A REVIEW OF ALTERNATIVES TO FENTHION FOR QUELEA BIRD CONTROL

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ABSTRACT

The red-billed quelea (*Quelea quelea*) is the most important avian pest of small grain crops in semi-arid zones of Africa. Fenthion, an organophosphate, is the main avicide used for controlling the pest but it is highly toxic to non-target organisms. The only readily available pesticide that could replace fenthion is cyanophos, but this chemical is also highly toxic to non-target organisms, although less so than fenthion, and may be more expensive; however, more research on its environmental impacts is needed. Apart from chemical avicides, the only rapid technique to reduce the numbers of quelea substantially is the use of explosives combined with fuel to create fire-bombs but these also have negative effects on the environment, can be dangerous and have associated security issues. The technique is labour intensive and in practice can only be deployed against small (<5 ha) colonies and roosts. An integrated pest management (IPM) approach is the most environmentally benign strategy but, apart from when circumstances permit cultural control measures, most IPM activities only have realistic chances of succeeding in controlling quelea in small (<10 ha) areas. For instance, mass-trapping, which also has the advantage of providing a food source, is suitable when quelea roosts and colonies are less than 5 and 10 hectares in area, respectively. Nevertheless with both traps and mist nets, care is needed to minimise non-target casualties. Other IPM measures are also reviewed and the advantages and disadvantages of different methods tabulated. A related figure provides a decision tree for choosing appropriate measures for different circumstances. If fenthion has to be used, means of minimising its use include ensuring that spraying is only conducted when crops are threatened and that the lowest dosages necessary are applied. Regular training of pest control workers in how to use

equipment correctly and in what to do in the case of accidental contamination of operators, and training of farmers on IPM principles and quelea biology through farmer field schools are recommended.

1. Introduction

The red-billed quelea (*Quelea quelea* Linnaeus) is the most important avian pest of small grain crops in Africa, causing damage up to the equivalent of US$ 88.6 million per annum at 2018 prices throughout semi-arid zones (Elliott, 1989a,b). At present, control is mostly by aerial and / or ground-spraying of organophosphate avicides, with fenthion (Queletox®) being the pesticide of choice. As the red-billed quelea is recognised as a migratory pest, such control is conducted by international agencies, Governments and commercial companies, although subsistence farmers can undertake other measures, included in this review, to reduce the birds' depredations. Regrettably, fenthion is toxic to humans and to other non-target organisms so alternatives to its use, reviewed here, are urgently sought. The red-billed quelea feeds principally on native grasses but when these are scarce the birds will attack the seed heads of crops. Principal amongst the latter are millet, sorghum, wheat, rice and teff. There are three subspecies of red-billed quelea: the nominate form *Q. q. quelea* occurs in West Africa from Senegal in the west to Sudan in the east; *Q. q. aethiopica* (Sundevall) ranges in East Africa from Ethiopia to southern Tanzania and *Q. q. lathamii* (Smith) is restricted to southern Africa (Cheke, 2014). All three of the subspecies are migrant pests which follow rainfall systems. As meteorological conditions vary from year to year, the locations and severity of quelea infestations also vary between seasons. In general, the birds breed 2 or 3 times a year, but up to 5 times per annum in East Africa, during and just after rainy seasons. Quelea coming from huge communal breeding colonies may attack crops. Damage also occurs in dry seasons when the birds continue to flock together and may roost in very high numbers. Both breeding colonies and roosts are the targets of control operations that take place after dark when the birds have settled down for the night. The birds also collect in "day-roosts" or "secondary roosts" during daytime (Ward and Zahavi, 1973) when they are susceptible to mass-trapping.

As the birds are migrant pests, responsibility for their control rests in some zones with international organisations. Thus, the Desert Locust Control Organization for Eastern Africa (DLCO-EA) uses its aircraft to treat member countries' infestations and the International Red Locust Control Organisation for Central and Southern Africa (IRLCO-CSA) has a similar role for its areas of responsibility. However, some countries such as Botswana, the Republic of South Africa and affected West African countries now undertake their own control duties. Although fire-bombs are used to destroy quelea breeding colonies and roosts in Botswana, South Africa, Kenya and elsewhere, the principal control agent in all areas is currently the organophosphate avicide fenthion (Queletox®; 640 UL; thiophosphoric acid or *O*,*O*-dimethyl-*O*-[3-methyl-4-(methylthio) phenylphosphorothiote], also known as Baytex, Lebaycid, Tignvon and OMS-2).

Fenthion, like other organophosphate compounds, acts by inhibiting acetylcholinesterase, which is essential for normal nerve function. When acetylcholinesterase is inhibited a build-up of acetylcholine results causing prolonged transmission of nerve impulses leading to death from respiratory failure. Fenthion can therefore injure or kill indiscriminately, with consequent adverse effects on non-target organisms (McWilliam and Cheke, 2004) including humans. Fenthion residues are now known to have a half-life of 45 days, almost twice a previous figure given by Meinzingen et al. (1989), and rainfall after sprays can cause fenthion to leach out of the soil and still be detectable five months later (Cheke et al., 2013). Additionally, persistence of fenthion residues in the air for 64 hours and in soil for 46 days was reported by van der Walt (2000).

To date, measures to control quelea birds without using fenthion have included the use of (a) alternative pesticides; (b) explosives/fire-bombs; (c) a variety of mass trapping methods, sometimes keeping the birds for food; (d) cultural control; (e) quelea resistant crops; (f) protecting vulnerable crops with repellents and netting and (g) scaring the birds, including the use of falcons. These will be described and discussed below under main headings of Chemical Control, Mechanical Control, Cultural Control and Biological Control. The information for this review is based on published and unpublished documents, obtained following library and internet-based literature searches for relevant terms, and the authors' own observations that were collated for presentation at a workshop to discuss the subject of this paper organised by the FAO's Rotterdam Convention Secretariat. The meeting was attended by representatives of 11 African countries and held in Khartoum, Sudan, on 4-5 April 2017 (see http://www.pic.int/Implementation/TechnicalAssistance/Workshops/WorkshopSudanApr2017/tabid/5895/language/en-US/Default.aspx). The workshop was convened following concerns over human safety and a proposal to list fenthion in Annex 3 of the Rotterdam Convention which, if accepted, would have led to the pesticide being subject to the Prior Informed Consent (PIC) procedure (see http://www.pic.int/Procedures/PICProcedure/tabid/1364/language/en-US/Default.aspx). The Rotterdam Convention is a multilateral Environment Agreement. Its principal objective is promotion of shared responsibility and cooperative efforts among parties in the international trade of certain hazardous chemicals, in order to protect human health and the environment. By its article 6, the convention allows developing countries and countries with economies in transition that are experiencing problems caused by any specific pesticide formulation to propose it for consideration as a Severely Hazardous Pesticide Formulation (SHPF). Such SHPFs will then be subject to the Prior Consent Procedure (PIC) applicable to the 160 parties of the Rotterdam Convention. Fenthion is scheduled for consideration for inclusion in 2019. After the Khartoum meeting, the text of the initial review was revised to include additional topics raised by the delegates, comments arising from the ensuing discussions and the reflections of the attendees. A summary of the advantages and disadvantages of the various methods is tabulated (Table 1) and, aiming to minimise pesticide usage, a decision tree recommending different approaches according to circumstances is provided (Figure 1), thereby collating current evidence about the various control methods available for use against quelea.

2. Alternatives to fenthion for quelea control

2.1. Chemical Control

2.1.1. Alternative pesticides

The most commonly used alternative avicide is another organophosphate, cyanophos (Falcolan 520 UL; OMS 226, $C_9H_{10}NO_3PS$ (*O*-(4-cyanophenyl) *O*,*O*-dimethyl phosphorothioate). Cyanophos is not registered for use in the United States of America where it is classified as an extremely hazardous substance. Similarly it is not registered for use in the European Union. Nevertheless, it has been used for quelea control in Senegal, Mauritania, Botswana, Ethiopia and elsewhere since it has lower toxicities (e.g. acute oral LD50 for rats 730 $mg.kg^{-1}$ and 3 $mg.kg^{-1}$ for quelea) than those of fenthion (acute oral LD50 for rats 250 $mg.kg^{-1}$ and 6-10 $mg.kg^{-1}$ for quelea). Cyanophos was tested in Tanzania but was not recommended for routine use. In contrast, it is a registered avicide in the Republic of South Africa where it is used for the majority of quelea control operations since fenthion is no longer available there (E. van der Walt, pers. comm., Nov. 2016). Cyanophos has the disadvantage of a delayed effect on mortality in comparison with fenthion (Allan, 1997), so use of cyanophos could lead to more secondary poisoning of non-target organisms than control with fenthion but few studies of the effects of cyanophos use in the field have been conducted. Mullié et al. (1999) studied non-target organisms after cyanophos spraying against quelea in Senegal and concluded that it seemed to be as damaging as fenthion but that the data were insufficient for adequate comparisons. Cheke et al. (2013) found that cyanophos was still present in soil, at concentrations of from 0.009 to 0.169 $\mu g.g^{-1}$, 41 days after a spray in Botswana (the maximum residue level for this compound is unknown but UK pesticide authorities recommend a default maximum residue level on food of 0.01 $\mu g.g^{-1}$; see https://secure.pesticides.gov.uk/MRLs/). Phoxim, also an organophosphate, has been tested as an alternative to fenthion (Pope and King, 1973) and Allan (1997) listed some other alternative chemicals such as mevinphos, another organophosphate. However, mevinphos is even more toxic than fenthion (acute oral LD50 for rats 3-12 $mg.kg^{-1}$ and 1.43 $mg.kg^{-1}$ for quelea), so it does not present a suitable alternative.

2.1.2. Bird repellents including narcotics

Alphachloralose is a narcotic agent added to bait grain or water that has been used in South African trials (Garanito et al. 2000) which leaves birds so weak that they can be easily picked up or killed, but its potential for affecting non-target organisms renders it unsuitable except, perhaps, in urban areas. Other possible chemicals with repellent abilities that could be used, but which have similar strictures against them, include 4-aminopyradine and aluminium ammonium sulphate, curb (ammonium sulphate) and trimethacarb (predominantly trimethylphenyl methylcarbamate). Use of mesurol, the carbamate methiocarb, a bird repellent, molluscicide and insecticide, also listed by Allan (1997), doubled yields of sorghum in Senegal and in Sudan reduced damage from 85 to 30% in experiments on sorghum and wheat. It is now banned by the EU either for direct use on crops or as a seed dressing. Use of repellents was reviewed by Bruggers (1989). The repellent 9,10 Anthraquinone is in use in Zimbabwe but it is not approved for use in the EU. Attempts have been made in South Africa to spray birds with wetting agents such as dilute molasses to prevent the birds from thermoregulating, but the large volumes required precluded regular use of the technique (E. van der Walt, pers. comm.).

2.2. Mechanical Control

2.2.1. Explosions

Explosions/fire-bombs are or were used to control red-billed quelea in Botswana, the Republic of South Africa, Kenya, Zimbabwe and elsewhere. They are often used in or near wetlands, where spraying with organophosphates is contra-indicated. The technique requires highly trained personnel, specialised equipment to transport the explosives safely, and time to deploy the firebombs at the base of vegetation where the birds are either roosting or nesting. This precludes their use except at small (<5 ha) sites. Cheke et al. (2013) described the method used in Botswana as follows: “The technique involves the detonation of 5 L plastic containers, filled with 2.5 L of a mixture of fuels: one-third diesel to two-thirds unleaded petrol was used in 2009 and 2010, but a 50 : 50 mixture of 1 L of diesel and 1 L of petrol was used in 2005; the addition of diesel keeps the flame alight longer than petrol alone, but also gives rise to smoke. Each plastic container (white opaque containers were used in 2005–2008, but green ones in 2009–2010) is placed beneath a bush where quelea birds are either nesting or expected to roost. Each container has an explosive charge placed beneath it. In 2005, this consisted of 150 g of Trojan C150 cast boosters, 38 × 120 mm of pentolite and a mixture of TNT and RDX, encased in yellow plastic [manufactured by Ensign-Bickford, (Pty) Ltd, South Africa]. Each booster had a hole drilled in the middle, through which red detonating cord (plastic cord, 8 $g.m^{-1}$; Auxim Tech. Ltd, China) was fed. At the ignition site, about 120 cm of yellow safety fuse of slow-burning (8–10 $mm.s^{-1}$) gunpowder was placed at the beginning of the cord, giving approximately 2.5 min between ignition and detonation for 1000 m of cord under >200 containers. The fuse was connected to an electric detonator cord containing a white powdered high-explosive core to set off the detonator. This created a shock wave to the detonating cord, along which it travelled at 6400 $m.s^{-1}$, exploding each booster in turn. In 2009 and 2010 the explosive used was Powergel™ (see www.oricaminingservices.com/download/file id 4292/for information on its toxicology), a commercially available ammonium nitrate product, with a detonation velocity of 1780 $m.s^{-1}$ [<6400 $m.s^{-1}$ for TNT (see above), and <8400 $m.s^{-1}$ for pentaerythritol tetranitrate (PETN), which was also used in years before 2006], mixed with aluminium powder to enhance its performance. These charges were connected by cordex fuse cord, made of powdered PETN, to a central electric detonator that started the reaction with 1 g of metallic-derived explosives or after being activated by a slow-burning safety fuse of gunpowder (black powder). When the explosion takes place, the fuel mixture is first splashed up onto the trees where it forms a mist and then ignites." In South Africa, the main explosions are preceded a few milliseconds earlier by a small detonation to scare the birds into the air to improve control and, in reed beds, the firebombs are raised on poles. In Kenya, small stones are sometimes placed in packages above the explosive apparatus. Allan (1997) also describes the method with particular reference to reed beds and he also discussed the drawbacks of the method including its expense and dangers. There is also a security issue given the involvement of explosives and suitably trained military personnel are often required to oversee the operations. This may explain why explosions are not used in Tanzania, for instance.

The method has obvious dangers for the operators and the environment immediately affected by the explosions, but provided that suitable precautions are taken threats to personnel, villagers and livestock can be minimised. It was long thought that explosions were less damaging to the environment than the use of fenthion (e.g. see Meinzingen et al., 1989, Allan, 1997) and Jaeger and Elliott (1989) describe people eating the blown-up birds as benefitting from "a much appreciated source of uncontaminated quelea for food". However, Cheke et al. (2013) showed that explosions are by no means environmentally benign. Many non-target organisms can be killed or maimed (see also reports cited in McWilliam and Cheke, 2004), soil is contaminated with concentrations of total petroleum hydrocarbons (TPHs) and phthalates (from the plastic) ranging from 0.05 to 130.81 (mean 18.69) $\mu g.g^{-1}$ and from 0 to 1.62 (mean 0.55) $\mu g.g^{-1}$, respectively, in the craters formed by the explosions, but the values declined to means of 0.753 and 0.027 $\mu g.g^{-1}$ at 10m away. Dead birds will also be contaminated and thus unfit to eat. One year after an explosion, mean TPHs of 0.865 and mean phthalates of 0.609 were still detectable in the soil. In addition, remains of the plastic did not degrade and littered the sites for years after an explosion, bushes and other vegetation were badly burnt, although the bushes tended to recover unless their trunks were broken, and craters were formed at each firebomb location damaging the soil. More than 1% of the area encompassed by the explosion was damaged in this way.

2.2.2. Nest destruction and chick harvesting

Bashir (1989) described how in some communities such as in western Sudan, quelea nests are destroyed by pulling them out of trees with hooks on the ends of long poles or by cutting down the nest trees or with fire including use of flame-throwers. Nest destruction is only useful if conducted after the birds have laid their eggs, otherwise the birds simply repair nests or move elsewhere to breed, and before any fledglings can fly. Amongst various control methods tried against birds in reed beds where chemical control was prohibited, Garanito et al. (2000) concluded that mechanical destruction of breeding and roosting habitat manually or using tractors dragging brushing equipment was the most cost-effective technique.

Removal of chicks from nests for later consumption for food is also widely practised. Pelham (1998) reported that up to 3.78 kg of chicks could be harvested per person per hour in

Zimbabwe. Reports of the use of quelea as a food source for the rural poor were reviewed and their implications discussed by McWilliam and Cheke (2004).

2.2.3. Trapping

It is well known that in many parts of Africa, people eat quelea as the birds provide a nutritious source of protein (Jaeger and Elliott 1989). Indeed quelea colonies are sometimes not reported to pest control authorities when the villagers want to exploit them for food. Various means of trapping the birds are described below. Quelea consumption for food varies regionally and with the preferences of different ethnic groups but it is known to occur in parts of Botswana, Cameroon, Chad, Ethiopia, Kenya, Nigeria, Senegal, Tanzania, Zambia and Zimbabwe. With the exception of organised operations such as that described in Zimbabwe (Pelham, 1998), most harvesting for food is restricted to small colonies (<10 ha), but see section 2.2.3.1.

2.2.3.1. Chad Traps

In Chad, farmers adapted nets used for fishing to capture quelea. One of three types of nets used were triangular, suspended on long hand-held poles, and held open in front of roosts and closed to capture birds frightened into them. In this way, on moonless nights at tree roosts about 1,200,000 birds were caught over nine weeks (Mullié 2000). As many as 20,000 could be processed per day by a team of six men for later sale in markets as plucked, fried and dried products. The trapping had a negligible effect on the quelea populations, although many such actions conducted by teams can lead to 7,000,000 bird captures over the course of a year, but the revenue from sale of the quelea as food partly compensated the villagers for their crop losses.

2.2.3.2. Kondoa basket traps

In Kondoa District, near Dodoma in Tanzania, farmers catch quelea using basket traps woven in star grass *Cynodon nlemfuensis* Vanderyst (Cheke, 2011). The technique is only used in dry seasons when traps are usually placed with the funnel-shaped opening uppermost near water where the birds come to drink when they are attending “daytime or secondary roosts” or else they are placed in fields. Each basket is baited with grain and heads of millet and, sometimes, with a decoy quelea bird to entice others into the traps. In this way 800 or more birds can be caught per trap per day. The birds are then collected through the hole on the opposite side of the trap after the lid has been removed. The birds are slaughtered, plucked, de-gutted and then prepared as food in a variety of ways (Mtobesya, 2012). So successful are the captures that surplus birds are sold at roadsides and elsewhere leading to profits that help the farmers to buy goods and pay for school fees (Mtobesya, 2012, Manyama et al., 2014).

2.2.3.3. Kondoa basket traps made of wire mesh

Given the success of the Kondoa basket traps in catching quelea, experiments were conducted with artificial versions made of wire-mesh (Mtobesya, 2012). The traps were deployed in the same manner as with the traditional model and found to be superior in their catching ability. Also, wire-mesh traps with 3 entrance holes caught more birds than those with 1 or 2 holes and all of the wire mesh versions caught more than traditional grass basket traps, with peak catches of all traps between 0800 and 1000 hours and between 1500 and 1700 hours (Mtobesya, 2012).

2.2.3.4. Funnel traps

Mitchell (1963) described how very large funnel traps could be used to trap pest birds such as red-winged blackbirds *Agelaius phoeniceus*, common grackles *Quiscalus quiscala*, common starlings *Sturnus vulgaris* and brown-headed cowbirds *Molothrusater* in the United States of America by luring them in with very bright lights (five 1,000 W floodlights). In 101 operations, 672,000 birds were caught and the three best catches yielded 80,000 – 120,000 birds per night. Similarly, such methods have been used to capture common starlings *Sturnus vulgaris* in Tunisia in stands of broad-leaved trees such as *Eucalyptus*, with up to 15,000 caught per night (Elliott et al. 2014). Trials of large funnel traps with attractant strong light have been conducted in Tanzania but with limited success (Elliott et al., 2014).

2.2.3.5. Miscellaneous indigenous trapping methods

Allan (1997) illustrated a variety of basket trap and the means to catch termites to bait it with. Other methods include stick and box traps for which a string is pulled to close the box onto the birds eating bait below, sticky bird lime attached to branches and throwing sticks into the midst of a quelea flock.

2.2.3.6. Mist nets

Mist nets are efficient means of catching flying birds but run the risk of catching non-target birds too, which may be killed or injured if not removed quickly from the nets by trained personnel. In a trial of mist-netting operations to catch quelea in Tanzania, nearly 4000 were caught in 5 days using an average of 18 mist-nets (12m long x 3m tall) per day. Although this total is minimal compared with the totals in pest flocks and is unlikely to be feasible except at small colonies (<5ha), the villagers nevertheless reported that attacks on their crops did decline during the catching (Elliott et al., 2014). If the method is used repeatedly near colonies with eggs rather than chicks, the birds may desert the colony. Mist nets can also be used to catch birds at roosts and have been deployed in Tanzania.

2.2.3.7. Roost traps

Mtobesya (2012) modified the trap roost concept (see section 2.3.6. below) by devising a “roost trap” consisting of netting that could be drawn over a rigid frame erected over a “trap roost” of *Typha* sp. grass. Once the birds had settled to roost the net was pulled over the roost trapping the birds which could then be chivvied into a funnel at one end for capture. Approximately 10,000 quelea were caught per night during trials conducted in Tanzania but the catch also included some non-target species although the majority of these were weaver bird species that sometimes also damage crops (Mtobesya, 2012).

2.3. Cultural Control

2.3.1. Planting and harvest time manipulation

Elliott (1979) and Bullard and Gebrekidan (1989) drew attention to how crop damage by quelea can be minimised if the timings of planting and harvesting can be arranged such that the crop can be harvested when there are few or no quelea present. This method is apt when irrigation facilities are available. Thus in the lower Awash river valley in Ethiopia if irrigated sorghum is planted in September it can be harvested in December when quelea are absent (Bullard and Gebrekidan 1989). Similarly, irrigated rice can be timed for harvesting in mid-May to mid-June in parts of Chad and Cameroon when there are no quelea pests there (Elliott 1979). Harvest time manipulation can also be achieved by growing early-maturing varieties of crops. Even if the latter do not completely escape attack they will be vulnerable for shorter periods than conventional crops (Bullard and Gebrekidan 1989).

2.3.2. Weeding

It is important for farmers to keep their fields as weed-free as possible since quelea are attracted to weed seeds and may thus attack crops that they might otherwise ignore (Luder, 1985, Rodenburg et al., 2014).

2.3.3. Alternative Crops

Crop substitution whereby a crop such as maize, which quelea birds do not attack, is planted instead of vulnerable crops such as millet or sorghum. As maize requires more water to thrive than do millet or sorghum, this measure will only succeed if there is adequate rainfall or irrigation is possible. The socio-economic aspects of substituting for small grain crops and the movement away from winter wheat and barley in Zimbabwe due to quelea attacks has been discussed by Mundy (2000). Other crops that are not attacked by quelea such as groundnuts could also be grown as substitutes.

2.3.4. Quelea resistant crops

Bullard and Gebrekidan (1989) described how plant breeders can produce crop cultivars that have morphological or chemical characteristics that are unpalatable to quelea and Tarimo (2000) reported how bird resistance in sorghum is imparted by the cyanogenic glycoside known as dhurrin. However, unless the majority of farmers in an area plant resistant varieties the birds will simply move away from them to seek more palatable cultivars nearby. Furthermore, resistant varieties with high concentrations of tannins are less palatable to people than conventional varieties. Gressel (2008) described possibilities for a genetic engineering approach to either (a) make sorghum varieties that produce dhurrin only in the developing seeds, thereby preventing livestock eating sorghum forage from being poisoned; and then have dhurrin completely self-destruct on maturity or (b) manipulate the morphology of the seed head such that seeds are more difficult to peck apart or less accessible. At present, these suggestions remain unrealistic and (a) would not benefit subsistence farmers much.

2.3.5. Protecting crops with netting

Allan (1997) described a variety of methods whereby nets were used to cover crops and thus prevent birds from attacking them and Elliott and Bright (2007) recommended covering rice fields with nets to reduce quelea damage in Nigeria. This was tested and found to be worthwhile, with damage varying from 0 to 4% with netting compared with 2.7 to 18.8 % with bird scaring. Yields ranged from 565 to 1,448 $kg.ha^{-1}$ with netting, but were 296 to 1,250 $kg.ha^{-1}$ with bird scaring (Ajayi et al., 2007).

Allan (1997) illustrated how black cotton threads and metallic tapes can be deployed over crops to deter quelea birds. Such methods may be appropriate for commercial farmers or for small-scale cropping but the expense and labour needed to erect and maintain the systems negates their value for subsistence farmers in general. There is also a tendency for quelea to become habituated to such methods and after a few days they may ignore them.

2.3.6. Trap roosts

As it is known that quelea often roost in stands of sugar cane *Saccharum officinarum* L. and Napier grass *Pennisetum purpurum* Schumach., these crops have been deliberately sown to act as “trap roosts” (Jarvis and La Grange, 1989, Allan, 1997). After settling into roosts, the birds then presented a discrete target that could be easily controlled with avicide. Ideally, the roosts should be planted 100m x 100m, with tracks for access on each side. They should also be grown within a few hundred metres of water where the birds can drink before roosting and away from other thickets or similar vegetation that the birds could move to.

2.3.7. Scaring

2.3.7.1. Scaring by humans

Bird-scaring methods were reviewed by Bashir (1989). These include visual techniques such as scarecrows, flag-waving and loud noises, created by elaborate systems of tins and rattles activated by pulling a connecting string or by cracking whips. In addition, missiles may be hurled at the birds or shot from catapults or mud is sometimes flicked at the pests from the ends of sticks. All such methods are time-consuming, often conducted by children who are thus absent from schools, and may be effective locally but scared birds will move to other fields where there are no scaring activities. In Ogun State, Nigeria, scaring costs may account for as much as 50% of production costs (Elliott and Bright, 2007).

2.3.7.2. Scaring with falcons

In Botswana, experiments have been conducted using lanner falcons (*Falco biarmicus*) to scare quelea away from sorghum crops in the Pandamatenga area (H. Modiakgotla, pers. comm., Gaemengwe, 2014). The farmers there reported that the method gave good results and they supported use of the method as it had led to good and high tonnages due to reduced bird damage (H. Modiakgotla, pers. comm., Oct 2016). The latter was estimated as 12.1% of sorghum heads damaged on average in 13 fields where falcons were not deployed, but was about half this figure at 6.3% in 6 fields where the falcons were flown (H. Modiakgotla, pers. comm.). However, use of falcons has only been tested in the commercial farms in the Pandamatenga area and has not been applied to protect crops grown by subsistence farmers.

[Table 1 near here]

2.3.7.3. Commercial bird-scaring devices

In Europe and elsewhere, machines that produce loud bangs at set intervals are available commercially for farmers (e.g. the Bangalore bird-scarer, http://www.nomorebirds.co.uk/bangalore%2Dbird%2Dscarer%7E230) and it is also possible to purchase varieties that produce species-specific alarm calls or predator calls to scare bird pests (e.g. http://www.birdstop.co.uk/bio-acoustic_bird_scarers.asp). This approach was tested against quelea using Bird X-Pellers (http://www.bird-x.com/) by Garanito et al. (2000) and trials with similar devices have been conducted at Pandamatenga in Botswana (H. Modiakgotla, pers. comm.). However, such devices are expensive and the birds are likely to become habituated to them, as they will to other noises used for scaring such as drum beats and tractor horns. An additional possibility is to develop an unmanned aerial vehicle (UAV) or drone that can fly over quelea gatherings and scare them with appropriate noises or with predator-shaped machines. Two such devices have recently been developed for other bird pests (BirdX, 2016). Other novel methods include use of laser beams such as the Agrilaser, either fixed or hand-held, to scare birds off crops (http://www.pestfix.co.uk/agrilaser-autonomic-laser-bird-dispersal-system.asp). However, they have a limited range (approx 600m) and are too expensive for use by subsistence farmers, but might be applicable in commercial farms.

2.4. Biological control

Barre (1974) reviewed the parasitology of *Q. quelea* to seek potential biological control agents, but failed to identify any pathogen capable of causing an epizootic that might limit the bird's populations. Barre recommended a worldwide survey of avian viruses occurring outside Africa and experimental checks to see if any were highly pathogenic to quelea.

Q. quelea are hosts to a variety of blood parasites (see Durrant et al., 2007 for surveys of some found in *Q. q. lathamii*), but none seem to cause morbidity. However, some taxa may be species specific and, if so, there is a possibility that future progress in genetic manipulation might allow the introduction of lethal forms of haematozoa.

Quelea are taken by a variety of predators (Thiollay, 1989) but these have a negligible effect on the huge numbers of the pest birds, except occasionally when flocks of storks and birds of prey locate breeding colonies.

Quelea and their colonies have a sharp and distinct odour, quite unlike that of any other bird's odour. Since many other species with acute olfactory abilities also have sharp odours, this suggests that odour-based cues serve a communication function in quelea. Likely functions include acting as either a group-specific identification mechanism and/or as a colony- or roost-locating mechanism for either new entrants to colonies, or roosts, and birds returning to their nests or roosts after foraging. In an attempt to identify any biologically active odours that might show promise as attractants to traps or as repellents, samples from birds of the nominate race *Q. q. quelea* were analysed but no compounds of interest were found (R. A. Cheke, D. R. Hall and D. Farman, unpublished data). Samples from other subspecies (*Q. q. lathamii* and *Q. q. intermedia*) were also analysed but again no promising compounds were detected. However, none of these samples were from actively breeding birds, which should be the subject of future research on this topic.

Feral pigeons (*Columba livia*) can now be controlled by using nicarbazin as a contraceptive, dispensed in maize mixtures (Albonetti et al., 2015), but unless places where only *Q. quelea* would be feeding this method would pose dangers to non-target birds.

3. Comparison of red-billed quelea control methods with the desert locust preventive control approach

Control of quelea is only advised when the birds are posing a direct threat to a crop (Ward 1972, 1973, 1979). The mere presence of the bird does not justify lethal control as they are often innocuous, especially when their preferred grass food is plentiful. Thus, strategies for dealing with the birds differ markedly from the "preventive control" approach (FAO 2001, van Huis et al., 2007, Magor et al., 2008) applied to other migrant pests such as the desert locust (*Schistocerca gregaria*), and the "strategic control" policy for control of the African armyworm (*Spodoptera exempta*) (Rose et al., 2000, Cheke and Tucker, 1997). For locusts and armyworm, control strategies require "off the crop monitoring" and lethal control as soon as the pest's populations rise. In this way, if all proceeds according to plan, the pest's population is prevented from reaching numbers high enough to cause severe damage to crops. Also, locusts and armyworm are remarkable insofar as they change "phase" from the solitarious state to the gregarious condition, a change associated with accelerating population growth (Cheke, 1978, 1995) that does not occur in birds. One of the aims of the strategic approach to locust and armyworm control is to ensure that the pests do not succeed in changing phase to become gregarious and swarm.

Elliott (2000a) pointed out that FAO's approach to quelea control was to adopt Integrated Pest Management (IPM) approaches whenever possible and only to use lethal control as a last resort. IPM approaches include many of the options listed above such as "modifying crop husbandry, planting time, weed reduction, crop substitution, bird scaring, exclusion netting etc." Elliott (2000b), in discussing management practices prevalent at the time in Eastern and Southern Africa, also emphasised that economic constraints and the environmental impact of pesticides were leading to consideration of more sustainable IPM approaches.

4. Recommendations for quelea control minimising the extent of fenthion use

4.1. Forecasting and control planning

Quelea breeding colonies are often not located in time to control them before the fledgling birds, the juveniles responsible for much of the crop damage at this stage in the birds' life cycles, have left their nests. Similarly, if birds which are attacking crops can breed successfully then the populations available to attack crops will be augmented. However, if the efficiency of control operations could be improved, then the quantities of fenthion used could be reduced. One way of improving the efficiency of control strategies is to detect the presence of suitable quelea breeding areas by satellite imagery (Wallin et al., 1992) or to forecast where the birds are likely to breed. Given that the birds' migrations and breeding opportunities are determined by patterns of rainfall (Ward, 1971), it is possible to devise forecasting systems to predict where the birds are likely to breed and, thus, to concentrate activities in search of the colonies to areas where the birds are likely to be for control purposes (Cheke et al., 2007). A scheme based on the model described by Cheke et al. (2007) that used satellite-derived rainfall data and knowledge of the threshold amounts of rainfall needed to (a) initiate the migrations at the start of seasons ("early rains migrations") and (b) to permit the birds to breed was maintained online as a forecasting system from 2001 to 2009, but fell into disuse when the funding for it ceased. That system was for southern Africa only, dealing with populations of *Q. q. lathamii*, but it is possible to develop a similar system for a pan-African set of forecasts and a prototype model for East Africa was developed (J. Venn and R. A. Cheke, unpublished, Mtobesya, 2012). Regrettably, no system of forecasting where quelea roosts will appear in dry seasons has been devised, other than a recommendation to survey sites known to be traditional insofar as they are used regularly year after year.

4.2. Fenthion dosages

There is marked variation in the dosages used by different control organisations. For instance at a workshop in Machakos, Kenya during May 2005, it was reported that Sudan controlled their birds successfully at rates of 1 $l.ha^{-1}$ (occasionally only 0.5 $l.ha^{-1}$), DLCO-EA usually used 2-4 $l.ha^{-1}$ but South Africa reported use of dosages ranging from 7 $l.ha^{-1}$ up to as high as 14 $l.ha^{-1}$. Clearly, less fenthion will be used if the dosage is minimised, with 2-4 $l.ha^{-1}$ recommended. Amounts used by Tanzania during the 2012-2016 period were mostly within this range and were generally lower in the later years (Table 2), a difference which was significant for the roosts (ANOVA, $p < 0.0001$) so an encouraging trend of gradual dosage reductions was achieved. Interestingly the dosages sprayed on colonies (sample mean 2.66) were consistently and significantly less than those deposited on roosts (sample mean 3.51; Welch two sample t test, $t = 8.82$, d.f. = 171, $p < 0.0001$), so if this result is also true elsewhere other control teams could probably minimise potential environmental damage by reducing dosages sprayed on roosts to the levels used on colonies without affecting control rates.

[Table 2 near here]

4.3. Fenthion application methods

Studies of environmental effects of fenthion applications revealed that in some cases sprays were conducted incorrectly with regard to speeds and directions of movements of ground-sprayers in relation to wind directions, failing to cease sprays when turning vehicles, incorrect nozzle positioning, equipment maintenance and missed targets during aerial applications (Cheke et al., 2013). Therefore regular training and supervision of pest control workers is recommended, as is correct use of equipment to minimise excessive contamination of the environment and risks to personnel. Furthermore use of the most appropriate equipment may reduce quantities of fenthion needed. For instance, in Tanzania use of ground-based sprays with Micronair AU8000 sprayers required 10% of the volume used by aircraft (B. Mtobesya, pers. comm., October 2016). Training of farmers in quelea biology and IPM principles for damage avoidance and minimisation through farmer field schools is advised. Spray operators also need to know what to do in the case of accidental contamination, which involves washing any affected area immediately with soap and water and discontinuing any further operations until the cause of the contamination has been corrected.

The use of unmanned aerial vehicles (drones) for spraying operations would ensure accurate targeting but to date the size of maximum possible payloads has precluded their use. Recent developments have succeeded in increasing payload possibilities up to 80 litres (E. van der Walt, pers. comm., Nov. 2016) so in future this technique may become usable.

5. Recommendations for quelea control without fenthion: a strategy for bird control using selected methods of control

The appropriate control measure to be adopted against quelea will vary depending upon the circumstances (Table 1). Most of the IPM measures described above will seldom be effective on their own, except at scales when infestations are small relative to massive swarms of millions of birds or huge breeding colonies: one colony in March 1998 at Malilangwe in Zimbabwe was 20km long and 1km wide, with nests at densities of 30,000 nests per hectare (Dallimer, 2000). Ideally, an economic cost-benefit analysis should be made prior to each control operation as the overall objective is to find the optimal level of pesticide use, taking into account the availability of non-pesticide alternatives and even compensation for crop losses. As proposed by Agne et al. (1995), an economic assessment of pesticide use needs to be considered within a framework that covers both the farmer's and society's points-of-view. Thus, the farmer would be expected to maximise expected net returns, with gross returns from control equal to prevented crop losses in monetary terms. In contrast, the aim of society in deciding how much pesticide or explosives to apply is to maximise net social benefit, taking into account negative externalities such as environmental contamination and health.

However, by combining judicious planning of crop choice and of planting and harvesting times before any expected quelea arrivals with environmentally benign control methods, the cultural control and IPM strategy will succeed under some circumstances. Nevertheless, faced with crop raids by huge quelea flocks, farmers and those in their country responsible for the control will have little choice other than to authorise lethal control with pesticides (cyanophos or other alternatives to fenthion) or explosives. The scheme outlined in Figure 1 is an attempt to provide guidelines on how to minimise chemical use and their unintended effects, together with suggestions on the circumstances under which alternative methods would be appropriate within the context of subsistence agriculture rather than commercial operations.

Table 1. Summary information on alternatives to use of fenthion for quelea control.

Method	Application	Mode of action	Advantages	Disadvantages	Socio-economic issues
Chemical Methods					
Cyanophos	Spray	Lethal organophosphate avicide.	Less toxic than fenthion. Colonies and roosts of any size can be treated	High risk of environmental impacts. (Mullié et al., 1999, Cheke et al., 2013) Killing action takes longer than fenthion, so could lead to more secondary poisoning than fenthion. (Allan, 1997)	More expensive than fenthion. (Fenthion costs approx. US$10 per litre [www.yufull.com]). Requires trained personnel and expensive equipment, e.g. applied by Government personnel or international control agencies.
Alphachloralose	Narcotic added to bait grain or water (Garanito et al., 2000)	Immobilises birds.	Minimal pollution.	Risk to non-target birds. Requires birds to be found and killed. Only possible for small sites (< 5ha)	Labour intensive.

Mesurol (Bruggers 1989)	Sprayed on seed heads of crops or applied as seed dressing.	Carbamate pesticide, active ingredient methiocarb. Repellent. Deters birds from crops. (Allan, 1997)		Risk to non-target birds and mammals. Highly toxic to aquatic fauna. Now not recommended for direct use on crops, only as seed dressing. Now banned by the EU.	Expensive. Approx. US$300 per litre. Labour intensive.
Mechanical Methods					
Explosions (Cheke et al., 2013)	Diesel/petrol-eum firebombs detonated beneath birds.	Lethal	No organophosphates or aircraft involved.	Risk to non-target birds and mammals. Petroleum product residues pollute soil. Vegetation damage. Fire and security risks. Only possible for small sites (< 5ha)	Expensive. Requires trained personnel and expensive equipment, e.g. applied by Government personnel.
Nest destruction and chick harvesting (Bashir 1989, Jaeger and Elliott, 1989)	Human intervention with sticks on poles or flame throwers	Lethal	No pollution. Provides source of protein.	Labour intensive. Often possible only on small scale (colonies <10ha) but see Pelham (1998).	Profits possible, if surplus chicks sold as food or livestock feed.

Trapping with Chad or basket traps or other trapping methods (Mullié et al., 2000, Mtobesya, 2012)	Human intervention with various trap designs.	Lethal	No pollution. Provides source of protein.	Labour intensive. Often possible only on small scale (areas <10ha).	Profits possible, if surplus birds sold as food or livestock feed, e.g. annual value of US$50,000 to 100,000 in Chad (Mullié et al., 2000).
Trapping with mist nets (Elliott et al., 2014)	Human intervention with various trap designs.	Lethal	No pollution. Provides source of protein.	Labour intensive. Often possible only on small scale (areas <10ha). Needs supervision to avoid non-target mortalities.	Profits possible, if surplus birds sold as food or livestock feed. Locally sourced nets at cost of only US$5 each.
Roost traps (Jarvis and La Grange, 1989, Allan, 1997, Mtobesya, 2012).	Planting of fodder crops to attract birds to roost, followed by spraying.	Lethal		High risk of environmental impacts. Possible only on small scale (areas <10ha).	Loss of area where crops could be planted.
Cultural Methods					
Planting and harvest date manipulation (Elliott, 1979,	Planting of fast-maturing crop varieties or early	Avoidance of quelea attacks on crops.	No pollution. Can be done on large scale	Not always possible. Requires knowledge of likely quelea movements into and out of cropped	Agronomic advice needed.

Bullard and Gebrekidan 1989)	harvesting to minimise risk of quelea at harvest. Planting of crops that are not susceptible to attacks.			zone. Alternative crops may not flourish in zone, especially in very arid areas.	
Netting crops (Elliott & Bright, 2007)	Covering crops with netting	Protective	No pollution.	Only on small scale. May just divert birds to crops with no netting present.	Expenditure on nets and poles or gantry to rig them on
Scaring by people (Bashir, 1989)	Farmers and their children scare birds	Birds frightened away from crops by waving and noise.	No pollution.	Labour intensive. Often possible only on small scale. May just divert birds to crops with no scarers present.	Prevents children attending school. Labour intensive.
Scaring with falcons (Gaemengwe, 2014)	Release of falcons near quelea flocks.	Birds frightened away from crops.	No pollution.	Requires trained birds and bird handlers. May just move quelea to fields where falcons not deployed.	So far only used by large scale commercial farmers not by subsistence farmers.

Biological Methods

No successful biological control

agents identified to date.

Table 2. Dosages of fenthion (litres.ha^{-1}) sprayed on quelea roosts and colonies in Tanzania during the 2012-2016 seasons. Means and standard deviations calculated from raw data on spraying operations reported by Mutahiwa (2016). n = sample size; SD = standard deviation.

Year	2012	2013	2014	2015	2016
Roosts					
Mean litres.ha^{-1}	4.79	4.03	4.20	2.72	2.98
n, SD	21, 3.95	12, 2.50	10, 2.85	30, 0.56	31, 1.92
Range	1.25 – 15	1.5 – 10	1.67 – 10	2.22 – 4.76	0.55 – 10
Colonies					
Mean litres.ha^{-1}	1.63	3.02	3.08	2.5	2.47
n, SD	11, 0.76	10, 2.92	33, 1.82	1, -	31, 1.92
Range	0.67 – 3.33	1.43 – 11.11	0.73 – 10	-	0.62 – 10

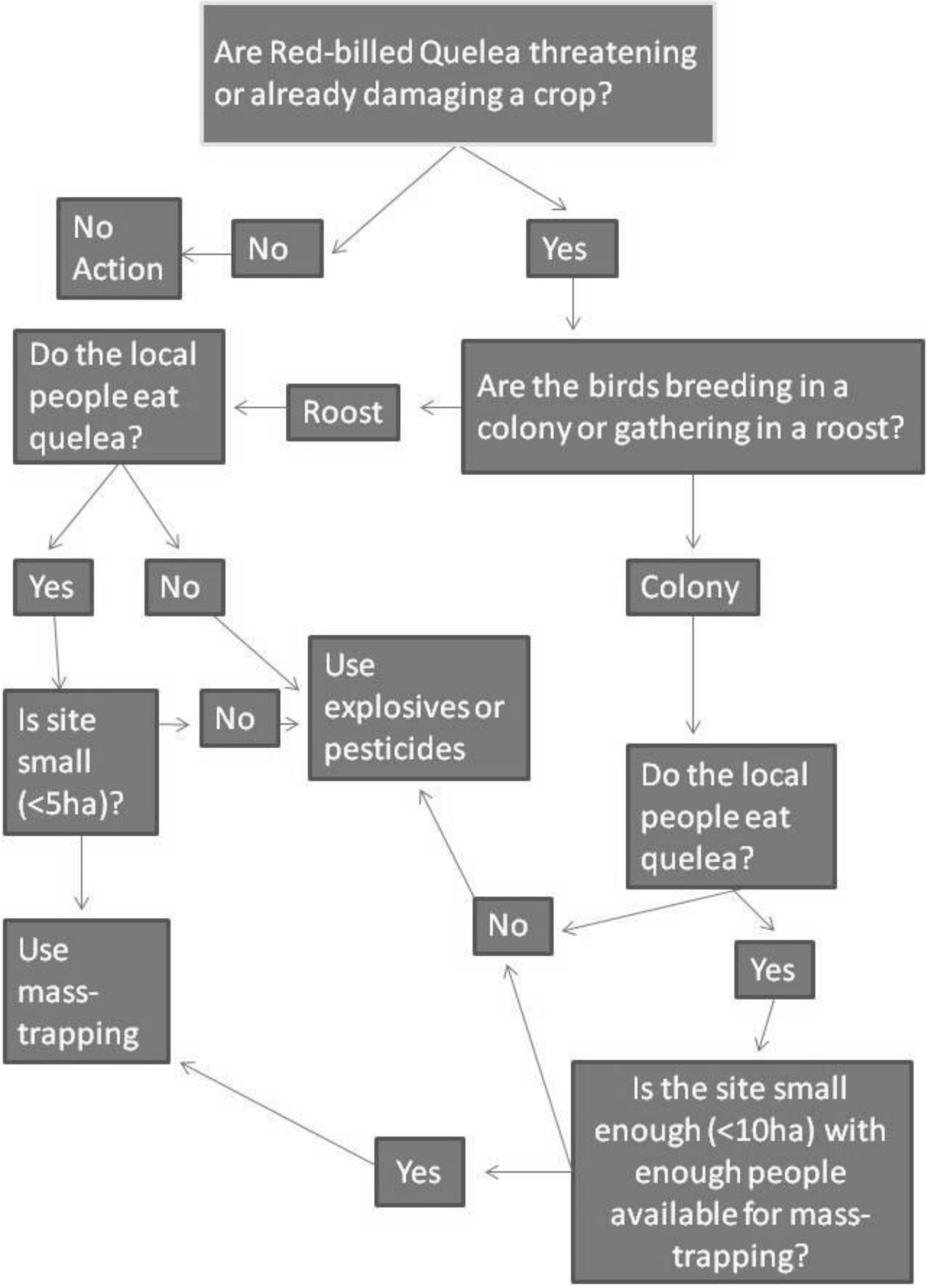

Figure 1. Flow diagram of decisions for planning quelea control by responsible authorities for subsistence farmers.

Disclaimer

The views expressed in this information product are those of the authors and do not necessary reflect the views or policies of FAO.

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