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Source: Journal of Orthoptera Research, 10(2) : 335-341

Published By: Orthopterists' Society

URL: https://doi.org/10.1665/1082-6467(2001)010[0335:WITPOB]2.0.CO;2

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Synthesis:

What is the place of biological control in acridid integrated pest management?

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Abstract

Control of grasshoppers and locusts has traditionally relied on synthetic insecticides, and for emergency situations, this is unlikely to change. Most locust control operations in Africa are conducted in 'crisis mode', and are affected by military situations which leave little room for flexibility. Nevertheless, there is a growing awareness of the environmental impact of acridid control options and the demand for a biological product is strong.

A decade of research on the entomopathogenic fungus *Metarhizium anisopliae* var. *acridum* has led to some very positive field results. Trials in Niger and Australia have shown that the fungus can be formulated and applied under standard operating conditions, and that control is effective and long-lasting. Most importantly, the products are highly selective, safe to use and we have not been able to detect any side-effects. This means that the natural enemy fauna is preserved and may contribute to control. *Metarhizium* is nonetheless slow-acting compared with chemical pesticides, and its place in an Integrated Pest Management framework needs to be considered with this property in mind.

We can see an emerging IPM framework, based on good detection and prediction, chemical pesticides for swarm control and real emergencies, and *Metarhizium* for outbreaks with no immediate risk of crop damage. With *Metarhizium* established as part of the IPM portfolio, there will be scope to explore further biocontrol options, such as the microsporidian *Nosema locustae* and the hymenopteran egg parasitoids *Scelio* spp.

Locust control - already IPM?

The place of biological control in locust integrated pest management (IPM), requires an assessment of the extent to which existing control operations can be considered IPM. There are many different definitions of IPM, but Kogan (1998) gives a useful working definition which is quite widely accepted: "IPM is a decision support system for the selection and use of pest control tactics, singly or harmoniously coordinated into a management strategy, based on cost-benefit analyses that take into account the interest of, and impact on, producers, society and the environment". According to this definition, it is not absolutely necessary to consider more than one control technology, but the control technology should be in harmony with social, economic and environmental factors. Current locust control technology relies heavily on chemical pesticides, applied in response to intensive and accurate surveys. This preventative control approach can be seen as a first step towards IPM. So although there is little excess or wastage of pesticides, there are concerns about the effect of repeated and combined abuses to the environment (Peveling, this issue, p.171). So one strong driving force for changing current practices is the concern for the environment. An important aspect of this is the issue of disposal of surplus pesticide stocks. Any well-run locust campaign will have at least some pesticide in reserve, and what to do with this at the end of the campaign is a problem. FAO is working with Crop Life International, the pesticide industry federation, to come up with solutions to this problem.

The second force driving research on biological control is the practical consideration of wishing to combine all available technologies and make use of synergies, rather than relying on a single 'silver bullet' solution — an approach which has repeatedly led to control failures in the past. There is an increasing realization that integrated schemes which take full account of natural forces and make good use of existing natural enemies, are more successful in the long run than those relying on a single technological solution which ignores ecological interactions.

Why biocontrol?

A range of potential IPM technologies has been explored during the 1990s, including botanical pesticides, pheromones and biological control. Although many interesting research results have been obtained which will be useful in understanding locust biology and developing locust IPM (See Krall *et al.* 1997 for a review), only biological control has fulfilled early expectations.

Biological control provides pest control solutions with unique properties. As well as being environmentally inoffensive, biological control agents are capable of self-propagation. Classical biological control provides the ideal solution, as the control agent becomes established and permanently reduces pest pressure. In situations where such a permanent solution does not work, inoculation and inundation biological control solutions are also environmentally benign, although not necessarily so cost-effective (Eilenberg *et al.* forthcoming).

Biological control of locusts is by no means a new concept. In South Africa, the Bacteriological Institute devel-

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oped and sold tubes of 'locust fungus' in 1898 (Plant Protection News 1992). Extensive research on *Metarhizium* was conducted in Argentina in the 1930s (Marchionatto 1934). Studies on the natural enemies of locusts and grasshoppers are also extensive (Greathead 1963, Shah *et al.* 1998, Lomer *et al*. 2001). The most interesting natural enemies selected for further study are *Nosema locustae*, *Entomophaga grylli*, *Scelio* spp., bacteria, viruses and the Hyphomycete fungi.

Nosema locustae.— A microsporidian, this was the first biological pesticide developed against acridids. It was registered and sold in the USA as NoLo bait, and extensive field trials were conducted in the USA, Canada, Mali, Cape Verde and Argentina. In the USA, *Nosema* dropped out of favor because its effect is slow, but current studies in Argentina and China indicate possible establishment and long-term impacts (Johnson 1997, Lange 1996).

Entomophaga grylli.— This is an impressive pathogen in the field, causing extensive epizootics (Paraiso *et al.* 1992). It is not a good candidate for development as a biopesticide as it is difficult to grow in artificial media, and infections are subject to environmental constraints. Its best potential is as a classical or neoclassical biological control agent. In this context, an Australian strain was introduced to the USA, but is not thought to have become established (Bidochka *et al.* 1996).

Scelio spp.— These Hymenoptera (Proctotrupoidea: Scelionidae) are found throughout the world, but there is some evidence for higher rates of parasitism in Australia than elsewhere (Baker *et al.* 1996). Researchwas conducted preparatory to importation of *Scelio diversicornis* into the USA, but owing to concerns for the potential impact on some rare and beneficial prairie grasshoppers, the importation was not in the end carried out. Currently, in West Africa, there are few concerns about indigenous or rare Orthoptera. However, in this part of the world, the ecological risk related with releasing an exotic egg parasite needs to be studied carefully.The release of *Scelio* species as a classical biological control agent, with establishment in their new environment in a sustainable way, would be an attractive option compared with digging egg pods (Lomer *et al.* 1999).

Selecting biocontrol agents in an IPM context

As shown in Fig. 1, it is important to address both time and scale in considering biological control agents for implementation. There is scope for both inundation and inoculation/classical biocontrol agents. There is no real expectation that biological control agents can be as fast-acting as chemical pesticides, but there are nevertheless many scenarios when a control agent acting within one generation is useful.

In this context, given the cost of rearing and delivery of macrobiological control agents, we must expect the emphasis to be on microbiological control agents. Bacteria and viruses are widely used as biopesticides against other pests, but are impractical in the context of acridid biocontrol, because they must be ingested and so are applied as baits. Given the poor infrastructure and vast areas to be covered, aerial application by ULV is the only feasible delivery method. By contrast, hyphomycete fungi are amenable to mass production, but invade through the cuticle and thus can be considered as contact biopesticides. In particular, oil formulations enable their use under conditions of low humidity not normally associated with fungal infections (Prior & Greathead 1989).

Seven independent programs have all selected isolates of *Metarhizium anisopliae* var. *acridum* as the most promising active agent in biopesticide preparations (Table 1). Early publications on *Metarhizium* for locust control refer to *Metarhizium flavoviride*. Early classifications were based on spore shape and size; however, the genus has now been reclassified by Driver *et al.* (2000) based on rDNA sequence data. This work places all the acridid-active isolates into a single new variety: *Metarhizium anisopliae* var. *acridum*.

Two research programs, in Africa and Australia, have gone on to develop commercial products based on *Metarhizium*. Although more research on *Metarhizium* isolates is always valuable, it is not entirely clear what is likely to be achieved through the development of further products based on other isolates. The cost of developing a commercial product from a virulent isolate has been estimated at between US $5-$15million (Dent & Lomer 2001). Competition is adequately served by the existence of two rival commercial products and in nondesert locust outbreak years, the international market for such products is hardly big enough for these products to survive. Some countries do prefer to exploit and protect indigenous biodiversity, but so far there is little evidence that a commercial biopesticide based on an exotic isolate would displace the native microflora. The principal concern would be that an exotic microorganism would have unexpected effects on the native nontarget organisms, but so far, the *M. anisopliae* var. *acridum* isolates appear to be remarkably homogeneous, both in their biochemical properties and their effects on nontarget organisms. More detailed studies in this area are on-going.

Properties of M. anisopliae var. *acridum.*— *Metarhizium* is not commonly found in desert conditions, but is found in seasonally extreme habitats such as the Niger flood plain. As such, it appears to be adapted to survive hot dry conditions, and this may partly explain its good spore stability. Under natural conditions, *M. anisopliae* var. *acridum* probably recycles at a low level in susceptible host species, and is able to survive from one season to the next in favorable microhabitats, particularly in the cadavers of infected insects (Shah *et al.* 1994, Thomas *et al.* 1996).

Metarhizium can be grown on artificial substrates. Mass production systems can be classified as being of two types: large-scale solid state fermentation, and production in small contained bags. In principle, the large-scale solid state fermentation systems should be more cost-effective (Swanson 1997). However, compared with other entomopathogenic fungi, *M. anisopliae* var. *acridum* appears to be less competitive, and this is why in mass production, problems of contamination often occur. For this reason, the small bag systems, where any contamination occurring can be contained, currently appear to be more cost-effective.

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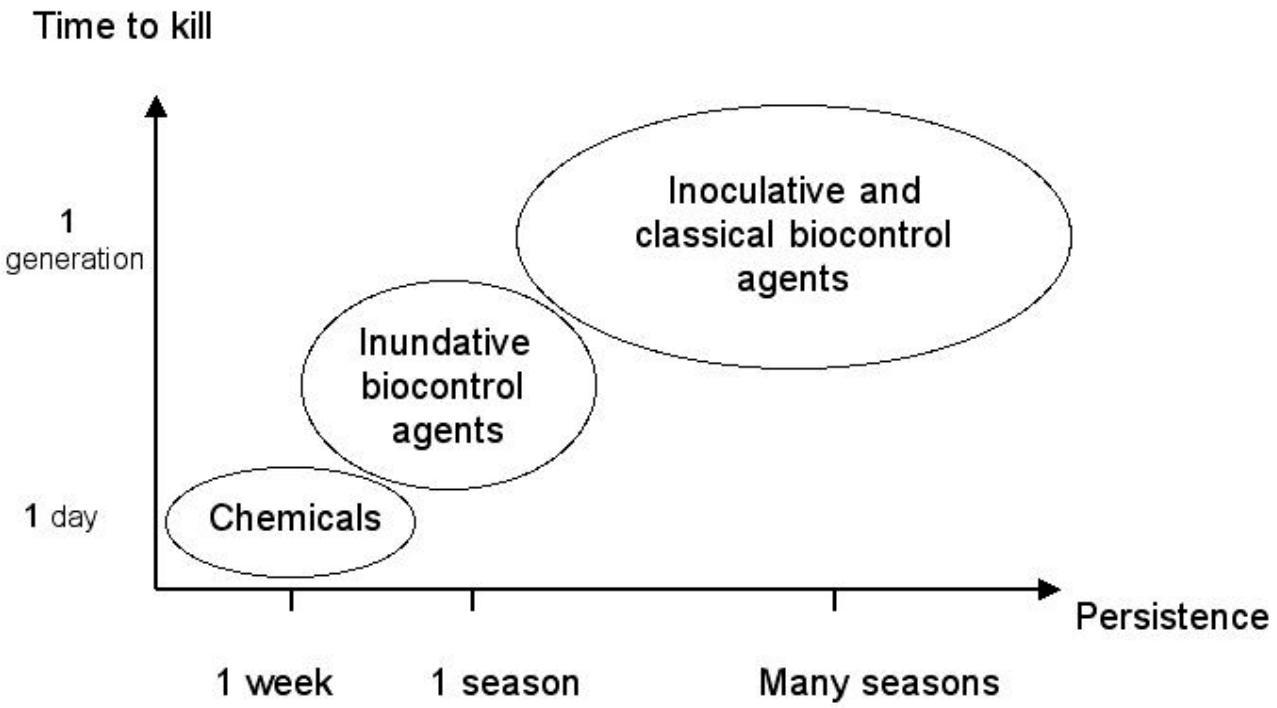


Fig.1. Considerations of time and scale affect selection of control agents for locust and grasshoppers.

Table 1. Programs involved in developing *Metarhizium anisopliae var. acridum* for microbial control of grasshoppers and locusts.

Source and number of isolate	Development agency(ies)	Trade name	Commercial company	Current status
Niger; IMI 330189	LUBILOSA	Green Muscle	BCP, South Africa	On sale, provisional reg. Sahel and S. Africa
Australia; FI 985	CSIRO, APLC	Green Guard	SGB, Australia	On sale, provisional reg. in Australia
Mexico; MaPL32, MaPL40	Instituto Tecnologico	None	None	In development
Brazil; CG 423	EMBRAPA, CIRAD	None	None	In development
Morocco; NK	CNLAA	None	None	In development
Madagascar; SP9	Govt. of Madagascar, MSU	None	None	In development
Eritrea; ER1	Govt. of Eritrea, MSU	None	None	In development

Abbreviations: NK - Not known; LUBILOSA - Lutte Biologique contre les Locusts et Sauteriaux, collaborative programme with CAB International Institute of Tropical Agriculture, Cotonou, Benin; CSIRO- Commonwealth Scientific and Industrial Research Organisation; APLC - Australian Plague Locust Commission; EMBRAPA - Empreas Brasiliera de Pesquisa Agropecuaria, Brazil; CIRAD - Centre International de Recherche Agricole pour le Developpement; MSU - Montana State University; CNLAA - Centre National de Lutte Anti-Acridienne.

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Technical characteristics of commercial Metarhizium products.— The particular features of *Metarhizium*-based biopesticides are as follows: they kill in 7-18 d (depending on temperature and thermoregulation), oil formulation removes the need for high relative humidity, and oil formulations developed are compatible with existing ULV spray equipment.

The technical properties of *Metarhizium* products are as follows. The product is produced as a green powder of uniform particle size, with a moisture content of 5-8%. The powder is not normally available to operators because it is allergenic, so although the product may be stored as powder, it is normally formulated as an oil concentrate before shipping. *Metarhizium* spores are inherently lipophilic, and are readily taken up into oil suspension. Different companies have slightly different formulations, which may help to keep the spores in suspension. UV protection is not normally included, as spore persistence in the field is adequate.

A model describing spore storage has been developed by Dr. T. Hong of Reading University. Storage times are critically dependent on moisture content — drying the spores below 5% gives some survival at 50°C, 12 mo at 35°C, and many years if kept cool [a maximum of 6 y was recently reported by N. Jenkins, CAB International, pers. comm.] (Hong *et al.* 2000). These storage properties are workable, but not ideal. *Metarhizium*-based biopesticides are living biological material, and will always need special attention compared with chemicals. How much of a constraint this will pose during large-scale locust campaigns remains to be seen. One advantage is that the disposal of surplus material does not pose a problem: leaving spore formulations exposed to tropical sunlight for a day or two will in general reduce the viability to close to zero.

Fig. 2 (from Langewald *et al.* 1999) shows the field performance of *Metarhizium* spores applied to Senegalese grasshopper populations in Niger. *Metarhizium* kills more slowly than the chemical pesticide standard (fenitrothion) but is much more long-lasting, and a single application gives season-long control. Similar results are reported by Hunter *et al.* (2001) against Australian plague locust in Australia. The extent to which this prolonged control effect is due to recycling, compared with good spore persistence remains the subject of some debate (Thomas *et al.* 1995, Arthurs *et al.* 1999). Pending the outcome of a definitive field experiment in which the persistence of *Metarhizium* would be compared in treatments with and without grasshoppers, the question remains open. However, it would be reasonable to suppose, on the basis of current field observations in a variety of environments, that recycling is the exception rather than the norm, requiring conditions of high humidity and reduced scavenger activity.

The principal constraint affecting operational use of *Metarhizium* appears to lie in the capacity of grasshoppers and locusts to thermoregulate above the permissive temperature for fungal growth (Blanford *et al.* 1998). This behavioral response to fungal infections has also been described for different orthopteran and fungus species (Carruthers *et al.* 1988, 1992). Under desert conditions, such as in the Karoo in South Africa, affecting the brown locust *Locustana pardalina*, are cold night temperatures combined with high day temperatures and the capacity of this locust to elevate its body temperature to several degrees above ambient, which can prolong incubation times to more than 20 d. A geographic information system (GIS) is currently being developed by CAB International to predict how long *Metarhizium* will take to kill locusts, and this will enable operators to avoid use of the product under unfavorable conditions.

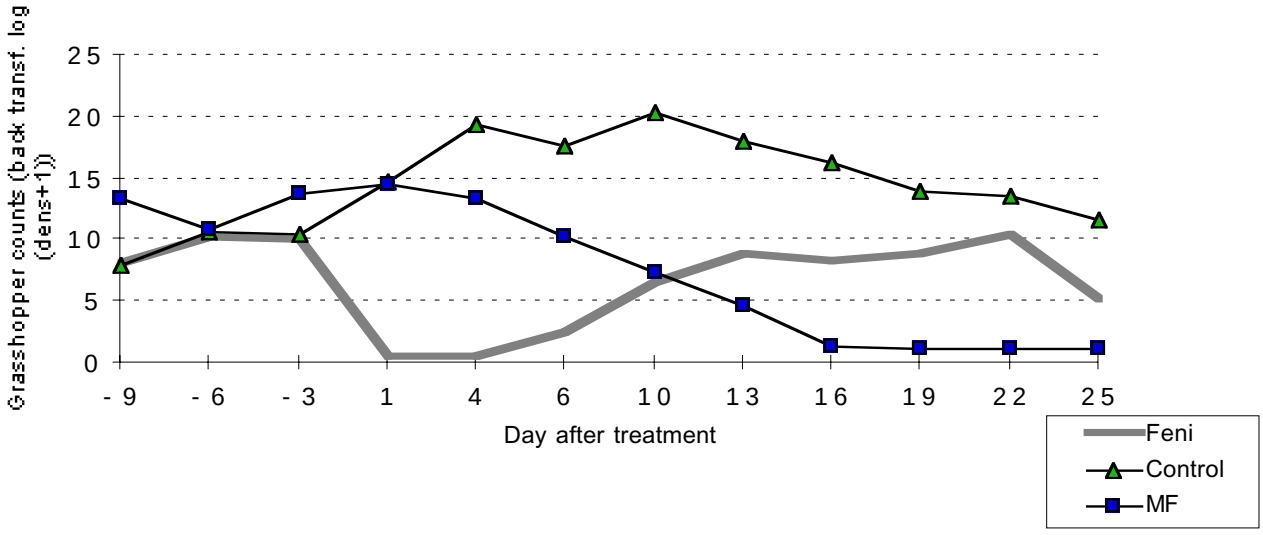


Fig. 2. The Senegalese grasshopper, *Oedaleus senegalensis* (Krauss), nymphs were treated in one of three ways in unreplicated 800 ha plots in Maine Soroa, Niger in 1997. Treatment one was fenitrothion at the standard dose, Treatment 2 was *Metarhizium* (Green Muscle) spores at 100g (=$5x10^{13}$) spores per ha, while Treatment 3 was an untreated control. Grasshoppers were counted on transects by four observers at 3-d intervals. For ANOVA, log+1 of the counts was used, while for the graph the counts have been back-transformed to grasshopper counts per square meter.

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Compatibility between IPM technologies.—The compatibility between chemical and biological control agents has been explored in several ways. Mixtures between chemical pesticides and *Metarhizium* can give good speed of kill (Douro-Kpindou *et al.* 2001). However, as such mixtures would need a separate registration and environmental impact evaluation, there has been little incentive to pursue this option.

Exploring how *Nosema* and *Metarhizium* could be combined is an interesting case. Probably, chemical pesticides would be used where there was an immediate risk of swarming and crop damage. *Metarhizium* would be used in situations of less urgency, while *Nosema* would be reserved for populations that showed no risk of developing to threatening levels in the current generation, but might pose a greater risk in the future.

Metarhizium with *Scelio* is another combination of great interest. In principle, the two agents should be fully compatible. *Scelio* has not yet been directly tested for susceptibility to *Metarhizium*, but related parasitic wasps have been shown to be unaffected by field applications of *Metarhizium* (Stolz 1999). Timing and placement of releases could readily be planned to reduce any possibility of contact between *Metarhizium* and *Scelio*.

Idealized biologically-based IPM scheme.— With the establishment of the most effective strains and species of *Scelio* and *Nosema locustae* as classical biological control, with periodic reintroduction to new areas, we would expect to see baseline locust and grasshopper populations lowered and the incidence of outbreaks reduced. Any impending outbreak would be treated with *Metarhizium*, which would enable the full panoply of opportunistic natural enemies, including birds and man, to have their impact. Only in cases of major emergency and serious large-scale outbreaks would chemical pesticides be used as a weapon of last resort.

Scale of IPM technologies.— Scale impacts on IPM technologies in three important ways. First, as shown in Fig. 3a, the scale of movement of the pest insect is important. Relatively sedentary pest species will be more readily affected by natural enemies than highly mobile species. Fig. 3b shows how the scale of movement of the pest insect influences the involvement of different actors in the treatments, while Fig. 3c shows how different actors and agents are effective at different scales of operations.

Conclusions

The availability of novel methods such as microbial control open a window of opportunity for the development of environmentally sound options for grasshopper and locust control, and for the integration of all stakeholders such as farmers, plant protection agencies and international organizations.

A future IPM strategy will include three different approaches. One component will consist of the release of exotic natural enemies such as *Scelio spp.* or *Nosema spp.* for long-term impact. This approach still needs a careful environmental risk assessment. The second component will be the preventative application of Green Muscle™, a product developed by the LUBILOSA program, which is based on the entomopathogenic fungus *M. anisopliae*. The third component is a reduced application of conventional insecticides in situations which are unsuitable for alternatives. Potential negative side effects of releases of exotic natural enemies need to be studied very carefully for their potential risk to indigenous nontarget species or natural enemies.

An IPM approach based on biological control needs GIS-based decision-making tools to determine zones of different ecological vulnerability, natural enemy distribution, grasshopper population dynamics, crop damage and *Metarhizium* efficacy under different climatic conditions.

The successful implementation of such an IPM approach will require training at all levels. A good understanding of biological control is necessary to convince plant protection officers and farmers that quick kill is only necessary when using curative control strategies. Participatory trials with plant protection officers and farmers will help to establish full confidence in these types of control strategies.

Acknowledgements

We acknowledge the International Institute of Tropical Agriculture, particularly the Plant Health Management Division Director, Dr. Peter Neuenschwander, for granting sabbatical leave on half pay for CL to develop these ideas. We also acknowledge the input of the LUBILOSA team, particularly Zakaria Ouambama, Ralf Peveling, Ine Stolz, Roy Bateman, Matt Thomas, Nina Jenkins, Chris Prior, David Dent, Dave Moore, Christiaan Kooyman, Hugo De Groote, Jane Gunn, Belinda Luke, O.K.Douro-Kpindou, Ignace Godonou, Firmin Obognon, Venance Ahomagnon, Comlan Gbongboui, Gabriel Heviefo, Armand Paraiso, Paresh Shah, the LUBILOSA donors — Swiss Development Cooperation (SDC), Canadian International Development Agency (CIDA), Netherlands Directorate-General for International Co-operation (DGIS), British Department for International Development (DFID), US Agency for International Development (USAID), Luxembourg Development. We thank the Association of Applied Acridologist International (AAAI) for financing a trip to Australia which resulted in discussions with Jeff Lockwood, Richard Milner, David Hunter, Carlos Lange and others, and development of the AAAI Biocontrol working group concept. we acknowledge the Royal Veterinary and Agricultural University, Frederiksberg, Copenhagen for providing office space and discussion, particularly Jørgen Eilenberg, Charlotte Nielsen, Susanne Vestergaard, Annette Bruun Jensen and Lene Thomsen.

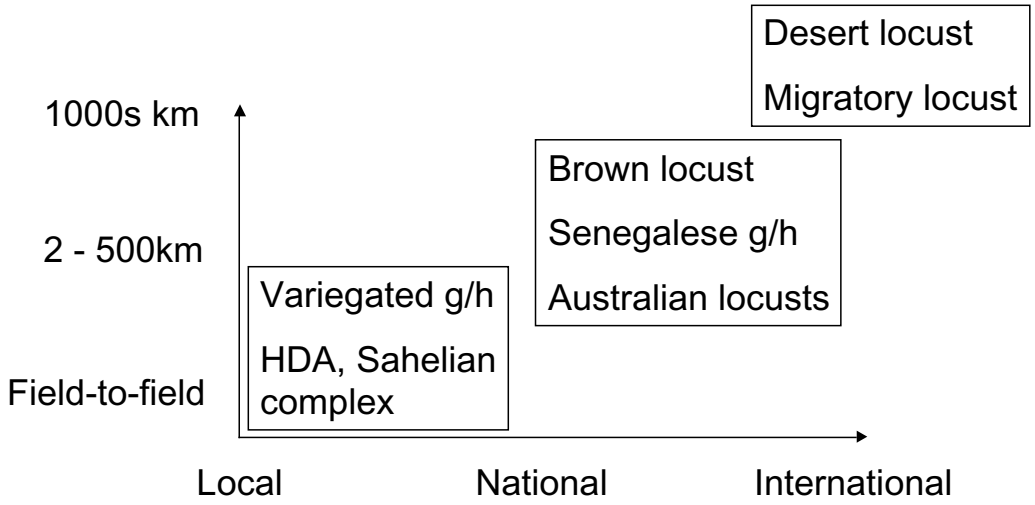
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a.



b.

Local	National	International
Plant protection service	Plant protection service	International organisations
NGOs	(Federal/ State service)	Plant protection service
Farmers		

c.

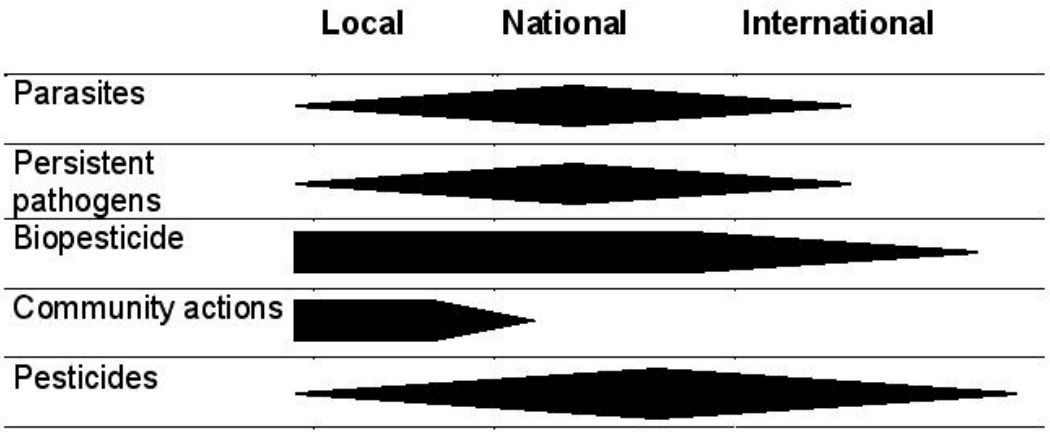


Fig. 3. A generalized IPM scheme for determining which control agents to use in locust and grasshopper control. Considerations of scale in locust and grasshopper IPM. **a.** Different species act over different scales, local, national or international, depending on the scale of their migrations. **b**. The scale of the locust migrations influences which principal actors will be involved in control operations. **c.** Similarly, different control agents are appropriate at different scales.

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