeds) for quelea colonies. Information on monthly rainfall was obtained from:

(a) The data-set of Hulme (1992), derived from interpolation of monthly rainfall totals from rain gauge observations. These data are distributed by the Climate Research Unit, University of East Anglia and are hereafter referred to as the CRU data. They provide monthly rainfall totals over land areas on a 2.5 degree latitude by 3.75 degree longitude grid and extend from 1900 to 1998.

(b) The NOAA Climate Prediction Center Merged Analysis of Precipitation (CMAP) product of Xie and Arkin (1997), which provides global (land and ocean) estimates of precipitation on a 2.5 degree latitude/longitude grid from 1979 to 2001. The estimates are derived from a combination of observations from surface rain gauges and satellite instruments.

(c) The University of Delaware rainfall product (UDEL), derived from land surface rain gauge observations, interpolated to a 0.5 degree grid, from 1900-1996

Monthly anomalies of sea surface temperature (SST) in the ‘Niño-3.4’ region of the central equatorial Pacific (5°N-5°S, 170-120°W) were used as an index of the state of the ENSO system. Global fields of key atmospheric and surface climatic variables, indicative of ocean boundary forcing (SST) and the atmospheric circulation (low level winds and surface pressure), were obtained from the National Center for Environmental Prediction Reanalysis data-set (Kalnay et al., 1996) as monthly data on a 2.5-degree global grid for the period 1948-present.

2.3.2.3. Methods

Statistical analysis of the historical record of quelea colony observations in southern Africa was undertaken to identify the characteristic spatial and temporal patterns (e.g. cyclicity). Subsequently, the extent to which inter-annual variability in quelea bird populations is sensitive to inter-annual variability in the climate of the region was established. The relationship of the space/time structure of quelea data with that of observed climate was assessed to determine the nature of the climatic controls on quelea activity. To quantify the relationship between quelea variability and climate, the standard techniques of correlation and composite analysis were used. The aim of composite analysis is to identify the characteristic climate associated with the major years of high and low quelea activity. The $Q$ (or $Q_{FD}$) data were ranked and the most extreme years of high and low values were identified. The number of years selected in these samples depended upon the length of the various climate data sets used. Mean anomalies of climate variables were then calculated for these samples at each grid cell. Thus, the degree to which quelea activity is (a) related to southern African climate and (b) predictable in the medium term from climate parameters was assessed.

2.3.3. Results

2.3.3.1 The mean distribution of reported quelea colonies
The mean annual distribution (Figure 1A) shows that quelea colonies are reported over a wide area of southern Africa, concentrated in northern South Africa, southern Zimbabwe and Eastern Botswana. The mean annual cycle (Figure 1B-G) shows that quelea colonies are more numerous and widespread in February, although there are no clear patterns of migration evident.

2.3.3.2 Temporal characteristics of the observed quelea record

The time series of quelea reports over southern Africa as a whole \(Q\) shows multi-decadal variability with prolonged periods of high quelea activity during the late 1950s to early 1970s and 1990s and low activity in the 1940s and mid 1970s to mid 1980s (Figure 2a). Spectral analysis of the \(Q\) time series revealed that a statistically significant peak occurs at 30 years, suggesting 30-year periodicity in quelea populations, reflecting the multi-decadal variability. However, confidence in this 30-year periodicity cannot be high due to the brevity of the record. There is also strong autocorrelation in the \(Q\) record with significant \((P<0.05)\) lags of 1, 2 and 3 years (but none in the first differenced data-set) and the partial autocorrelation coefficient for a lag of one year is also significant \((P<0.05)\). This multi-decadal variability and autocorrelation in the quelea data may reflect endogenous population dynamics.

2.3.3.3. Association of quelea population and climate

2.3.3.3.1. Area averaged quelea indices at the sub-continental scale

During the most recent decades from 1980-2001 (for which we have satellite estimates of precipitation) there are significant positive correlations between \(Q\), \(Q_{FD}\) and \(Q_{DT}\) and seasonal surface CMAP rainfall over an extensive region of southern Africa centred on eastern Botswana (Figure 3a). An index of the CMAP rainfall over the region 20°-30°S and 25°-30°E, broadly coincident with the mean quelea distribution (see Figure 1a), during December has a significant positive correlation with \(Q\) of 0.55 \((P<0.01)\). Equivalent correlations between \(Q_{FD}\) and \(Q_{DT}\) and precipitation are similar though slightly weaker. However these results include the years when no colony reports were received, so to test for the effects of rainfall on variation in colony numbers it is more appropriate to exclude the years when zero colonies were reported. Figure 4 illustrates the adjusted data, for which \(r = 0.50\) \((P<0.05)\), but as the trend may not be linear a non-parametric coefficient may be more appropriate: in this case Spearman’s Rank Correlation = 0.51 \((P<0.05)\).

For the period 1979-1998 correlations of \(Q\) (and \(Q_{FD}\) and \(Q_{DT}\)) and CRU surface rainfall are substantially weaker. Significant correlations are restricted to limited regions of Namibia and South Africa (Figure 3b). Similarly, weaker correlations between \(Q\) and CMAP occurred during 1979-1998. It appears, therefore, that much of the apparently strong correlation over 1979-2001 is associated with the major peaks in quelea reports in 1999 and 2000. There are no significant correlations between \(Q\) and CRU precipitation during the 1955-75 period of apparent high quelea activity. In addition, the \(Q\) time series was filtered using a 21-year running mean to isolate the low frequency variability component (dominated by periodicity near 30 years) and the high frequency variability component \((Q_{HF})\). Correlation of \(Q_{HF}\) with CRU and CMAP rainfall revealed no improvement in the strength of the associations.

Composites of precipitation during years of extreme high and low \(Q\) and \(Q_{FD}\) also reveal an inconsistent picture. Given the recent ‘trend’ in quelea reports since the late 1980s we favour the use of the \(Q_{FD}\) data for selection of extreme years. Recent years of high \(Q_{FD}\) are associated with above average rainfall over much of the northern parts of southern Africa including Botswana and Zimbabwe, but not over that part of South Africa (Figure 5a) where quelea reports are most common (Figure 1). However, over the long term (1940-1996) the extreme high \(Q_{FD}\) years over the entire record show minimal and inconsistent rainfall anomalies over southern Africa (Figure 5b).

It is possible to refine further the selection of years for composite analysis by combining those years in which there were both large absolute numbers of quelea colonies reported \((Q)\) and a large increase from the previous year \((Q_{FD})\). These years can be considered to represent conditions when quelea are assumed to be in significant numbers to breed well and take advantage of possibly favourable feeding conditions. However, the composite analysis of these years (1956, 1988, 1964 and 1968) again reveals inconsistent results, with minimal rainfall anomalies reported in the UDEL and CRU rainfall data (Figure 6a) but positive anomalies (up to about 70mm month\(^{-1}\)) identified from the NCEP rainfall product over the primary breeding area (Figure 6b).

2.3.3.3.2 Area averaged quelea indices at the regional scale
The sub-continental area-averaged quelea index \( Q \) was devised to quantify the quelea populations across southern Africa as a whole and to facilitate investigation of the relationship with the large-scale climate. However, given that the spatial distribution of quelea reports (Figure 1A) shows a number of key ‘hotspot’ regions it is appropriate to investigate these regions individually. This should also further minimise the influence of the non-standardised reporting procedures characteristic of the data set as a whole. It is likely that the reporting procedure is relatively consistent within individual localities, at least over shorter periods of a decade or so. Five key ‘hotspot’ regions were identified, based on the absolute magnitude of observations throughout the entire record (Figure 1).

Correlation and composite analysis again revealed that variability in quelea reports in these regions shows an inconsistent relationship with precipitation at the same locations. The results are too numerous to present in detail and we present only the results for one of these regions, the 1-degree grid cell centred on 25S, 29E, near the Springbok flats (SF) region in northern South Africa. The time series of \( Q \) at this location \( (Q_{SF}) \) (Figure 2c) is broadly similar to that for the subcontinental scale \( Q \) (Figure 2a) with quelea reports concentrated in the 1950s-60s and particularly the late 1980s onwards. \( Q_{SF} \) has significant correlations with CMAP rainfall in this region (CMAP(SF)) during the January to March period, with the strongest correlation \( (r = 0.63, P < 0.01) \) in February. If the zeroes are disregarded then \( r = 0.65 \) (\( P<0.02 \)) but with the non-parametric test Spearman’s rank correlation \( = 0.51 \), which is also significant \( (P<0.05; \text{one-tailed test}) \) (Figure 7). Correlations of CMAP(SF) with \( Q_{FD(SF)} \) and \( Q_{DT(SF)} \) are similar. However, the correlations are dominated by a single observation (year 2000) in which the highest quelea reports coincided with peak rainfall. If this observation is omitted then the correlation becomes non-significant. Furthermore, the correlation with CRU rainfall (for the cell centred on 25°S, 29°E) over the longer period (1940-1998) is not significant \( (r=0.06) \). Composite analysis of January-February CMAP rainfall over the SF region shows that the three highest \( Q_{FD(SF)} \) years (2000, 1997, 1991) experienced anomalous high rainfall \((+1.985 \text{ mm.day}^{-1})\) and that the three lowest years (2001, 1998, 1992) had lower than average rainfall \((-1.252 \text{ mm.day}^{-1})\), although the difference in mean rainfall between these two samples is not significant. Quelea report variability in the other ‘hotspot’ regions selected generally showed a weaker relationship to local rainfall.

2.3.3.3 Effects at a Distance (Global teleconnections)

The \textit{El Niño}-Southern Oscillation phenomenon is the dominant mode of climate variability in the tropics and is known to exert a substantial influence on climate variability in the southern Africa region (for a review see Mason and Jury, 1997). Despite the absence of an unambiguous relationship between the numbers of quelea colonies and rainfall it is possible that quelea populations are sensitive to a combination of climatic parameters of which rainfall may be only one. However, there are no significant correlations between the sub-continental or regional scale indices of quelea colony numbers and the \textit{Niño}3.4 index of Equatorial Pacific SSTs. Nor are there any significant correlations between the \( Q \) (or \( Q_{FD} \)) and de-trended SSTs anywhere in the Pacific region.

Climate variability in southern Africa is not affected solely by ENSO related variability in the ocean-atmosphere system, but to variability in the adjacent ocean basins unrelated to ENSO and to the rather more unpredictable chaotic internal dynamics in the mid-latitude regions (Todd and Washington, 1999). Correlations of \( Q \) (and \( Q_{FD} \)) with SST yielded little evidence of a systematic influence from the adjacent oceans. The absence of significant results is of course consistent with the absence of a clear relationship between observed quelea colonies and rainfall.

2.3.4. Conclusion

There is some evidence that in recent decades the number of quelea colonies is sensitive to climate variability and that wet conditions during the austral summer months favour increases in quelea populations. However, these associations are relatively weak and there is a lack of consistency in the relationship between quelea and climate (a) over space and time, and (b) between different rainfall data-sets. For this reason, the link between quelea and climate is not sufficiently clear or well defined to form the basis for seasonal predictions of quelea populations. The results are nonetheless important for a number of reasons. First, they point to the need for a standardised observed data-set. Second, they highlight the complexity of quelea population dynamics, which are likely to be related to both endogenous controls and migration patterns. Finally, although we could find no consistent evidence of a link between climate and quelea that is usable for seasonal forecasting, we cannot discount the existence of a more complex and possibly non-linear relationship. Further work is required in these regards if the relationship with climate is to be fully understood and quantified.
2.3.5. Acknowledgements

Images were provided by the NOAA-CIRES Climate Diagnostics Center, Boulder Colorado (from their Web site at http://www.cdc.noaa.gov/) and by the KNMI Climate Explorer (http://www.climexp.knmi.nl).

2.3.6. References


Figure 1. The mean distribution of reported breeding Quelea colonies (mean colonies per year) in Southern Africa. (a) annual averages in the Okavango, NE Botswana / SE Zimbabwe; the Springbok flats, S. Mozambique and the northern Free State; (b-g) monthly averages: November (b) December (c) January (d) February (e) March (f) April (g). The boxes in (a) refer to the location of ‘hotspot’ regions of peak Quelea colony reports.
Figure 2 a-c. Time series of (a) annual total Quelea reports over Southern Africa ($Q$) (b) first differences of annual total Quelea reports over Southern Africa ($Q_{FD}$) (c) annual total Quelea reports over the Springbok Flats, South Africa (24.5-25.5S, 28.5-29.5E) ($Q_{SF}$).
Figure 3. Correlation coefficients between the annual total of Quelea reports over Southern Africa (Q) and (a) December-February gridded CMAP rainfall estimates and (b) December-February CRU rainfall.
Figure 4. Relationship between December CMAP rainfall (mean mm per day, averaged over the region 20°-30°S, 25°-30°E) and annual total Quelea reports over Southern Africa ($Q$) over the period 1980-2001, omitting years with no reports.
Figure 5. Composite rainfall anomalies from (a) CMAP data (mm day$^{-1}$) during recent years of high quelea activity (high $Q_{FD}$ values) in 1994-1999; (b) UDEL estimates during years of high Quelea activity (first difference values $Q_{FD}$) in the long-term data-set 1940-1996 (cm month$^{-1}$).
Figure 6. Composite rainfall anomalies during years of both high annual total Quelea ($Q$) and annual Quelea first difference values ($Q_{FD}$) (a) from the UDEL product (cm.month$^{-1}$) (b) from NCEP reanalysis rainfall (mm month$^{-1}$).
Figure 7. Scatterplot of February CMAP rainfall (mean mm per day for the 2.5° grid cell centred on 25°S, 29°E) and annual total Quelea reports (omitting zeroes) for the 1-degree grid cell centred on the Springbok Flats area 25°S, 29°E ($Q_{(SF)}$). The point for the year 2000 is the one in the top right of the diagram with highest values on both axes.
Figure 8. Correlation of annual total Quelea reports in Southern Africa ($Q$) with global seasonal SSTs at approximately 1 month lag.