Operational-scale application of entomopathogenic fungi for control of Sahelian grasshoppers

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SUMMARY

Locusts and grasshoppers regularly threaten agricultural production across large parts of the developed and developing worlds. Recent concerns over the health and environmental impacts of standard chemical control measures have led to a demand for alternative, more environmentally benign control technologies. Here we present the results of a field study to investigate the potential of inundative biological control for control of grasshoppers in the Sahelian region of Africa. The biocontrol agent was an oil-based biopesticide formulation of a naturally occurring entomopathogenic fungus, *Metarhizium flavoviride*. This was applied at a rate of 21 ha⁻¹ to a total area of 150 ha using standard equipment normally used for the application of chemical pesticides. Twenty-one days after application, an 80% reduction in grasshopper populations was recorded in treated plots, relative to control populations in equivalent unsprayed areas. We think that this is the first operational-scale application of a biopesticide to demonstrate significant population reductions of key Sahelian grasshopper pests. This represents a substantial development in locust and grasshopper control, and should open the way for a new era of integrated control strategies where reliance on conventional chemicals is reduced.

1. INTRODUCTION

Locusts and grasshoppers enjoy a notoriety shared by few other agricultural pests or diseases. During this century alone, eight major plagues of desert locust, *Schistocerca gregaria* (Forskål), varying in length between 1 and 22 years, have threatened agricultural production across an invasion area of more than 20% of the world's land surface (Steedman 1990). A suite of other locust and grasshopper species and species assemblages cause much more regular and, through their cumulative effects, more significant damage throughout Africa, the Middle East, Australia, parts of Asia and North and South America (OTA 1990; Steedman 1990; Lomer & Prior 1992; Jenkins 1994).

In recent years, the challenge of controlling these ubiquitous pests has fallen largely to synthetic chemical insecticides. Fenitrothion, a short-persistent organophosphate with a half-life of around 24 h (Sekizawa *et al.* 1992), is one of the most widely used chemical insecticides for locust and grasshopper control (Steedman 1990; Joffe 1995; Milner 1997). However, compared with persistent organochlorides such as dieldrin, the effectiveness of these non-persistent

chemicals is limited, often requiring repeated applications within a season or large-scale blanket sprays to achieve more than temporary relief (Brader 1988). Furthermore, the extensive use of even these non-persistent chemicals has led to substantial concerns over health and environmental impacts (to humans, animals, birds, invertebrates and soil micro-organisms) of this conventional approach, particularly in fragile ecosystems such as the Sahel (OTA 1990; Joffe 1995). This concern is also shared by landholders in Australia (Jenkins 1994).

In this report we present the results of a study which examines the potential of a biological pesticide, based on a naturally occurring entomopathogenic fungus, to provide an effective, environmentally benign alterna-

Table 1. *The wind speed, air temperature (shade) and relative humidity recorded during spray application in the three treated plots*

plot	wind speed (m/s) and direction	temperature (°C)	relative humidity (%)
1	2–4 NW–S	26.0–27.5	55–66
2	1–3 W–S	27.5–30.0	64–53
3	2–4W–SSW	26.0–28.0	50–60

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tive to chemical control. The aim of the study was to establish the feasibility of operational-scale production, formulation and application of a biopesticide for grasshopper control in sub-Saharan Africa. To this end, the present report focuses on the basic result which demonstrates significant population reductions of a key Sahelian grasshopper species using microbial control methods. We believe that this is the first time that this has been achieved, and represents a substantial development in locust and grasshopper control.

2. MATERIALS AND METHODS

The study was conducted during the middle of the rainy season in August 1995 near Maine-Soroa, in south-east Niger Republic, West Africa. The field site was located at 13° 17' 22" N, 12° 07' 26" E and comprised a typical area of open savannah, with mixed-grass and forb vegetation ranging from 5 to 25 cm in height and a few scattered *Acacia* and *Balanites* trees. Fourteen grasshopper species were recorded at the site including several species of potential economic importance (as defined by Popov 1989) such as *Acrotylus longipes* (Charpentier), *Aiolopus simulatrix* (Walker), *Cryptocatantops haemorrhoidalis* (Krauss), *Diablocatantops axillariss* (Thunberg) and *S. gregaria*. However, the site was dominated (more than 80%) by *Oedaleus senegalensis* (Krauss), the most important grasshopper pest in the Sahel (Cheke 1990).

The biopesticide comprised an oil-based formulation consisting of 50% Ondina EL oil and 50% Shellsol T, of spores of the green muscardine fungus, *Metarhizium flavoviride* Gams & Rozsypal (Deuteromycotina: Hyphomycetes). A fluorescent tracer (2.5% Lumogen) was also added to the formulation. The fungal isolate used was a single conidial isolate of IMI (International Mycological Institute) 330189 obtained from the grasshopper *Ornithacris cavroisi* (Finot) in Niger. Spores for the trial were produced 'locally' in a low capital cost, intermediate-technology production facility in the Republic of Benin. Hyphomycete fungi such as *Metarhizium* are generally not pathogenic to non-target invertebrates (Goettel *et al.* 1990), and pose minimal risk to humans (Siegel & Shaddock 1990) and domestic animals and wildlife (Saik *et al.* 1990). The biopesticide used in the present study has passed The Pest Management Regulatory Agency, Health Canada (PMRA) standards for medium-scale field testing in trials up to 1000 ha.

The field trial was designed with six, square, 50 ha plots, each separated from their nearest neighbour by more than 250 m. Three of these plots were selected at random for treatment with the fungus, giving a total treated area of 150 ha. Spores were applied at 4.2×10^{12} ha⁻¹, at a volume application rate of 21 ha⁻¹ using a vehicle mounted ULVA-Mast MK II sprayer. This is standard equipment normally used for spraying chemical pesticides at ultra-low-volume rates for locust and grasshopper control. Treatment of the three plots took place in the early morning on three consecutive days. The wind speed, air temperature and relative humidity during treatment are given in table 1. Control plots received no spray treatments as previous studies have shown the blank oil formulation to have negligible effects on grasshopper populations in the field (e.g. Shah 1994; Lomer *et al.* 1997). Furthermore, the trial was designed to test the efficacy of the biopesticide 'product' which includes any impact of the formulating agents.

Grasshopper densities were assessed in each plot by carefully estimating the number of grasshoppers in 1 m² quadrats positioned at 4 m intervals along each of 4 × 100 m transects radiating from the centres of the plots along the

diagonals (i.e. 25 counts per 100 m transect). Counts were conducted in the cool of the morning so that movement of insects between quadrats was minimal. Counts were made on the day of treatment immediately before spraying, and then at 3 d intervals for 21 d post-treatment. These were analysed as a split-split-plot design with individual quadrat counts nested within transects within plots. Log (*n* + 1) transformed population counts were compared between treatment and control plots using multivariate analysis of covariance (pre-treatment counts as covariates) with repeated measures in SPSS for Windows 6.1.

Samples of approximately 100 grasshoppers were collected by sweep netting from the centre of each plot shortly after spraying and thereafter on days 3, 6, 9, 15 and 21. These samples were incubated in laboratory cages for 21 d and disease and mortality levels were recorded daily. During the incubation period, any dead insects were removed from the cages so that no horizontal infections could occur. Risk of infections from contact between live insects is very low (Bateman *et al.* 1993) and control insects were maintained in a separate room so that there was no risk of contamination. A further 50 insects were collected from the centre of each sprayed plot after treatment and were examined under UV light for the presence of spray droplets. Similarly, over 100 vegetation samples (leaves, stems or whole plants) were collected at random from the central sampling zones of each treated and control plot to evaluate spray coverage.

The infectivity of the spray residue was monitored using a field bioassay technique described in Jenkins & Thomas (1996) and Thomas *et al.* (1996*a, b*). This technique involves taking populations of uninfected grasshoppers from control plots and exposing them sequentially in the field in open-bottomed 0.5 m² cages to bioassay for changes in infectivity of the sprayed environment through time. As this is quite labour intensive, and given that the treated plots shared similar vegetation, grasshopper density and environmental conditions at the time of application, the measurements of residual infection were restricted to just one of the sprayed plots. Four cages were placed at the centre of this plot in a representative area of natural vegetation 2 h after treatment and 30 uninfected, third instar *O. senegalensis* were placed inside each. After 72 h of exposure the grasshoppers were removed from the cages. No food was added during this period as the natural vegetation was considered sufficient. The groups of 30 insects were then transferred to the laboratory and incubated for 21 d to monitor mortality and infection as described above. This procedure was repeated 3, 6, 9 and 12 d after spraying. Unfortunately, during the 12–15 d sample the cages were disrupted by cattle so no data are available for this final period. On each date the cages were placed in a new position and any naturally occurring grasshoppers or predators removed prior to introduction of the test grasshoppers.

3. RESULTS AND DISCUSSION

The results of the population counts are shown in figure 1. Initially, both treated and non-treated populations were observed to decline at similar rates. This is in line with high mortality expected for first, second and third instar nymphs, which dominated the plots at this time (Waloff 1972). However, from day 6 onwards populations in the treated and control plots began to diverge, with the treated populations declining continuously until the end of the assessment period. This happened in spite of some eclosion and immigration which, although unquantified, was ap-

Figure 1. Mean ($\pm$ s.e.) population densities of grasshoppers in treated (open squares) and control plots (closed squares) after application of an oil-based formulation of the fungal entomopathogen *Metarhizium flavoviride*. Control plots received no spray treatment.

Figure 2. Infectivity of spray residue from one treated plot measured using a field bioassay technique. The data points give mean ($\pm$ s.e.) infection from the four field cages corrected to give risk of infection per day. An exponential regression is fitted to these data to give an instantaneous risk of infection, r , from contact with the spray residue of $r = 0.489 \exp(-0.90t)$; $R^2 = 0.60$; half-life of residue = 7.7 d. Further details of this technique are given in the main text and in Thomas *et al.* (1996b, 1997).

parent in all plots. Analysis of these population counts revealed a significant difference between treated and control populations across time ($F = 386.32$, $p < 0.001$). Individual analyses by date revealed that the treated and control populations differed significantly at the 5% level from day 9 onwards (MANOVA at day 9: $F = 98.41$, $p < 0.001$). Correction of changes in the treated population densities for changes in the control population densities using Henderson–Tilton’s (1955) formula revealed the efficiency of the biopesticide application to be 80% after 21 d.

Examination of vegetation samples for spray droplets using a UV light revealed uniform spray coverage across the three plots with 92% ($n = 352$) of the vegetation samples hit by at least one droplet and a mean ($\pm$ s.e.) number of droplets per cm² of vegetation of 7.3 ± 0.55 . No droplets were observed in the control plots.

Previous field trials in the Sahelian environment have indicated that contact with spores from the spray

residue provide an important route of infection. Spores can persist for several days after spraying and half-lives of spray residues of 5–7 d are typical (Thomas *et al.* 1996b, 1997). Results of the field bioassay experiments in the present study also revealed the spray residue to be highly infective. The mean percentage mortality of grasshoppers exposed to the spray residue on days 0–3 and 3–6 after spraying both exceeded 74%. By correcting the mean percentage mortality on each exposure date to give infection risk per day, a single expression for the instantaneous risk of infection through time can be derived (Thomas *et al.* 1996b, 1997). This is shown in figure 2 and reveals infectivity of the residue to have a half-life of 7.7 d.

Part of the contribution of the residual infection to total mortality can be seen from the cage incubation data for the grasshoppers collected at various times after spraying (figure 3). These data reveal that the percentage infection of grasshoppers collected in the treated plots immediately after spraying reached 77%

Figure 3. Results from the cage incubation studies for grasshoppers collected from the treated plots at various times after spraying. The lines show cumulative percentages of grasshoppers with visible *Metarhizium* sporulation after 21 d incubation for the different sampling days. Data for the three plots are pooled. No *Metarhizium* infections were recorded from the control insects during the study.

($n = 322$) after 21 d. This is lower than expected from the level of direct spray impaction indicated by the fluorescent tracer, which showed 90% of the grasshoppers sampled to be marked with at least one droplet and a mean ($\pm$ s.e.) number of droplets per insect of 6.9 ± 0.88 . Thus it appears that not all insects contacted directly by the spray go on to become infected. The reason for this is unclear but it is likely that a threshold number of spores is required to cause infection, and given that 15% of those individuals marked showed just 1–2 droplets, it is possible that some of these may have escaped infection. It is also possible that some individuals can escape infection through moulting before spores have had a chance to penetrate the cuticle. These factors are currently being investigated further.

For the day 3 samples, the percentage sporulation had risen to 85% ($n = 296$), indicating increased infection through contact with spores in the spray residue. Following this, the percentage sporulation showed a steady decline, eventually falling to 9% ($n = 176$) for the sample collected on day 21. This change in the level of infection through time is a consequence of a number of factors acting on the field population (see Langewald *et al.* 1997). For example, with a half-life of 7.7 d the spray residue should continue to infect individuals beyond day 3 and increase total infection towards 100% (Thomas *et al.* 1996*b*, 1997). However, this cannot be measured directly from the cage incubation samples because sweep netting only records live insects, and cumulative disease incidence in the field is increasingly underestimated as insects begin to die (Thomas *et al.* 1996*b*, 1997). Furthermore, eclosion and immigration contribute new individuals to the field populations at various times after spraying. These individuals are exposed to different levels of infectivity as the spray residue decays and may take longer than 21 d to die or may escape infection altogether. Finally, studies by Thomas *et al.* (1995, 1996*a*), which reveal the potential for horizontal transmission of the pathogen after spraying and persistence between seasons in

fragments of infected cadaver, suggest that the effects of the biopesticide may be more prolonged than those indicated in the first few weeks after application. This said, although cadavers were observed in the treated plots from day 6, these were far fewer than expected and many appeared to be predated or scavenged by ants and tenebrionid beetles (*Zophosis* sp.). This loss of new sources of inoculum is likely to have a marked effect on the extent of horizontal transmission although pathogen cycling cannot be ruled out altogether. Thus, infection levels are determined by both the functional and numerical responses of the pathogen and the spatial and temporal dynamics of the host. With just 21 d of observation, therefore, the overall impact of the biopesticide pathogen is difficult to quantify, even in plots as large as 50 ha.

One apparent problem with the biopesticide, revealed in figure 1, is that unlike a fast-acting chemical where mortality may be almost immediate, the pathogen does not cause significant mortality until after day 6. Thus the pathogen could be interpreted as having only limited efficacy. However, it is a misconception that the slow action of microbials makes them ineffective for locust and grasshopper control as not all control scenarios demand instant 'knock-down'. As in the present study, much of the treatment of locusts and grasshoppers can be done in non-crop habitats where control is preventive rather than curative (Prior & Streett 1997). Indeed, the current FAO policy for control of the desert locust favours early intervention with preventive measures (Joffe 1995). Under these circumstances slow speed of kill need not be a limitation, especially as feeding may be reduced some time before death (Moore *et al.* 1992).

A number of projects around the world are trying to develop microbial insecticides for locust and grasshopper control (e.g. Cunningham 1992; Johnson *et al.* 1992; Lobo-Lima *et al.* 1992; Prior *et al.* 1992; Baker *et al.* 1994; Zimmermann *et al.* 1994) and several studies have demonstrated significant population reductions of grasshoppers following microbial applications (e.g.

Johnson & Goettel 1993; Baker *et al.* 1994; Douro-Kpindou *et al.* 1995; Thomas *et al.* 1996*b*, 1997; Lomer *et al.* 1997; Milner 1997). However, these have been at relatively small experimental scales (under 10 ha) against species or life stages of limited mobility. Furthermore, results of studies in North America have proved to be very variable with environmental factors, particularly temperatures above 35 °C, appearing to severely limit the performance of particular pathogen species and isolates at certain times (Goettel *et al.* 1995; Inglis 1997*a, b*). In contrast, the results presented here show significant population reduction of a highly mobile pest (as stated above, immigration was apparent even at the centres of the plots), at operational scales of application under harsh Sahelian climatic conditions. Although climatic factors were not monitored, an indication of conditions can be gained from microclimate recordings taken at the study site as part of a separate investigation conducted during August 1996 when environmental conditions were similar to those of the present study. These revealed an average day-time soil temperature range (measured in the sun) of 50–55 °C with a maximum of 60 °C; an average day-time air temperature range (in the sun) of 34–36 °C with a maximum of 38 °C; and an average day-time internal body temperature range for fifth instar *O. senegalensis* nymphs of 33–40 °C with a maximum of 46 °C (S. Blanford, Imperial College, personal communication).

It is stressed that the production and application technology used in this study are accessible to the majority of countries threatened by locusts and grasshoppers. Current costs of treatment per hectare are comparable with those of conventional chemical control (Swanson 1997). Ongoing research into mass production technology is likely to reduce this further. Thus, this study represents a major breakthrough in confirming the potential of oil formulations of *M. flavoviride* as working, environmentally benign, alternatives to chemical insecticides. Given that the isolate used (and other isolates of *M. flavoviride*) has been shown in both laboratory and field studies to be virulent against a range of Acrididae, including the desert locust (Bateman *et al.* 1993; Prior *et al.* 1995), this should enable the present-day reliance on chemical insecticides to be lessened and create significant opportunities for the development of new integrated strategies in locust and grasshopper control. This supports the recommendations of The World Bank and others (e.g. TAMS 1989; OTA 1990; USAID 1991) who consider placement of desert locust control within the context of integrated pest management a desirable goal (Joffe 1995).

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