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Review

World's Best Practice Locust and Grasshopper Management: Accurate Forecasting and Early Intervention Treatments Using Reduced Chemical Pesticide

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Abstract: World's Best Practice management of locusts and grasshoppers requires accurate forecasting that helps determine where and when surveys are preferentially conducted so that infestations can be found quickly as part of ensuring early intervention treatments. Using survey data downloaded directly into a Geographic Information System (GIS), as well as rainfall and other factors important in the population dynamics of the species concerned, models within the GIS provide forecasts of future developments. The GIS provides forecasts of likely events and is used by locust and grasshopper experts to make decisions; that is, the forecasting is part of a Decision Support System for improved locust and grasshopper management. Surveys are generally conducted by ground vehicles, but for locusts, surveys by aircraft can be an important way to rapidly find bands. In Australia, dense bands can often be seen from an aircraft flying overhead at a height of 300 m, and similar detection of bands of the desert locust by aircraft has been conducted in Somalia. Swarms can be detected by ground vehicles, but because swarms move, surveying by aircraft is also an important way of locating swarms for treatment. When locust infestations are found, they are rapidly treated as part of early intervention preventive management. However, it is generally recognized that it is extremely difficult for landholders alone to protect crops against locusts and grasshoppers, so government intervention is often necessary. These organizations use a variety of treatment techniques to reduce the amount of chemical pesticide applied either by strip spraying or treating very dense infestations, such as roosting swarms, or using biopesticides. These techniques, as used in a number of countries, have proven to be very effective in managing locust populations while reducing the risk to the natural environment and human health.

Keywords: locusts; grasshoppers; management; World's Best Practice; biopesticides

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1. Introduction

Locusts and grasshoppers are one of the most devastating pests of agriculture. This group of insects contains hundreds of pest species and affects the livelihoods of one in every ten people worldwide [1–3]. Locusts and grasshoppers are profoundly different from other pests; their populations can quickly grow to catastrophic levels, and some species form very dense swarms (Figure 1) and dense bands that in a very short time can cause a great deal of damage (Figure 2). Swarms of locusts can migrate hundreds of kilometers, rapidly damaging pastures and crops in the invaded areas, which can be disastrous for both the food security and livelihoods of the rural populations in affected areas, leading to major economic, social, and environmental impacts. The rapid increase and sudden invasions mean it is extremely difficult for landholders to protect their crops, so government intervention is often necessary. This intervention not only needs to be local and national but also international in many instances, particularly with locusts, whose migrations commonly are from one country to another as a transboundary threat [4]. Many locust organizations use a strategy of preventive management which involves a rapid response to reduce populations through intervention early in outbreaks, continuing treatments every generation thereafter [2,5–10].

Figure 1. A swarm of the South American locust, *Schistocerca cancellata,* over a crop in northwest Argentina. Photo courtesy of Héctor Medina.

Figure 2. Crop damage by a band of the Australian migratory locust, *Locusta migratoria,* in Queensland, Australia.

The actual implementation and the degree of success of the preventive management programs varies greatly between locust and grasshopper species and depends on a wide range of factors. For locusts with localized outbreak areas, including the red locust *Nomadacris septemfasciata* (Audinet-Serville, 1838) in southern Africa, the African migratory locust *Locusta migratoria migratorioides* (Reiche and Fairmaire, 1849), and the South American locust *Schistocerca cancellata* (Serville, 1838), treatments in localized outbreaks as suggested by Uvarov [11] were able to successfully prevent plagues many years [5,6,8,12]. But, other species, like the desert locust, *Schistocerca gregaria* (Forsskål, 1775) [8,13,14] and the Australian plague locust *Chortoicetes terminifera* (Walker, 1870) [15,16], are very widespread, so preventive management can reduce the size and duration of plagues at best [17,18]. Outbreaks of these widespread species are often international in nature, and transboundary movement is common [4], making regional cooperation between countries in management programs essential. Robust mechanisms need to be put in place to ensure continuous financial support at national and international levels so that treatment programs can be put in place in a timely manner. While financial support at some level for such international cooperation can be ensured for species that have frequent outbreaks, continuing financial support has often proven to be very difficult for species that have sporadic outbreaks. During the long periods between outbreaks, there are other more pressing immediate financial priorities such that resources for locust management are downgraded, leading to a lack of preparation when outbreaks return [17,18] and making early intervention less effective [19–21]. To overcome the reduced resources that can occur during recessions, some organizations like the Australian Plague Locust Commission and the CLCPRO in west Africa have reserve funds that provide resources for rapid response and early intervention against outbreaks [22].

The treatment options available depend very much on the level and types of gregarization exhibited on the continuum from "true" locusts [23] to grasshoppers. Some species, like the migratory locust, *L. migratoria,* and the desert locust, *S. gregaria,* have all features associated with locusts, such as dense bands, dense swarms, long-distance migration, and phase change, while others, like the Australian plague locust, have all these characteristics except phase change. Some locusts, like the spur-throated locust, *Austracris guttulosa* (Walker, 1870), rarely form bands but have very dense swarms that migrate [24], while others, like the Moroccan locust *Dociostaurus maroccanus* (Thunberg, 1815) and the Italian locust *Calliptamus italicus* (Linnaeus, 1758) in Eurasia [3] and the small plague grasshopper *Austroicetes cruciata* (Saussure, 1888) [3] in Australia, have small bands and phase change but swarms of low density that move only tens of kilometers. With locusts that have stages that are dense, treatments are concentrated, leading to reduced pesticide use. But, of course, there are many species of grasshoppers that rarely if ever form bands or swarms, and these often require widespread treatments. Regardless of where on this continuum from locusts to grasshoppers a species is, treatments have a high monetary cost, often many millions of dollars [21], and use large amounts of chemical insecticides that can have serious side effects on the environment and human health. The banning of many of the chemical pesticides previously used for locust and grasshopper control has led to a much more judicious use of the remaining chemical pesticides available and has led to the inclusion of biopesticides in many management programs [7,25].

2. Basis of Preventive Management: Forecasting Where Infestations Are Likely

Preventive management programs rely on early intervention and rapid response, but locusts and grasshoppers can be found in habitats that cover hundreds of thousands of km^2 or even more, and finding localized infestations in such large areas is a very difficult task. Locating infestations can be made easier by having a system that provides relatively accurate forecasts as to when and where outbreaks are more likely. Resources can be set aside for possible treatment programs and surveys, and monitoring can then be concentrated in areas more likely to be infested.

The basis of any forecasting system is an understanding of the critical factors leading to population increase in the species concerned, and such an understanding is best provided by regular research on population dynamics as occurs for the desert locust [26], the Australian plague locust [7,27], and the migratory locust in China [25]. For many locust and grasshopper species, their management relies on models of population dynamics contained in a Geographical Information System that makes forecasts using data on rainfall/vegetation conditions, temperature, and locust surveys (in real time). The accuracy of the models is based on continuing research on the critical factors in the population dynamics of the species concerned, including an analysis of the accuracy of previous forecasts. And, of critical importance, is adjusting forecasts in real time based on changes revealed by incoming surveys and meteorological data. However, the forecasts are not an end in themselves but are part of a Decision Support System (DSS), where experts apply these forecasts to their locust management systems as occurs in Australia [27], China [25], and, for infestations of the desert locust, west Africa to India/Pakistan [26].

The DSS is a computer-based system that consists of layers of information, starting with a base map of habitats favored by the locust or grasshopper concerned. The favored habitats for the Australian plague locust were determined by ground-truthed Landsat satellite imagery [16], and similar studies have been conducted for the desert locust [26] and other species. Data from locust surveys are downloaded into the DSS, and in the Australian and FAO systems, these data are downloaded directly from the field [26,28]. All field data from locust surveys, reports, and treatment programs are geo-referenced using a global positioning system and downloaded and transmitted by satellite and internet to headquarters. In the FAO system, the data are stored in databases at national and international levels for analysis and distribution to all desert locust regions [29,30]. Similar systems are in operation in Australia [27], China [26,31], and western USA, where the CAse-based Rangeland Management Advisor (CARMA, http://carma.unk.edu) (accessed 10 October 2024), an advisory system for managing grasshopper infestations, has been successfully used since 1996 [32]. These systems allow data to be analyzed in real time, allowing forecasts to be made, alerts to be given, and extra resources to be made available where and when required as a basis for more effective preventive management programs.

However, forecasts rely on having a reasonably good understanding of the critical factors that lead to population increase. For arid and semi-arid zone species, like the desert locust and the Australian plague locust, rainfall and the resulting vegetation condition are often of critical importance for population increase, and there is often a migratory circuit between various rainfall areas [30,33]. However, for other species, less vegetation than normal favors outbreaks, such as with the migratory locust in Indonesia, where outbreaks follow drought [34], or with grasshoppers in China, where overgrazing promotes outbreaks [35]. For some species, like the spur-throated locust in Australia [24] and the migratory locust in China [36], the association with rainfall is quite complex, while for some grasshoppers, the relationship with weather factors is not very clear [37] and can be mitigated by biotic factors, such as natural enemies [38]. Even so, rainfall either directly through effects on vegetation growth or indirectly through other factors contributes to outbreaks of many locust and grasshopper species, so estimates of rainfall are commonly required as part of modeling their population dynamics. While the National Bureaus of Meteorology or websites like the NOAA Climate Prediction Center (https://www.cpc.ncep.noaa.gov) (accessed on 10 October 2024) can provide rainfall data and interpolation estimates, these often need to be supplemented by satellite imagery of vegetation conditions, especially for arid to semi-arid areas where there are few rainfall stations. The FAO website is a good example of the many types of information used to determine where rainfall has occurred, such as interpolated estimates of rainfall distribution, the Normalized Difference Vegetation Index (NDVI) of vegetation condition, and soil moisture estimates (https://www.fao.org/locust-watch) (accessed on 10 October 2024). The FAO website includes the increasingly important forecasts of likely future rainfall, though research on improving the accuracy of such predictions is continuing.

The Australian plague locust undertakes long-distance migrations at night, commonly at heights of 300–1000 m, and the Australian Plague Locust Commission (APLC) uses the Bureau of Meteorology wind trajectories at these heights to estimate the direction and distance of possible migrations [33]. For the desert locust, whose migrations are mainly during the day, the windy program (https://www.windy.com) (accessed on 10 October 2024) is useful as is the NOAA program (https://www.cpc.ncep.noaa.gov) (accessed on 10 October 2024) while in Mexico, the Ventusky weather program is used (https://www.

ventusky.com) (accessed on 10 October 2024) (Mario Poot, pers. comm.). In Australia, substantial studies using radar were conducted for a number of years [33], and they proved so useful that the APLC has a permanent radar site near Bourke (30° S) situated between the summer breeding areas in inland Queensland (Latitude 23–28° S) and the autumn spring breeding areas further south (Latitude 31–36° S) as part of detecting migrations between the northern and southern parts of the migratory circuit of the Australian plague locust [33].

3. Survey of Locusts and Grasshoppers

For many species of locusts and grasshoppers, outbreaks can be localized in small parts of a large potentially infested area, and finding these localized infestations rapidly requires the surveys to be concentrated where locusts/grasshoppers are more likely to be. When surveys are conducted, they should concentrate on where adults, particularly laying adults, were seen, where forecasts indicate that conditions are particularly favorable, and in habitats favored in the past. Reports or observations of where laying has been seen can be useful in both locating some of the infestations and in confirming the forecast hatching dates and early stages of nymphal development. An important source of information as to where infestations can come from local people, and regular liaison with locals is an important way of rapidly locating infestations. All these methods help *concentrate* surveys where infestations are more likely, but of course, some surveys should be conducted elsewhere because information obtained, and forecasts made rarely detect all possible favorable areas.

When a nymphal infestation is found, there should be a quick search to see if there are other infestations nearby. If there are other infestations, many organizations bring in search teams to determine if treatments are required. But Symmons [39] suggested that finding and treating a substantial proportion of locusts by ground vehicles during upsurges is often not possible because vehicles can only travel slowly across the country, particularly in areas where terrain is difficult to navigate and roads are few. To overcome this limitation, the APLC carries out aerial surveys whenever some locust bands are found, and bands of the Australian plague locust can often be seen from an aircraft flying overhead at about 300 m above ground level, with the dark band front contrasting with the eaten areas behind the band (Figure 3).

In Australia, extensive studies over many years have determined the conditions under which bands are more likely to be visible, which for the Australian plague locust is when they are marching [40]. On mild days (maximum temperatures near 25 °C), bands march, and are most visible from the air, from late morning to mid-afternoon, extending from mid-morning to late afternoon when it is hot (maximum 30 °C or so). On very hot days (approaching 40 °C), visibility is limited to the morning, and from about midday onwards, the bands roost on the vegetation to escape the heat and are rarely visible from the air. In Australia, aerial survey is the method of choice in locating dense band infestations and has proven to be a rapid method of efficiently and effectively managing large-scale locust infestations.

Other species that form bands are also likely to be visible from the air, though the situations when bands are visible may be slightly different. For example, in Somalia during 2020–2021, bands of the desert locust were seen from an aircraft flying at a height of 30 m above ground level [41]. The author has seen bands of the migratory locust and Moroccan locust that are quite dense and should be visible from aircraft. And, in situations where aircraft are expensive, drones may prove a useful way of detecting bands, and initial studies on this aspect are underway.

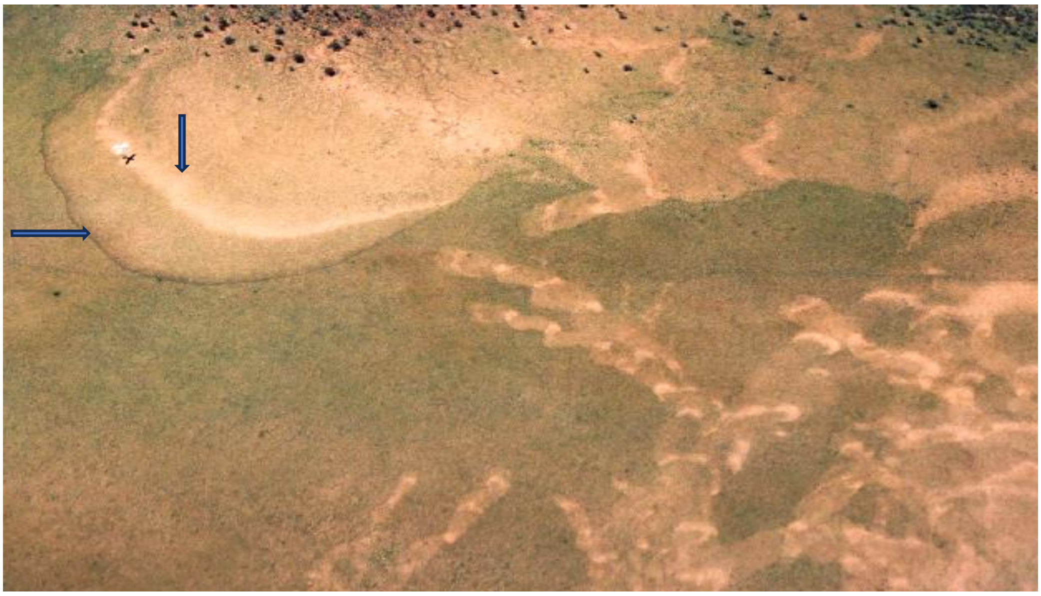

Figure 3. Bands of the Australian plague locust, *Chortoicetes terminifera,* as seen from an aircraft flying at a height of 300 m. The arrow on the right points to a band that is more than 500 m long with a dense band front where locusts are at densities of several thousand/m^2. Behind the band front are the pale eaten-out areas and the downward arrow points to the very pale area where the band roosted overnight and nearly completely ate out the vegetation. Many smaller bands and their eaten-out areas are also clearly seen.

As with surveys for nymphs, surveys for adults should concentrate in areas forecast as likely to be more favorable, though reports by local people are also very important because adults are so visible, particularly when they are flying. When adult infestations are found, vehicles can be useful in searching the area, but for species that form swarms, aerial survey by aircraft is often essential because swarms can quickly move away from the locations where they were first reported or seen.

4. Locust and Grasshopper Control Using a Variety of Techniques

4.1. Preventive Management with Reduced Chemical Pesticide Use

Many chemical pesticides have been banned [42], including some used until recently for locust and grasshopper management, and there is increasing scrutiny of the environmental side effects [43–45] of those that remain. Consequently, World's Best Practice management involves implementing a strategy of early intervention preventive management with reduced chemical pesticide use. Treatments need to be preventive in that much of the control is conducted *before* locusts or grasshoppers reach crops, not only early in outbreaks and upsurges but also against nymphs before they reach the very damaging adult stage. A variety of techniques are used that reduce the area sprayed by chemical pesticides and include the use of biopesticides that allow treatments wherever locusts and grasshoppers are found, including in environmentally sensitive areas and on organic properties.

Treatments of nymphal infestations by farmers are an important contribution to the management of locusts and grasshoppers, and these treatments are often with water-based sprayers because that is the type of equipment farmers tend to have. However, it is generally recognized that it is extremely difficult for farmers to protect their crops from locusts and grasshoppers on their own, so many treatment programs have government intervention at district, provincial, and/or national levels. And, for locusts like the desert locust, the Central American locust, and the South American locust, and for locusts in Central Asia, intervention at an international level is often required because of the transboundary movement of these pests.

As far as spray application is concerned, vehicle mounted or aerial Ultra-Low-Volume (ULV) spraying is becoming the method of choice [26]. ULV spraying allows for more exact control of the droplet spectrum so that there is less waste from very small droplets that drift away or from very large droplets that can contain much more than a lethal dose and often miss the target locusts and vegetation, as droplets fall rapidly to the ground, especially when vegetation is sparse. But ULV application requires well-calibrated equipment and staff training in application techniques; this expertise is not always present, so the more readily available and less expensive water-based sprayers are still commonly used in many countries.

4.2. Chemical Pesticide Spraying of Nymphs: Blanket Treatments vs. Strip Spraying

While farmers commonly treat individual bands or dense patches with their ground equipment, blanket treatment of nymphal and adult infestations has been a common way of treatment by government entities, particularly when using vehicle-mounted sprayers or aircraft. However, in recent years, treatment of only parts of the infested area has become increasingly important. In Australia, where aerial surveys often detect band infestations, treatments using strip spraying with fipronil have been common for many years. Strips of pesticide are applied from a height of 10 m and can be applied by flying into the wind so that the pesticide is deposited in a relatively narrow strip. Often, a strip is sprayed every 300 m, though with late instar bands that march longer distances [40], strips can be applied every 500 m [7]. While fipronil is banned for use in many countries, the APLC uses fipronil under a special government permit, which allows an application at a very low dose (0.6 g/treated ha) in narrow strips in the desert to semi-desert areas far from crops (APLC, pers.com). In the USA, spraying of chemical pesticide in strips has been adapted to grasshoppers, which do not move very far. Reduced Agent Area Treatments (RAATs) are used where alternate strips are sprayed at a lower than previously used dose [46–48]. In Somalia, during the 2020–2022 desert locust upsurge, locust bands were detected from an aircraft and then treated with the insect growth regulator teflubenzuron applied in strips every 300 m. A mortality of 90–99% was reported after 4–8 days [41]. Strip spraying of nymphal infestations has proven to be a valuable method and needs to be adapted to other species. Spraying in strips 300 m apart results in about a 2/3 reduction in application costs and the amount of chemical pesticide used, the latter limiting the side effects on the environment. Equally important is the dramatic reduction in the time taken for treatments, which is particularly important during major upsurges where large areas need to be treated in the limited time that nymphs are present.

4.3. Treatments of Flying vs. Roosting Swarms

While treatment of flying swarms is common, aircraft spraying of swarms that fly at heights of hundreds of meters can be difficult, as aircraft often must keep flying higher and higher to stay above the swarm and when they do, spray can travel large distances, including off target. With species that roost in trees, like the desert locust, the South American locust, and the Central American locust, roosting swarms can be very dense (Figure 4) and cover a small fraction of the area of flying swarms ([41], Mario Poot, pers comm) and so can be treated with a much-reduced amount of pesticide. Roosting is most prevalent from the late afternoon to the early morning, so surveys and treatments should be conducted then, either by a ground vehicle or by an aircraft. However, aerial surveys during the day can also be useful. In Somalia during 2021–2022, aircraft searched for the very visible large flying swarms and used wind direction to determine the direction that the swarms might have moved. The search and treatment of swarms when they roosted were conducted in the late afternoon and evening. Roosting swarms were also treated in the Yucatán in Mexico during late 2023, when 60 small dense (Figure 4) roosting swarms of the Central American locust were treated either with ground equipment or by air; experiments are planned for using drones to locate and treat roosting swarms (Mario Poot, pers. comm).

Figure 4. Dense roosting swarm of the Central American locust, *Schistocerca piciefrons piciefrons*, in Yucatán, México. The locusts are so dense that the brown color of the locusts completely covers the tree such that no green of the leaves is visible. Photo courtesy of Mario Poot Pech.

4.4. Biopesticides: An Important Part of Treatment Programs

Chemical pesticides have many side effects, and these have been increasingly elucidated, including their impact on human health, the environment, and non-target organisms/biodiversity [20,43,45,49–55]. These side effects have led to increasing restrictions on the widespread use of chemical pesticides and the outright banning of some of them [42], such that biopesticides are an increasingly important part of World's Best Practice preventive management of locusts and grasshoppers (Table 1). Trials with the *Metarhizium acridum* biopesticide Green Guard (BASF, Sydney, Australia) demonstrated a 90–95% mortality of nymphal bands within 2 weeks [56], which led to the first operational use of *Metarhizium* biopesticide in Australia in the year 2000 when nearly 25,000 ha of bands of the Australian plague locust were treated [7,56]. Visits by the author to Mexico in the same year led to experiments with *Metarhizium* biopesticides and follow-up experiments that resulted in 85- > 95% mortality of bands in the field [57,58], which led to the regular use of *Metarhizium* against the Central American locust for over a decade [59]. Trials with *Metarhizium* in China began soon after [60], and operational use of local isolates of *Metarhizium (M. anisopliae* [61]) and *Nosema locustae* biopesticides followed and have been increasingly used [25] such that about half of treatments of locusts and grasshoppers in China are now with biopesticides (Zhang, pers. comm.), making China a world leader in their use. Biopesticides have also been used by the FAO in Timor Leste against the migratory locust near rivers (Green Guard in 2007), in Tanzania against the red locust in flooded lakes (Green Muscle in 2009), and against the desert locust in Somalia, where 11 tons (at a dose of 50–75 g/ha) of the Novacrid biopesticide (Eléphant Vert, Meknès, Morocco) were used between 2019 and 2021 [41]. While biopesticides are often used where chemical pesticides should not be used (environmentally sensitive areas, organic properties, or where landholders do not want chemical pesticides), in Australia, Mexico, and China, biopesticides are also used elsewhere as part of an overall program to limit the side effects of chemical pesticides on the environment. This top-down approach that mandates biopesticide use as part of the management program has been instrumental in the rapid expansion of biopesticide use in these countries. Biopesticides need to be made part of locust and grasshopper management programs generally because, as said by Mario Poot (pers. comm.), without a biological alternative, there is a clear danger that, in the face of international and local restrictions on the widespread use of chemical pesticides, significant locust and grasshopper infestations will not be able to be treated.

Table 1. Commercial *Metarhizium* and *Nosema* biopesticides used in locust and grasshopper management.

Origin	Species	Commercial Name	Biopesticide Strain
Africa	*M. acridum*	Green Muscle	IMI 330189
Africa	*M. acridum*	Novacrid	EVCH 077
Australia	*M. acridum*	Green Guard	FI-985
China	*M. anisopliae*	--	CQMa102
China	*N. locustae*	--	AL200804
México	*M. acridum*	Metacridum	MaPL40

The use of biopesticides has been limited by two main factors: delayed mortality compared with chemical pesticides and a higher price for the actual product. In many cultures, rapid high mortality is thought of as "efficient", leading to a cultural barrier to the widespread use of biopesticides, and even where they are regularly used as in China, there are impediments to be overcome in their use [61]. The high, but not complete, level of mortality obtained with biopesticides recognizes that locusts and grasshoppers are an essential component of a healthy rangeland ecosystem [62] in that these insects stimulate plant growth and participate in nutrient cycling and the food chain [63]. While chemical pesticides can cause nearly complete mortality, this mortality occurs not only against the target pest but also with their natural enemies. Mortalities of more than 90% are common with both *Metarhizium* biopesticides [9,56,60] and *Nosema* [64–66], but these high levels of mortality against the target pest are achieved while preserving natural enemies [60,67], which can then help keep the pest populations in check. And, with *Nosema* biopesticides used in China against grasshoppers, infections are passed on to their offspring, so that infections continue in subsequent seasons and reduce pest numbers for several years [64,68].

Metarhizium spores survive on the vegetation for some days, and it has been shown in Australia that locust bands entering the treated area a week after treatment pick up a lethal dose and die [56]. The mortality of nymphs that pick up spores from the vegetation has led to strip spraying of *Metarhizium* at 150–200 m intervals in some of the treatments in Australia, and similar experiments have been conducted recently against the desert locust in Africa, with very promising results (Lemine Hamouny, pers. com). Strip spraying with *Metarhizium* could prove to be an important way of countering the perceived higher cost of *Metarhizium* biopesticides. However, even with blanket treatments, the total cost per hectare for treatment programs using biopesticides is only marginally more than that with chemical pesticides when one factors in the *total cost* of the program, including personnel, vehicles, equipment, and aircraft, of which the cost of the actual pesticide product is a small part. And, of course, it is becoming increasingly important as part of World's Best Practice to include the cost of the environmental side effects of using chemical pesticides, a cost which has rarely been considered in the past.

One of the supposed limitations to the use of biopesticides is a possible lack of efficacy when it is very hot because there is little development of *Metarhizium* above 37 °C in the laboratory [69,70]. However, in the field, mortality is often more rapid at high temperatures, reaching 80% within 10 days instead of 12–15 days when temperatures are less [56,60,71]. At high field temperatures, there is limited development of *Metarhizium* in the middle of the day when it is very hot, but the high temperatures at night mean that *Metarhizium* develops from late afternoon, all night, and until mid-morning. Critical to the long period of development when it is very hot is the fact that *Metarhizium acridum* resumes development as soon as the temperatures decline from being very hot [72]. Other biopesticides like *Beauveria bassiana*, *Metarhizium anisopliae*, *M. robertsi*, and *M. brunneum* have a refractory period of many hours after being exposed to high temperatures [72], such that mortality from these products is much delayed when it is hot.

While biopesticides are more commonly used against nymphs, *Metarhizium* was used in a substantial way against locust swarms in Somalia during 2021, mainly when swarms were roosting, such that much less biopesticide was used, reducing costs. And high levels of mortality resulted both with locusts collected and placed in cages (83% died within 14 days) [41].

Overall, then, biopesticides have been integrated into some management programs (Australia, Mexico, China, and recently Africa), which demonstrates that biopesticides can and should form a significant part of locust and grasshopper management. The expansion of the use of biopesticides in other countries with locust/grasshopper outbreaks will require not only a program of both research that demonstrates effectiveness but also an education program as to the benefits of biopesticides to overcome both political and perceived operational impediments to the widespread implementation of biopesticides as an essential part of local management programs.

5. Conclusions

Preventive management of locusts and grasshoppers relies on relatively accurate forecasting as to when and where outbreaks are likely so that infestations can be found and treated early. Accurate forecasting depends on a relatively clear understanding of the population dynamics of the species concerned, and research on these aspects needs to continue leading to improved models and forecasting, especially in the face of the effects of man-made alterations to the environment. Recent studies have shown that land clearing for agriculture has provided a much larger area suitable for the South American locust [73], while for the Australian plague locust, there are suggestions that climate change may reduce outbreaks in the near future [74]. In such potentially changed circumstances, research is essential to ensure the continued accurate forecasting needed for early intervention preventive management, and such studies should integrate the latest techniques of artificial intelligence and machine learning algorithms.

Ground survey is still the predominant way of finding infestations, but when infestations are detected, aerial survey techniques are a rapid method not only to determine their extent but also to locate the densest areas requiring treatment. Treatments have relied on the widespread use of chemical pesticides, but in the face of increasing restrictions on their use, it is important that management programs introduce the variety of techniques necessary to reduce the amount of chemical pesticides used. Biopesticides need to be part of all management programs, and when chemical pesticides are used, the amount applied should be reduced by spraying roosting swarms of adults when they occur and by applying spray in strips for nymphs. However, some of the chemical pesticides used for strip spraying are facing increasing restrictions such that there needs to be substantial research on adapting the remaining chemical pesticides to strip spraying, even if it means placing the strips closer together. Research is also needed on aerial detection for the many species for which a ground survey still predominates, and for all species, the use of drones needs to be investigated as a method of rapidly detecting infestations, even for spotting and spraying. The latter techniques could dramatically reduce the amount of pesticide used, allowing for much-reduced side effects on the environment for chemical pesticides and reduced costs for biopesticides. Of course, all techniques need to be adapted to the biology and behavior of the species concerned and to the equipment available to the management organization as part of adapting World's Best Practice management to the local situation.

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References

1. Lecoq, M. Desert locust threat to agricultural development and food security and FAO/International role in its control. *Arab Soc. Plant Prot.* **2003**, *21*, 188–193.
2. Zhang, L.; Lecoq, M.; Latchininsky, A.; Hunter, D. Locust and grasshopper management. *Ann. Rev. Entomol.* **2019**, *64*, 15–34. [CrossRef] [PubMed]
3. Lecoq, M.; Zhang, L. *Encyclopedia of Pest Orthoptera of the World*; China Agricultural University Press: Beijing, China, 2019.
4. FAO Food and Agricultural Organization Locust Watch Central Asia and Caucasus 2024. Available online: https://www.fao.org/locust-watch/en (accessed on 10 October 2024).
5. Gastón, J. *Síntesis Histórica de las Invasiones de Langosta en la Argentina. Publicación Miscelánea 433*; Secretaria de Estado de Agricultura y Ganaderia de la República Argentina: Buenos Aires, Argentina, 1969; 30p.
6. Bahana, J.W.; Byaruhanga, E.K. Advances and review of strategies for red locust plague prevention: The control of red locust, *Nomadacris septemfasciata* (Serville) into the 21st century. *Insect Sci. Appl.* **1999**, *19*, 265–272. [CrossRef]
7. Hunter, D.M. Advances in the control of locusts (Orthoptera: Acrididae) in eastern Australia: From crop protection to preventive control. *Aust. J. Entomol.* **2004**, *43*, 293–303. [CrossRef]
8. Magor, J.I.; Lecoq, M.; Hunter, D.M. Preventive control and desert locust plagues. *Crop Prot.* **2008**, *27*, 1527–1533. [CrossRef]
9. Zhang, L. Advances and prospects of strategies and tactics of locust and grasshopper management. *Chin. J. Appl. Entomol.* **2011**, *48*, 804–810. Available online: http://www.ent-bull.com.cn/viewmulu.aspx?qi_id=660&mid=16987&xuhao=2 (accessed on 10 October 2024). (In Chinese)
10. Showler, A.T.; Ould Babah Ebbe, M.A.; Lecoq, M.; Maeno, K.O. Early intervention Against desert locusts: Current proactive approach and the prospect of sustainable outbreak prevention. *Agronomy* **2021**, *11*, 312. [CrossRef]
11. Uvarov, B.P. Biological and ecological basis of locust phases and their practical application. In Proceedings of the Fourth International Locust Conference, Cairo, Egypt, 22 April 1936; Government Press: Cairo, Egypt, 1937. Appendix 7, 16p.
12. Hunter, D.M.; Cozenzo, L.E. The origin of plagues and recent outbreaks of the South American Locust, *Schistocerca cancellata* (Orthoptera: Acrididae) in Argentina. *Bull. Ent. Res.* **1990**, *80*, 295–300. [CrossRef]
13. Uvarov, B.P. The aridity factor in the ecology of locusts and grasshoppers of the old world. In *Arid Zone Research. VII. Human and Animal Ecology: Reviews of Research*; UNESCO: Paris, France, 1957; pp. 164–168.
14. Waloff, Z. The upsurge and recessions of the desert locust plague: An historical survey. *Anti-Locust Mem.* **1966**, *8*, 111.
15. Hunter, D.M. Distribution of the Australian plague locust in the Channel Country and adjacent areas. In *Australian Plague Locust Commission*; Ann. Report 1980–1981, Research; Supplement Australian Government Publishing Service: Canberra, Australia, 1982; pp. 46–54.
16. McCulloch, L.; Hunter, D.M. Identification and monitoring of Australian plague locust habitats from Landsat. *Remote Sens. Env.* **1982**, *13*, 95–102. [CrossRef]
17. Gay, P.; Lecoq, M.; Piou, C. Improving preventive locust management: Insights from a multi-agent model. *Pest Manag. Sci.* **2018**, *74*, 46–58. [CrossRef] [PubMed]
18. Gay, P.; Lecoq, M.; Piou, C. The limitations of locust preventive management faced with spatial uncertainty: Exploration with a multi-agent model. *Pest Manag. Sci.* **2020**, *76*, 1094–1102. [CrossRef] [PubMed]
19. Lecoq, M. Recent progress in desert and migratory locust management in Africa. Are preventive actions possible? *J. Orthopt. Res.* **2001**, *10*, 277–291. [CrossRef]
20. Lockwood, J.A.; Schowler, A.T.; Latchininsky, A.V. Can we make locust and grasshopper management sustainable? *J. Orthopt. Res.* **2001**, *10*, 315–329. [CrossRef]
21. Belayneh, Y.T. Acridid pest management in the developing world: A challenge to the rural population, a dilemma to the international community. *J. Orthopt. Res.* **2005**, *14*, 187–195. [CrossRef]
22. Strategic Review of the Australian Plague Locust Commission (APLC) 2012. 37p. Available online: https://www.agriculture.gov.au/sites/default/documents/aplc-strategic-review-2012.pdf (accessed on 10 October 2024).
23. Song, H. Density-dependent phase polyphenism in Nonmodel locusts: A minireview. *Pysche* **2011**, *2011*, 741769. [CrossRef]
24. Hunter, D.M.; Elder, R.J. Rainfall sequences leading to population increases of *Austracris guttulosa* (Walker) (Orthoptera:Acrididae) in arid north-eastern Australia. *Aust. J. Entomol.* **1999**, *38*, 204–218. [CrossRef]
25. Zhang, L.; Hunter, D.M. Management of locusts and grasshoppers in China. *J. Orthopt. Res.* **2017**, *26*, 155–159. [CrossRef]
26. Food and Agricultural Organization Desert Locust. 2024. Available online: https://www.fao.org/locusts/en (accessed on 10 October 2024).
27. Deveson, E.D.; Hunter, D.M. The operation of a GIS-based decision support system for Australian locust management. *Entomol. Sin.* **2002**, *9*, 1–12. [CrossRef]

28. Australian Plague Locust Commission. 2024. Available online: https://www.agriculture.gov.au/biosecurity-trade/pests-diseases-weeds/locusts (accessed on 10 October 2024).
29. Cressman, K. The use of new technologies in desert locust early warning. *Outlooks Pest Manag.* **2008**, *19*, 55–59. [CrossRef]
30. Cressman, K. Desert Locust. In *Biological and Environmental Hazards, Risks, and Disasters*; Sivanpillai, R., Ed.; Elsevier: Amsterdam, The Netherlands, 2016; pp. 87–105. [CrossRef]
31. Li, L.; Zhu, D.; Ye, S.; Yao, X. Design and implementation of geographic information systems, remote sensing, and global positioning system–based information platform for locust control. *J. Appl. Remote Sens.* **2014**, *8*, 084899. [CrossRef]
32. Hastings, J.; Latchininsky, A.V.; Schell, S.P. Sustainability of grasshopper management and support through CARMA. In Proceedings of the 42nd Hawaii International Conference on Systems Sciences (HICSS 2009), Waikoloa, HI, USA, 5–8 January 2009; IEEE Computer Society: Washington, DC, USA, 2009; pp. 1–10. [CrossRef]
33. Deveson, E.D.; Drake, V.A.; Hunter, D.M.; Walker, P.W.; Wang, H.K. Evidence from traditional and new technologies for northward migrations of Australian plague locusts, *Chortoicetes terminifera* (Walker) (Orthoptera: Acrididae) to western Queensland. *Austral Ecol.* **2005**, *30*, 928–943. [CrossRef]
34. Lecoq, M.; Sukirno. Drought and exceptional outbreak of the oriental migratory locust in Indonesia. *J. Orthopt. Res.* **1999**, *8*, 153–161. [CrossRef]
35. Cease, A.J.; Elser, J.J.; Ford, C.F.; Hao, S.; Kang, L.; Harrison, J.F. Heavy livestock grazing promotes locust outbreaks by lowering plant nitrogen content. *Science* **2012**, *335*, 467–469. [CrossRef] [PubMed]
36. Stige, L.C.; Chan, K.S.; Zhang, Z.B.; Frank, D.; Stenseth, N.C. Thousand-year-long Chinese time series reveals clmatic forcing of decadal locust dynamics. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 16188–16193. [CrossRef]
37. Joern, A. What are the consequences of non-linear ecological interactions for grasshopper control strategies? In *Grasshoppers and Grassland Health. Managing Grasshopper Outbreaks without Risking Environmental Disaster: NATO Science Series 2. Environmental Security—Vol. 73*; Lockwood, J.A., Latchininsky, A.V., Sergeev, M.G., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2000; pp. 131–144. [CrossRef]
38. Baker, G.L. The seasonal abundance of dipterous and mermithid parasites of the wingless grasshopper *Phaulacridium vittatum* (Sjost) in the Central Tablelands of New South Wales. In Proceedings of the 3rd Australasian Conference on Grassland Invertebrate Ecology; Lee, K., Ed.; Government Printing Division: Adelaide, Australia, 1982; pp. 169–176.
39. Symmons, P. Evaluating recent locust research. In *New Strategies in Locust Control*; Krall, S., Peveling, R., Diallo, B.D., Eds.; Birkhäuser Verlag: Basel, Switzerland, 1997; pp. 2–8. Available online: http://link.springer.com/chapter/10.1007/978-3-0348-9202-5_1 (accessed on 10 October 2024).
40. Hunter, D.M.; McCulloch, L.; Spurgin, P.A. Aerial detection of nymphal bands of the Australian plague locust (*Chortoicetes terminifera* (Walker)) (Orthoptera: Acrididae). *Crop Prot.* **2008**, *27*, 118–123. [CrossRef]
41. Owour, A.; McRae, H.D. The control of the desert locusts (*Schistocerca gregaria*) in Somalia during the upsurge between 2019 and 2021. *Outlooks Pest Manag.* **2022**, *33*, 221–226. [CrossRef]
42. Gensch, L.; Jantke, K.; Rasche, L.; Schneider, U.A. Pesticide risk assessment in European agriculture: Distribution patterns, ban-substitution effects and regulatory implications. *Environ. Pollut.* **2024**, *348*, 123836. [CrossRef]
43. Everts, J.W.; Ba, L. Environmental effects of locust control: State of the art and perspectives. In *New Strategies in Locust Control*; Krall, S., Peveling, R., Diallo, B.D., Eds.; Birkhäuser Verlag: Basel, Switzerland, 1997; pp. 331–336. [CrossRef]
44. Samways, M.J. Can locust control be compatible with conserving biodiversity? In *Grasshoppers and Grassland Health. Managing Grasshopper Outbreaks without Risking Environmental Disaster*; Lockwood, J.A., Latchininsky, A.V., Sergeev, M.G., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2000; pp. 173–180. Available online: http://link.springer.com/chapter/10.1007/978-94-011-4337-0_12 (accessed on 10 October 2024).
45. Smith, D.I.; Lockwood, J.A.; Latchininsky, A.V.; Legg, D.E. Changes in non-target arthropods populations following application of liquid bait formulations of insecticides for control of rangeland grasshoppers. *Int. J. Pest Manag.* **2006**, *52*, 125–139. [CrossRef]
46. Lockwood, J.A.; Schell, S.P. Decreasing economic and environmental costs through Reduced Area and Agent Insecticide Treatments (RAATs) for the control of rangeland grasshoppers: Empirical results and their implications for pest management. *J. Orthopt. Res.* **1997**, *6*, 19–32. [CrossRef]
47. Lockwood, J.A.; Anderson-Sprecher, R.; Schell, S.P. When less is more: Optimization of reduced agent-area treatments (RAATs) for management of rangeland grasshoppers. *Crop Prot.* **2002**, *21*, 551–562. [CrossRef]
48. McNary, T.J.; Shambaugh, B.A.; Elliston, R.J.; Brown, C.L. Cooperative rangeland grasshopper suppression in Wyoming (USA) in 2010. *Metaleptea* **2011**, *31*, 10–12.
49. Food and Agriculture Organization. *PGSE—Plan de Gestion Sanitaire et Environnementale Relative à la lutte Antiacridienne à Madagascar*; Food and Agricultural Organization: Rome, Italy, 2013; 103p. Available online: http://www.fao.org/3/a%E2%80%93bl257f.pdf (accessed on 12 October 2024).
50. Henschel, J.R. Locust times—Monitoring populations and outbreak controls in relation to Karoo natural capital. *Trans. R. Soc. S. Afr.* **2015**, *70*, 135–143. [CrossRef]
51. Peveling, R. Environmental conservation and locust control—Possible conflicts and solutions. *J. Orthopt. Res.* **2001**, *10*, 171–187. [CrossRef]
52. Rachadi, T.; Foucart, A. Barrier treatment with fipronil to control desert locust *Schistocerca gregaria* (Forskål, 1775) hopper bands infesting a large area in Mauritania. *Int. J. Pest Manag.* **1999**, *45*, 263–273. [CrossRef]

53. Samways, M.J.; Lockwood, J.A. Orthoptera conservation: Pests and paradoxes. *J. Insect Conserv.* **1998**, *2*, 143–149. [CrossRef]
54. Latchininsky, A.V.; Schell, S.P. *Grasshoppers in the West: Identification and Management*; Cooperative Extension Service Bulletin B-1171; University of Wyoming: Laramie, WY, USA, 2006. Available online: https://www.wyoextension.org/agpubs/pubs/B1171_poster.pdf (accessed on 10 October 2024).
55. van der Valk, H. The impact of locust and grasshopper control on beneficial arthropods in West Africa. In *Ecotoxocology: Pesticides and Beneficial Organisms*; Haskell, P.T., McEwen, P., Eds.; Chapman & Hall: London, UK, 1998; pp. 372–380. [CrossRef]
56. Hunter, D.M.; Milner, R.J.; Spurgin, P.A. Aerial treatment of the Australian plague locust, *Chortoicetes terminifera* (Orthoptera: Acrididae) with *Metarhizium anisopliae* (Deuteromycotina: Hyphomycetes). *Bull. Entomol. Res.* **2001**, *91*, 93–99. [CrossRef]
57. Hernández-Velazquez, V.M.; Hunter, D.M.; Barrientos-Lozano, L.; Lezama-Guiterrez, R.; Reyes-Villanueva, F. Susceptibility of Schistocerca piciefrons (Orthoptera: Acrididae) to *Metarhizium anisopliae* var. *acridum* (Deuteromycotina: Hyphomycetes): Laboratory and field trials. *J. Orthopt. Res.* **2003**, *12*, 89–92. [CrossRef]
58. Barrientos-Lozano, L.; Hunter, D.M.; Alvila-Valdez, J.; Garcia-Salazar, P.; Horta Vega, J.V. Control biológico de la langosta *Schistocerca piceifrons* (Orthoptera: Acrididae) en el noroeste de Mexico. *Vedalia* **2005**, *12*, 119–128.
59. Barrientos-Lozano, L.; Song, H.; Rocha-Sanchez, A.Y.; Torres-Castillo, J.A. State of the art management of the Central American zlocvust *Schistocerca piciefrons piciefrons* (Walker, 1870). *Agronomy* **2021**, *11*, 1024. [CrossRef]
60. Zhang, L.; Hunter, D.M. Laboratory and field trials of Green Guard^{TM} *Metarhizium anisopliae var. acridum* (Deuteromycotina: Hyphomycetes) against the oriental migratory locust (*Locusta migratoria manilensis*) (Orthoptera: Acrididae) in China. *J. Orthopt. Res.* **2005**, *14*, 27–30. [CrossRef]
61. Li, H.M.; Kadzamira, M.A.T.J.; Ogimmodede, A.; Finch, E.; Xhu, J.Q.; Romney, D.; Luke, B. Lessons learned and challenges of biopesticide usage for locust management—The case of China. *Sustainablility* **2023**, *15*, 6193. [CrossRef]
62. Belovsky, G.E. Do grasshoppers diminish grassland productivity? A new perspective for control based on conservation. In *Grasshoppers and Grassland Health. Managing Grasshopper Outbreaks without Risking Environmental Disaster*; Lockwood, J.A., Latchininsky, A.V., Sergeev, M.G., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2000; pp. 7–30. [CrossRef]
63. Latchmininsky, A.V.; Sword, G.; Sergeev, M.; Cigliano, M.M.; Lecoq, M. Locusts and grasshoppers: Behavior, ecology, and biogeography. *Psyche—J. Entomol.* **2011**, *2011*, 578327. [CrossRef]
64. Zhang, L.; Yan, Y.; Wang, G.; Zhang, Z.; Pan, J.; Yang, Z. A preliminary survey on the epizootics of infection of *Nosema locustae* among grasshoppers in rangeland. *Acta Agrestica Sin.* **1995**, *3*, 223–229. Available online: http://manu40.magtech.com.cn/Jweb_cdxb/CN/10.11733/j.issn.1007-0435.1995.03.007 (accessed on 10 October 2024).
65. Gong, A.; Liu, X.; Jiang, X.; Zhang, L. Transmission of *Nosema locustae* disease in grasshopper populations in Qinghai grassland. *Chin. J. Biol. Control* **2003**, *19*, 118–121. Available online: http://en.cnki.com.cn/Article_en/CJFDTOTAL-ZSWF200303006.htm (accessed on 10 October 2024).
66. Fu, X.J.; Hunter, D.M.; Shi, W.P. Effect of *Paranosema (Nosema) locustae* (Microsporidia) on morphological phase transformation of *Locusta migratoria manilensis* (Orthoptera: Acrididae). *Biocontrol Sci. Technol.* **2010**, *20*, 683–693. [CrossRef]
67. Hunter, D.M. Credibility of an IPM approach for locust and grasshopper control: The Australian example. *J. Orthopt. Res.* **2010**, *19*, 133–137. [CrossRef]
68. Zhang, L.; Lecoq, M. Nosema locustae (Protozoa, Microsporidia), a biological agent for locust and grasshopper control. *Agronomy* **2021**, *11*, 711. [CrossRef]
69. Ouedraogo, A.; Fargues, J.; Goettel, M.; Lomer, C.J. Effect of temperature on vegetative growth among isolates of *Metarhizium anisopliae* and *M. flavoviride*. *Mycopathologia* **1997**, *137*, 37–43. [CrossRef]
70. Milner, R.J. *Metarhizium filavoviridae* (FI985) as a promising mycoinsecticide for Australian acridids. *Mem. Entomol. Soc. Can.* **1997**, *171*, 287–300. [CrossRef]
71. Finch, E.A.; Li, H.M.; Cornelius, A.; Styles, J.; Beeken, J.; Cheng, Y.M.; Wang, G.J.; Qui, G.G.; Luke, B. An updated and validated model for predicting the performance of a biological control agent for the oriental migratory locust. *Pest Manag. Sci.* **2024**, *80*, 442–451. [CrossRef] [PubMed]
72. Keyser, C.A.; Fernandes, E.K.K.; Rangel, D.E.N.; Roberts, D.W. Heat-induced post-stress growth delay: A biological trait of many *Metarhizium* isolates reducing biocontrol efficacy? *J. Invert. Pathol.* **2014**, *120*, 67–73. [CrossRef] [PubMed]
73. Scattolini, M.C.; Piou, C.; Medina, H.; Iglesias, R.; Cerquetti, A.; Cigliano, M.M. Environmental factors associated to breeding areas of the South American locust *Schistocerca cancellata* on a regional scale. *Austral Ecol.* **2024**, *49*, e13568. [CrossRef]
74. Wang, B.; Deveson, E.D.; Waters, C.; Spessa, A.; Lawton, D.; Feng, P.; Liu, D.L. Future climate change likely to reduce the Australian plague locust (*Chortoicetes terminifera)* seasonal outbreaks. *Sci. Total Environ.* **2019**, *668*, 947–957. [CrossRef]