CROP PROTECTION PROGRAMME

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

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FINAL TECHNICAL REPORT

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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 US$45 million (Elliott 1989), equivalent to US$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

Elliott, C. C. H. (1989) The quelea as a major problem in a food-deficient continent. pp. 90-99 in P. J. Mundy & M. J. F. Jarvis (eds) *Africa's Feathered Locust*. Baobab Books, Harare, Zimbabwe.

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/quel) 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.

Outputs

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 (Willemse 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, Acrididae, 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 exposed 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.
[1]Mostly Parathion. (n) number of sites examined, if reported.

Location	Birds of Prey poisoned *N.ind*	*N.sp*	Other birds poisoned *N.ind*	*N.sp*	*Reference*
Botswana					
Kgatleng	Eagles and buzzards		?	?	Da Camara Smeets 1987
	Eagles, kites, owls				Simmons 1987
Maun (7)	155	2			Liversedge 1990
Tuli Block (1)	28	2			McWilliam 1996
Tuli Block (1)	9	2	7	5	McWilliam 1996
Francistown	Large Nos.				Tyler 1998
	70	3			Bruggers *et al.* 1989
Kenya					
Mt. Kenya	41	9	>100		Thomsett 1987
Galana (2)	6	2	44	17	Bruggers *et al.* 1989
Njoro			61	14	Keith *et al.* 1994
Gicheha			22	8	Keith *et al.* 1994
Senegal					
Senegal			?	>7	Mullié *et al.* 1991
Senegal R. (2)	2	1	45	>10	Mullié *et al.* 1999
Somalia					
Various (7)			17	50	Becker & Amir 1993
South Africa					
Transvaal[1] (16)	63	3	409	68	Tarboton 1987
Soetdoring	6	1	9	6	Colahan & Ferreira 1989
Nylsvlei	>62 species - raptors, owls, water birds & passerines				Trendler *et al.* 1992, Yeld 1993, Verdoorn 1999
Dwaalboom	>150	>10	?	>4	McAllister 1993, Yeld 1993 Verdoorn 1999
Country-wide	7	3	>107	3	Bouwman & Lötter 1998
Orange Free (2)	3	?			van der Walt 2000
Country-wide	3,509 (1674 from sprays and 1835 from explosions) Non-target kills from 150/799 control operations				Lötter & Kieser 2001, Lötter & Powell 2003
Sudan					
Gedarif	>100	?			Meinzingen *et al.*1989
Tanzania					
Shinyanga	1	1	15	11	Meinzingen *et al.* 1989
Zimbabwe					
			Waterfowl		La Grange & Jarvis 1977
Dichwe			157	42	Talbot 1977
Bindura			23	54	Jarvis & La Grange 1989
Country-wide	267 Non-target kills of 26 species from 11 control ops.				Stiles 1995
Aisleby			Crowned Crane		Townsley 2000
Country-wide	26	6	>1817	>82	Couto 2002♣

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 50Rand/ha compared to some 3000R/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 organophospate 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.

Abbasov, T.G.	1985	[Effect of organophosphorus pesticides on laying hens]. Veterinarya 1: 63-43. (Russian) (Ab).	bird chicken
Alekseev, A.P. & Abbasov, G.G.	1983	[Dynamics of accumulation of sulfidofos (fenthion) in cattle after treatment for tick infestation]. In: Veterinarnaya entomologiya i akarologiya (Ed. by A.A. Nepoklonov), pp. 290-292. (Russian) (Ab).	cattle
Ali, A.M. & Abdel-Gawad, K.H.	1980	The impact of aerial chemical treatment for the control of cotton pests on field rodents. In: Proceedings of the 1st Conference of the Plant Protection Research Institute, Cairo, 1980. Vol. 3. Cairo, Plant Protection Research Institute, pp 275-278.	mammals
Ames RG, Narveson RS, Mengle DC & Womeldorf D	1988	Cholinesterase depression in California municipal and mosquito abatement district pesticide applicators. J.Am.Mosq.Cont.Assoc. 4(4): 539-541. (Rep)	human mammal
Anon	1984	Pesticides in the third world: not yet ready for the 'banned wagon'. The International Council for Bird Preservation Newsletter 6(3):5-7. (Rep)	birdgr, birdpr, birdin, birdom
Arzone A & Patetta A	1987	Research on the action of flucythrinate, propiconazole pyridafenthion and quinalphos on honeybees. Apic.Mod. 78(5) 179-186. (Abs) Italian	bees pollinators honeybees
Baunok, I.	1984	Analysis of airborne pesticides at selected sites in South Africa. South African Journal of Science, 80:277-279. (Rep)	air
Beiswenger RE	1990	The status and recovery of the endangered Wyoming toad, Bufo hemiophrys baxteri. 75th Ann.Meeting of Ecol.Soc.America, Conf.paper Bull.Ecol.Soc.Am. 71(2 Suppl.) 88-89. (Abs)	amphibia toad Bufo-hemiophrys
Belisle AA & Swineford DM	1988	Simple, specific analysis of organophosphorus and carbamate pesticides in sediments using column extraction and gas chromatography. Environ.Toxicol.Chem. 7: 749-752. (Rep)	sediment
Borthwick PW & Stanley RS	1985	Effects of ground ULV applications of fenthion on estuarine biota. III. Response of caged pink shrimp and grass shrimp. J.Florida Anti-Mosquito Assoc. 56(2): 69-72. (Abs)	crustacea shrimp Palaemonetes Penaeus
Borthwick, P.W., Clark, J.R., Montgomery, R.M., Patrick, J.M. & Lores, E.M.	1985	Field confirmation of a laboratory-derived hazard assessment of the acute toxicity of fenthion to pink shrimp, Penaeus duorarum. Aquatic Toxicology & Hazard Assessment: Eighth Symposium. Soc. for Testing Materials, Philadelphia. pp. 177-189(Rep)	shrimp, crustaceae, Penaeus_duorarum, fish
Bruggers RL, Jaeger MM, Keith JO, Hegdal PL, Bourassa JB, Latigo AA & Gillis JN	1989	Impact of fenthion on non-target birds during Quelea control in Kenya. Wildl.Soc.Bull. 17: 149-160. (Rep)	raptors birdpr eagle goshawk falcon owl insects foliage millet
Chacko MJ, Bhat pk, Rao LVA, Singh MBD, Ram CSV	1983	Influence of some contact insecticides on adults of Cryptolaemus montrouzieri. Proc.Second Ann.Symp.Plantation Crops PLACROSYM II, 1979, Kerala, India. pp.258-262. (Abs)	predator Coccinellidae Cryptolaemus
Chacko MJ, Singh MBD & Ram CSV	1983	Effect of repeated applications of fenthion on larval stages of Coccophagus cowperi, a parasite of Coccus viridis on coffee. Proc.Second Ann.Symp.Plantation Crops. PLACROSYM II, 1979 pp.294-297. (Abs)	parasitoid Coccophagus
Clark JR, Borthwick PW, Goodman LR, Patrick JM, Lores EM & Moore JC	1987	Comparison of laboratory test results with responses of estuarine animals exposed to fenthion in the field. Environ.Toxicol.Chem. 6(2): 151-160. (Abs)	crustacea fish Mysidopsis shrimp Palaemonetes Penaeus minnow
Clark JR, Middaugh DP, Hemmer MJ, Clements BW, Dukes JC & Rathburn CB,	1985	Effects of ground ULV applications of fenthion on estuarine biota. I. Study design and implementation. J.Florida Anti-Mosquito Assoc. 56(2): 51-62. (Abs)	aquatic-organisms
Clark, J.R., Borthwick, P.W., Goodman, L.R., Patrick, J.M.,Jr., Lores, E.M. & Moore, J.C.	1987	Effects of aerial thermal fog applications of fenthion on caged pink shrimp, mysids and sheepshead minnows. Journal of the American Mosquito Control Association, 3:466-472. (Rep)	crustacea fish marine-water

Costa LG, Galli CL & Murphy SD (Eds.)	1987	Toxicology of pesticides: Experimental, clinical and regulatory perspectives. Meeting, Riva del Garda, Italy, 1986. NATO ASI(Advance Science Institute) Series H: Cell biology, vol 13 (Lib)	mammal human
Cripe CR, O'Neill EJ, Woods ME, Gilliam WT & Pritchard PH	1989	Fate of fenthion in salt-marsh environments. I. Factors affecting biotic and abiotic degradation rates in water and sedimant. Environ.Toxicol.Chem. 8(9): 747-758. (Abs)	sediment water
de Bruijn J & Hermens J	1993	Inhibition of acetylcholinesterase and acute toxicity of organophosphorous compounds to fish: a preliminary structure-activity analysis. Aquat.Toxicol. 24(3,4): 257-274. (Lib)	fish guppy Poecilia
de Luca d'Alessandro E & Pasquarella	1988	Antiparasitic agents: organophosphorus compounds. Clin.Terap. 126:(6) 435-444. (Abs)	mammal
De Weese, L.R., McEwen, L.C., Settimi, L.A. & Deblinger, R.D.	1983	Effects on birds of fenthion aerial application for mosquito control. Journal of Economic Entomology, 76(4):906-911. (Rep)	bird, birdom, birdin, birdgr blackbird phalarope sparrow
Eichelberger, J.W. & Lichtenberg, J.J.	1971	Persistence of pesticides in river water. Environmental Science and Technology, 5(6):541-544. (Rep)	water
Emteres, R., Abdelghani, A.A. & Anderson, A.C.	1986	Subacute toxicity of fenthion to New Zealand white rabbits (Oryctalagus cunticulus). Environmental Technology Letters, 7:27-30.	rabbit mammal
Estenik, J.F. and P.F. Federle	1975	The susceptibility of an adult damselfly, Ischnura verticalis, to selected insecticides Ohio J.Sci. 75(2):81, 1975 (Rep)	damselfly, Ischnura_verticalis, Insecta
Farage-Elawar M & Francis B M	1987	Acute and delayed effect of fenthion in young chicks. J.Toxicol.Environ.Hlth. 21: 455-469. (Rep)	chicks bird
Ferguson F (2)	1988	Long term effects of systemic pesticides on honey bees. in: Bee keeping in the year 2000. Proc. Second Aust.& Internat. Beekeeping Congr., July 1988, Queensland, Australia. pp.137-141. (Apic.Abs.42/2) Lib	honeybees
Fletcher, M.R. & Hardy, A.R.	1983	Pesticides and the environment. In: M.A.F.F. Pesticide Science Reference Book, 252(83):39-49. (Rep)	insects, honeybees, birds, mammals
Garrido, A.	1986	Feasibility of integrated pest management for citrus orchards in Spain. In: Cavalloro, R. & Di Martino, E. (eds) Integrated pest management in citrus groves. A.A. Balkema, Rotterdam, pp 549-556.	predators, parasitoids, natural_enemies
Haas, W. & Beck, P.	1979	Zum Fruhjahrzug palaarktischer Vogel uber die westliche Sahara. Journal fur Ornithologie, 120(3):237-246. (En) (Rep)	birdom
Hale RC	1989	Accumulation and biotransformation of an organophosphorus pesticide in fish and bivalves. Mar.Environ.Res. 28(1-4): 67-72. (Abs)	mollusca Crassostrea-gigas fish Cyprinodon-variegatus
Hall, R.J. & Kolbe, E.	1980	Bioconcentrations of organophosphorus pesticides to hazardous levels by amphibians. Journal of Toxicology and Environmental Health, 6:853-860. (Rep)	amphibians, birds, mammals
Hanazato T	1991	Pesticides as chemical agents inducing helmet formation in Daphnia ambigua. Freshwater Biol. 26(3): 419-424. (Abs)	aquatic-invert crustacea Daphnia
Hanazato, T. & Kasai, F.	1995	Effects of the Organophosphorus insecticide Fenthion on phyto- and Zooplankton communties in experimental ponds. Environ.Pollut. 88(3):293-298. (AB). (Rep).	phyto and zooplankton in ponds
Hart ADM	1990	The assessment of pesticide hazards to birds: the problem of variable effects. Ibis 132(2): 192-204. (Rep)	birds sparrow Passer-montanus geese Branta-bernicla
Hatakeyama S & Sugaya Y	1989	A freshwater shrimp (Paratya compressa improvisa) as a sensitive organism to pesticides. Environ.Pollut. 59(4): 325-336. (Lib)	shrimp crustacea Paratya shellfish Moina Daphnia biomonitor

Hatakeyama S, Shiraishi H & Sugaya Y	1991	Monitoring of the overall pesticide toxicity of river water to aquatic organisms using a freshwater shrimp Paratya compressa improvisa. Chemosphere 22(1-2): 229-235. (Rep)	bioassay crustacea shrimp Paratya
Hennessey MK, Nigg HN & Habeck DH	1992	Mosquito (Diptera:Culicidae) adulticide drift into wildlife refuges of the Florida Keys. Environ.Entomol. 21(4): 714-721. (Lib)\	insects Papilio Anaea Strymon plant cactus Belocephalus
Huber SJ, Poschenrieder G & Wallnofer PR	1980	Effect of pesticides and the corresponding metabolites on growth and respiration of some soil microorganisms. J.Plant Dis.Prot. 87 (9): 533-545. (Rep) German	soil_biota bacteria fungi Pseudomonas Nocardia Alternaria Fusarium
Hunt KA, Bird DM, Mineau P & Shutt L	1991	Secondary poisoning hazard of fenthion to American kestrels. Arch.Environ.Contam.Toxicol. 21(1): 84-90. (Lib)	birdpr Falco
Hunt KA, Bird DM, Mineau P & Shutt L	1992	Selective predation of organophosphate-exposed prey by American kestrels. Anim.Behav. 43(6): 971-976. (Abs)	birdpr kestrel Falco
Hurley S & Fenton MB	1980	Ineffectiveness of fenthion, zinc phosphide, DDT, and two ultrasonic rodent repellers for control of populations of little brown bats (Myotis lucifugus). Bull.Environ.Contam.Toxicol. 25:503-507. (Rep)	mammal bats Myotis
Isom BG	1989	Biomonitoring. J.Water Pollut.Control Fed. 61(6): 1117-1121. (Rep)	water sediment biomonitoring
Jahnke, H.E.	1976	Tsetse flies and livestock development in East Africa. Weltforum Verlag, Munchen, West Germany.	land
Jindal R & Singh J	1989	Toxicity of pesticides to the productivity of a freshwater pond. Indian J.Environ.Health 31(3): 257-261. (Abs)	water aquatic-ecosystem biota
Kazanovskii, E.S.	1987	[Residues of organophosphorus insecticides in tissues of deer and their significance in meat inspection]. Veterinariya, 2: 86-69. (Russian) (Ab).	deer mammal
Keith JO, Ngondi JG, Bruggers RL, Kimball BA & Elliott CCH	1991	Fenthion contamination and effects in wetland roosts treated for bird control in Kenya. Final Report, FAO Crop Protection Project, KEN/85/009 26pp. + 9 Tables & 2 diagrams	birdpr raptors water plants aquatic-inverts fish insects amphibia
Keith JO, Ngondi JG, Bruggers RL, Kimball BA & Elliott CCH	1994	Environmental effects on wetlands of Queletox applied to ploceid roosts in Kenya. Environ.Toxicol.Chem. 13(2): 333-341.	birdpr raptors water plants aquatic-inverts fish insects amphibia
Kikuchi T, Kamel M, Okubo S & Yasuno M	1992	[Effects of the insect growth regulator methoprene and organophosphorus insecticides against non-target aquatic organisms in urban drains.] Jap.J.Sanit.Zoology 43(2): 65-70. (AbsRevAgEnt81/2) Japanese	water Isopoda Asella Ephemeroptera Cloeon chironomid mollusc Physa
Kilincer N, Cobanoglu S & G rkan MO	1990	[Side effects of some pesticides on beneficial arthropods, Trichogramma turkeiensis Kostadinov and Phytoseiulus persimilis A.H. in the laboratory.] Proc. of 2nd Turkish National Congress of Biol. Control, Izmir, Turkey 1990. pp.273-281.(Turkish)	predators insects Trichogramma Phytoseiulus
Kling, D.B.	1986	[Pathology of the ovaries of Sarotherodon leucostictus after intoxication with lebaycid]. Zeitschrift fur Angewandte Zoologie, 73(1):75-92. (In German) (AB)	fish
Kling, D.B.	1986	[Reproductive activity and reproductive success in Sarotherodon leucostictus after parental exposure to lebaycid]. Zeitschrift fur Angewandte Zoologie, 73(2):145-157. (In German) (AB).	fish
Koeman, J.H., Balk, F. and Takken, W.	1980	The environmental impact of tsetse control operations: a report on present knowledge. FAO Animal Production and Health Paper 7 Rev.1. FAO, Rome. 71 pp. (Rep)	mammals birdom reptiles fish amphibia insects crustacea arachnids
Kreitzer JF & Fleming WJ	1988	Effects of monocrotophos and fenthion on discrimination, acquisition and reversal in northern bobwhite, Colinus virginianus. Environ.Toxicol.Chem. 7(3): 237-240. (Abs)	bird bobwhite Colinus_virginianus
Krishnamurthy, V.V. & Sree_Ramulu, U.S.	1982	Studies on rice bran and rice bran oil. VI Pesticides accumulation in the rice bran. Madras Agric. Journal 69:820-821 (Rep)	

Leuck, D.B. & Bowman, M.C.	1968	Residues of fenthion and five of its metabolites: their persistence in corn and grass forages. Journal of Economic Entomology, 61(6):1594-1597	
Lewis DL, Baxter GT, Johnson KM & Stone MD	1985	Possible extinction of the Wyoming toad, Bufo hemiophrys Baxteri. J.Herpetol. 19(1): 166-168. (Abs)	amphibia toad Bufo
Ludwig GM	1993	Effects of trichlorfon, fenthion, and diflubenzuron on the zooplankton community and on production of reciprocal-cross hybrid striped bass fry in culture ponds. Aquaculture 110(3/4): 310-319. (Lib)	aquatic-inverts zooplankton fish bass Rotifera crustacea copepods
Macek, K.J. & McAllister, W.A.	1970	Insecticide susceptibility of some common fish family representatives. Transactions - American Fisheries Society, 1:20-27. (Rep)	fish bioassay
Mallet VN, Dunguay M, Bernier M & Trottier N	1990	Evaluation of HPLC - UV for the multi-residue analysis of organophosphorus pesticides in environmental water. Internat.J.Environ.Anal.Chem. 39(3): 271-279. (Abs.WRA23/12) Lib	water
Mane U H & Akarte S R	1988	Toxicity of lebaycid to 3 freshwater lamellibranch molluscs in different seasons. Pesticides (Bombay) 22:51-56. (Rep)	mollusc Indonaia_caraeleus Lamellidens_corrianus
Mane, U.H., Akarte, S.R. & Kulkarni, D.A.	1986	Acute toxicity of fenthion to freshwater lamellibranch mollusc, Indonaia caeruleus (Prashad 1918), from Godavari River at Paithan - a biochemical approach. Bulletin of Environmental Contamination and Toxicology, 37:622-628.	mollusc
Mani M & Krishnamoorthy A	1990	Further studies on the safety of pesticides to Anagyrus dactylopii Hym.(Encyrtidae) and Cryptolaemus montrouzieri (Coleoptera:Coccinellidae). J.Biol.Control 4(2): 80-85. (Abs)	parasitoid Anagyrus predator Cryptolaemus Coccinellidae
Manikowski S	1988	Aerial spraying of Quelea. Trop.Pest Manage. 34(2): 133-140. (Rep)	bird predators mammal reptile
Maru S (1)	1990	Outflow of pesticides from a paddy lysimeter as affected by the water solubility. J.Pestic.Sci. 15(3): 385-394. (Rep)	soil-water water
Mathavan S (Ed.)	1985	Proceedings of the first Indian symposium of odonatology. Madurai Kamaray Univ., Madurai. 240pp.	aquatic-inverts Odonata Bradinopyga Tholymis Brachythemis
Mathavan, S. & Jayakumar, E.	1987	Long-term effects of pesticides (fenthion & temephos) on growth and fecundity of an aquatic bug Laccotrephes griseus. Ind. J. Experimental Biol. 25:48-51 (Rep)	aquatic_invertebrates, insect, bug, hemiptera, Laccotrephes
McIlroy JC	1985	Observations on the sensitivity of some Australian birds, and the feral pig, to the organophosphorus insecticide, fenthion ethyl. Australian Wildlife Res. 12(2): 331-335. (Abs)	birds
McKenney CL & Matthews E	1990	Alterations in the energy metabolism of an estuarine mysid (Mysidopsis bahia) as indicators of stress from chronic pesticide exposure. Mar.Environ.Res. 30(1): 1-19. (Abs.Aq7/6)	crustacea Mysidopsis
McKenney CL, Matthews E, Lawrence DA & Shirley MA	1985	Effects of ground ULV applications of fenthion on estuarine biota. IV. Lethal and sublethal responses of an estuarine mysid. J.Florida Ant-Mosquito Assoc. 56(2): 72-75. (Abs)	crustacea Mysidopsis
McKenney, C.L.	1986	Influence of the organophosphate insecticide fenthion on Mysidopsis bahia exposed during a complete life cycle. I Syrvival, reproduction, and age-specific growth. Dis. Aquat. Org. 1: 131-139 (Rep)	crustaceae, Mysidopsis_bahia, shrimp
Mohamed AI, Nair GA, Abbas HL & Kassam HH	1992	Effects of pesticides on the survival, growth and oxygen consumption of Hemilepistus reaumuri Audouin & Savigny 1826 (Isopoda:Oniscidea). Trop.Zool. 5(2): 145-153. (Lib)	crustacea woodlouse Isopoda arthropod Hemilepistus
Moore JC, Lores EM, Clark JR, Moody P, Knight J & Forester J	1985	Effects of ground ULV applications of fenthion on estuarine biota. II. Analytical methods and results. J.Florida Anti-Mosquito Assoc. 56(2): 62-68. (Abs)	water sediment fish shrimp
Muley D V & Mane U H	1987	Pesticide induced alterations in the rate of oxygen uptake of freshwater gastropod, Viviparus bengalensis (Lamarck). J.Anim.Morphol.Physiol. 34: 171-176 (Rep).	mollusc aquatic_invert.

Murugadass S, Jaykumar E & Krishnan M	1988	Toxicity of fenthion and chlorpyrifos on the predatory behaviour of Rantra filiformis (Hemiptera:Nepidae). Pollut.Res. [India] 7(1/2): 71-76. (Abs)	predator Hemiptera Rantra aquatic_inverts
Nunamaker, R.A., Harvey, A.J. & Wilson, W.T.	1984	Inability of the honey bee colonies to rear queens following exposure to fenthion. Am. Bee J. 124:308-309 (Rep)	bee, insect
O'Keeffe M, Eades JF & Strickland KL	1983	Fenthion residues in milk and milk products following treatment of dairy cows for warble fly. J.Sci.Food Agric. 34(2): 192-197. (Lib)	milk
O'Neill EJ, Cripe CR, Mueller LH, Connolly JP & Pritchard PH	1989	Fate of fenthion in salt-marsh environments. II.Transport and biodegradation in microcosms. Environ.Toxicol.Chem. 8(9): 759-768. (Abs)	sediment
Pope, G.G. & Ward, P.	1972	The effects of small applications of an organophosphorus poison, fenthion on the weaver-bird Quelea quelea. Pesticide Science, 3(2):197-205.	general
Powell, G.V.N.	1984	Reproduction by an altricial song bird the red-winged blackbird in fields treated with the organophosphate insecticide fenthion. Journal of Applied Ecology, 21(1):83-96. (AB,Lib)	birdom red_winged-blackbird
Rajukkannu K & Doraisamy P	1985	Insecticide residues in rice. Madras Agric.J. 72(4): 203-206. (Abs)	plant crop
Raman K & Uthamasamy S	1984	Effect of insecticide application on rice growth. Internat.Rice Res.News. 9(2): 20. (Lib)	crop rice
Regupathy, A., Habeebullah, B., Kuttalam, S., Balasubramanian, M., & Manavalan, R.S.A.	1982	Dissipation of dimethoate, methyl demeton and fenthion in mango fruits. International Journal of Entomolgy, 1:7-9.	
Samuel SD, Venkatesulu K & Chacko MJ	1981	Influence of insecticides on Cryptolaemus montrouzieri. 1. Effect of residues of Cythion, Ekalux, Lebaycid and Metacid on grub. J.Coffee Res. 11(4):126-128. (Abs)	predator Cryptolaemus
Schafer, E.W., Jr.	1984	Potential primary and secondary hazards of avicides. In: D.O. Clark (ed.) Proceedings 11th Vertebrate Pest Conference, pp 217-222. (Rep)	birds, mammals
Selvanayagam M & Vijaya J	1989	Degradation of persistent insecticides by aquatic bacteria as sole source of carbon. J.Environ.Biol. 10(4): 399-407. (Abs.Ecol91/1) Lib	water bacteria Pseudomonas Bacillus
Seuge J & Bluzat R	1983	Chronic toxicity of three insecticides (carbaryl, fenthion, lindane) in the freshwater snail Lymnaea stagnalis. Hydrobiologia 106: 65- .	mollusc Lymnaea
Shim, J.C. & Self, L.S.	1973	Toxicity of agricultural chemicals to larvivorous fish in Korean rice fields. Tropical Medicine, 15:123-130. (Rep)	fish
Smith, G.J., Spann, J.W. & Hill, E.F.	1986	Cholinesterase activity in black-crowned night-herons exposed to fenthion-treated water. Archives of Environmental Contamination and Toxicology, 15:83-86. (Rep)	bird birdpi black-crowned night-heron
Subramaniam, T.R., Thirumurthi, S., Asaf Ali, K., Thangavel, P. & Shanmugam, A.	1974	Residues of fenthion and carbaryl in sweet potato tubers. South Indian Horticulture, 22(3):137. (Rep)	plants, sweet_potato, crop
Sun F, Wang SC & Ku TY	1984	Effects of degradation in toxicity of insecticides on the survival and reproductive rate of maize weevils. Plant Prot.Bull.(Taiwan) 26(1): 55-62. (Abs) Chinese	
Tabaru, Y.	1985	[Studies on chemical control of a nuisance chironomid midge (Diptera:Chironomidae) part 3. Japanese Journal of Sanitary Zoology, 36(4): 303-308. (Japanese) (Ab).	fresh-water annelid oligochaete gastropod
Tagatz ME & Plaia GR	1985	Effects of ground ULV applications of fenthion on estuarine biota. V. Responses of field and laboratory estuarine benthic communities. J.Florida Anti-Mosquito Assoc. 56(2):76-81. (Abs)	aquatic-biota crustacea annelid chironomid
Tagatz, M.E.	1986	Some methods for measuring effects of toxicants on laboratory- and field-colonized estuarine benthic communities. In: Cairns J. Jr. (ed.) Community toxicity testing, ASTM STP 920. American Society for Testing and Materials, Philadelphia. pp 18-29.	mollusca, annelida, crustacea, otherinverts

Takken, W.F., Balk, F., Jansen, R.C. & Koeman, J.H.	1977	Observations on side effects of insecticides used in experimental applications against tsetse flies in Upper Volta. Netherlands Agricultural University, Wageningen, Holland, 45 pp. (Lib)	birdom, fish, insects, crustacea, birdin
Takken, W.F., Balk, F., Jansen, R.C. & Koeman, J.H.	1978	The experimental application of insecticides from a helicopter for the control of riverine populations of Glossina tachinoides in West Africa. VI. Observations on side effects. PANS, 24(4):455-466. (Rep)	birdom, birdin, fish, crustacea, insects, arachnids
Thirumurthi, S., Palaniswamy, P., Subramaniam, T.R. & Kannammal,S.	1973	Effect of aerial spraying on non-target organisms inhabiting rice swamps. Madras Agric. J. 60: 873-874 (Rep)	invertebrates_aquatic, insect, crustaceae, amphibia, fish
Thompson CQ & Tucker JW	1989	Toxicity of the organophosphate insecticide fenthion, alone, and with the thermal fog carriers, to an estuarine copepod and young fish. Bull.Environ.Contam.Toxicol. 43(5): 789-796. (Lib)	fish crustacea Copepoda seatrout menhaden Acartia-tonsa
Thompson, A.R. and Edwards, C.A.	1974	Effects of pesticides on nontarget invertebrates in freshwater and soil. In: Pesticides in Soil and Water. Soil Science Society of America, Inc., pp 341-386. (Rep)	air, soil, insect, insectlarvae, otherinverts, molluscs
Tietze NS, Hester PG, Hallmon CF, Olson MA & Shaffer KR	1991	Acute toxicity of mosquitocidal compounds to young mosquitofish, Gambusia affinis. J.Am.Mosq.Control Assoc. 7(2): 290-293. (Abs)	fish Gambusia
Uzakova, G.U.	1985	[Toxicity of sulfidofos (fenthion) for fowls]. Veterinariya, 4: 58-60. (Russian) (Ab).	bird chicken
Uzakova, G.U.	1985	[I. Effect of sulfidofos (fenthion) on the development of chick embryos. II Toxicity of sulfidofos (fenthion) for laying hens]. Dezinfektsiya i sanitariya produktov zhivotnogo proiskhozhdeniya, pp 149-156. (In Russian) (AB).	bird chicken
Van Dyk, L.P., Greef, C.G. & Brink, J.J.	1975	Total population density of Crustacea and aquatic Insecta as an indicator of fenthion pollution of river water. Bulletin of Environmental Contamination and Toxicology, 14:426-431. (Lib)	insects, insectlarvae, crustacea
Vassiliou, G., Fytizas, R. & Ioannou, A.	1985	Toxic effects on the mosquito-fish from insecticide air-sprays against Dacus oleae. Med.Fac.Landbouww.Rijsuniv. Gent 50/3a: 917-924 (Rep)	fish, mosquito-fish, Gambusia
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Wiemeyer SN & Sparling DW	1991	Acute toxicity of four anticholinesterase insecticides to American kestrels, eastern screech-owls and northern bobwhites. Environ.Toxicol.Chem. 10(9): 1139-1148. (Lib)	birdpr owl Otus-asio kestrel Falco birdom Colinus bobwhite

2.2.5.1. References

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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_{DT}); (b) the first difference of quelea colony numbers (Q_{FD}) at time t (in years) is derived from:

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

This is based on the assumption that the reporting methods should not vary greatly from one year to the next and thus Q_{FD} (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 (http://climate.geog.udel.edu/~climate/html_pages/README.ghcn_clim.html)

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 ($P<0.05$, 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 $mm.day^{-1}$) and that the three lowest years (2001, 1998, 1992) had lower than average rainfall (-1.252 $mm.day^{-1}$), 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.

2.3.3.3.3 Effects at a Distance (Global teleconnections)

The *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 *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

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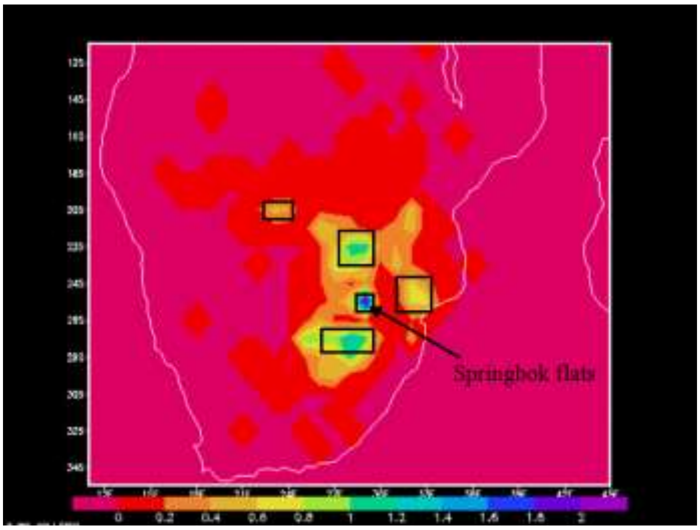

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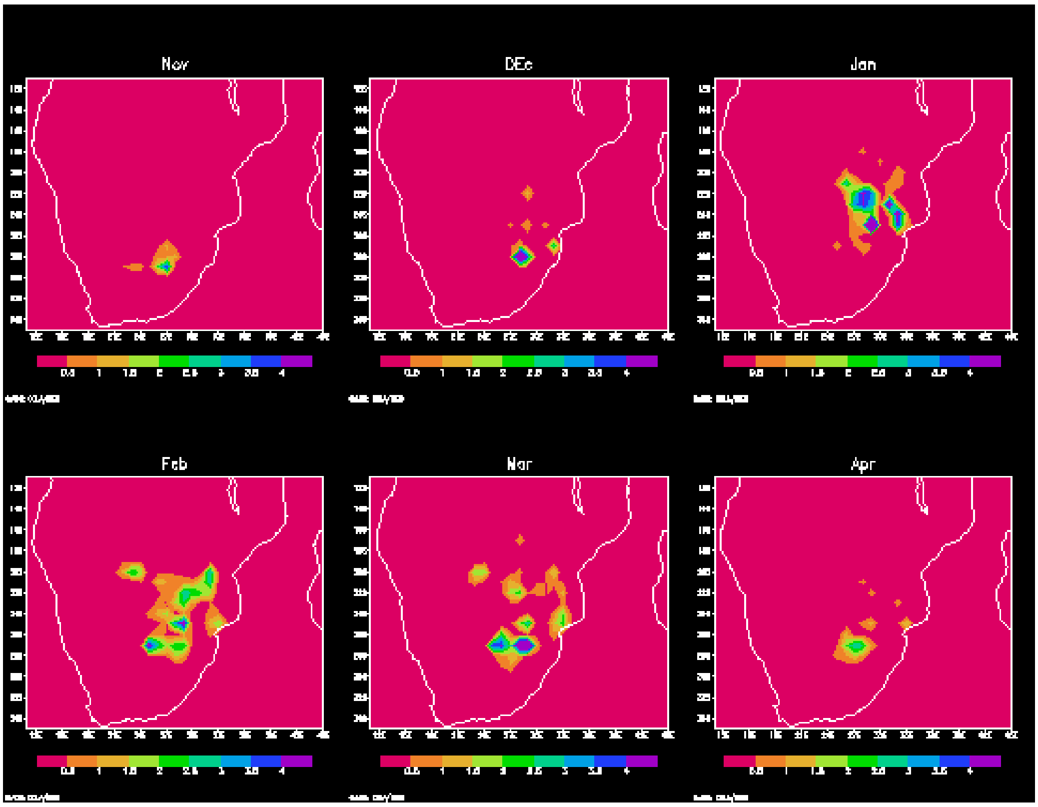


Figure 1. The mean distribution of reported breeding Quelea colonies (mean colonies per year) in Southern Africa. (a) annual averages in the Okavango, NE Botswana / SE Zimbabwe; the Springbok flats, S. Mozambique and the northern Free State; (b-g) monthly averages: November (b) December (c) January (d) February (e) March (f) April (g). The boxes in (a) refer to the location of 'hotspot' regions of peak Quelea colony reports.

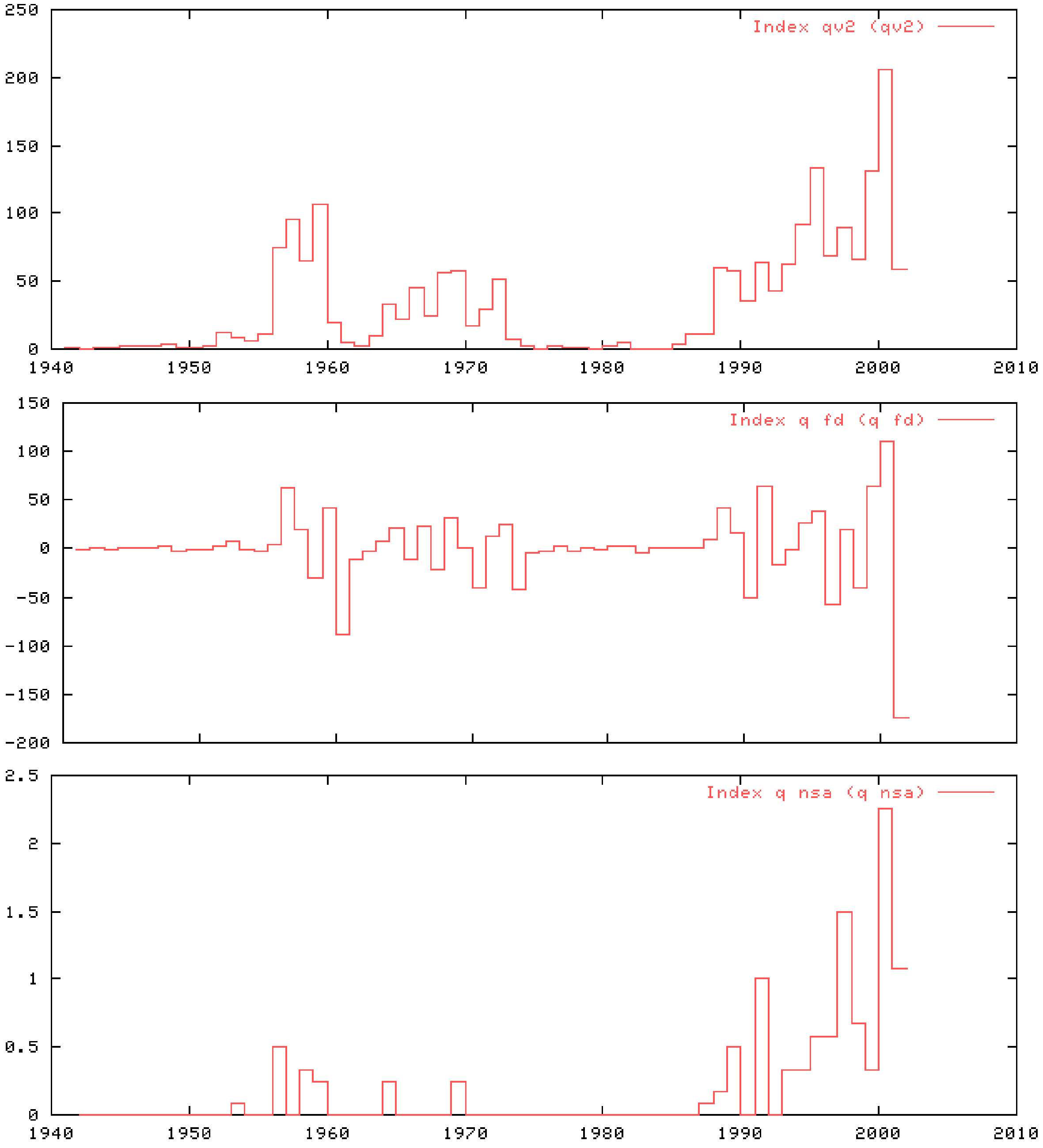


Figure 2 a-c. Time series of (a) annual total Quelea reports over Southern Africa (*Q*) (b) first differences of annual total Quelea reports over Southern Africa (Q_{FD}) (c) annual total Quelea reports over the Springbok Flats, South Africa (24.5-25.5S, 28.5-29.5E) ($Q_{(SF)}$).

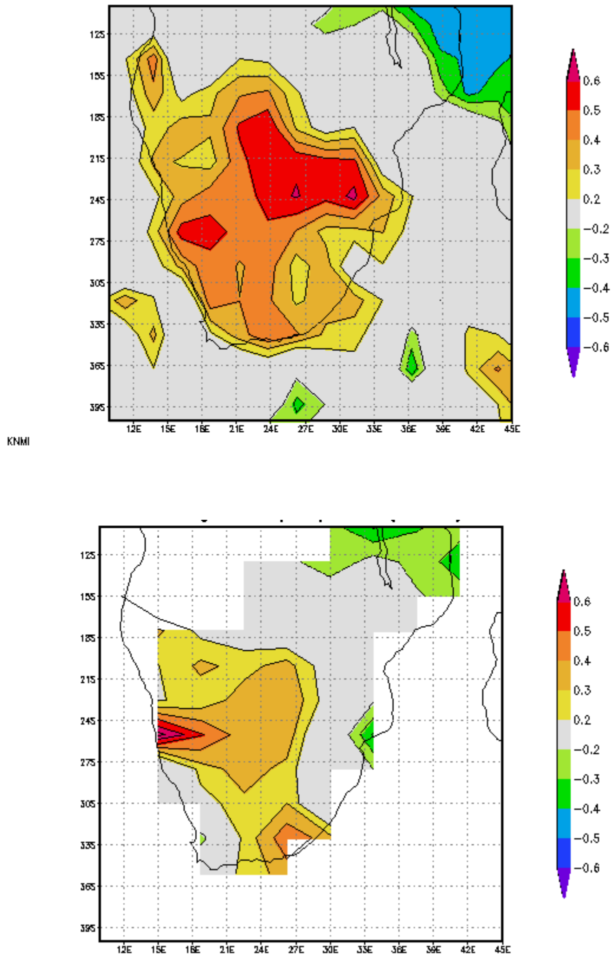


Figure 3. Correlation coefficients between the annual total of Quelea reports over Southern Africa (*Q*) and (a) December-February gridded CMAP rainfall estimates and (b) December-February CRU rainfall.

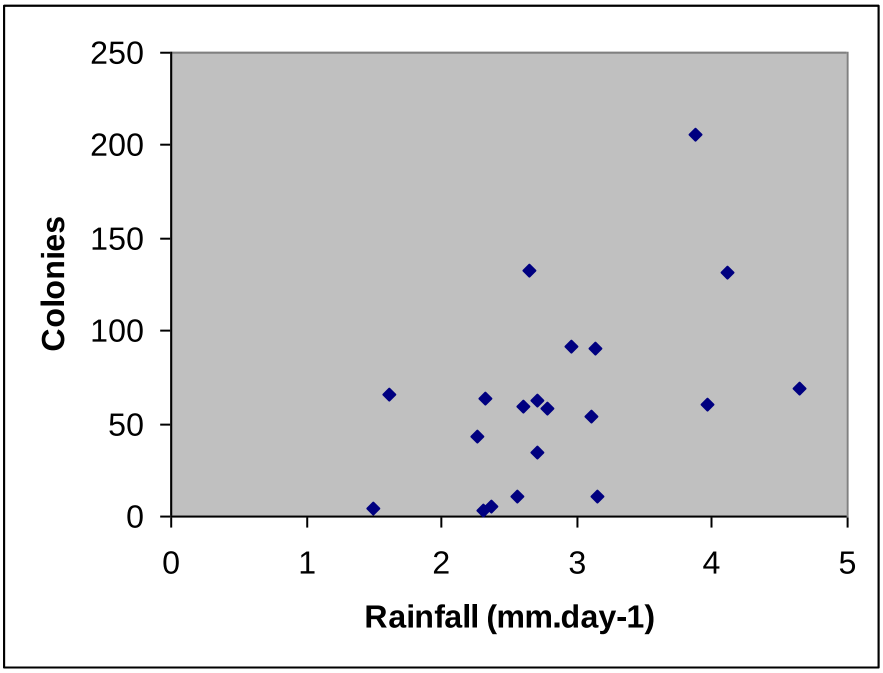
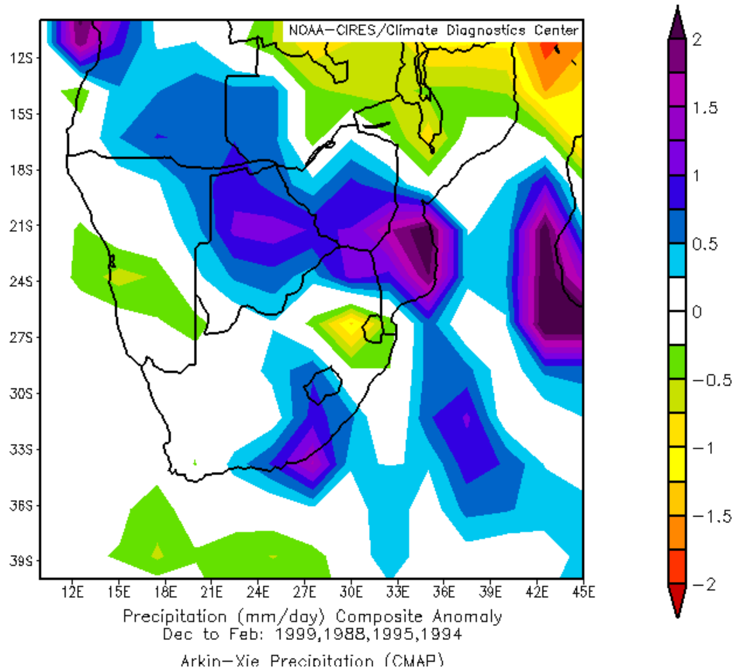


Figure 4. Relationship between December CMAP rainfall (mean mm per day, averaged over the region 20°-30°S, 25°-30°E) and annual total Quelea reports over Southern Africa (*Q*) over the period 1980-2001, omitting years with no reports.



(a)

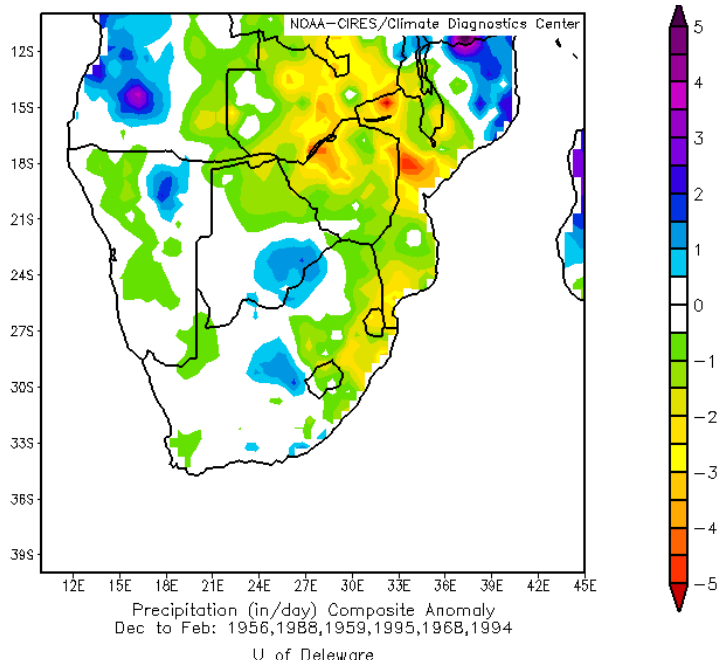


Figure 5. Composite rainfall anomalies from (a) CMAP data (mmday^{-1}) during recent years of high quelea activity (high Q_{FD} values) in 1994-1999; (b) UDEL estimates during years of high Quelea activity (first difference values Q_{FD}) in the long-term data-set 1940-1996 (cm month^{-1}).

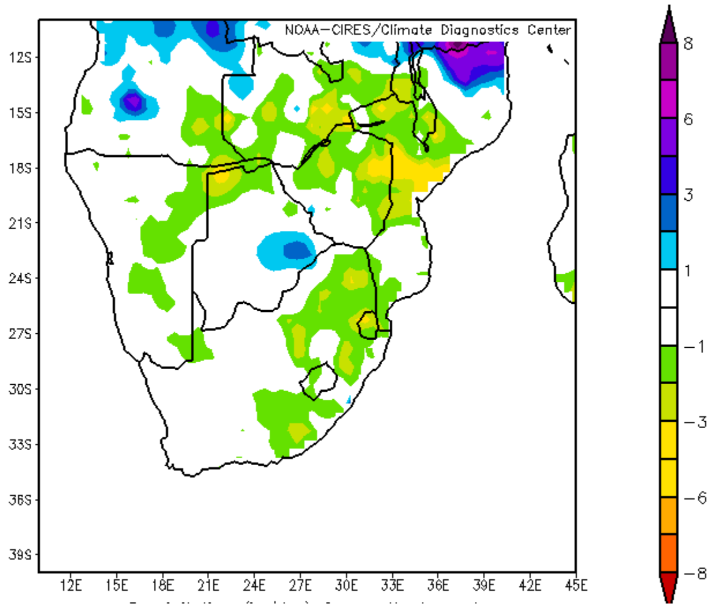


Figure 6a

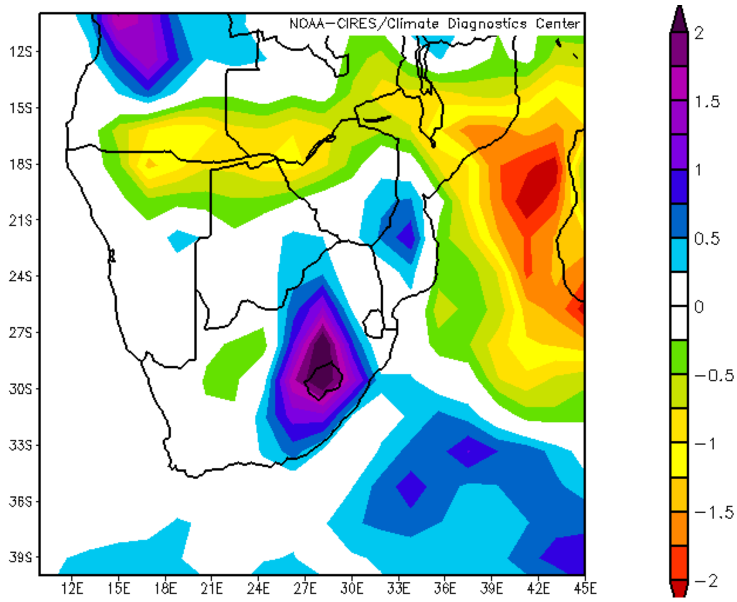


Figure 6b

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 ($mm\ month^{-1}$).

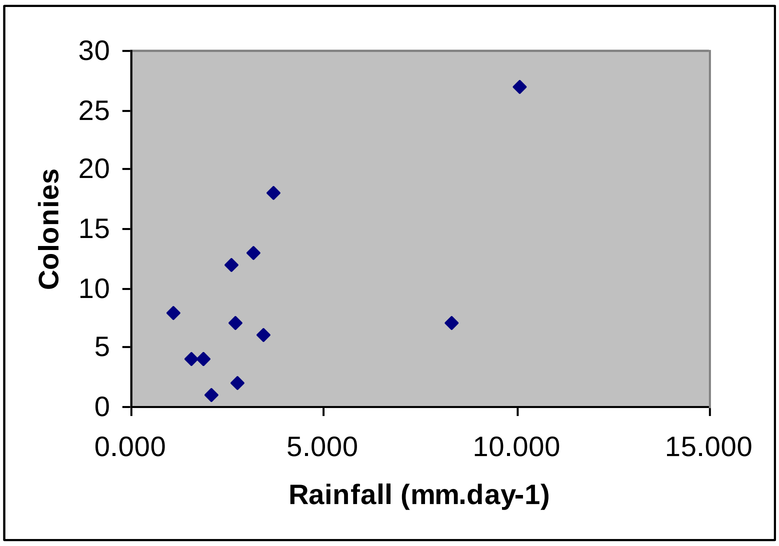


Figure 7. Scatterplot of February CMAP rainfall (mean mm per day for the 2.5° grid cell centred on 25°S, 29°E) and annual total Quelea reports (omitting zeroes) for the 1-degree grid cell centred on the Springbok Flats area 25°S, 29°E ($Q_{(SF)}$). The point for the year 2000 is the one in the top right of the diagram with highest values on both axes.

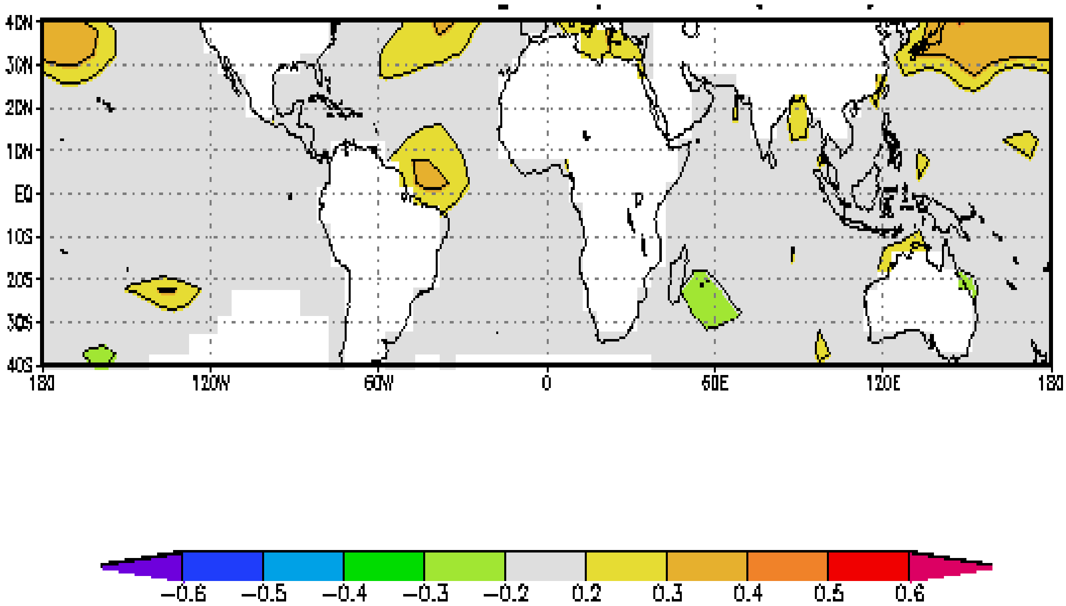


Figure 8. Correlation of annual total Quelea reports in Southern Africa (*Q*) with global seasonal SSTs at approximately 1month lag

2.4. Report on Output 3: Increased knowledge of the key relationships between environmental factors and quelea migrations and breeding activities.

Migrations and breeding by Quelea are stimulated by rain. The “early rains migrations” start after enough rain has fallen to initiate germination of grass seeds, rendering them unavailable as food to the birds. Sudden large scale departures after the first such rains in November and December in southern Africa have been noted in Zimbabwe (Plowes 1953, 1955, Dallimer 2001, this report), Zambia (A.J. Tree, pers. comm.) and Botswana (Ward & Jones 1977). That the threshold of rainfall needed to cause sufficient widespread germination of seeds, and to stimulate quelea populations to initiate their early-rains migrations, is about 60-70 mm was confirmed from rainfall data associated with instances when early rains migrations were observed (Table 2.4.1).

Table 2.4.1. Threshold of Rainfall Required for Early-rains Migration.

Taxon	Country	Site	Date	Rainfall (mm)	Source
Q. q. lathamii	Botswana	Samedupi	November 1971	66.5	Ward & Jones (1977)
Q. q. intermedia	Tanzania	Arusha	November 1969	69.0	Ward & Jones (1977)
Q. q. intermedia	Tanzania	Makuyuni	Nov/Dec 1970	68	Ward & Jones (1977)
Q. q. lathamii	Zimbabwe	Bulawayo	23 November 1997	67	This report
Q. q. lathamii	Zimbabwe	Norton	18-19 November 1998	61.9	Dallimer (2001)

Information on the thresholds of rainfall required to permit breeding by quelea is more complicated as this requires sufficient rainfall to have fallen and sufficient time to have elapsed since the first germination by the grass seeds. Luder (1985) devised a set of criteria for deciding when a season had started (a minimum of 35mm falling in three days and no continuous dry spell of two weeks within a month of onset) and recommended that evidence of quelea breeding should be sought five weeks after the criteria had been met. Data in Gaston (1973) and Gaston & Lamarque (1976) suggest that *c.*300mm of rain is sufficient for the development of annual grasses and subsequently the seeds (and insects) needed to permit colony formation but that, depending on soil type, as little as 200mm or as much as 450mm of rain might be necessary. Data collated during this project support the contention that breeding can take place only if more than 240mm of rain have fallen and at least six weeks have passed since the threshold for the start of the early rains migration has been exceeded. For instance, the 60mm threshold had been exceeded by the end of November 1971 at Maun in Botswana where a further 354mm fell during December 1971 and January 1972, after which many colonies were located from 10 February onwards (Jones & Ward 1976). Further evidence for the 240mm figure was derived from recent observations at two sites in Namibia. A site at Alwyn Farm (19º18’S, 18º51’E) was studied for four seasons (1995-96 to 1998-99), and a second site at Wilde Farm (19º10’S, 18º45’E) was also studied during 1996-97, 1997-98 and 1998-99 with the following results:

1995-96

Alwyn Farm

Although 103 mm of rain fell between 7 September and 5 December 1995, less than 60 mm fell within any 10-day period and germination is presumed not to have occurred. This quantity was therefore ignored. Germination was then presumed to have occurred when 72 mm fell between 2 and 11 January

1996, but the cumulative total of this amount plus the succeeding rainfall reached only 234 mm by the time the rains ceased on 28 February. No queleas bred, probably because although there had been grass seed germination this was followed by insufficient rain to sustain grass growth.

1996-97

Alwyn Farm

Only 41 mm fell in November 1996, followed by a month's dry gap. This initial amount was therefore ignored. During the three days 25-27 December 1996, 99 mm then fell, when germination was presumed to have occurred. A total of 321 mm fell by the end of January, exceeding the 240 mm threshold, but presumably in too short a period (4-5 weeks) for new grass to have fully set seed. Conditions suitable for breeding should have occurred by mid-February (420 mm total). The final total for the season was 553 mm, but no queleas bred. Although germination and subsequent grass growth was adequate, the queleas presumably short-stopped elsewhere where rainfall had also been good. By the time queleas might have arrived from any previous breeding attempts elsewhere, conditions suitable for breeding would have been over.

Wilde Farm

The threshold amount was not exceeded before late December (only 40 mm between 11 November and 25 December). However, 65 mm then fell in 12 days (102 mm in 13 days (70 mm in 2 days)) between 26 December and 8 January), sufficient to cause germination. 300 mm had fallen by 28 January and 525 mm by the end of the rains on 29 March. No queleas bred, probably because although germination and subsequent grass growth was good the queleas short-stopped elsewhere, as suggested for Alwyn Farm (see above).

1997-98

Alwyn Farm

In September 1997 23 mm fell, which can be ignored. In late October 1997, 91 mm fell during two weeks which might have caused germination but there followed a dry 6-week gap, so that this initial rainfall should be ignored and any germination probably died back. In the 2 weeks to 4 January 96 mm then fell (82 mm in 10 days) and good germination should have occurred, but the ensuing rainfall was sporadic in small amounts, totalling only 199 mm by the end of the rains on 2 April. No queleas bred probably because, despite adequate germination, the total rainfall was below the 240 mm threshold necessary to sustain grass growth.

Wilde Farm

Rainfall sporadic in small amounts; insufficient rain in any 10-day period between September and the end of December to cause germination. No rain at all January – March. No queleas bred as there had been insufficient rain for grass seed germination or, if germination had occurred patchily, it was insufficient for subsequent growth.

1998-99

Alwyn Farm

Insufficient rainfall (24 mm) in October-November 1998 to cause germination. In 10 days at the end of December, 59 mm fell, probably sufficient to cause germination because it had been preceded by 24 mm in the second week of December. A total of 330 mm had fallen by 28 March, exceeding the 240mm threshold. Queleas bred. A colony was founded on *c.*1 April (chicks 5-7 days old on 22/23 April), possibly by queleas that had just finished previous breeding attempts elsewhere (e.g. in the Okavango delta area of Botswana).

Wilde Farm

Insufficient rainfall fell in any 10-day period from early November to mid-December to cause germination. However, 74 mm fell between 28 December 1998 and 1 January 1999, and the cumulative total by 25 March was 371 mm, thus exceeding the 240 mm threshold. Queleas bred, with a colony founded at the end of March (abandoned chicks on 30 April).

To summarise, in 1995-96 and 1997-98, the rainfall was below 240mm and no queleas bred. Although when this threshold was exceeded in 1996-97 no queleas bred either, in the two instances when quelea did breed at these sites in Namibia, more than 240m of rain had fallen.

It had been hoped when this output was proposed that the outcome of the research described under output 2 (above) would have been more informative and have led to an interplay between initial hypotheses and newly derived relationships to improve the model described in the following section (2.5). It was also hoped that further insights would have been gained on means of predicting quelea occurrences in the medium-term, perhaps by using predictions of ENSO events. However, no unequivocal relationships were apparent.

Further insight into the effects of environmental conditions on quelea migrations has been obtained from results of running the model described in section 2.5. In particular, patterns of rainfall in 2001/2002 suggested that, following initial simultaneous precipitation in both the NW and SE extremities of the birds' geographical range, the two main areas where the 60mm threshold had been exceeded expanded towards each other. This left only a zone across Namibia, Botswana and Zimbabwe where there would still have been seed on the ground available for the birds. This suggests that birds from the north-western and the south-eastern dry season quarters would have converged and probably met in the remaining dry zone rather than being parts of separate migratory systems. If this convergence does occur, it would account for the results of DNA analyses conducted during the previous project (R6823) showing that genetic variability of *Q. q. lathamii* within southern Africa showed no association with their geographical origin (Dallimer 2001, Dallimer *et al*. 2003).

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2.5. Report on 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.

2.5.1. Introduction and Model Rationale

A model was created to predict where and when populations of the Red-billed Quelea bird *Quelea quelea lathamii* could breed. It is intended that forecasts from it will help control teams in southern Africa to identify where and when crops are likely to be damaged and to target their operations against nesting colonies more effectively. Hitherto, such planning has been difficult, as quelea birds are long distance migrants, moving up to 2,500 km 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 move to areas where the seeds have yet to germinate. When rain reaches these areas, the birds are forced to move again, usually returning in "early-rains migrations" in the direction whence they came. By this time sufficient rain needs to have fallen to exceed another threshold within a restricted period for the new grass to have produced fresh seed. Breeding may then commence. Over the following 3-4 months the birds then undertake further, previously unpredictable, "breeding migrations" to areas elsewhere wherever adequate rainfall will permit them to breed. It is the young, newly fledged, birds that cause most damage to agriculture.

Given the dependence of quelea activities on rainfall, a model was devised that uses spatio-temporal information on rainfall throughout southern Africa derived from satellite imagery. The model is intended to provide only short-term predictions using information on rainfall alone as real-time inputs. The initial spatial scale chosen at the start of the development phase in 2001 was 1º X 1º squares with time steps of 1 week, but during 2002 the resolution of the model was improved to squares of 0.5º X 0.5º. The model accumulates rainfall data throughout a quelea season (September – May), starting at the beginning of September (calendar week 36, model week 1). For each square, the following questions are asked at the end of each week:

What was the total rainfall during the current week?
What was the total rainfall during the current week plus the previous week?
What was the total rainfall during the current week plus the previous 4 weeks?

The rainfall was estimated as 1 hour of Cold Cloud Duration (CCD cold cloud duration at –38°C or below) being equivalent to 3mm of rain.

Using the above data, the current version of the model (used in 2002/2003) then invokes the following algorithms:

Algorithm 1:
IF the total rainfall during the current week in a particular square OR if the total rainfall during the current week plus the previous week in a particular square > 60mm, THEN the season starts in that square. This is because the threshold of 60mm (see section 2.4 above) has been exceeded and the early rains migration would have been stimulated. Breeding cannot begin until 6 weeks have elapsed after the season has started, as this time is needed for the germinating plants to set seed, provided that the next threshold (240mm, see section 2.4 above, making the 300 in total necessary for breeding) has also been exceeded. To signal the start of the season in a square, it is changed from white to green on the output.

Algorithm 2:
IF > 6 weeks have elapsed since the season started in a square AND the total rainfall during the current week plus the previous 5 weeks in that square > 240mm (additional to the 60mm already fallen, giving overall total of 300mm necessary for breeding) THEN breeding is possible in that square. On the output, a square is changed from green to red. When breeding has started, quelea will be expected to remain in a square for 6 weeks (5 weeks breeding, 1 week of post-breeding recovery to regain condition).

Algorithm 3:
IF 6 weeks have elapsed since breeding was first possible in a square, it is now less suitable for the initiation of breeding. On the output, a square is changed from red to yellow. Such squares are now less suitable for initiation of breeding but breeding birds may persist there.

When the season is likely to have ended at the end of May, the system is stopped. Alternatively, if all squares have passed both the 60mm and the 240mm thresholds and 6 weeks have elapsed since the week when the latter occurred, the system will also be stopped. This is when there will be no further squares available to become suitable and all previously suitable ones are no longer suitable for the initiation of breeding.

2.5.2. Operation and calibration of the quelea rainfall model

The model was programmed in a Microsoft EXCEL spreadsheet in which worksheet cells represented every degree square for 2001/2002 or every 0.5 X 0.5 of a degree square, for 2002/2003, of the southern African region. The cell value is given by a formula which implements the model criteria described above. The model was run each week of the 2001/2002 and 2002/2003 seasons and seven days of CCD values were input for every run.

Each week, CCD files were acquired from the Bradford University Remote Sensing Ltd (BURS) Primary Data User System (PDUS, for Meteosat satellite download -Eumetsat) installed at NRI, moved to a data analysis computer, and converted to Image Data and Analysis (IDA) format (DOS satellite data analysis software). The files were displayed in the Windows Display (WinDisp) image processing software and this was used to produce a Comma Separated Value (CSV) file of the maximum value within each degree square. This file was read into EXCEL to form the basic CCD data file for each week. A flow diagram of the procedures is given in Figure 9.

The CCD values were plotted for each day of the week and summed for the current week's values. The previous seven weeks' values were also required and were stored on separate worksheets. The previous week's model was then opened in EXCEL and a macro was run that deleted the CCD data from the model and copied each week's CCD and model data into the previous week's worksheet. The current week's CCD data were then copied into the 'empty' model and these were saved as the new model for the current week. A bit-map was created from the EXCEL output and this was pasted into the web-site.

The values of variables used in the above final version of the model were chosen for the runs in 2002/2003 in the light of calibration exercises that involved changing the values of different parameters to achieve the best fit with the observed events in 2001/2002. The best agreement with results for 2001/2002 was achieved with a value for the second threshold of 210mm. However, owing to operational problems no rain data had been collected for the first three weeks of September 2001 and some loss of rain data also occurred during January and February 2002. Thus, the 210 threshold may have provided the best fit only because it would have compensated in part for these losses. Therefore, for the 2002/2003 runs, the threshold was raised to 240mm, which is in accordance with the results described in section 2.4, and also reflects the increased rain rate to be estimated by using a CTT of -38ºC instead of -40ºC. Table 2.5.1 gives the values of different parameters that were varied and the various combinations used. The rainfall estimates were derived solely from satellite thermal infrared (IR) data, which provide estimates of cloud top temperature (CTT). Rainfall is estimated from this on the assumption that high (cold) clouds are more likely to produce rainfall. For a particular grid cell the Cold Cloud Duration (CCD) was derived from the number of hours during a day when the CTT was lower than a fixed CTT threshold (in this case 235K [-38ºC]). The CCD was then converted to a rainfall total from an empirically derived relationship in which 1 hour of CCD is equated to 3mm of rain. The value to judge whether the threshold has been exceeded was the average of the values for each pixel within the square, but in the earlier trials the maximum value was used. The CCD method employed latterly was the Geo-stationary Earth-orbiting Satellite (GOES) Precipitation Index (GPI) of Arkin & Meisner (1987). However, for the initial 2001-2002 runs a threshold of –50ºC, instead of -38ºC (see Menz 1997), and 2.5mm, instead of 3mm, of rain per hour of CCD were used in the quelea model, following experience with armyworm forecasting in Tanzania (Tucker & Holt 1999). Following the calibration exercise, -38ºC was reverted to for 2002-2003. However for 2003/2004 and other future seasons, to be managed by staff of the Southern Africa Development Community (SADC), -40ºC will be used as this is the value that they use routinely for their CCD collections. Other parameters that were varied were the quantity of rain needed for the second threshold, the period during which it could accumulate and the period between it having been exceeded before an area was deemed as less suitable for the birds to breed in (Table 2.5.1).

To help the user to interpret the results a reference map (Figure 10) was created showing all the degree squares where *Quelea quelea lathamii* have been known to breed in the region (and hence the habitat was suitable). Similarly on the output maps, squares where there have been no known records of *Q. q. lathamii* at all (where the habitat is presumably inimical to them) were denoted with a dark background. Thus if a square became red but was in unsuitable habitat, e.g. a forest zone where quelea are unknown, this would be evident.

Table. 2.5.1. Different combinations of values of variables used when calibrating the model using the 2001/2002 season data. CTT. = Cloud top temperature (ºC); R = mm of rain equated with 1 hour of Cold Cloud Duration (CCD); RR= Rainfall required for first threshold (mm); T2T = time between passing of first threshold and when second threshold can first be passed (weeks); P2T = Period during which rain can have fallen for accumulation of second threshold value (weeks); R2T = Rainfall required for second threshold; Rainfall calculated based on maximum value in a square (MAX.) or on average values of all pixels in a square (AVE); T = Time after second threshold exceeded before breeding initiation becomes less likely (weeks). Size of square used in grid: 1X1 = 1degree X 1 degree; 0.5 X 0.5 = half a degree X half a degree.

CTT	R	RR	T2T	P2T	R2T	Max or Ave.	T	Sq-uare Size	Comments
-50	2.5	60	6	5	300	Max	5	1X1	Underestimated rainfall in South Africa
-50	3	60	6	5	300	Max	5	1X1	Underestimated rainfall in South Africa
-50	3	60	6	5	250	Max	5	1X1	Underestimated rainfall in South Africa and overestimated in Zimbabwe
-50	3	60	6	5	200	Max	5	1X1	Overestimated rainfall throughout
-50	3	60	6	5	250	Max	5	1X1	Underestimated rainfall in South Africa and overestimated in Zimbabwe
-50	3	60	5	5	250	Max	5	1X1	Underestimated rainfall in South Africa and overestimated in Zimbabwe
-50	3	60	6	5	250	Max	4	1X1	Underestimated rainfall in South Africa and overestimated in Zimbabwe
-40	3	60	6	8	300	Ave	5	1X1	Underestimated rainfall in South Africa
-40	3	60	6	7	300	Ave	5	1X1	Underestimated rainfall in South Africa
-40	3	60	6	6	270	Ave	5	1X1	Underestimated rainfall in South Africa
-40	3	60	6	8	270	Ave	6	1X1	Underestimated rainfall in South Africa
-40	3	60	6	8	250	Ave	5	1X1	Underestimated rainfall in central Botswana and South Africa
-40	3	60	6	6	240	Ave	6	1X1	Underestimated rainfall in central Botswana and South Africa
-40	3	60	6	6	210	Ave	6	1X1	Best fit for 2001/2002 data, but R2T of 210 used to compensate for some loss of rain data at start of season (first 3 weeks of September) and in January and February.
-38	3	60	6	6	240	Ave	6	0.5 X 0.5	Used for 2002/2003 season. R2T increased to 240 to compensate for CTT of –38 used instead –40 and presumed adequate rain data collection throughout season.

Figure 9. Diagram of the procedures involved in the running of the quelea model.

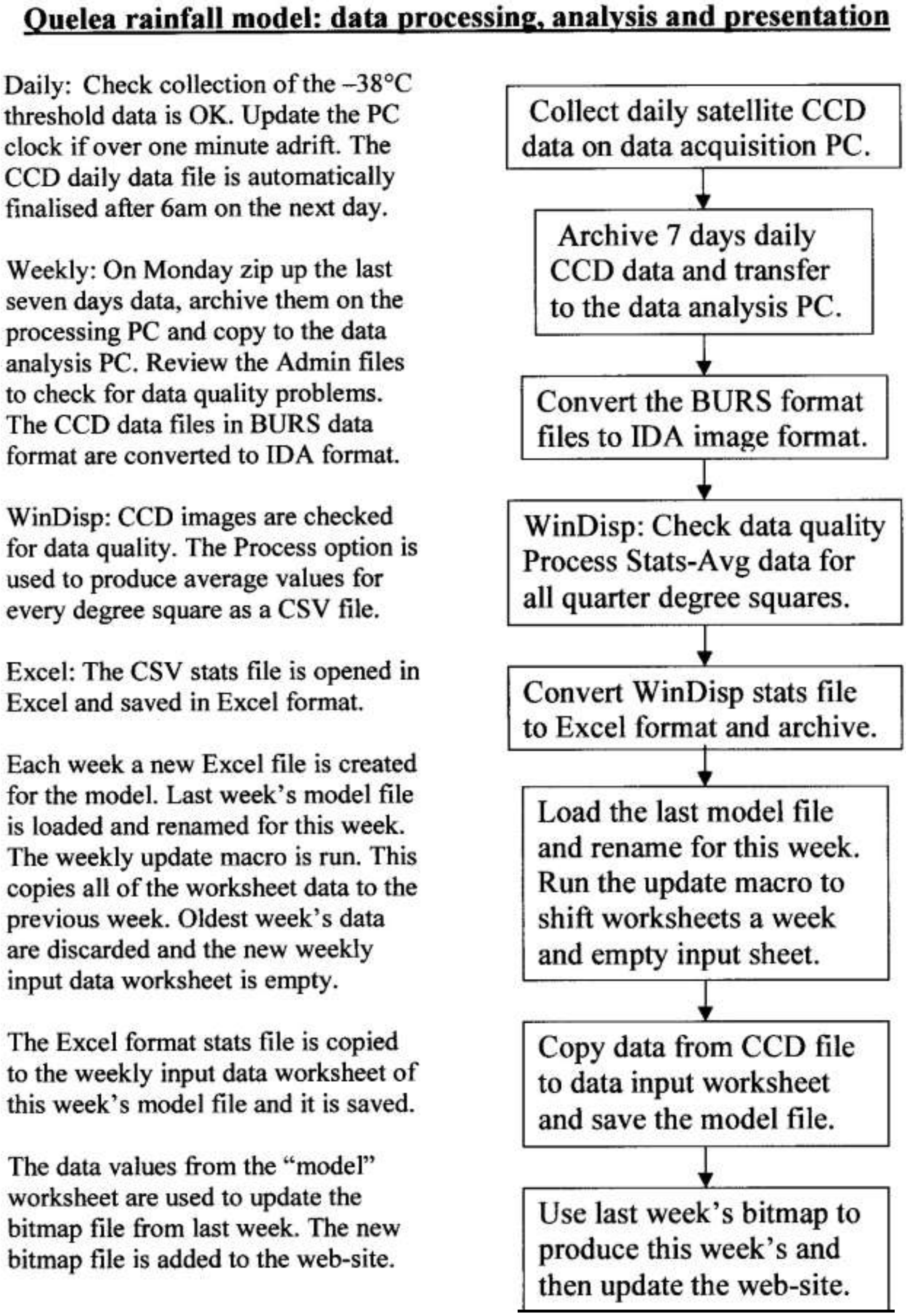
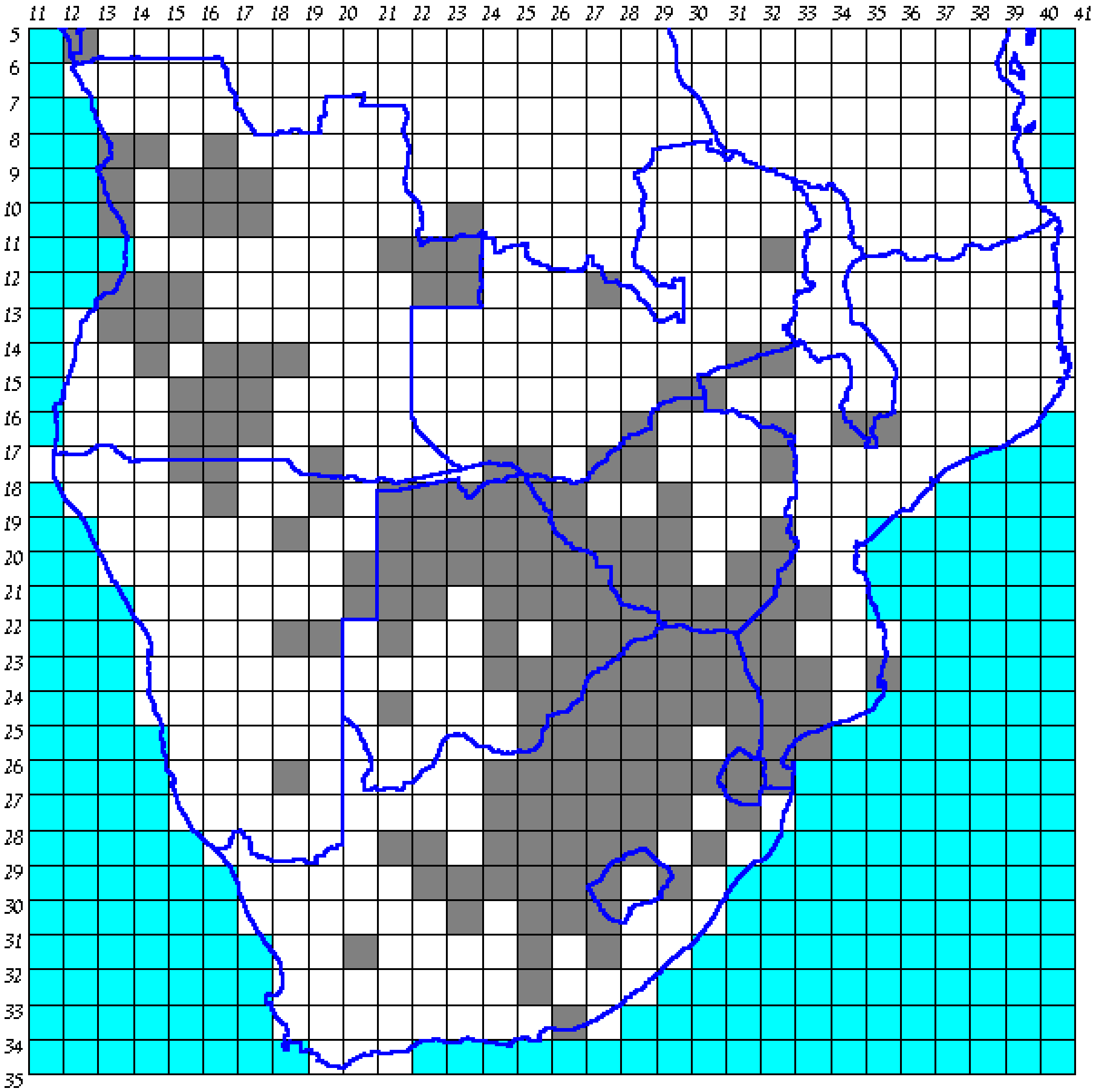


Figure 10. Map showing degree squares where *Q. q. lathamii* has been known to breed (squares filled in with grey).



2.5.3. Results from the model during the 2001-2002 season

The model was not ready at the start of the season. The first model run was completed for the week ending 23 September 2001. The model predicted that in 2001 early rains migrations started simultaneously at opposite ends of the quelea geographical range i.e. Angola and south-eastern South Africa. By mid-November the model was predicting that the birds would have been concentrated into restricted parts of Botswana and into the area surrounding where the Zimbabwe, South Africa and Mozambique borders coincide. At the same time, the first area suitable for breeding would have been in Eastern Angola close to the Zambian border. This zone gradually expanded but only Angola and Zambia and the Caprivi strip of Namibia were involved until the end of December, when breeding could take place in Botswana, Zimbabwe, Mozambique and Malawi as well. At this time the first unsuitable areas were signalled and these expanded until the beginning of February 2002 when they split the breeding areas into separate eastern and western groups. The pattern was broadly consistent with observed events, as 42% of breeding records were within squares predicted to be suitable, 51% were next to squares deemed suitable and none was in a white squares, where the season had never started.

2.5.3. Model outputs in 2002-2003.

The model was run at weekly intervals from the week ending 8 September 2002 with the maps displayed on the web-site (http://www-web.gre.ac.uk/directory/NRI/quel/Index.htm). As explained above under algorithm descriptions, during the model runs each square was allocated a colour according to one of four possible conditions, as follows. (1) WHITE - insufficient rain has fallen to allow germination of grass seeds and permit activities associated with the start of a quelea breeding season; (2) GREEN - sufficient rain (>60mm) has fallen to allow grass seed germination, forcing birds to initiate their early rains migrations away from that square; (3) RED - six weeks have passed since condition 2 started and sufficient rain (>240mm, i.e. making 300mm in total) has fallen during the preceding 6 weeks to allow breeding to occur; and (4) YELLOW - breeding is unlikely to be initiated as more than 6 weeks have elapsed since breeding became possible.

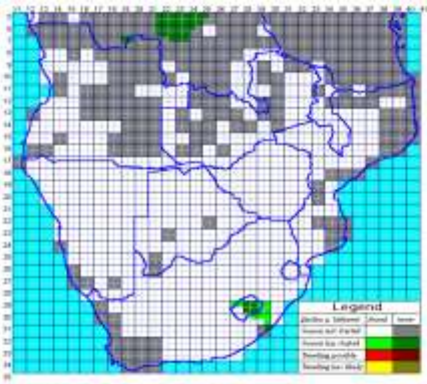
The 2002-2003 season was markedly different from the events recorded in 2001-2002 (see figs. 11 and 12 for samples of output during the season). At the start of the season, the first area to go green was Lesotho and areas surrounding it to the SE and NW and was soon followed by a strip along the SE coast of South Africa. By the end of September a strip of land stretching north-westwards into SE Botswana became green, matched by zones in Angola and the Democratic Republic of the Congo at the opposite pole of the quelea distribution. More scattered rain fell soon afterwards with the 60mm threshold exceeded elsewhere in Botswana, Zimbabwe, southern Mozambique and eastern central Namibia. It was not until the week ending 29 October that the first possibility of breeding was signalled, when red squares appeared in South Africa, SE of Lesotho and in the SE of the Democratic Republic of the Congo. By the end of the next week, breeding would have been possible in Lesotho, in South Africa in areas surrounding Lesotho and in Angola. An area in central South Africa NW of Lesotho became red soon afterwards but not until the week ending 15 December did the first red squares appear in Botswana and Namibia. By the end of 2002, breeding would have been possible throughout much of South Africa and in Swaziland and in southern Mozambique, followed soon after by parts of Zambia, central Mozambique and northern and southern extremes of Botswana, the Caprivi strip and adjoining parts of NE Namibia, southern Angola, Zambia and Zimbabwe. Thereafter two clear blocks separated by a drought-stricken middle region became apparent.

That the model was consistent with quelea events was supported by the first reports of quelea breeding in South Africa coming from Klerksdorp and Bethlehem, NW and N of Lesotho respectively, in early November. At the same time colonies were reported from Chokwe in Mozambique. In January 2003, 29 colonies covering 198ha were controlled in the Free State and Limpopo provinces of South Africa near sorghum and millet crops. At the same time the first colony of the season in Botswana was reported from the south of the country in a square predicted by the model to be suitable. The model forecast led directly to the finding of this colony in a zone usually unaffected by the birds. Subsequently breeding in Botswana was reported in February and March but only in the NW. Substantial breeding was, however, reported in South Africa throughout the period January-April, with birds spreading from NW of Lesotho and into the Springbok flats area. With the exception of the two colonies reported from Mozambique which were in an exceptional habitat anyway, beside irrigated rice, all the colonies reported during 2002/2003 were in zones predicted by the model to have achieved suitable status (Fig. 13).

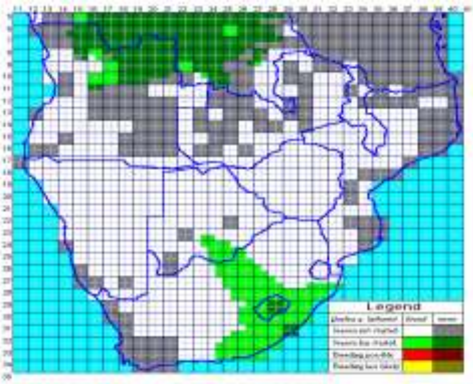
Figure 11. Samples of outputs from the quelea forecasting model 2002/2003. Legend and output for weeks ending 9 September 2002, 29 September 2002, 27 October 2002 and 1 December 2002.

Rainfall thresholds

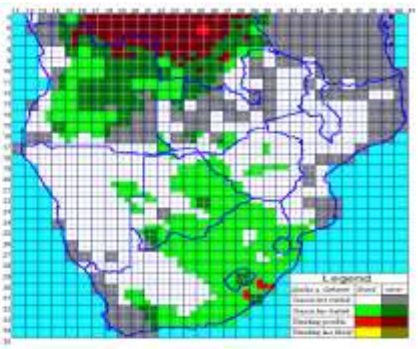
	Quelea recorded	Q. not recorded	Rainfall
Season not started			< 60 mm
Season has started			> 60 mm in 2 weeks
Breeding possible			+ 240 mm in next 6 weeks
Breeding less likely			6 more weeks elapsed



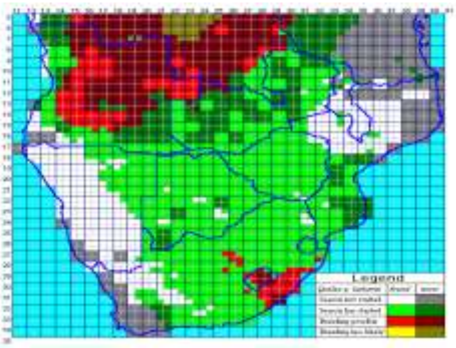
8 Sept



29 Sept

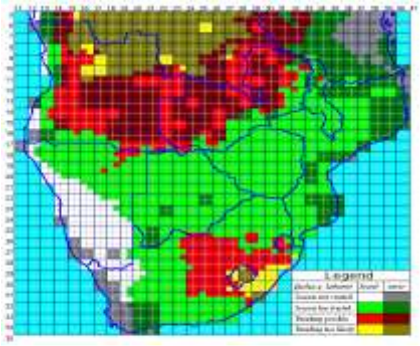


27 Oct

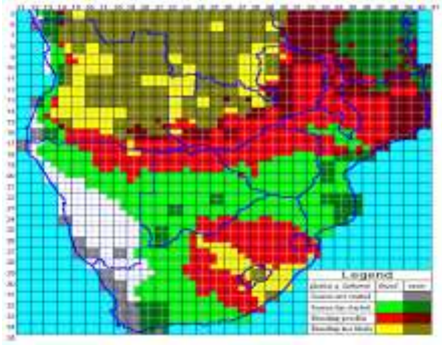


1 Dec

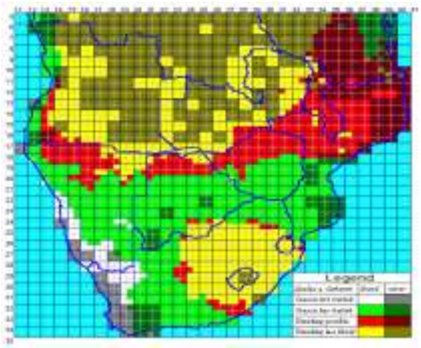
Figure 12. Samples of outputs from the quelea forecasting model 2002/2003. Legend as in figure 11. Output for weeks ending 22 December 2002, 26 January 2003, 16 February 2003, 16 March 2003, 13 April 2003 and 4 May 2003.



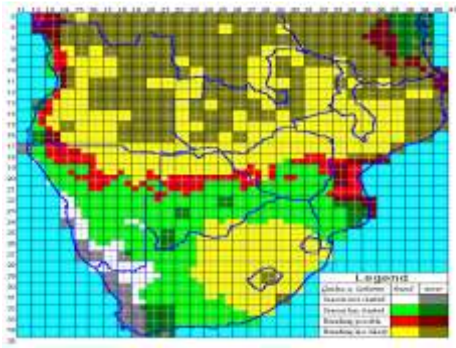
22 Dec



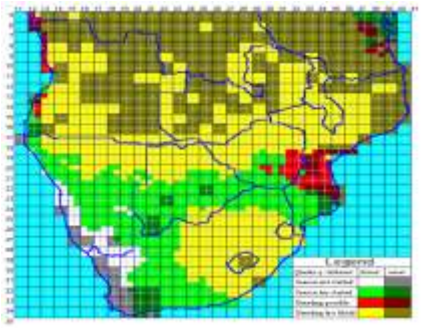
26 Jan



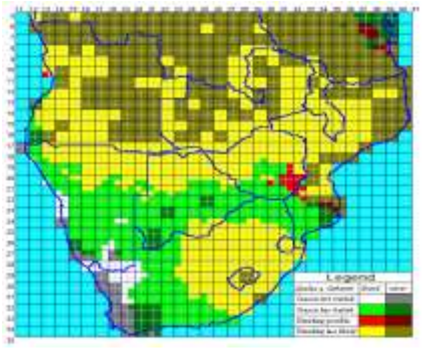
16 Feb



16 Mar

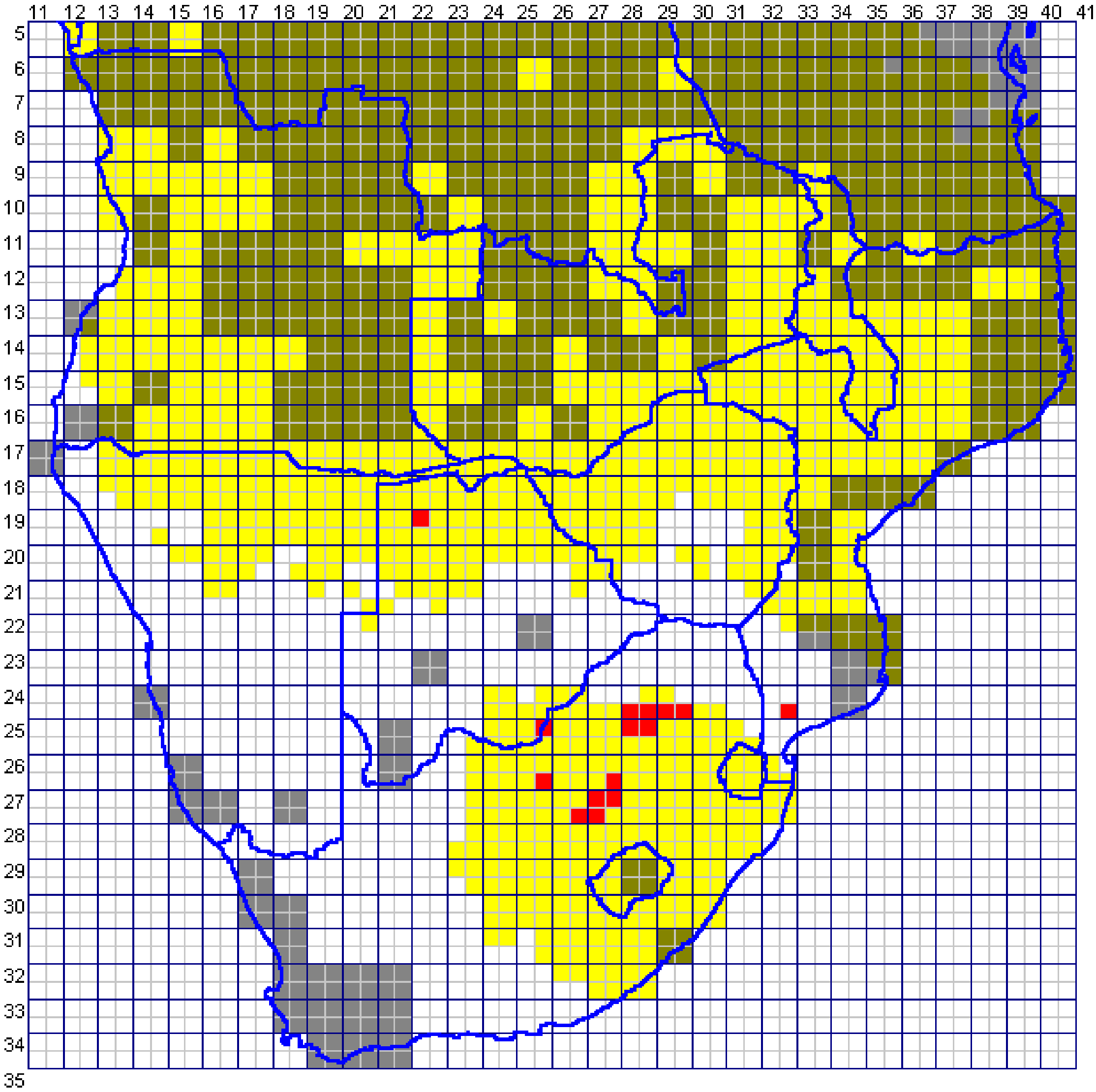


13 Apr



4 May

Figure 13. Map of locations of reported breeding by *Q. q. lathamii* in southern Africa during 2002/2002 (red dots) and distribution of areas where the threshold of 300mm of rainfall had been exceeded by the end of the season (yellow). Darkened squares denote areas where *Q. q. lathamii* has never been reported to breed.



2.5.4. Possible Sources of Error

Additional model validation exercises in future seasons will shed further light on the accuracy of the thresholds used. If they are too high they will lead to delays in the signalling of the starts of seasons and to underestimates of quelea breeding activity. Similarly, discrepancies in the minimum periods of rainfall and or intervening dry periods between the threshold events could lead to inaccurate predictions. However, the most likely sources of errors are in the estimates of rainfall from the CCD data. It is known that these become less accurate, the further south in southern Africa that they are used. Indeed it may become necessary to have separate algorithms according to location or utilise results from recent advances in satellite rainfall estimation, as explained below.

Like many other applications the predictive model for Quelea prediction requires reliable estimates of the quantities and distribution of rainfall at small time and space scales. Due to the absence of sufficient reports from synoptic weather stations, rainfall estimates derived from satellite data are utilised. However, the accuracy of satellite estimates is limited. Although geo-stationary satellite platforms provide the necessary high temporal sampling, the relationship between rainfall and cloud top temperature (CTT), as estimated from the infrared (IR) sensors, is relatively weak and not robust in space and time. Rainfall estimates with far greater accuracy are available from Precipitation Radar (PR) and passive Microwave (MW) sensors, whose observations are directly sensitive to rainfall itself rather than to cloud top characteristics. However, these suffer from poor temporal sampling, due to their necessary placement on low-earth orbit.

The model uses the Geo-stationary Earth-orbiting Satellite (GOES) index but there are well known limitations to the GOES Precipitation Index (GPI) approach (Todd *et al.*; 1995; 1999; 2001, Xu *et al.*, 1999, Huffman *et al.*, 2001). Specifically,

1. The rainfall coefficient is known to vary in space and time reflecting variability in the relationship between cloud and rainfall related to variability in cloud microphysics, associated with meteorology and climate.
2. The optimum CTT threshold is known to vary in space and time reflecting variability in the relationship between cloud and rainfall related to climatic variability. Indeed, a CTT threshold of 235K will identify only deep convective cloud systems and is likely to underestimate rainfall from 'warm' rainfall processes such as shallow convection and orographically enhanced rainfall.

These limitations in the CCD (and GPI) methods can be accounted for by locally calibrating (a) the optimum CTT threshold and (b) the rainfall coefficient (or similar), locally in space and time through statistical analysis of the IR data with some source of collateral rainfall estimates. This collateral calibration data can be provided by interpolated fields of gauge data (Todd *et al.*, 1995; 1999) where available. Alternatively, relatively infrequent observations of rain rate from satellite microwave sensors on low-earth orbiting satellites can be used in regions, such as Southern Africa, where gauge data are inadequate. The Microwave and Infra-Red Rainfall Algorithm (MIRA) (Todd *et al.* 2001) enables estimation of rainfall at the smallest possible space and time scales. The algorithm uses coincident microwave and infra-red (IR) observations to calibrate the optimum CTT threshold and CTT/rain rate relationship on a grid cell basis, through a probability distribution equalisation procedure.

A comprehensive evaluation of MIRA (Todd *et al*., 2001) showed that the optimum CTT thresholds and CTT/rain rate relationship are highly variable in space and time, in line with other similar findings (Todd *et al.*, 1995; 1999, Xu *et al*., 1999; Huffman *et al*., 2001). As a result, MIRA showed improvements in rainfall estimate accuracy in comparison to the GPI at a range of space-time scales. These studies provide ample evidence that both the CTT thresholds and the CTT/rain rate relationship should be locally calibrated to ensure sensitivity to broad scale variation in the dominant cloud micro-physical processes. Using archived IR and MW satellite data it would ultimately be possible to develop MIRA products from 1987 to present.

Recent geo-stationary satellite sensors have improved spectral capabilities with multiple channels in the optical visible and infrared (VIS/IR) wavelengths. The forthcoming Meteosat Second Generation (MSG) satellite will record in a total of 11 VIS/IR wavelengths. These additional channels are likely to provide greater information on cloud (and hence rainfall) characteristics, in comparison to CTT alone. Artificial Neural Networks (ANN) facilitate the formulation of highly non-linear relationships between rainfall and multiple cloud characteristics inputs such as these multiple VIS/IR channel observations.

Bellerby *et al.* (2001) describe a technique in which an ANN is used to define this complex relationship between multi-spectral VIS/IR data from the GOES geo-stationary satellite and rainfall derived from space-borne precipitation radar data. The results showed improved accuracy in relation to both the IR-only GPI and the combined MW/IR MIRA methods. The application of this ANN approach to Meteosat Second Generation (MSG) data is likely to result in further improvements in estimate accuracy.

2.5.4. References

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Menz, G. (1997) Regionalization of precipitation models in East Africa using Meteosat data. *Int. J. Climatol*. 17: 1011-1027.

Todd, M.C., Barrett, E.C., Beaumont, M.J. and Green, J., 1995: Satellite identification of rain days over the upper Nile river basin using an optimum infrared rain/no rainthreshold temperature model. *Journal of Applied Meteorology* 34 (12) 2600-2611.

Todd, M.C., Barrett, E.C., Beaumont, M.J. and Bellerby, T.J., 1999: Estimation of daily rainfall over the upper Nile river basin using a continuously calibrated satellite infrared technique. *Meteorological Applications*, 6, 201-210

Todd, M.C, Kidd, C.K., Kniveton, D.R. and Bellerby, T.J., 2001. A combined satellite infrared and passive microwave technique for estimation of small scale rainfall over the global tropics and subtropics. *Journal of Atmospheric and Oceanic technology*,
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Xu, L., Gao, X., Sorooshian, S., Arkin, P.A., 1999**:** A microwave infrared threshold technique to improve the GOES Precipitation Index. *J. Appl. Met.*, **38**, 569–579**.**

2.5.5. Future Plans

The model will continue to be run until the end of March 2004 (subject to approval of follow-on application) and during March 2003 was transferred to users in the the Regional Remote Sensing Unit (http://www.sadc-fanr.org.zw/rrsu/rrsutxt.htm) of the Southern Africa Development Community (SADC).. The Remote Sensing unit is part of the Food, Agriculture and Natural Resources (FANR) unit (http://www.sadc-fanr.org.zw/) of SADC which coordinates forecasting for famine prevention measures and predicting droughts. The SADC already collects CCD data for rainfall estimates (see e.g. http://www.sadc-fanr.org.zw/rrsu/satimg/CCD/March2003.htm). The forecasts are currently based only on one set of parameters but if threshold values of rainfall, for instance, were varied then forecasts could be provided simultaneously to giving a range of expectations. Also, at present the system uses the same algorithm for each square in the grid but the accuracy of the rainfall estimates and the effects of rain on germination rates will vary spatially, e.g. where the soils differ in absorbency. Improvements to the model could take these factors and others, such as the presence of irrigation schemes which may have localised effects on rates of germination or plant growth, could be included on the output maps.

2.6. Conclusions and Impact

(1) A quelea short-term forecasting system has been created.
(2) The short-term system devised has been calibrated using data for the 2001/2002 season and validated with 2002/2003 data.. The model could be improved by using more sophisticated methods of rainfall estimation.
(3) No simple method for medium-term forecasts was established but promising lines for future research to develop medium-term predictors were identified.
(4) Significant autocorrelations, up to lags of three years, and a significant partial autocorrelation at a lag of one year were found within the quelea time series. These results suggest that endogenous dynamics are involved, implying that very high populations will only occur if there had been high populations in the preceding season and that, even if the climate is suitable, there will not necessarily be an abundance of quelea birds.
(5) The environmental effects of quelea control are substantial, but means to minimise them were identified.
(6) Protocols for future environmental impact assessment (EIA) work were proposed that need to be tested in the field.
(7) The forecasting system has been disseminated widely to control planners, through ICOSAMP and other routes, and could 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. Target institutions have requested assistance with EIA work and quelea forecasts.

Outputs: supplementary comments

All outputs were achieved with the exception of (a) Validations of model predictions with quelea breeding data for 1999/2000 and 2000/2001. These analyses proved to be impossible as the archived CCD data-sets were found to have extensive gaps in their coverage for these seasons. Thus, without a continuous rainfall record it was impossible to estimate when rainfall thresholds had been exceeded; (b) an original plan to set-up the model within a GIS platform was abandoned in favour of an internet world wide web-based system. To provide a GIS system on-line would have been prohibitively expensive in terms of software acquisition and programming time.

Contribution of Outputs to Developmental Impact

The outputs will contribute to the reduction of poverty and enhancement of the livelihoods of the rural poor in semi-arid regions of Southern Africa by increasing the likelihood that colonies of Red-billed Quelea birds will be found and controlled before the birds have been able to damage cereal crops grown by resource-poor farmers. The outputs will also lead to reduced environmental damage if recommendations on minimising effects of chemical sprays on non-target organisms are adopted. To improve uptake of this output it is recommended that field-work be conducted on environmental impacts of quelea control, perhaps paid for partly by host Governments, to aid the development of a standardised protocol to be adopted by countries within the SADC region.

Promotion pathways to the target institutions and thence to the beneficiaries include postings on the internet world wide web through the quelea model and ICOSAMP web-sites, through reports, publications and other dissemination outputs despatched to staff in agricultural organisations charged with controlling quelea birds. A principal uptake pathway is through the Food, Agriculture and Natural Resources (FANR) unit of the Southern Africa Development Community (SADC) who will be responsible for the future running of the quelea model, to be hosted on their web-site. In order to ensure a successful transfer it is recommended that their system is run in parallel with the NRI-based one for one year as a cross-check. This would also allow further validation and possible improvements to the model system, such as output that provides probabilities of the accuracy of the forecast and forecasts using upper and lower limits of different variables.

Dissemination Outputs

The following outputs on quelea were produced during the course of the project:

JONES, P. J., CHEKE, R. A., MUNDY, P. J., DALLIMER, M. & VENN , J. F. (2000) Quelea populations and forecasting based in southern Africa. Pp. 139-150 in Cheke, R.A., Rosenberg, L.J. & Kieser, M. (eds.) *Proceedings of a Workshop on Research Priorities for Migrant Pests of Agriculture in Southern Africa*, Plant Protection Research Institute, Pretoria, South Africa, 24-26 March 1999. Natural Resources Institute, Chatham, UK.

ZACCHI, L., COX J. R., CHEKE R. A., VAN DER WALT, E. & HARVEY, P.J. (2000) Biodegradation of fenthion by *Phanerochaete chrysosporium*. Pp. 191-201 in: *Workshop on Research Priorities for Migrant Pests of Agriculture in Southern Africa*. Plant Protection Research Institute, Pretoria, 24-26 March 1999. Cheke, R. A., Rosenberg, L. J. and Kieser, M. (eds). Natural Resources Institute, Chatham, UK.

JONES, P. J., CHEKE, R. A. & DALLIMER, M. (2000) *Quelea* migration in Africa. Abstract in Astheimer, L. B. & Clarke, M. F. (eds.) Proceedings of the 2nd. Southern Hemisphere Ornithological Congress (SHOC), Griffith University, Brisbane, Australia, 27 June – 2 July 2000. *Birds Australia Report Series* no. 9: 97.

CHEKE, R. A. (2001) DFID CPP Project on forecasting Quelea breeding in southern Africa. Abstract, p. 13. ICOSAMP Workshop, 2-4 May 2001, Pretoria, South Africa.

CHEKE, R. A. (2001) Information requirements for the Quelea Project on forecasting Quelea breeding in southern Africa. Abstract, p.15. ICOSAMP Workshop, 2-4 May 2001, Pretoria, South Africa.

CHEKE, R. A. (2001) Visit to the Republic of South Africa to attend the Information Core for Southern African Migrant Pests (ICOSAMP) Workshop, Pretoria, 27 April to 5 May 2001. Unpublished Back-to-the-Office report.

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Information on quelea breeding localities were supplied to BBC camera crews embarking on a filming project for the "Planet Earth" series hosted by Sir David Attenborough to be broadcast on BBC television.

Acknowledgements

We are grateful for the financial support of the DFID Crop Protection Programme and for the assistance of our many collaborators in agricultural and other departments dealing with quelea in Botswana (M. Modise, R. Kgosi, T. Moruti), Mozambique (J.Varimelo), Namibia (P. Barnard, P. Shiyelekeni, R.Simmons,) South Africa (L. Geertsema), Swaziland (M. Mbuli) and Zimbabwe (P.J.Mundy, T. Couto) and to colleagues in SADC (S. Machiri, S. de Keyser) and IRLCO-CSA (J. Ngondi Katheru). Particular thanks are due to M. E. Powell (formerly Kieser) for our links with the ICOSAMP project, to T. Couto, E. van der Walt and L. Lötter for information on effects of quelea control on non-target species and to Wendy and Remi Borello for much assistance in Botswana.

Biometricians Signature

The projects named biometrician must sign off the Final Technical Report before it is submitted to CPP. This can either be done by the projects named biometrician signing in the space provided below, or by a letter or email from the named biometrician accompanying the Final Technical Report submitted to CPP. (Please note that NR International reserves the right to retain the final quarter's payment pending NR International's receipt and approval of the Final Technical Report, duly signed by the project's biometrician)

I confirm that the biometric issues have been adequately addressed in the Final Technical Report:

Signature:	
Name (typed):	Mrs. Flavia Jolliffe
Position:	Statistician, Natural Resources Institute, University of Greenwich
Date:	20 June 2003

SEE ATTACHED
LETTER

Natural Resources Institute

Professor R.A. Cheke
Natural Resources Institute
University of Greenwich at Medway
Central Avenue
Chatham Maritime
Kent
ME4 4TB

20 June 2003

Dear Bob,

Re project R7967 (ZA 0467)

I have looked at the statistical aspects of the final technical report of this project on forecasting movements and breeding of the Red-billed Quelea bird in southern Africa and improved control strategies, as you requested.

I indicated that clarification might be needed as regards the correlations referred to in 2.3.3.3 and mapped in Figure 3. If I understood correctly, for each area a measure of rainfall and number of birds was available for (a sample of) several years and a correlation coefficient between these two variables was found for each area. I also made some suggestions as regards figures 4 and 7.

As far as I can tell from the report and from the discussions with you, the biometric issues have been adequately addressed in this project.

Yours sincerely

Flavia Jolliffe

(Mrs) Flavia Jolliffe BSc, DIC, CStat
NRI Associate, Honorary lecturer in statistics at the University of Kent

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