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Insecticide Use against Desert Locust in the Horn of Africa 2019–2021 Reveals a Pressing Need for Change

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Abstract: The desert locust upsurge in the Horn of Africa over 2019–2021 led to a total of 1.6 million ha being treated with broad-spectrum organophosphate and pyrethroid insecticides in Ethiopia and Kenya, while insect growth regulators and the entomopathogenic fungus *Metarhizium acridum* were applied in Somalia. Environmental monitoring was largely absent, with limited surveys conducted in Kenya and Ethiopia. Overdosing of fenitrothion of a 960 g/L formulation in Kenya led to non-target mortality, including birds and honeybees. In Ethiopia, chlorpyrifos and malathion applications coincided with a honey production decline of 78% in 2020 compared to pre-upsurge levels. The use of *M. acridum* on nearly 253,000 ha was a breakaway from previous campaigns, in which its successful application in Somalia against both hopper bands and swarms shows that the persistent and pervasive use of organophosphate insecticides can no longer be justified. Furthermore, future procurement of organophosphate insecticides and possibly insect growth regulators could become increasingly problematic due to measures enacted by the European Union. It is recommended that the complementary impact of *M. acridum* and bird predation on locusts should be considered in an integrated management approach for both swarm and hopper control.

Keywords: *Schistocerca gregaria*; East Africa; chlorpyrifos; fenitrothion; malathion; deltamethrin; teflubenzuron; *Metarhizium acridum*; environmental monitoring; honeybees; bird predation

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1. Introduction

Desert locust *Schistocerca gregaria* (Forskål, 1775), hereinafter referred to as DL, upsurges and plagues can destroy harvests and pastures over vast areas and potentially plunge entire communities into famine. Locusts have two different phases: solitary and gregarious [1]. At low densities, individuals are solitary. When their numbers and densities increase, they become gregarious [1]. Gregarious wingless nymphs, so-called hoppers, congregate in bands moving together. The adult gregarious locusts can eat the equivalent of their body mass daily and form dense swarms that can move over long distances [2]. The 2003–2005 DL upsurge claimed to have destroyed 80–100% of crops in affected areas [3], inflicting a major impact on food security and rural livelihoods through (i) food shortages; (ii) strong price movements in domestic markets; (iii) loss of grazing areas; (iv) distress sales of livestock at low prices to meet the subsistence needs of the households and to buy feed for the remaining animals; (v) early transhumance of the herds; (vi) increased tension between transhumance pastoralists and local farmers over resources; and (vii) extensive migration to urban areas [3].

In 2018 a new DL threat to livelihoods developed in the Middle East, spreading westwards in 2019 and 2020 to the Greater Horn of Africa and eastwards to India and Pakistan. In this paper, we apply a definition of the Horn of Africa that includes the following countries under the Food and Agriculture Organisation of the United Nations

(FAO) campaign, namely Djibouti, Eritrea, Ethiopia, Kenya, Somalia, South Sudan, Sudan and Uganda [4].

It is suggested that warming anomalies in the Indian Ocean Dipole caused by climate change gave rise to a multitude of cyclones, which brought about unusual rainfall and vegetation greening, triggering the development of gregarious DL populations [4]. Multiple generations of breeding were undetected, allowing the upsurge to transpire [5,6]. Of note, such extreme weather events may become more frequent in the (near) future under climate change [6,7].

In the three countries that are central to this paper, namely Ethiopia, Kenya and Somalia, the massive invasions of DL overwhelmed existing control capabilities [8]. These countries were selected for the analysis because they were the most affected by the desert locust incursion in the region, and verifiable data were made available from FAO-deployed experts in the field [9]. The locust invasion in Ethiopia and Somalia has been described as the worst in 25 years, whereas Kenya faced its most significant outbreak in 70 years [9]. To control the upsurge, Ethiopia and Kenya initially applied previously-stored insecticides aimed at other agricultural pests, which were in most cases unfit for purpose, being too toxic or lacking efficacy against locusts [10]. These compounds belonged to various chemical families, such as organophosphates, carbamates, pyrethroids, and neonicotinoids, which will be further detailed in Section 3.2.

The FAO, whose mandate includes DL monitoring, forecasting and control, procured "conventional" insecticides, namely chlorpyrifos, malathion and fenitrothion (organophosphates) and deltamethrin (pyrethroid), as well as the insect growth regulator (IGR) teflubenzuron and the bio-insecticide *Metarhizium acridum* to control the upsurge [11]. These substances were chosen in consultation with the affected countries and financed through donor contributions. The selection and specifications would have needed to comply with the assessments by the Pesticide Referee Group (PRG), which was renamed into Locust Pesticide Referee Group (LPRG) in 2021 [12,13].

Overall, in all but one affected countries, broad-acting compounds that affect not only DL but also non-target organisms were the order of the day. A viable biological alternative, *M. acridum*, which has been commercially available for the past two decades, was only used operationally in Somalia [14–16]. Therefore, in this study, the differences in DL control in Kenya, Ethiopia and Somalia with respect to environmental health impacts and in comparison to past campaigns are analysed. The needed changes to achieve sustainable locust management are discussed based on the following questions:

1. What changes in the choice of insecticides have been made as compared to previous DL campaigns? What are the differences in insecticide choice among the three countries between August 2019 and December 2021?
2. Which environmental side-effects were observed, and how were these impacts assessed?
3. How could the control of DL populations, dominated by chemical insecticides, be replaced by biological management using *M. acridum* and other nature-based solutions, in particular, predators such as locust-eating birds?

2. Materials and Methods

This paper examined primary and secondary data sources to answer the research questions. Both qualitative and quantitative data types were used. A historical overview of two previous DL upsurges and a review of environmental health side-effects were conducted via examination and synthesis of existing scientific literature, environmental reports, media sources and through correspondence with specialists. However, verifiable quantitative information on environmental health impacts proved to be difficult to obtain as no such studies, and very limited monitoring had been done during the 2019–2021 campaign. Only three FAO environmental and human health monitoring reports, two in Kenya [15,16] and one in Ethiopia [17], were available. In the absence of surveys, the results of experimental studies since 1989 on the impact on birds from both chemical and biological locust control in Africa were analysed [18–21]. Systematic assessment of human health side effects is beyond the scope of this study.

To compare DL control in Ethiopia, Kenya and Somalia, daily summarised information on the use of insecticides between August 2019 and December 2021 was obtained from the FAO Locust Hub website [22], and detailed monthly information from October 2019 to December 2021 was obtained from the FAO's SWARMS database provided by the Senior Locust Forecaster [23]. FAO information from the 2019–2021 campaign relied on the "eLocust" data system, which now represents the foundation of the FAO's desert locust early warning system (EWS). The functioning of the EWS is as follows. The data are used for assessing the current situation, forecasting its developments, and planning a response at all levels [24]. The handheld eLocust device transmits data by Inmarsat to the respective National Locust Control Centre (NLCC). The data are imported into a custom geographic information system, GIS (RAMSES), used by each NLCC. From RAMSES, data are sent to the FAO's Desert Locust Information Service, where these are checked and corrected before importing into a custom global GIS (SWARMS) that is used to analyse the field data [24].

Data extracted from the field database were the following: Application Type (barrier or full cover), Control Method (air, vehicle, backpack or handheld), Pesticide Name (in our study, we analysed six FAO-procured pesticides, i.e., chlorpyrifos, malathion, fenitrothion, deltamethrin, *M. acridum* and teflubenzuron), Date (of application), Country (only Ethiopia, Kenya and Somalia), Latitude (decimal degrees), Longitude (decimal degrees), Pesticide Quantity Sum (litres), Protected Area Sum (hectares protected by barrier treatments) and Sum Area Treated. The SWARMS data, however, were incomplete. Hence, missing data (aerial spray data only) for Kenya from March to October 2020 were obtained from the FAO's Field Operations Officer [25] and verified using the data in the FAO Mission Report [26].

Data on FAO-recommended insecticides for locust control and insecticides assessed for efficacy and environmental and human health impacts were retrieved from the PRG [12] and LPRG [13] assessment reports. Data on nationally authorised insecticides were retrieved from official websites and publications of the national insecticide registration authorities or other relevant governmental bodies of Ethiopia [27], Kenya [28] and Somalia [29]. The Moroccan registration authority [30] was also included for comparative purposes since the country has mirrored efforts to avoid the insecticides that are no longer allowed in the European Union (EU).

Landcover data used in this paper were sourced from the European Space Agency's WorldCover 2020 [31] with a resolution of 10 m and a 75% overall accuracy based on Sentinel-1 and 2 data. The WorldCover products are delivered in a regular latitude/longitude grid (EPSG:4326) with the ellipsoid WGS 1984 (Terrestrial radius = 6378 km) as 3 × 3-degree tiles. The legend includes 11 generic classes that describe the land surface at 10 m: "Tree cover", "Shrubland", "Grassland", "Cropland", "Built-up", "Bare/sparse vegetation", "Snow and Ice", "Permanent water bodies", "Herbaceous Wetland", "Mangrove" and "Moss and lichen".

3. Results and Discussion

This section proceeds to address the research questions over three sections. Section 3.1 provides a historical review of the past two DL campaigns with a focus on the protection of environmental and human health and their legislative implications, as well as insecticide regulation. Section 3.2 compares the recent campaigns in Kenya, Ethiopia and Somalia, analyses respective environmental reports and considers the impact of the applied insecticides on birds and especially on honeybees and apiculture. The case for *M. acridum* is introduced. Section 3.3 focuses on the role of bird predation in relation to the effect of *M. acridum* on DL.

3.1. Historical Review: The 1986–1989 Plague and the 2003–2005 Upsurge

During previous DL plagues and upsurges, most notably the 1986–1989 plague and the 2003–2005 upsurge, it became increasingly clear that unpreparedness for rapidly developing gregarious locust populations leads to panic interventions and the use of unsuitable insecticides, either by their inefficacy or by their toxicity for human health and the environment. Several essential lessons were learnt, which led to important improvements in insecticide choice and protecting human and environmental health [3,32,33]. It is therefore relevant to summarise these to address the deviations, compliances and innovations during the 2019–2021 upsurge.

According to Showler et al. [5], during the 1986–1989 DL plague, 25 million ha of land in 23 countries were treated against DL. This was the last campaign in which the Persistent Organic Pollutant (POP) organochlorine insecticide dieldrin was used, mainly in barrier treatments. In a barrier treatment, typically, only one or two 50–100 m wide spray swaths per km are treated [34] as opposed to a blanket spray. Other persistent organochlorines, such as aldrin, DDT and Lindane, all of which were later listed in the Stockholm Convention on POPs due to their mutagenic, teratogenic or carcinogenic characteristics and resistance to degradation when released into the environment, were also used in the campaign [35]. In addition, organophosphates such as dichlorvos, diazinon and parathion and the carbamate propoxur were applied [33]. Many of these products, such as diazinon and dichlorvos, are highly toxic to vertebrates, including humans and birds [36].

The indiscriminate use of broad-spectrum insecticides, with the potential for human intoxications and the lack of properly executed environmental side-effect studies, led to:

1. The establishment of an independent group of scientists, the PRG, whose role was to advise the FAO on efficacy trials and the choice of insecticides having the least environmental and human health impact;
2. A multi-compartment pilot study to quantitatively assess environmental side-effects of the insecticides fenitrothion, chlorpyrifos and diflubenzuron [37] and the subsequent establishment of the Locustox Project (later CERES/Locustox Foundation), which conducted research into the environmental and human health effects of locust control insecticides in West Africa [38], and;
3. A consortium called LUBILOSA (Lutte Biologique contre les Locustes et Sauteriaux) was formed to develop a mycoinsecticide, which was selective towards acridids (locusts and grasshoppers) [39].

During the 2003–2005 upsurge, organochlorines that had been used on a large scale during the 1986–1989 plague were replaced by organophosphates and carbamates, both cholinesterase inhibitors. The 2003–2005 upsurge started in Western Africa, extending from Senegal to Chad. During the campaign, 12.9 million hectares were sprayed against DL, with the dominant control agents being the organophosphates chlorpyrifos, fenitrothion and malathion and the pyrethroid deltamethrin [3]. Their high and acute toxicity would cause mobile locust targets to die on a large scale and rapidly. However, the use of these insecticides could also lead to a re-invasion of locusts within weeks [18], see Appendix A, Figure A1.

The upsurge was characterised by a number of issues concerning human and environmental health, such as a lack of trained personnel, a lack of personal protective equipment, a lack of equipment for the safe destruction and disposal of empty insecticide containers, excess insecticides in storage post-campaign, impurities in the physical and chemical properties of insecticides [40] and soil contamination at loading sites [41]. However, efforts to prevent environmental and human health impacts were also made and are explored in the following subsubsection.

3.1.1. Protection of Environmental and Human Health and Relevant Regulations

Ever since Rachel Carson's (1962) "Silent Spring" [42], scientists have warned about the adverse effects of chemical pest control, including on their natural predators—birds, mammals, reptiles, insects and spiders. Furthermore, acridid control has been documented to lead to secondary outbreaks, either within the same year [43] or the next year [44]. Consequently, after the 1986–1989 DL plague, the FAO produced a series of specialised guidelines. Three guiding documents relevant to the protection of the environment and human health were developed and subsequently promoted in DL interventions:

1. The evaluation of data from field trials on the efficacy and selectivity of insecticides on locusts and grasshoppers [12,13];
2. The Desert Locust Guideline 6: Safety and Environmental Precautions [45] (currently under revision);
3. The Manual for the Implementation of Environmental, Health and Safety (EHS) Standards for the Control of Locusts [46], which was based on the Commission for Controlling the Desert Locust in the Western Region (of the DL distribution area) "Cahier des charges environnementales" but was only published after the 2019–2021 upsurge.

Due to growing concerns over the use of synthetic insecticides and the absence of new products evaluated for locust control, in 2021, the LPRG report [13] placed renewed emphasis on the least toxic compounds that had already been evaluated in relation to human health and environmental impacts, provided they are effective against the locust target. To give more guidance to affected countries, insecticides with verified dose rates were listed by priority, as had already been done in a previous 2014 edition of the PRG report [12]. Table 1 provides the full list of LPRG-approved insecticides. The bio-insecticide *M. acridum* was presented as Priority 1 for it is selective to acridids with no impact on other organisms [18,20], and IGRs as Priority 2. The LPRG further recommended countries speed up the registration of *M. acridum*. Broad-spectrum neurotoxic insecticides, such as fipronil and organophosphates malathion, chlorpyrifos and fenitrothion, were placed last at Priority 3.

Table 1. Verified dose rates of insecticides for DL control. Adapted and simplified from Tables 2a and 7 in LPRG [13]. Blanket dose rates are for both adults and hoppers.

Insecticide	Priority	Dose Rate (g a.i./ha) [1]			Speed of ACTION	Primary Mode of Action
		Blanket	Intra-Barrier	Overall		
M. acridum	1	50	-	-	Slow	Mycosis
triflumuron	2	25	75.6	10.7	Slow	Chitin synthesis inhibition
teflubenzuron	2	30	n.d.	n.d. [2]	Slow	Chitin synthesis inhibition
diflubenzuron	2	30	100	14.3	Slow	Chitin synthesis inhibition
lambda-cyhalothrin	3	20	-	-	Fast	Na channel blocking
deltametrhrin	3	12.5 or 17.5	-	-	Fast	Na channel blocking
malathion	3	925	-	-	Medium	AchE inhibition
fipronil	3	-	4.2	0.6	Medium	GABA receptor blocking
fenitrothion	3	400	-	-	Medium	AchE inhibition
chlorpyrifos	3	240	-	-	Medium	AchE inhibition

[1] A blanket dose rate is the dose of an insecticide used on the entire surface area. The overall dose rate is used when an insecticide is sprayed in a barrier treatment where only strips of a given surface area are being treated to protect a larger area. In general, this is with a higher dose rate within the sprayed strips (barriers). Overall dose rate refers to the total active ingredient used in the sprayed barriers divided by the surface of the protected area. [2] LPRG [11] did not establish an overall dose rate for teflubenzuron. Based on 52,000 L used to protect 159,000 ha in Somalia, obtaining 98% efficacy in May and June 2021, the dose rate of teflubenzuron was 9.8 g a.i./ha [47].

3.1.2. Locust Insecticides and International Registration

Chlorpyrifos, fenitrothion and malathion are considered moderately hazardous, Class II, but acutely toxic to bees [48]. These organophosphates are commonly referred to as nerve agents because they inhibit the enzyme cholinesterase. Chlorpyrifos is a possible [49] and malathion a probable human carcinogen [50]. Organophosphates are also groundwater pollutants and reproductive and developmental toxicants [51]. Fenitrothion is registered in the USA only for containerised ant and roach baits in child-resistant packaging [52]. In the EU, it only has an authorisation as an insecticide on tomato and grapevine. However, the acute, short- and long-term risks to birds and the long-term risk to mammals from the uptake of contaminated food items were assessed as high in tomato and grapevine outdoor uses. Consequently, further risk refinement steps are necessary to address the risk to birds and mammals [53]. Based on studies on the impact of DL control using chlorpyrifos and fenitrothion on birds, Mullié [18] concluded that the use of both compounds in DL control should be discontinued. In addition, high dermal chlorpyrifos toxicity resulting in mass mortality in reptiles (*Acanthodactylus* lizards) has been documented previously in Mauritania [54] and population declines and mortality observed in Niger [55]. Furthermore, chlorpyrifos is classified as presenting the third highest risk by contact exposure to honeybees out of a list of 92 pesticides assessed [56]. LPRG lists all assessed organophosphate insecticides as presenting high risks to bees and other pollinators [13].

On 18 August 2021, the U.S. Environmental Protection Agency announced it would end the use of chlorpyrifos on all food products nationwide, whereas a decision on phasing out most non-agricultural applications was adopted in 2001 [49]. In 2019, the European Food Safety Authority declared that chlorpyrifos poses "*concerns related to human health, in particular in relation to possible genotoxicity and developmental neurotoxicity*" [57]. On 6 December 2019, the EU announced that it would no longer permit sales of chlorpyrifos after 31 January 2020 [58].

The EU further proposed chlorpyrifos to be listed in Annex A to the Stockholm Convention on POPs in October 2020, and a draft risk profile was published in April 2022 [59]. As a reason for this proposed listing, EU Council Decision 2021/592 (2021) states that:

> *"Although chlorpyrifos has been phased out in the Union, it appears that it is still used as a pesticide and dispersed in the environment outside the Union. Due to the potential for long-range environmental transport of chlorpyrifos, the measures taken nationally or at Union level are not sufficient to safeguard the high level of protection of the environment and human health. Wider international action is therefore necessary".*

Furthermore, the EU Commission's Implementing Regulation 2022/801 of 20 May 2022 did not approve fipronil, diflubenzuron, teflubenzuron and triflumuron for use in the EU market. Of note, non-approval for the EU market does not automatically imply that the risks are unacceptable in the EU. It can also mean a voluntary retraction by the registrant (a more effective alternative available; possible additional studies needed for re-approval are too expensive; the market too small, etc.). Nevertheless, the argument for the non-approval of diflubenzuron was the formation of a metabolite 4-chloroaniline, which was considered genotoxic and a reproductive toxicant.

If the LPRG [13] list of agents for DL control (presented in Table 1) is examined from the EU regulations perspective, only two pyrethroids remain available. Consequently, future procurement of organophosphate insecticides and possibly the IGRs listed for DL control could become increasingly problematic. Especially that the donor community, which includes the EU, is currently financing the bulk of insecticide provisions through the FAO, it could face increasing public scrutiny. Furthermore, the fear of insecticide residues in exported food crops could force the affected countries to adapt their legislation. The example of Morocco demonstrates that this process has already started in anticipation of EU measures. Only four insecticides are currently registered for locust control in Morocco: deltamethrin, lambda-cyhalothrin, diflubenzuron and *M. acridum* [30]. In Morocco, deltamethrin and lambda-cyhalothrin, both pyrethroids, can be used for control of swarms on, respectively, crops and non-cropland, whereas *M. acridum* and diflubenzuron are for selective control of hopper bands. A derogation can still be issued for remaining stocks of malathion and chlorpyrifos in case of a locust upsurge/invasion for use in desert areas.

3.2. The 2019–2021 DL Campaign in Ethiopia, Kenya, and Somalia

More than one million litres of "conventional insecticides", i.e., chlorpyrifos, malathion, fenitrothion, deltamethrin and the IGR teflubenzuron, were delivered to the region [31]. The number of litres provided by the FAO regrettably does not inform us about product concentration. To address this limitation, in the following Section 3.2.1. Environmental Monitoring in

Kenya and Ethiopia, we investigated cases where the data on product concentration and dose rates were known. Of note, 13,000 kg of *M. acridum*, theoretically enough to treat 650,000 ha, were procured for Somalia [60]. However, according to Owuor and McRae [14], from 2019 to 2021, a lower total of 11,000 kg was used (average dose rate at 39.3 g/ha).

In addition, according to the United States Agency for International Development's Programmatic Environmental Assessment [10], at the beginning of the upsurge, diazinon, which was approved in Ethiopia for DL control, was applied. The same source notes that the following non-PRG-listed insecticides were registered in Kenya by December 2019 for DL control: imidacloprid 10 g/L (ULV), cyanophos 500 g/L (ULV) and cypermethrin 50 g/L (EC). Several more products, such as acetamiprid 100 g/L and emamectin benzoate 20 g/L, could be imported through the extension of their approvals in the event of an emergency [10]. Of these products, cypermethrin was used from January to May 2020, as well as fipronil 12.5 g/L, at least until November 2020 [16] and carbosulfan 200 g/L, aside from the PRG [10] (2014) approved insecticides. Chlorpyrifos was also mentioned in [61] as being used by the Pest Control Products Board (PCPB) to the Ministry of Agriculture for DL control in Kenya. Although approved by the PRG [12] and PCPB [28], it was not in the schedule of insecticides in Kenya procured through the FAO. Furthermore, against the strong recommendations of Brader et al. (2006) that "the involvement of village and phytosanitary brigades in the chemical locust control campaign operation be stopped on safety grounds . . . " [3], Kenya provided four-day training to some 500 National Youth Service staff for scouting and control, mainly using Emulsifiable Concentrate (EC) insecticides and knapsack sprayers [15,26]. Training, however, was insufficient, and spraying took place unsupervised [26]. In Somalia, no insecticides were available prior to the outbreak, and all products used were imported and distributed by the FAO's representation in Somalia.

Table 2 depicts the differences in the three countries considered in this paper with respect to FAO-procured insecticides and areas treated. In Ethiopia, malathion and chlorpyrifos were primarily used; in Kenya, deltamethrin and fenitrothion, respectively, whereas in Somalia, *M. acridum* and teflubenzuron were the dominant insecticides (Table 2). The FAO Locust Hub database [22] indicates that of the total surface area of 1.60 million hectares treated in these three countries during the campaign, malathion was the most used product—43.5% of the surface area, followed by chlorpyrifos (27.5%) (Table 2). *M. acridum* came third with 15.8% of the total surface area treated—a novelty compared to previous campaigns. In Ethiopia and Kenya, the use of *M. acridum* was primarily for experimental rather than operational purposes. The exact amount used in Kenya was not reported. It is worth reiterating that during the 2003–2005 DL upsurge, malathion and chlorpyrifos were also the dominant insecticides.

Table 2. Total surface area (ha) treated from 1 August 2019 to 31 December 2021. Data from the FAO Locust Hub [22]. From the available data, it cannot be deduced with certainty if some areas received multiple treatments. Missing aerial spray data for Kenya from March to October 2020 were obtained and added from the FAO's Field Operations Officer [25]. These data had been uploaded to the SWARMS database, but not found there. *M. acridum* was used on a few 100 s ha in Kenya, but information was unavailable.

Insecticide	Ethiopia	Kenya	Somalia	Total	%
chlorpyrifos	440,610			440,610	27.48
malathion	679,380	2050	15,732	697,162	43.49
fenitrothion	35	32,136		32,171	2.01
deltamethrin		72,048		72,048	4.49
M. acridum	102	*	252,689	252,791	15.77
teflubenzuron			68,761	68,761	4.29
triflumuron			400	400	0.02
other	14,285	3187	21,705	39,177	2.44
Total	1,134,412	109,421	359,287	1,603,120	100

* *M. acridum* was used on a very limited scale in Kenya, but no data were reported in the FAO Locust Hub database.

Figure 1 demonstrates that there were three control peaks. The first was in April 2020 in Ethiopia and Kenya. The second and largest peak was from October 2020 to February 2021 in all three countries, and the third was in June 2021, primarily in Somalia. From June onwards, treatments were almost exclusively carried out in Somalia (Figure 1).

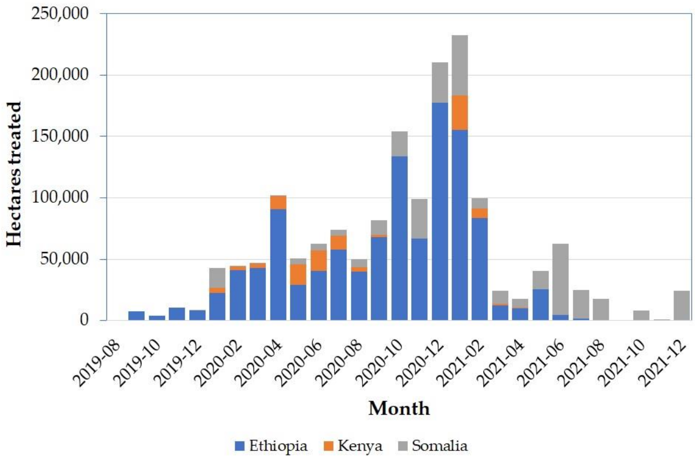

Figure 1. Monthly surface area treated (ha) from August 2019 to December 2021. Data are from the FAO Locust Hub [22].

Figure 2 shows that the vast majority of treatments were done in natural habitats. It also emphasises that in the border region between Ethiopia (Somali Region) and Somalia (Somaliland) on the Ethiopian side of the border, organophosphates were used, and in Somalia, a bio-insecticide and an IGR were applied in the same habitats and with comparable results. Figure 2 also shows that the main areas treated against DL overlap with areas important for honey production, which are located in particular in the south-west of the country [62].

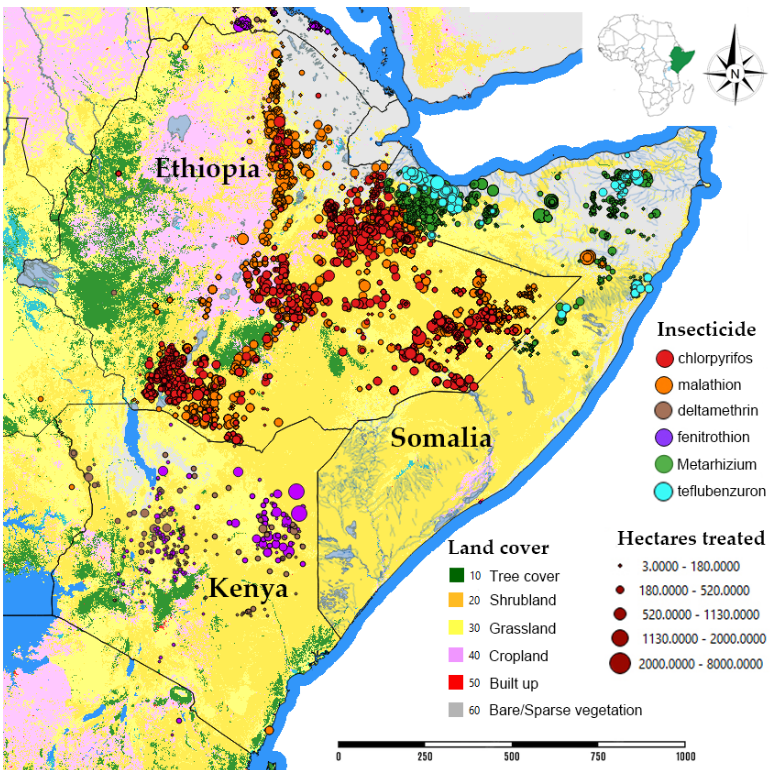

Figure 2. DL treatments from October 2019 to December 2021. Treatment data for Kenya are incomplete. Landcover in 10 m × 10 m resolution tile size 3 × 3 degrees [31].

3.2.1. Environmental Monitoring in Kenya and Ethiopia

Environmental impact monitoring was very limited during the campaign in East Africa. In the absence of surveys, knowledge of the impact of DL control on the environment is sparse. Nevertheless, based on the intrinsic ecotoxicity of products used, including insecticides not recommended for DL control, and from field research during previous campaigns since 1989, among others in the FAO Locustox Project [37,38] and during the 2003–2005 upsurge, it can be safely assumed that negative environmental side effects were widespread but remained largely unreported, with externalities unaccounted for [50,63]. Environmental field monitoring of side effects in Kenya was funded by the FAO during two missions between June and August 2020 in eight sites in Turkana County (in all sites, deltamethrin was applied) and five sites in Samburu County (one site treated with fenitrothion and four sites with deltamethrin) [15] and between October 2020 and January 2021 in two sites in Samburu County (one site with *M. acridum* and one site fipronil), and two sites in Marsabit County (both sites with deltamethrin) and two in Kitui County (both sites with fenitrothion) [16]. The sites consisted of shrubland, pastoral areas with or without trees, agricultural fields mainly with cereals and beans, and sensitive habitats with beehives and small settlements.

On the three sites treated with fenitrothion that were monitored in Kenya, the product concentration was 960 g a.i./L which immediately predisposed the control operations for overdosing. In Samburu County, the insecticide was applied at a rate of 34 L/ha, which equals to a dose rate of 32,640 g a.i./ha (instead of the recommended dose rate of 400 g a.i./ha) by untrained applicators on cultivated land with settlements and sensitive habitats, leading to intoxications by the control agents, soil contamination, phytotoxicity (in maize) and mortality of nontarget arthropods, including honeybees [15]. The second site, consisting of low-lying farm fields and grazing areas with settlements, was treated with 125 L of fenitrothion on 120 ha (i.e., application rate 1.04 L/ha and dose rate 1000 g a.i./ha) with a vehicle-mounted sprayer in Kitui County and was visited at least six days post-spray. Bird mortality was observed in one locality within the sprayed area, but no information was provided on the methodology applied and if any systematic searches were carried out. Seven birds were found dead, among which were the white-browed sparrow weaver *Plocepasser mahali* and the red and yellow barbet *Trachyphonus erythrocephalus*. In addition, patches of scorched vegetation and insecticide spillage within the boundaries of a primary school were identified. Fortunately, no students were present. In the third site, also in Kitui County, 400 L of fenitrothion were sprayed on 270 ha of low-lying farming fields with mainly cereals at a dose rate of 1422 g a.i/ha (application rate 1.48 L/ha) and visited 12 days post-spray. Despite the finding of dried dead beetles (Coleoptera), the monitoring team concluded there were no side effects, but it is not clear on which information this was based. We conclude that the late visits after fenitrothion treatments by the monitoring team hampered inference on the scale of the side effects.

Figure 3 shows that aerial spraying with fenitrothion also led to systematic overdosing. A more thorough investigation of the environmental and human health impact of the use of fenitrothion in Kenya has not been conducted. Dedicated monitoring requires quantitative observations immediately following treatments and preferably collecting the same type of observations before treatment. At least observations in untreated and comparable control sites need to be made [45]. Furthermore, to quantify bird mortality, an inevitability from such high dose rates of fenitrothion, thorough field searches during several days following sprays are needed [21]. Birds affected by anticholinesterase poisoning rapidly become debilitated and seek shelter on the ground as they are unable to fly. From the monitoring reports, it is not clear how this was dealt with in the field. Mullié and Keith [21] found up to 7% mortality in bird populations and a >60% reduction in bird numbers after fenitrothion spraying of 825 g a.i./ha in savannah habitats in Senegal, and a >40% reduction in numbers after 485 g a.i./ha. Based on [23] and with average bird densities of 2 individuals per hectare [64], a minimum mortality of thousands of birds and displacement of up to ten times those numbers are to be expected owing to overdosed fenitrothion treatments.

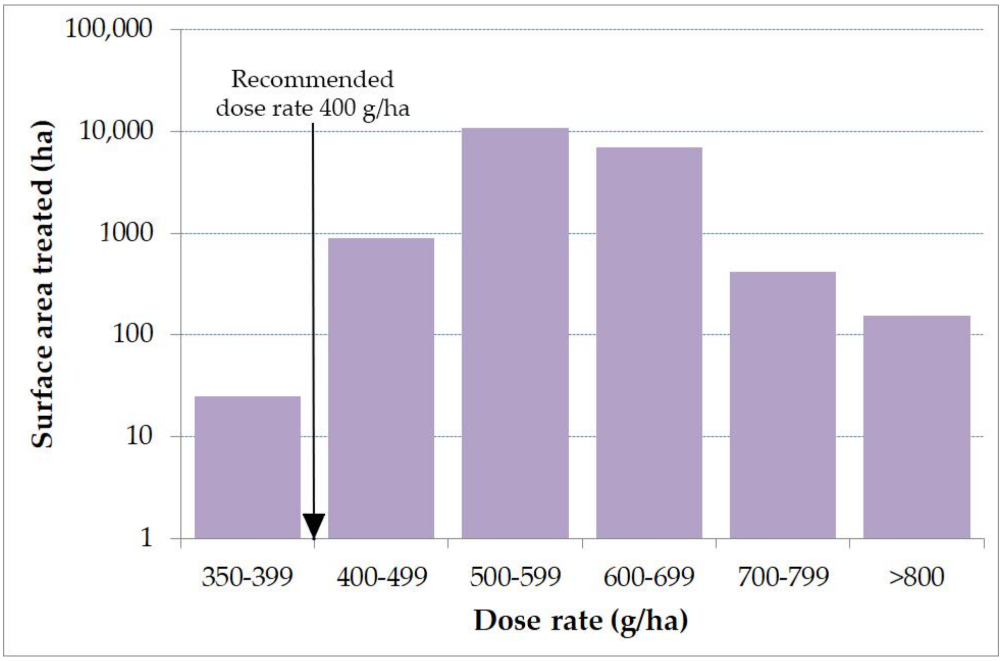

Figure 3. Dose rates of fenitrothion (g a.i./ha) in Kenya, January–April 2021, after 111 aerial treatments on 19,222 ha. The recommended dose rate is 400 g/ha. Data from the FAO SWARMS, detailed by FAO field operations officer [25].

Video footage shown on the Kenyan NTV broadcasting channel in April 2020 showed dead and debilitated superb starling *Lamprotornis superbus*, Fischer's starling *Spreo fischeri* and wattled starling *Creatophora cinerea*, reportedly affected by a spray of carbosulfan in Marsabit. Wattled starlings are considered typical "locust birds" [65] and may have been gorge-feeding on the poisoned locusts. All uses of carbosulfan were banned in April 2015 in 13 West-African countries based on high toxicity for birds and human health concerns [66].

After treatments with insecticides, locust-eating bird species are expected to gorge on the overly abundant prey [67]. Yet gorge-feeding is not included in risk-assessment procedures for locust control, and therefore risks of insecticides with relatively high acute toxicity may be underestimated [18]. Among the LPRG [13] locust insecticides, fenitrothion, chlorpyrifos and fipronil pose the greatest risks to gorge-feeding birds [68].

The monitoring in Ethiopia [17] mentioned that three spray planes crashed, of which one was loaded with an unquantified amount of unspecified insecticide, causing the death of the pilot. The crash site in Arsi Zone, Shirka Woreda, in the middle of agricultural fields, was subsequently fenced and treated with compost to enhance the biological degradation of the spilt insecticide. Results from this, as well as if any residue analysis was carried out, remain unknown. Furthermore, the emptying of twenty 200-litre drums of chlorpyrifos (4000 L) by burglars and subsequent theft of these and 18 empty drums near the western border of Borena National Park was reported. This site was also fenced, ploughed, treated with compost and watered. The results of any follow-up activities, such as residue analysis of soil and groundwater are unknown [17].

3.2.2. Pollinators and Apiculture

During the 2003–2005 DL upsurge, it was found that in Senegal, the loss of pollination was the second most significant externality amounting to €1790,112 at 2007 prices [63]. A logical recommendation stemming from this important finding would have been restrictions on the use of bee-toxic compounds in future upsurges and, if such compounds were deemed necessary, informing beekeepers to protect their hives during treatments. The monitoring reports by Mutia [15,16] and Lemma [17] confirmed that communication with communities was poor. In Ethiopia, precautionary measures were neither taken by beekeepers nor by the field staff of the Ministry of Agriculture [17].

Of note, honeybees are one among many bee species present in treated landscapes. The drylands of the Horn of Africa are some of the world's most diverse areas for the pollinator. Hundreds of species have been collected from just a single location in Turkana, Kenya [69]. Despite the paucity of quantitative data from Kenya, there is evidence of an impact of DL control on bees. One beekeeper in East Samburu County in 2020 reputedly lost all bees in four out of his five hives, whereas the numbers in the fifth had considerably decreased in the days following both aerial and ground spraying against DL [70]. The products sprayed were not reported. Furthermore, ground treatment with 170 L of fenitrothion 960 g a.i./L on a 5 ha area (32,640 g a.i./ha; recommended dose rate 400 g a.i./ha) unsurprisingly resulted in heavy bee mortality with 1296 dead bees counted in the four hives that were inspected in Samburu County [15]. A beekeeper in Kitui County, possessing 25 hives since 2009, stated that in 2020 honey production in his hives dropped from 7–10 kg per hive to 3–7 kg or a reduction of about 30–40%. Another beekeeper from Makueni County also found a reduction in honey production from mid-2020 onwards [71].

Based on the type and quantities of insecticides used, the timing of spraying and the presence of hives, Worku et al. [62] highlighted that DL control in Ethiopia was expected to have a detrimental effect on honeybee colonies, honey yield as well as quality due to the loss of pollen and nectar and chemical spray hazards (see also Figure 2). Honeybees are exposed to chemicals not only through spray but also through residues in pollen and nectar. The impact on honeybee colonies includes mortality, delayed brood development, and reduced adult longevity [62]. This was confirmed by data presented by Lemma [17], who reported significant mortality in honeybees after the use of chlorpyrifos 240 g/L and malathion 925 and 960 g/L in Ethiopia. In two districts in South Omo Zone (Male and Hamer) in Southern Nations, Nationalities, and Peoples' Region, 1329 hives were found empty. In a random sample in the Male Woreda of 57 hives of six beekeepers, 53 (93%) were found affected by locust spraying, whereas, of 50 hives of a single owner far from sprayed areas, only one had mortality. In Eastern Haraghei, Oromia, the loss of five hives was reported [17].

Unfortunately, these reports lack scientific rigour by only presenting circumstantial evidence and not testing for a causal relationship between colony health and DL control. Nevertheless, while the aforementioned limitations and other factors such as drought or locusts devouring flowering plants and causing pollen and nectar loss must be factored in, the balance of probability of wide-spread adverse effects on pollinators remains very high given the choice of insecticides, the application by inexperienced agents in both Ethiopia and Kenya, gross overdosing as has been shown during monitoring (Figure 3) and the lack of precautionary measures [15].

Of note, historically, Ethiopia has been the largest natural honey producer in Africa and ranks within the top ten producing countries in the world [72]. Ethiopia relies heavily on conventional apiary systems, in which approximately 96 percent of all hives fall into the traditional class [73]. There are approximately 15,000 honeybees per average hive, each yielding an average of 9 kg of honey per annum [73]. According to both Gratzer et al. [73] and Muhammed [74], Ethiopia has 0.91 beekeepers/km^2, 6.01 colonies per beekeeper and 5.60 colonies/km^2 from a total rural area of 1.12 million km^2, implying a total of 1.01 million beekeepers, with each possessing an average of 6.9 hives as of 2020.

As shown in Figure 4, official data reported by Ethiopia as published in FAOSTAT [72] from 2010 to 2018 reveal that annual national honey production was growing at an average of 4% per annum, but in 2019 and 2020, honey production precipitously fell by a combined 46 million tonnes or 78%, while hive numbers were stable in both years at around 7 million, suggesting that the collapse in production was not due to a contraction in sector size, but a result of an impact on honeybees. Since there were no notable increases in predation or pathogen prevalence during the upsurge [75], the plausible causal factor contributing to such a dramatic decline was the pervasive use of chemical insecticides to control the DL upsurge, reaffirmed by the aforementioned survey data reported for the country.

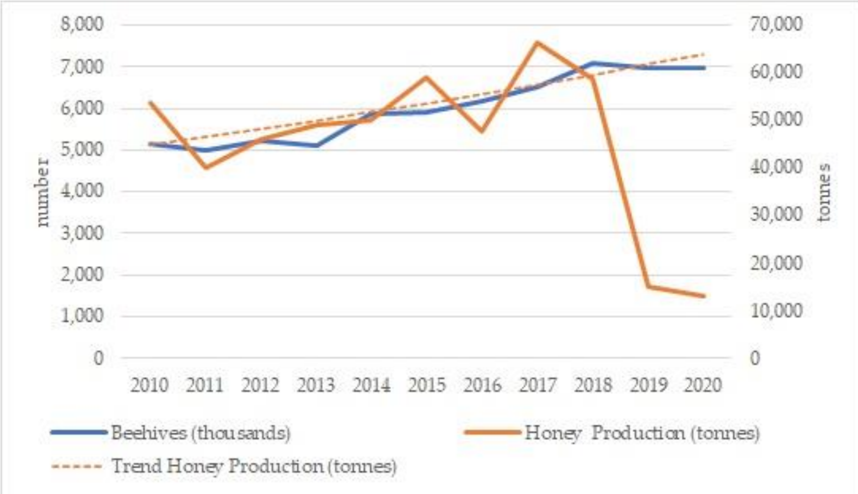

Figure 4. Beehives and honey production in Ethiopia, 2010–2020. Source: FAOSTAT [72].

To add further credence to our hypothesis, there is a strong positive (statistical) correlation between honeybee numbers and honey production. Therefore, high bee mortality would imply a high fall in honey production and vice versa (since correlation does not imply causality). Furthermore, we have no knowledge that other national-level pest outbreaks coincided with the regional desert locust upsurge, which would have also potentially required large-scale chemical control. Another candidate factor that could explain the trends in Figure 4 was Ethiopia's response to the COVID-19 pandemic. However, the economy of Ethiopia is largely agriculture-based, in which, according to the Word Bank, over 70% of the population is employed; consequently, given the importance of this sector, agricultural output was not significantly affected by COVID-19 measures [76]. In fact, looking at the evidence, we can see from officially reported data to FAOSTAT [72] that food (cereal) production in Ethiopia actually increased in 2019 from 2018 and continued to rise in 2020.

As noted previously, chlorpyrifos and malathion were dominant control agents in Ethiopia and are both well known to pose the highest risk to honeybees [63]. Furthermore, Figure 1 demonstrates that land was treated for 24 consecutive months. No month was pesticide-free for two years, including during flowering times and honey harvesting times.

Moreover, the combined loss in beekeeper honey revenue for 2019 and 2020 is estimated at US$305 million, using world export unit values [72] multiplied by the deviations from an exponential trend fitted to honey production quantities. Bees, however, provide ecosystem services in the form of pollination to flora and fauna. Their pollination services are estimated to be worth over 15 times the value of all hive products together [76]. If these values were taken into account alongside the loss in honey revenues and the cost of recolonising hives, the "true costs" of insecticide use could be in the realm of billions of US Dollars.

3.2.3. The Case for *M. acridum*—An Alternative Agent in Locust Control

According to information obtained from the FAO Locusts and Transboundary Plant Pests and Diseases Team Leader [77], the cost of procured chemical insecticides ranged from 10 to 30 USD/ha treated or protected and *M. acridum* around 315 USD/kg or 15.75 USD/ha treated excluding diesel fuel prices as the carrier. This would imply that *M. acridum* is within the same price range as chemical insecticides but lacks the external costs to environmental and human health. Nevertheless, the large-scale introduction of *M. acridum* for DL control has been hampered by perceived higher costs, a lack of trust in their efficacy and speed of action (Table 3), as well as a lack of long-term vision, preparedness and a strategy to apply biocontrol agents in-time.

Table 3. Specific traits of chemical insecticides and *M. acridum* in acridid control. Arguments highlighted in shaded cells are frequently used to justify the use of chemical insecticides. (Adapted from Mullié [18]).

Issues	Chemical Insecticides Assessed for Efficacy and Side-Effects by PRG (See [10,11] for Details)	*M. acridum* (Trade Names Green Muscle® and Novacrid®)
Legislation and use	Reviewed for efficacy and side-effects by LPRG [10,11] (2014, 2012), widespread registration and use by government agencies to control acridids.	Until 2020, hardly used for locust control (except for in Tanzania and Madagascar) and minor use for grasshopper control in the Sahel despite proven efficacy. Since November 2019, Novacrid® has been registered in nine Sahelian countries (CILSS). Provisional sales authorisations obtained in 2020 in Kenya, Ethiopia and Somalia.
Speed of action/meteorological dependency	Rapid knockdown and fatality (hours) post-treatment leaving massive quantities of dead and decaying arthropods strengthening confidence of users. Specific windows for wind speeds (drift), rain and temperature (convection) during and post-spray. Efficacy slightly dependent of ambient temperature.	No knock-down, mortality 80–90% in 2–3 weeks post-treatment, undermining confidence of users. Predators and scavengers remove dead and debilitated insects as they become available. Rains during or post-spray have either no impact or may enhance efficacy, ambient daily temperatures need to be sufficiently long between (20)25 and 35(40) °C for optimal efficacy.
Persistence	Rapid degradation (days) on vegetation under field conditions. IGRs and fipronil persist longer and are recommended for barrier treatments only. Chlorpyrifos degrades slowly in soil.	Viable spores persist from seven days to two months providing medium-term effect against re-invasion. Subsequent bird predation may keep populations below economic threshold until next rainy season. Other studies found some carry-over effect of viable spores into the next year. Efficacy when used as barrier treatment inconclusive.
Stability, use and storage	Formulations well developed with known shelf-lives, storage, transport and use without problems. Some formulations are corrosive for ULV spray equipment or carriers (planes, vehicles). Training of applicators is a prerequisite.	Much shorter development history of formulations. Formulated product may settle on bottom of containers, clogging Micronair® sprayers leading to frequent cleaning/loss of time, some complaints about short shelf-life of formulated product. Dry spores have known shelf-life and can be stored and formulated *in situ*. Training of applicators is a prerequisite.Does not require other equipment than already in use to apply chemical insecticides.
Non-targets	Non-selective. Most kill non-target arthropods including natural enemies, some also birds, reptiles and other vertebrates and/or deprive them of their arthropod prey. Migration of birds from sprayed plots. Fipronil and neonicotinoids are extremely toxic for social insects.	Selective. No negative impact on non-target species, including honeybees, except on other Orthoptera. Numbers of acridivorous birds remain stable or increase post-spray (immigration). Significant increase of *Oedaleus senegalensis* eggpod parasitation by diptera (Bombyliidae; cf. *Systoechus* sp.) found at 18.75 and 37.5 g viable spores/ha.
Use on locust hopper bands	During large outbreaks and plagues most products (except IGRs and fipronil) are not efficient because of lack of residual action. Therefore, new hatchlings need new treatments, especially as natural enemies may have been reduced by earlier spray.	Very effective and efficient on hoppers, remains infectious during weeks to even months. This way, newly hatched hoppers will be attacked within the infectivity period of *M. acridum* and by increased natural predation, e.g., by birds.
Use on adult locusts and grasshoppers	Widely used for control of acridids under all conditions. Indiscriminate use of chemical insecticides can cause upsurges later in the season or the next year because invertebrate locust egg predators and parasitoids have been killed.	Proven efficacy against adults, can be used in ecologically sensitive areas. First time successful use against (highly mobile) large groups/swarms of adults in Somalia during 2020–2021.
Insecticide costs and externalities	Relatively cheap (10–30 USD/L) when supplied through FAO but hidden direct and indirect costs from side-effects (externalities such as reduced pollination, soil contamination or human intoxications not perceived as costs of treatments and hence unmet by society).	Product was available during campaign for FAO at *c.* 315 USD/kg (15.75 USD/L) excl. diesel fuel as carrier, with no externalities. Therefore "true costs" of biological insecticides are potentially less than economic costs per hectare sprayed of chemical insecticides, without the negative side-effects of the latter.
Human toxicity	Slightly to moderately hazardous, sublethal effects and casualties have been reported during campaigns. Should not be sprayed on crops or in the vicinity of human settlements, withholding times apply, killed acridids should not be eaten. Use of PPE compulsory.	Unlikely to present hazard under normal use. Can be sprayed on crops. No withholding time. Use of PPE less stringent, although recommended.
Livestock, fisheries and (organic) farming	Slightly to moderately hazardous. Livestock should be removed prior to spraying. Not compatible with organic farming and fisheries. Most products not registered for use on crops. Withholding times and re-entry intervals apply.	Unlikely to present hazard under normal use. No particular safety measures required, although direct spray on livestock should be avoided. Fully compatible with organic farming and fisheries, no withholding times or re-entry intervals.
Protected and sensitive areas	Should not be used in protected areas and buffer zones for environmentally sensitive areas, such as wetlands, which limits its use.	Safe to be used in protected areas and near environmentally sensitive areas such as wetlands. No negative impacts of spraying near water bodies known.

In general, National Plant Protection Organisations (NPPOs) in most African countries are not eager to use *M. acridum* on a large scale for reasons summarised in the shaded cells of Table 3, and operational use until now remains low. In Australia, on the other hand, the use of *M. acridum* (Green Guard®) has been part of an Integrated Pest Management (IPM) system for gregarious locusts in about 10–12% of all treatments since 2000 [78] since it is compatible with organic beef production [79]. In China, there has also been substantial use of *M. acridum* and *Paranosema locustae*. While such products were used there in only 5% of treatments during 2004, their use has increased to over 30% in the years prior to 2017, which amounts to more than 100,000 ha per year sprayed. These applications of bio-insecticides against locusts and grasshoppers were reported as more than all the rest of the world combined [80]. *M. acridum* was also successfully used in 2009 on a total of 10,000 ha in the Iku-Katavi National Park, the Lake Rukwa plains and the Malagarasi River Basin in Tanzania against red locusts *Nomadacris septemfasciata* [81]. The rapid intervention markedly reduced red locust infestations, thereby preventing a full-blown invasion that could have affected the food crops of around 15 million people in the region [81].

A major boost for the operational use of *M. acridum* was made when it was donated alongside the IGR teflubenzuron for the treatment of DL in Somalia during the most recent upsurge [14]. Years of protracted crisis in Somalia have left the country without a functional NPPO as well as institutions responsible for the regulation of insecticide imports, use and safe disposal. The lack of stability and safety due to the ongoing political crisis and conflict in the country meant that Priority 1 and 2 control agents, namely *M. acridum* and IGRs [13], were the safest choices eliminating the risks associated with neurotoxic organophosphates [14].

Other factors taken into consideration are that the mainstay of Somalia's economy is the export of livestock, including sheep, goats and camels, with millions of live animals being annually shipped to the lucrative markets in the Middle East (Saudi Arabia, UAE, Kuwait and Qatar) providing earnings for the country's pastoralists. According to the Observatory of Economic Complexity [82], in 2020, Somalia was the 11th largest exporter of sheep and goats in the world. DL co-exist in the same habitat with livestock and often feed on the same shrubs and trees preferred by both goats and camels, which rendered the use of Priority 3 products (see Table 1) a concern [14].

An additional factor that informed the decision to use *M. acridum* was that a large number of agro-pastoralists in Somalia who had embarked on apiculture activities for revenue diversification in order to de-risk and safeguard their livelihoods, and in light of the inherent danger of organophosphates towards bees and other non-target organisms [14]. The high demand for honey and beeswax ensures a stable alternative source of income for rural communities, especially when a drought affects both livestock and crop production [14]. Still a relatively modest producer of honey, Somalia protected their apiculture by using a bio-insecticide and an IGR [14]. It is of interest and somewhat surprising to note that neighbouring Ethiopia and Kenya could have opted for Priority 1 and 2 insecticides based on the same ecological argument. Counterintuitively, these countries were supplied by the FAO with Priority 3 chemicals with destructive effects on bee colonies despite Ethiopia being the largest honey producer in Africa, while Kenya ranked third [72].

In a presentation in June 2022 to the Commission for Controlling the Desert Locust in the Central Region, McRae [47] showed that in 2021, aerial survey and control teams in Somalia marked and treated 250 swarm targets covering 80,000 ha using *M. acridum* at 50 g per litre and 1 litre per hectare. Efficacy assessments were conducted in June and July when 1850 kg of the bio-insecticide dosed in 32,000 L of diesel were applied at a dose rate of 58 g/ha, which successfully treated 32,000 ha of swarms consisting of immature individuals [16]. Through a combination of cage sampling, in-field survey observations and the use of a locally supported GIS to track and map treated swarms, the assessments of the bio-insecticide showed that 50% mortality was reached after 9 days and over 83% mortality was observed in 14 days [47]. Field studies confirmed that although locusts are still able to fly and need surveillance to avoid them from being sprayed for a second time, swarms start to disintegrate in days, and more importantly, locusts lose appetite. One such swarm of 500 ha in Baringo County, Kenya, in July 2020 remained for days without much movement in a rather densely populated area and could not be treated chemically [25]. Despite temperature conditions (14–26 °C) being less than favourable, it was eventually decided to use the bio-insecticide. The swarm was subsequently monitored for 24 days, during which it reduced considerably in size, eventually splitting up into three swarmlets of approximately 120 ha in total. Considerable predation by raptors was observed from day 15 onwards, and local farmers and herders stated that the locusts were not affecting crops [25]. Other large-scale field studies confirm the observations described showing that *M. acridum* has the same efficacy against hoppers as to immatures or adult DL (e.g., Mullié et al. [19]).

3.3. Bird Predation and M. acridum: Towards a Novel Approach in Locust Control

It is generally assumed that birds can be important predators of relatively small DL populations (up to 15 million individuals) and eliminate them, but are less effective in larger populations [83,84]. Table 4 shows that the proportion of locusts eaten by birds varies widely depending on geography, time of the year and the presence of birds during the life cycle of the locusts.

Table 4. Proportion of DL populations eaten by birds in various localities throughout Africa. Smaller hopper populations can be eliminated before last moult by bird predation.

COUNTRY	STAGE	POPULATION (MILLIONS)	EATEN BY BIRDS (%)	SPECIES	OBSERVATION DAYS	SOURCE
ERITREA	adult	tens	4 daily	*Aquila* sp., *Ciconia ciconia*, *F. biarmicus*, *Leptoptilos crumenifer*, *Milvus* sp.	few	Smith 1953 [85]
ERITREA	1st–5th	15.2	52.6	*Milvus* sp., *Ciconia abdimii*, *Motacilla* sp.	14	Ashall and Ellis 1962 [86]
E. AFRICA	adult	up to 5000	0.25–6	all birds	outbreak	Elliott 1962 [87]
ERITREA	2nd–adult		4	*Oenanthe* sp., "kestrels",	23	Greathead 1966 [83]
MAURITANIA	2nd–4th	0.13–0.5	97.5–99.5	*Cursorius cursor*, *Passer luteus*, *P. simplex*, *Lanius* sp.	4–11	Wilps 1997 [88]
MAURITANIA	2nd–4th	1.1	95	*Cursorius cursor*, *Passer luteus*, *P. simplex*, *Lanius* sp.	4–11	Wilps 1997 [88]
MAURITANIA	hoppers	0.02	>75	*Cursorius cursor*, *Passer luteus*, *P. simplex*	-	Culmsee 2002 [89]
SUDAN	2nd	12	3 daily, 30–50 in total	*Motacilla flava*	21	Mullié 2009 [90]

The 4% daily predation rate found by Smith [85] would reduce a locust population in 17 days by 50%. Ashall and Ellis [86] found that small populations of locust hoppers, in general, completely disappeared before fledging due to the activities of avian predators. They concluded that "the evidence strongly suggests that there is no need to control such populations by chemical means". Similar results and conclusions were obtained in Mauritania by Wilps [88].

Even more interesting are the high predation rates on populations of either hoppers or adult DL that previously had been treated with *M. acridum* [91,92]. Gregarious hopper bands in Algeria and Mauritania containing some tens to hundreds of thousands of individuals were eliminated by birds in less than one week. In the latter trial, it was found that golden sparrows were among the prime natural enemies of the fourth instars of DL [90]. Several other detailed studies showed that avian predation of locusts and grasshoppers even increased after treatment with *M. acridum* [19,20], likely because of the acridids' basking behaviour.

When acridids are affected by the fungus, they move up in the vegetation to bask in the sun to induce behavioural thermoregulation (fever) above the fungus' lethal temperature [87,93,94]. This, however, exposes locusts to predators. In a study by Mullié et al. [19] two species of falcons, common kestrels *Falco tinnunculus* and lanners *F. biarmicus*, were the dominant avian predators. After spraying, kestrels took significantly ($p < 0.05$) more of larger female locusts (75–80%) than smaller males (20–25%). Interestingly, Dean [95] found a similar avian preference (75%) for females in the red locust when they were less active during oviposition. As the falcons preyed on all locusts, not only individuals that were affected by the bio-insecticide, they enhanced the impact of *M. acridum* by removing large adult females (reduction of reproductive potential) [19] and by chasing flying locusts, i.e., individuals arguably less or not impacted by *M. acridum* [21]. The falcons continued hunting even after their prey became substantially depleted, an important finding corroborated by similar observations on grasshopper predation by cattle egrets in Nigeria [96].

The numerical response of acridivorous birds, increasing after the use of *M. acridum*, selective feeding on female DL and extended presence of predators without a negative impact on their survival are substantial ecological advantages that should be considered when choosing between broad-spectrum chemical and specialist entomopathogenic locust control. Importantly, bird predation and *M. acridum* are fully compatible, whereas chemical insecticides such as fenitrothion and chlorpyrifos negatively impact birds.

However, the current LPRG risk assessment procedure [13] falls short when it comes to:

1. Modelling probability of bird mortality in the field [97];
2. Including indirect effects such as prey depletion (e.g., Peveling et al. [54]) and;
3. Including behavioural aspects, most notably gorge-feeding in exposure estimation [18,79].

To more realistically assess avian risks of insecticides currently used or intended for future use in locust and grasshopper control, these aspects need to be considered.

4. Conclusions: The Road to Sustainable Locust Management

The developments during the 2019–2021 DL upsurge in East Africa followed a predictable trend of excessive organophosphate use. The insecticide choice in Ethiopia (chlorpyrifos and malathion, both organophosphates) and Kenya (deltamethrin and fenitrothion, respectively, a pyrethroid and an organophosphate) was essentially the same as during the upsurge in 2003–2005 in West Africa. Nevertheless, the upsurge was the first in which efficacy assessments documented and demonstrated the successful operational use of the bio-insecticide *M. acridum*, although this was limited to a single country, i.e., Somalia (nearly 253,000 ha treated from 1 August 2019 to 31 December 2021). While challenges to applying *M. acridum* have been identified and advanced planning, as well as training, are needed [14] (also see Table 3), Somalia's example demonstrates that *M. acridum* can be effectively applied against all DL growth stages. Furthermore, it is worth reiterating that *M. acridum*, unlike organophosphates, protects the environment and human health as well as shows a medium-term effect against re-invasion (Table 3 and Figure A1 in Appendix A) and is the only Priority 1 insecticide recommended since 2014 [12].

M. acridum has been thoroughly and convincingly tested in scientific experiments in the field as well in the laboratory as a locust and grasshopper control insecticide since the early 1990s, so for more than 30 years. These tests preceded successful procedures needed for official registration of *M. acridum* (as Green Muscle®, Green Guard® or Novacrid®) in a large number of countries, inside and outside Africa, most notably Australia since 2000, therefore for the past 22 years. The question is not so much if *M. acridum* has efficacy against acridids or safety for the environment, users and the general public, all are confirmative, but if countries independent of their economic situation are willing to maintain an early warning system which would facilitate advanced planning and early action.

It is thus concluded that *M. acridum* must be handed a dominant place in early control strategy, and (1) *M. acridum* alone or (2) in combination with acridivorous birds can keep or bring acridids below economic thresholds. The combination of *M. acridum* and predation by locust-eating birds is particularly suitable for nymphal stages, in situations before they develop to threaten crops, pastures and ultimately livelihoods. Such a management option might even give added impetus for restoring degraded habitats in known outbreak areas by re-greening and by decreasing or modifying grazing pressure, thereby offering opportunities for increases in bird numbers while reducing habitats favoured by locusts. Application of selected chemical insecticides, in particular pyrethroids, assessed by the LPRG [13] and in accordance with the EU regulation, as well as following the example of Morocco, might be considered for cases when (1) and (2) are insufficient at reducing DL populations.

Consequently, the LPRG should take the lead in bringing their latest report [13], in accordance with the most recent views of the EU, by discontinuing the use of organophosphates for DL control and further evaluating the suitability of other control agents. "History repeating itself" should be avoided: when dieldrin was banned in Europe and the USA in the mid-1970s, it took another 15 years before the FAO eventually commissioned a desk study of the environmental impact and potential hazard of dieldrin in tropical and hot arid climates [98]. After this study, the use of dieldrin for locust control in African countries was eventually discontinued.

Unsurprisingly, given the experiences from previous campaigns, environmental side effects, including mortality of honeybees and birds, were reported in Ethiopia and Kenya. The use of an unsuitable 960 g a.i./L formulation of fenitrothion predisposed the control to gross overdosing, causing great environmental damage, including bird and bee mortality [15,16]. Based on previous research on the dose rates used in Kenya, acute mortality of birds and reproductive impairment likely affected thousands of birds. Indirect effects, due to their insect food depletion, likely further increase these numbers.

In Ethiopia, the mortality of bees and the abandoning of hives were reported during monitoring. According to official data on Ethiopian honey production, honey output collapsed from almost 59,000 tons in 2018 to around 15,000 tonnes and 13,000 tonnes, respectively, in 2019 and 2020 (Figure 4). While the DL campaign alone cannot explain such a dramatic decline, the widespread use of malathion and chlorpyrifos is considered to be an important plausible contributing factor. As both products are known to be highly toxic to bees and crop production areas in Ethiopia and overlap with those treated against DL [62], a severe loss of pollination potential is suspected. This is corroborated by a similar impact in Senegal during the 2003–2005 campaign, with pollination loss being the second most important externality of DL control [63]. Given the importance of pollinators to ecosystems and food systems and the suspected sheer scale of their mortality, especially honeybees, from chemical insecticide use in the 2019–2021 upsurge, this paper makes a call for an independent and scientific-led inquiry into the recurrent use of organophosphates, and moreover, why systematic environmental impact monitoring did not take place during the recent campaign when the vulnerability of pollinators and other non-target organisms to such chemicals has been known for decades.

Indeed, three FAO monitoring programmes yielded negligible data for analysing environmental and human health externalities. While monitoring teams in Ethiopia and Kenya observed some side effects, they were largely unable to grasp the utter magnitude of the potential environmental impact. This was partially caused by the limited geographical coverage of the missions and their short duration. Most importantly, the observations were delayed by up to two weeks post-spray and without a pre-treatment baseline for comparison, rendering inference futile.

The lack of adequate environmental monitoring propagates the "false economy" of persistent and pervasive broad-spectrum insecticide use, in which only the fiscal costs and benefits (e.g., saving crops from locusts) are considered. If "true costs", namely the externalities on the environment and human health from hazardous chemical insecticide applications as well as the benefits of protecting pastoral systems, apiculture and non-targets were factored-in, *M. acridum* not only would stand as the most sustainable but also as the most economically feasible (cheapest) control agent (and the example of Somalia clearly demonstrates this).

The LPRG report [13] noted that locust control campaigns continue to rely heavily on broad-spectrum organophosphate insecticides, presumably because these are readily available for procurement and are at "low cost". The LPRG [13] stipulates that external costs such as removal of obsolete stocks or economic losses, e.g., endured by beekeepers, should be accounted for but do not explain how to monitor externalities of locust control. The only mention in the current Guideline 6 is the following: "In the end, the expected (economic) benefits of a given control strategy will have to be weighed against the expected environmental and health costs" [45] (p. 13, par. 3). Pending the second edition, the LPRG has an opportunity to elaborate on the ways to strengthen environmental and human health monitoring, and to measure external costs.

We recommend that future donor contributions to protect livelihoods from the impact of locust infestations should set aside sufficient funds for "true cost" accounting analyses. Given DL can invade 20% of the total land surface of the world [99], further research in selective insecticides while applying proven early warning and early action technologies, is needed to safeguard livelihoods, food security, as well as environmental and human health. Such research efforts, alongside systematic environmental monitoring, would pave the road towards sustainable locust management.

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Appendix A

The organophosphates led to a rapid and >95% locust decline, followed by complete recolonisation by three weeks post-spray. *M. acridum* took 10–15 days to reach a 70–90% decline and kept acridid densities below 20% of pre-treatment values until one month post-spray. From then on, differences with controls became slightly less but remained significant for another one to two months in one experiment, but in another experiment, significant differences remained throughout the entire experiment until seven months post spray, when the experiment ended (from Mullié [100,101] and Mullié and Gueye [102,103]).

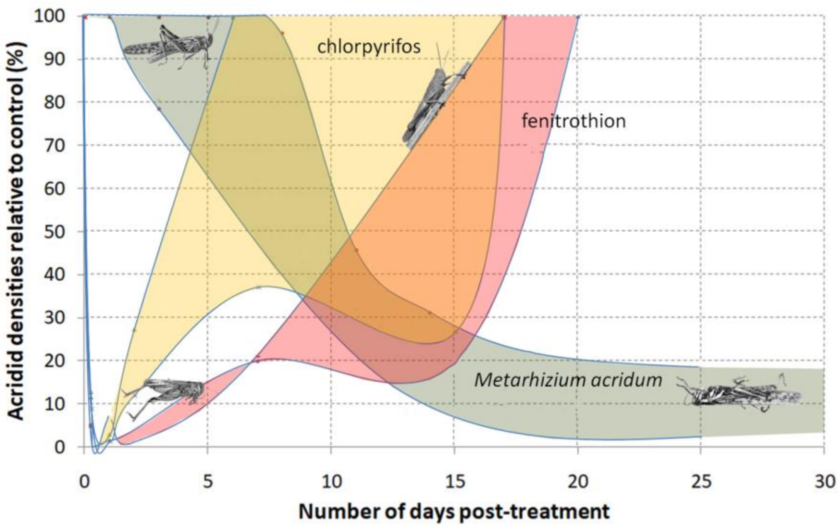

Figure A1. Densities of acridids in the first month following sprays with either chlorpyrifos, fenitrothion or *M. acridum*.

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