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Author: Peveling, Ralf

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Synthesis:

Environmental conservation and locust control — possible conflicts and solutions

Ralf Peveling

Institut für Natur-, Landschafts- und Umweltschutz (NLU) – Biogeographie, Universität Basel, St. Johanns-Vorstadt 10, 4056 Basel, Switzerland. E-mail: ralf.peveling@unibas.ch

Abstract

In contrast to pests developing in close association with a particular host crop, locusts and grasshoppers are often controlled in natural or semi-natural landscapes, exposing structurally and functionally diverse communities to agrochemicals, chemicals to which they are not adapted. This suggests that insecticide-induced perturbations may be severe. On the other hand, with acridids being highly mobile, exposure of non-target biota at any one location tends to be rare, and insecticides might be seen as yet another component in a canon of stochastic and deterministic, natural or human-induced environmental catastrophes and selective forces, shaping communities and ecosystems. Moreover, habitat loss is by far the most important single threat to biodiversity, so why should doubt be cast on the potential and resilience of populations to recover from occasional insecticide stress? This paper reviews the environmental impact, as well as ecological and conceptual characteristics of acridid pest control. It concludes that ecologically significant risks may arise, in particular in ecosystems exposed to multiple stressors. Four priorities in ecological risk assessment and acridid pest management are proposed: 1) delimitation and characterization of sensitive areas within locust and grasshopper habitats, 2) ecosystem-specific, long-term field studies and operational monitoring, 3) real-time stewardship of control campaigns, with adequate participation of stakeholders, and 4) incorporation of the precautionary principle into decision-making and risk management.

Key words

Locust, grasshopper, control, insecticides, environmental impact, ecological risk assessment, sensitive areas, biodiversity conservation, precautionary principle

Introduction

Few insect taxa raise such controversial, and often irrational, views and feelings as acridids. In Central Europe, many grasshoppers are nowadays considered as indicators of biodiversity and ecosystem quality, and sometimes even as flagship species, *i.e.*, "popular, charismatic species that serve as symbols . . . to stimulate conservation awareness and action" (Samways *et al.* 1995). In other parts of the world, however, they remain feared pests of crops and pastures, and may trigger control campaigns of considerable scale and intensity. While the status of both locusts and grasshoppers as pests of rangeland may presently be questioned (Wilps & Diop 1997, Belovsky 2000), status as pests of crops is certainly not. The potential to bring havoc to crops is generally acknowledged, and the debate is rather on control strategies than on whether acridids are worth controlling (van Huis 1994, Krall *et al.* 1997, Lomer *et al.* 1999, Lecoq 2000, Lockwood *et al.* 2000).

With five locust and several grasshopper species, the latter occurring at densities similar to locusts, semiarid and arid Africa is particularly at risk, and control touches on the issue of food security. Thus, locust and grasshopper outbreaks in Africa and other parts of the world are managed in the same way as natural catastrophes such as floods or drought, and elicit similar emergency responses, technical and financial, from national governments and the international community.

Only in the aftermath of the 1986-89 plague of the desert locust, *Schistocerca gregaria* Forskål, was the question raised: at what environmental costs were the postulated benefits of control achieved? However, few environmental impact data on which to base an analysis had been collected during this campaign. Therefore, the "locust community" set off to do better in the future by launching extensive research into the effects and side-effects of existing control agents and strategies, and the development of environmentally sound alternatives (Everts 1990, Lomer & Prior 1992, Krall *et al.* 1997). This initiative received further backing by recommendations in Agenda 21 to reduce environmental risks of pesticides and to conduct assessments of activities likely to have negative impact on biological diversity (UNCED 1992, UNEP 1992).

More than one decade later, knowledge of pesticide behavior in different areas and environmental settings has greatly improved, providing a better basis for locust and grasshopper control in an integrated pest management context. However, outbreaks continue to ignite controversy on issues such as intervention thresholds, choice of products and extent of control. Examples are the 1997-2000 outbreak of the Malagasy migratory locust, *Locusta migratoria capito* (Saussure), and the ongoing plague of Italian locust, *Calliptamus italicus* (L.) and other grasshoppers in Central Asia.

In this paper, I will examine ecological and conceptual characteristics of locust and, to a lesser extent, grasshopper control, and bring the most controversial issues into perspective, as well as some which have as yet received less

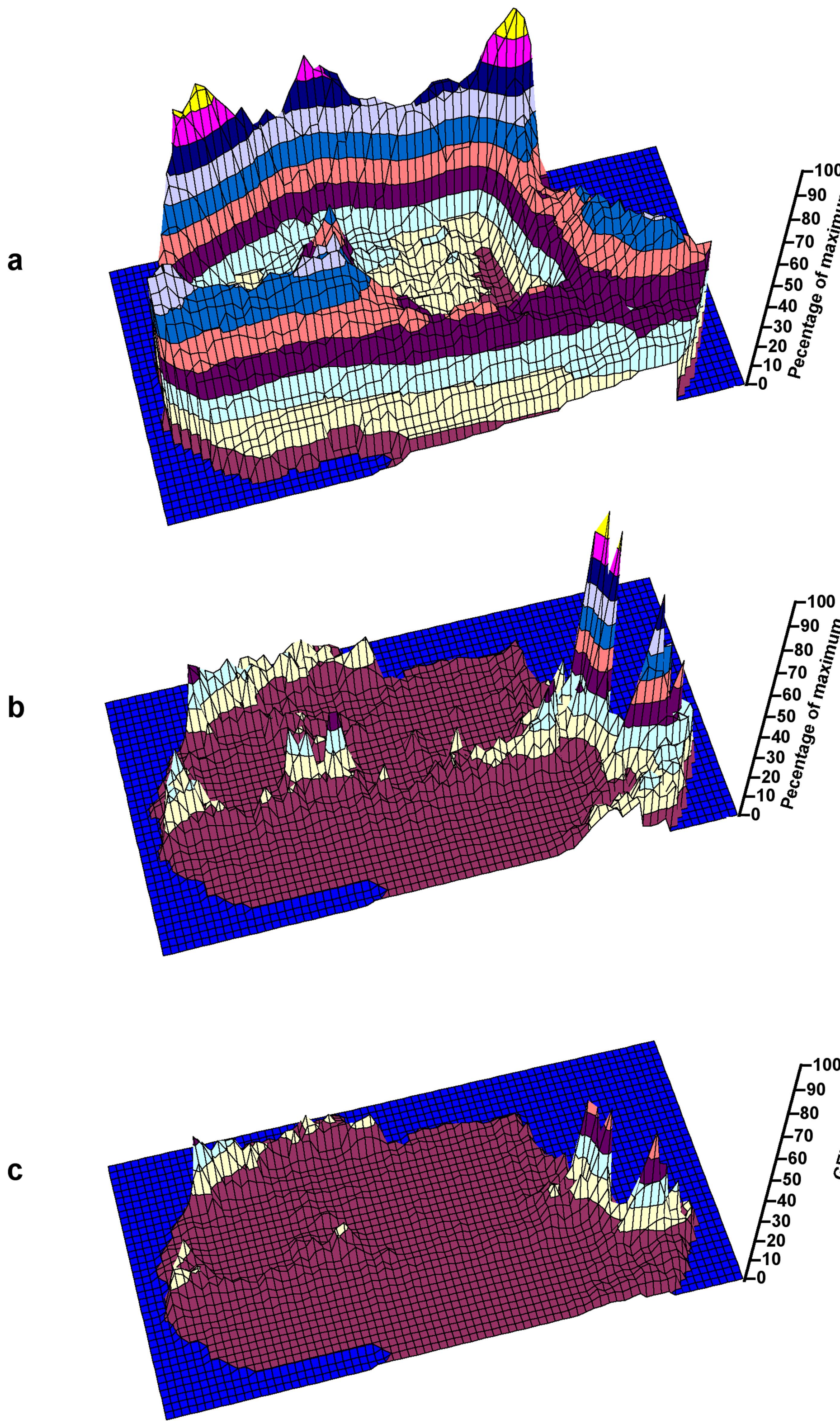

Plate 1. In Africa north of the equator, **a**) relative species richness (RSR) of reptiles, **b**) relative frequency of occurrence (RFO) of desert locust and **c**) geographical exposure index (GEI) for reptiles. RSR is the degree square number of Saharan species as percentage of the highest number; RFO is the degree square frequency of occurrence as percentage of the highest frequency; GEI is the product (X 100^{-1}) of these terms.

attention. My intention is to elucidate and compare views, attitudes and empirical evidence as a first step, and to discuss how the schism between purely control-oriented (hit the target) or environmental (spare the nontarget) mindsets in locust management can be bridged. My hypothesis is that ecosystems are increasingly less able to tolerate and recover from insecticide stress, and that they deserve the most cautionary approach to acridid pest control. Most of my personal experience stems from Africa and Madagascar, and I am, therefore, aware of some regional bias.

Setting the stage - ecological risk assessment and disturbance ecology

The compatibility of locust control with environmental protection can be examined in the practical context of ecological risk assessment (EPA 1998) and in the theoretical context of disturbance ecology (*e.g.*, Holling 1992).

The two central elements of ecological risk assessment (ERA) are characterization of ecological effects and characterization of exposure. Results of these analyses are stressor-response profiles and exposure profiles, which in turn are used to estimate the magnitude and ecological significance of risk, to weigh the identified risk against the presumed benefit of the stressor, and to develop risk management measures. At first glance, ERA of locust control (= control agent plus its underlying use pattern) appears to be a straightforward exercise. However, given the variety of receptor ecosystems and biota, the variable temporal and spatial scale of control, and the possible additional risk from other stressors, general conclusions are difficult to draw, and assessments have to be made case by case.

In a more general sense, chemicals released into ecosystems can be considered disturbances, "similar in mode of action to natural disturbances such as fires, windstorms, and species invasions" (Weinstein & Birk 1989). Disturbance ecology suggests that the ecological impact of disturbance is inversely correlated to its frequency, and that ecosystem response depends on the relative novelty of the disturbance. Thus, the most dramatic effects on ecosystems are expected if disturbance events are intensive but rare (White & Jentsch 2001).

Disturbance may affect both community structure and ecological function. In ecosystems with high biodiversity, the latter appears to be less sensitive to perturbations than the former, owing to an overlap in ecological function among species (Odum 1985, Schindler 1990, Polis *et al.* 2000). This so-called functional redundancy operates over different spatial and temporal scales and enhances the system's ecological resilience to disturbance or disruption (Naeem 1998, Peterson *et al.* 1998, Walker *et al.* 1999). For example, less sensitive species may increase in abundance as more sensitive ones decline, taking over their role — or part of it — as ecological service providers. Therefore, the ecological consequences of species loss due to perturbations may not be visible immediately. However, high extinction rates eventually translate into reduced resilience and render ecosystems more vulnerable to disturbance (Peterson *et al.* 1998). Likewise, systems with low complexity and diversity such as agroecosystems lack sufficient functional redundancy and are, therefore, more sensitive to disturbance than diverse systems (Polis *et al.* 2000).

Contrary to pests developing in close association with particular host crops, locusts are mainly controlled in natural or seminatural landscapes, exposing structurally and functionally diverse communities not adapted to, or co-selected by, agrochemicals. This suggests that perturbations may be severe. On the other hand, with acridids that are highly mobile, exposure of non-target biota at any one location tends to be rare, and insecticides might be seen as yet another component in a canon of stochastic and deterministic, natural or human-induced environmental catastrophes and selective forces, shaping communities and ecosystems. Thus, the ecological significance of locust control is a function of its scale, frequency and relative magnitude within the prevailing disturbance regime.

A major difficulty of ecological risk assessment and disturbance analysis is the establishment of cause-effect relationships which is often confounded by different disturbance histories and interactions between different stressors, which together form a unique disturbance regime. Despite recognition of the problem, cumulative impact assessment (CIA) is not as yet an established instrument in environmental management (Devuyst 1993). When exposed to multiple stressors, one stress may predispose organisms to increased susceptibility to other stresses (Weinstein & Birk 1989). Ecotoxicological research on the response of organisms, in particular terrestrial animals, to multiple stressors with dissimilar modes of action is as yet relatively rare (Verhoef 1996). In one study, carabid beetles living along a gradient of heavy metal contamination, showed different tolerances towards additional toxic (organophosphate insecticide) as well as non-toxic (food deprivation) stressors (Stone *et al.* 2001).

Use patterns and exposure

To elucidate typical use patterns of control agents, three key issues have to be addressed, 1) the kind of (agro-) ecosystems and biomes subjected to control operations, 2) the prevailing control agents and strategies and 3) the spatial and temporal scale of control.

Kind of (agro-) ecosystems.— Grasshopper infestations of crops are directly controlled in the field, along field borders and in surrounding fallow or waste land. Similar to locusts, such populations may originate from distant breeding grounds, where they may be controlled or not, but also from breeding within or in the vicinity of the field itself. Examples of relatively close crop-grasshopper associations are the Italian locust, *C. italicus*, the Senegalese grasshopper, *Oedaleus senegalensis* (Krauss), and the rice grasshopper, *Hieroglyphus daganensis* Krauss (COPR 1982). In this setting, grasshoppers share resources with the crop (*e.g.*, substrate, humidity) and use it as a habitat and food source. Thus, as in most agricultural pest situations, sprayed and protected area are the same. In economic terms, investment (control), benefit (yield gain), as well as part of the environmental costs (*e.g.*, hazards to beneficials), are variables or components of the same agroecosystem. This means that most of the costs are internalized.

This coincidence does not always exist in grasshopper control, and only rarely so in locust control. One noteworthy exception is the Tokar Delta in the Sudan, an important area for the cultivation of millet and sorghum and at the same time a breeding area of both African migratory locust, *Locusta migratoria migratorioides* (Reiche & Fairmaire), and desert locust. In most cases, however, locust control is conducted in nonagricultural ecosystems or rangeland. This implies that the benefit is generated far away from the actual spray area. An important difference to direct crop protection as outlined above, is that environmental costs are largely externalized because the risk of negative, pesticide-induced within-crop effects such as secondary pest infestations or pest resurgence is low. In other words, the environmental harm, if any, is not to the detriment of the beneficiary of locust control (the farmer), at least not immediately, and may not even come to his or her attention.

The natural and seminatural landscapes subjected to grasshopper and locust control represent all major open landscape biomes below the boreal zone, including temperate steppe and grasslands, tropical and subtropical savannahs and open woodland, as well as semideserts and deserts. Many of these wilderness areas are considered a priority for conservation. This topic will be addressed below.

Control agents and strategies.— The agents predominantly used against locusts, in particular in emergency situations, comprise broad-spectrum insecticides of the organophosphate (OP), carbamate and pyrethroid families. Some of these are not only toxic to invertebrates but also to fish and wildlife, a risk which governmental and non-governmental organizations, farmers, livestock breeders and the general public are increasingly reluctant to accept. Persistence, the panacea and Pandora's box of the organochlorine era, has had a careful revival, in that molecules have been designed to show moderate to high persistence, no bioaccumulation and low vertebrate toxicity. These molecules are members of the benzoylurea, phenylpyrazole and chloronicotinyl families and provide some residual toxicity which can be exploited in barrier treatment (Cooper *et al.* 1995) or reduced agent-area treatment (Lockwood & Schell 1997).

The operational use of biocontrol agents such as entomopathogenic fungi is as yet relatively limited in scale, but may become more important in the future since commercial production has now begun in Africa and Australia (Kooyman *et al.* 1997, Price *et al.* 1999, Langewald & Cherry 2000, Hunter *et al.* 2001). Interestingly, the introduction of mycopesticides in Australia appears to have been demand-driven rather than donor-initiated (as in some developing countries). Biocontrol agents, though considered *a priori* less hazardous than synthetic chemicals, are not without risks, and views on their safety differ considerably, in particular with respect to exotic agents (Lockwood 1993; Carruthers & Onsager 1993; Strong & Pemberton 2000, 2001).

The environmental risk not only depends on the kind of agents but on how they are used, *i.e.*, on the prevailing use pattern and control strategy. In general, preventive control implies focused and repeated control over relatively small outbreak areas, creating a small scale X high frequency exposure regime. Curative control, on the other hand, involves less frequent, but often larger scale control measures (large scale X low frequency regime). Prerequisites of preventive control are adequate monitoring and forecasting systems, in order to detect and combat the locusts in a timely fashion. In curative control, preference is given to fast-acting insecticides since the actual threat to croplands is higher. In preventive control, knock-down is less important and both slow and fast-acting agents are used.

Spatial and temporal scale.— The spatial and temporal scale of control operations varies considerably among target species and regions (Table 1). Many grasshoppers and some locusts such as the Australian plague locust, *Chortoicetes terminifera* (Walker), and the South African brown locust, *Locustana pardalina* (Walker), do not seem to undergo prolonged recession periods and warrant control in most years. In the case of brown and Australian plague locust, pesticide disturbances are frequent but patchy, since the total outbreak area is very large compared to the actual surface treated.

In contrast, during desert and migratory locust plagues, treatments may extend over vast areas, depending on the invasion range of the respective species. In some cases, small outbreak areas can be sprayed at relatively high frequencies. An example is the floodland breeding areas of the red locust, *Nomadacris septemfasciata* (Serville), in eastern and South-eastern Africa.

The examples show that locust and grasshopper control can reach high intensity and frequency in some areas. It is therefore important to understand pressures on these areas and their ecological traits, and to elucidate their capacity to cope with pesticide stress.

Zones of conflict – hotspots and endangered ecoregions

In environmental economy there is still no standard system to measure "existence values" (Pearce & Turner 1990) or environmental assets that do not have an immediate potential as a resource. Notwithstanding these uncertainties, two interlinked values have been proposed as measurable endpoints and indicators of environmental health, sustainability and biodiversity. Even though disturbances *sui generis* are the driving forces of biotic diversity on evolutionary time scales, anthropogenic disturbances leading to a loss in biodiversity at a particular place and time are considered undesirable on human time scales. This notion is not merely philosophical but is substantiated, as mentioned before, by the observation that biodiversity, apart from being a resource, provides ecological insurance through functional redundancy. In other words, biodiversity increases the ability of ecosystems to withstand disturbance or species removal (Peterson *et al.* 1998). Therefore, human-induced disturbances, including insecticide stress, can be measured and weighed with respect to their capacity to cause or contribute to a loss in biotic diversity.

It is widely acknowledged that habitat alteration, fragmentation and destruction due to agriculture, logging, min-

Table 1. Spatial and temporal scale of locust and grasshopper control.

Target acridid	Spatial scale	Temporal scale	Remarks	Source
North American grasshoppers	~ 15 million ha	annually (1977-86)	USA (federally executed programs only)	(1)
South American plague locust	515,690 ha	1984-88	Mato Grosso, Brazil (aerial treatments only)	(2)
Central Asian grasshoppers and locusts	> 2.5 million ha	annually	Kazakhstan	(3)
Desert locust	> 25 million ha	1986-89	Africa to India	(4)
Red locust	1,000 to > 20,000 ha	annually (1983-88)	Zambia and Tanzania (fenitrothion only)	(5)
Brown locust	219,000 hopper bands (size ≤ 0.5 ha); 25,600 swarms	1988-95	South Africa	(6)
Malagasy migratory and red locust	~ 4.2 million ha	1997-2000	protected area (barrier and blanket treatments)	(7)
Australian plague locust	178,100 ha	2000	Australian Plague Locust Commission (APLC) (treatments only)	(8)

(1) Carruthers & Onsager 1993, (2) Lecoq 2000, (3) Kambulin 2000, (4) Peveling 2000, (5) Gadabu 1994, (6) Samways 2000, (7) Lecoq 2001, (8) Walker & Hamilton 2001.

ing and fossil energy exploitation, are the greatest threats to biodiversity. In response to these threats, several approaches have been made to set priorities for biodiversity conservation (Dinerstein & Wikramanayake 1993; Olson & Dinerstein 1998; Mittermeier *et al.* 1998, 2000). They aim to "focus conservation efforts on areas with the greatest concentration of biodiversity and the highest likelihood of losing significant portions of that biodiversity" (Mittermeier *et al.* 1998). In the following, I will examine where locust and grasshopper control may fall into conflict with international conservation priorities. My objective is to identify, on a global scale, conservation priority areas where the large-scale and/or frequent use of insecticides against acridid pests might be critical from an ecological risk and environmental policy point of view. The idea is not to provide a comprehensive overview but to demonstrate how this important issue can and should be incorporated into the framework for ecological risk assessment.

Hotspot approach.— Hotspots are "natural environments containing exceptionally large numbers of endangered species found nowhere else" (Wilson 2002). An area qualifies as a hotspot if it contains 0.5% or 1,500 of all known vascular plant species as endemics and if less than 25% of its original extent remains (Mittermeier *et al.* 1998, 2000). The 25 terrestrial hotspots in their actual extent comprise less than 1.5% of the total land surface but harbour approximately 44% of all vascular plants as endemics and at least 66% of all vascular plants. Even though the hotspots are defined on the basis of plant endemism, they are equally hot for animals, containing at least 62% of all non-fish vertebrate species, of which approximately 35% are endemic. Among these hotspots, at least four have experienced grasshopper or locust control on a considerable scale: the Brazilian Cerrado, the Mediterranean Basin (African part), the succulent Karoo in South Africa and the island of Madagascar (Fig. 1).

The Global 200 or representation approach.— This approach uses a finer scale than the hotspot approach and considers 136 terrestrial ecoregions as priority areas for conservation (Olson & Dinerstein 1998). These ecoregions have been selected on the basis of their biological distinctiveness (species richness, endemism, taxonomic uniqueness, *etc.*) and conservation status, representing "the most distinctive examples of biodiversity" within major habitat types (biomes) and biogeographic realms. About 58% of the 136 terrestrial *Global 200* ecoregions overlap partly or entirely with the 25 hotspots (Mittermeier *et al.* 2000), and at least 12 of those classified as vulnerable or critical/endangered are frequently

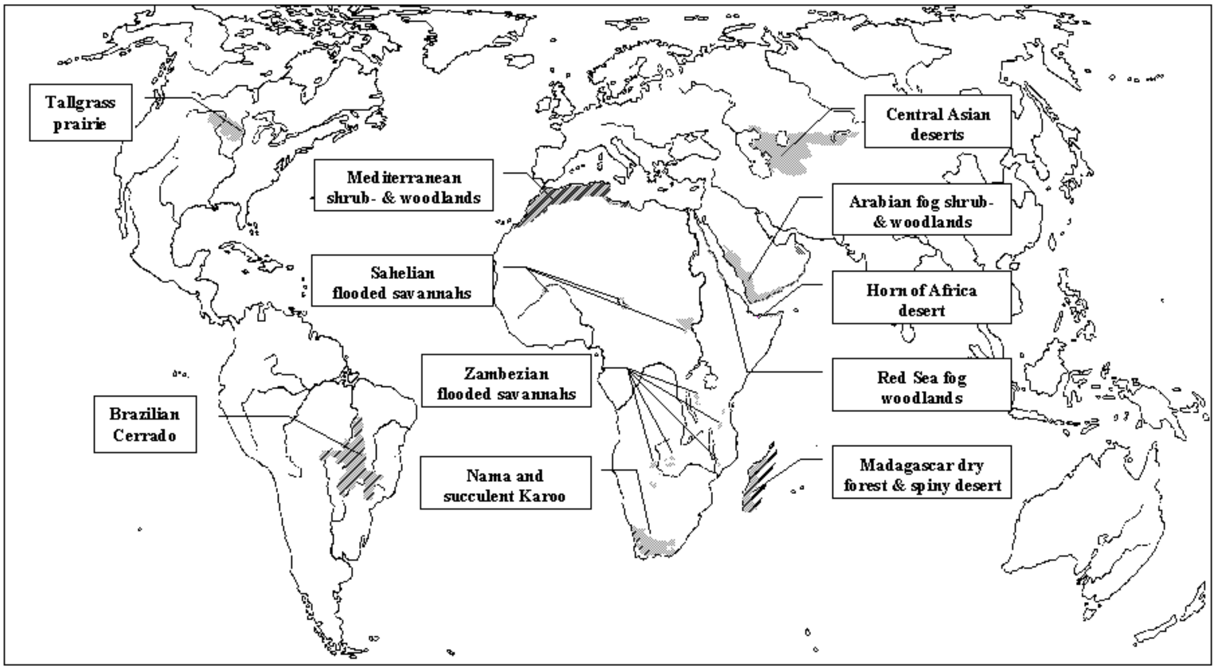

Fig. 1. Zones of conflict: *Global 200* ecoregions (grey) and hotspots (hatched) affected by grasshopper or locust control. For further explanations see text and Table 2.

affected by grasshopper or locust control (Fig. 1): 1) North American tall grass prairie, 2) Brazilian Cerrado woodlands and savannahs, 3) Central Asian deserts, 4) Mediterranean shrublands and woodlands, 5) Arabian fog shrublands and woodlands, 6) Red Sea fog woodlands (Red Sea coastal plains), 7) Horn of Africa desert, 8) Sahelian flooded savannahs, 9) Zambezian flooded savannahs, 10) Karoo deserts and shrublands, 11) Madagascar dry forest and 12) Madagascar spiny desert. Characteristics of these ecoregions, their conservation status and the main pest acridids within them are summarized in Table 2.

A common trait of these ecoregions is that they are under considerable human pressure even without locust control, and that original habitats therein are highly fragmented. The crucial question from a conservation biology perspective is whether the isolation of subpopulations is enhanced by antilocust insecticides acting as chemical barriers, and whether this affects the viability of populations and the functional integrity of ecosystems (Naeem 1998). I address this topic further down when presenting environmental impact case studies.

Another noteworthy issue is that human activities in some of the conservation priority areas may have either aggravated or diminished acridid pest problems, depending on the ecology of the species, thereby affecting the intensity and scale of control. For example, deforestation created new grassland habitats for the graminivorous Malagasy migratory locust, whereas breeding habitats in traditional outbreak areas of the African and Asian subspecies (Niger flood plain and Amu Darya delta of the Aral Sea) deteriorated due to the drainage and desertification of former flooded grassland (Gapparov & Latchininsky 2000).

Geographical exposure index.— A locust-specific procedure to identify areas of conflict between biodiversity conservation and acridid control interests is currently under investigation in our own research and will be briefly explained here (Rieger & Peveling, unpublished). We use information on wildlife species richness (α-diversity) and desert locust frequency of occurrence, to calculate a geographical exposure index (GEI) for different biota. The GEI assumes that high desert locust frequency implies high control intensity. It describes, in a deterministic sense, the likelihood at which areas supporting high biotic diversity are exposed to desert locust control operations. It can, therefore, be used as a measure of risk. An example for reptiles with predominantly Saharan distribution is given in Plate 1. We consider reptiles particularly important because they have been largely neglected in previous environmental risk assessments (Everts & Ba 1997), despite their high diversity in arid regions (Mittermeier *et al.* 2000).

The GEI was calculated in three steps. We first mapped relative species richness (RSR) north of the equator on a degree-square grid, using data from Le Berre (1989). RSR values are highest in the Nile delta, a center of dispersal of Ethiopian, Mediterranean and Arabian taxa, and in the western Mediterranean (Morocco, Tunisia). We then mapped the relative frequency of occurrence (RFO) of desert locust on the same grid, using historical data from 1930-1987 (Natural Resources Institute, UK). The map highlights the

Table 2. Endangered ecoregions and hotspots affected by locust or grasshopper control.

No	Global 200 ecoregion [1]	Status [2]	Important locust and grasshopper species (remarks)	Global hotspot [3]
(1)	North American tallgrass prairie	CE	*Melanoplus sanguinipes*, North American grasshopper complex	
(2)	Brazilian Cerrado woodlands and savannahs	V	*Rhammatocerus schistocercoides* (easternmost part)	Cerrado
(3)	Central Asian deserts	CE	*Calliptamus italicus*, *Locusta migratoria migratoria* (Amu Darya delta outbreak area)	
(4)	Mediterranean shrublands and woodlands	CE	*C. italicus*, *Dociostaurus maroccanus*, *Schistocerca gregaria* (invasion area)	Mediterranean Basin
(5)	Arabian fog shrublands and woodlands	V	*S. gregaria* (outbreak and invasion area)	
(6)	Red Sea fog woodlands	CE	*L. migratoria migratorioides*, *S. gregaria* (Red Sea coastal plains outbreak area)	
(7)	Horn of Africa desert	V	*S. gregaria* (outbreak area)	
(8)	Sahelian flooded savannahs	V	*L. migratoria migratorioides* (Niger flood plain outbreak area), *Oedaleus senegalensis*	
(9)	Zambezian flooded savannahs	CE	*Nomadacris septemfasciata* (*e.g.*, Kafue flats, Lake Rukwa and Buri outbreak areas)	
(10)	Karoo deserts and shrublands	CE	*Locustana pardalina* (Nama Karoo outbreak and Succulent Karoo invasion area)	Succulent Karoo
(11)	Madagascar dry forest	CE	*L. migratoria capito* (invasion area), *N. septemfasciata*	Madagascar hotspot
(12)	Madagascar spiny desert	CE	*L. migratoria capito* (outbreak area), *N. septemfasciata*	Madagascar hotspot

[1] Terminology and delimitation according to Olson & Dinerstein (1998); for a recent revision of the Global 200 ecoregions see http://www.panda.org/global200; for African ecoregions, see National Geographic (2001) or http://www.nationalgeographic.com/africa. [2] V = vulnerable, CE = critical/endangered. [3] According to Mittermeier *et al.* (1998, 2000)

importance of the outbreak area along the Red Sea coast and the Horn of Africa, and shows breeding areas in the Tamesna desert (Niger), Mauritania and North-western Africa. The GEI was calculated according to GEI = REP X RFO X 100^{-1} (range: 0-100). The corresponding map shows the highest risk to reptile diversity in the recession area along the Red Sea coast and Horn of Africa (Central Region in FAO terminology), and a relatively high risk in the Moroccan steppe and succulent thicket invasion area. In contrast, areas such as the Nile delta, though supporting high reptile diversity, do not bear any risk simply because desert locust frequency of occurrence is very low. This confirms that preventive control systems for the Red Sea outbreak area, as initiated by the FAO-EMPRES project (Emergency Prevention System for Transboundary Animal and Plant Pests and Diseases), should pay particular attention to the high biodiversity of this zone. This problem has in fact been addressed in a recent mapping project in Eastern Africa which aims to identify and delineate areas particularly sensitive to pesticide contamination (Wiktelius *et al.* 2001). They comprise populated areas, protected areas, wetlands (including oases) and areas with high concentrations of migratory birds. The emphasis is on birds and epigeal arthropods, in particular tenebrionids (Wiktelius, pers. com.), but it is certainly worthwhile to extend these studies to reptiles and other wildlife.

We acknowledge that the spatial resolution of our GEI system is as yet relatively low, but we are confident that larger scale maps can be produced with more geo-referenced desert locust and biodiversity data becoming available. These maps can assist in designing management solutions to the ecological and biogeographical peculiarities of the respective target areas.

Environmental impact

Having outlined some exposure scenarios and geographical foci of acridid pest control, we can now shift our attention from "where it happens" to "what happens". Ecotoxicological impacts of chemical stressors, while forming a continuum, have been divided into 1) direct biological effects, 2) indirect biological effects and 3) ecosystem level effects which integrate direct and indirect responses (Harwell & Harwell 1989). 1) Direct effects comprise lethal (primary and secondary poisoning) and sublethal (*e.g.*, physiological or behavioral disruption) toxicity to individuals. These effects on organisms may lead to population reductions, but not necessarily so, since enhanced survival rates due to reduced intraspecific competition may offset individual losses. 2) Indirect effects concern disruptions of trophic interactions (herbivore-plant, predator-prey, parasitoid-host) as well as changes in competitive interactions (*e.g.*, competitive release). 3) Ecosystem level effects may arise if keystone taxa and ecological key processes (*e.g.*, primary production, nutrient cycling, pollination) are adversely affected. Naturally, the knowledge of these effects decreases with receptor complexity, that is from the individual and population level to the community and ecosystem level, while its ecological significance increases.

Most of our experience on pesticide hazards stems from agriculture and concerns effects within agroecosystems and those resulting from (unintentional) releases into other compartments, for example, due to spray drift or surface runoff. Less experience has been gained from deliberate insecticide uses in natural and seminatural landscapes. These uses include, apart from acridid pest control, treatments against disease vectors (*e.g.*, tsetse flies) and lepidopteran forest pests (*e.g.*, gypsy moth) (Barrows *et al.* 1994, Peveling & Nagel 2001). A common trait of these different receptor ecosystems is their high level of complexity, which distinguishes them from most agroecosystems. Thus, environmental impact data from these sectors complement each other, and I will occasionally refer to findings from forest pest and disease vector control when discussing side-effects of grasshopper and locust control.

Direct effects.— The bulk of environmental impact studies of acridid pest control focuses on invertebrates, in particular arthropods (*e.g.*, Beyers *et al.* 1995; Balança & de Visscher 1995, 1997a, 1997b; Everts *et al.* 1997, 1998; Stewart 1998; Peveling *et al.* 1999a). Not surprisingly, these studies show that a wide range of nontarget arthropods are inevitably killed when using broad-spectrum insecticides. Other insecticides offer some degree of specificity and put mainly those taxa at risk that share developmental and ecological traits with acridids, for example, the presence of sensitive life stages, similar activity patterns and similar feeding regimes (*e.g.*, Tingle 1996, Peveling *et al.* 1999b, Sokolov 2000).

It has been proposed that environmental monitoring should concentrate on beneficial organisms such as pollinators, natural enemies of primary or secondary pests and detritivores (Everts & Ba 1997, van der Valk & Niassy 1997). However, natural arthropod communities cannot be as easily sorted into beneficial, harmful or adiaphorous organisms as those from agroecosystems. For example, some authors rank termites as serious pests of rangeland, competing with livestock for forage and enhancing erosion (Bax *et al.* 1997, Pearce 1997), whereas others emphasize their role as keystone organisms (Redford 1984), ecosystem engineers (Jones *et al.* 1994, Lavelle *et al.* 1997) and "remediators" of degraded soils (Mando & Brussaard 1999). Moreover, the ecological role of many biota is not known at all. Thus, the selection of indicators of pesticide hazard is often somewhat arbitrary, depending on their perceived importance and, not least, their mere availability. This complicates extrapolation from individual studies.

An even more difficult task is to lend ecological meaning to the pesticide-induced population declines or increases, which vary largely among taxonomic groups and along temporal and spatial scales. There is a tremendous amount of uncertainty related to the interpretation of such effects. Nonetheless, unless higher tier information is available (see below), risks can be classified, as a rule of thumb, according to assessment schemes for terrestrial beneficial organisms in agroecosystems (EPPO 1994, Hassan 1998). Suggested classes for low, medium and high risk are respective population reductions of < 25%, 25-75% and > 75% (FAO 2000). Within certain limits, pesticide-induced effects are regarded as acceptable if recovery to, or near to, predisturbance levels is not compromised.

The most sensitive issue in acridid pest control is the risk to wildlife (Johnston 2001, Story & Cox 2001). Historically, hazards to wildlife were mainly caused by organochlorine (OC), OP and carbamate insecticides. OCs have now largely disappeared, but the use of OPs and carbamates continues. When used according to specifications, most modern chemical pesticides pose relatively low environmental risks. This is achieved by using molecules or combinations of molecules of moderate vertebrate toxicity and/or by reducing exposure through use restrictions. As far as mammals are concerned, only a few cases of poisoning have been reported, and these were mainly attributed to the misuse of pesticides (Fairbrother 2001). However, several incidents associated with acridid pest control have been reported for birds and reptiles (*e.g.*, Mullié & Keith 1993, Lambert 1997a). One of the most recent and spectacular examples is the poisoning of thousands of Swainson's hawk (*Buteo swainsoni* Bonaparte) in their overwintering areas in the Pampas of Argentina (Di Silvestro 1996, Goldstein *et al.* 1999, Scollon *et al.* 2001). Large-scale mortality of this medium-sized raptor was attributed to the consumption of grasshoppers killed by OPs, in particular monocrotophos – an unfortunate, yet frequent, coincidence between high bird densities and extensive grasshopper control. A relationship between mortality and exposure to carbamates or OPs could also be established for several raptor species in California, using "forensic investigative techniques" (Hosea *et al.* 2001). Such sophisticated techniques are seldom at hand in Africa and other parts of the world. Therefore, cause-effect relationships cannot always be established, and reported incidences of acute pesticide poisoning often remain invalidated and anecdotal. Even so, whenever birds aggregate to feed on grasshopper or locust concentrations, there is a risk of secondary poisoning (with OPs and carbamates). For example, in semiarid and arid Australia, locusts weakened by or dying from OP treatments provided the main food source for several avian predators, thereby posing a serious risk of secondary poisoning (Story & Cox 2001). In general, given the remoteness and extent of the areas where control operations are conducted, and the lack of opportunities to monitor their environmental impact, there is reason for concern that many cases of poisoning remain undetected or unreported.

As mentioned earlier, reptiles have only rarely been included in environmental surveys for grasshopper and locust control, despite their high diversity and key role in many locust habitats (Everts & Ba 1997). With regard to environmental contaminants and pesticides, reptiles are the least studied group of all vertebrates (Lambert 1997a, Hopkins 2000, Pauli & Money 2000, Story & Cox 2001). Considering behavioral, physiological and life-history traits, a particularly high risk can be anticipated for lizards. This is due to attributes, and their likely consequences (in parens), such as diurnal activity (enhanced exposure), prevalence of insectivory (secondary poisoning), low metabolic rate (reduced detoxification), susceptibility to endocrine disruption (impeded reproduction) and low dispersal capacity (slow recolonization), to mention all but a few (Cloudsley-Thompson 1991, Costa 1995, Lambert 1997b, Ankley & Giesy 1998, Guillette 2000, Niewiarowski 2000, Sparling *et al.* 2000).

The tough and scaly skin of reptiles may be thought to present an impermeable barrier to contaminants. However, this does not hold for lipophilic compounds such as insecticides, and the skin may form a significant route of exposure to environmental contaminants (Palmer 2000). The myth of the impermeable squamate integument was also challenged by results from our own research. We found mass mortality of fringe-toed lizards (*Acanthodactylus* spp.) during desert locust control operations with chlorpyrifos at recommended dose rates which could not be attributed to the consumption of contaminated insects. Laboratory toxicity tests with *A. dumerili* Milne-Edwards at the CLAA (Centre de Lutte Antiacridienne) field station in Mauritania and cholinesterase analyses in Senegal, revealed high dermal toxicity of chlorpyrifos and confirmed the importance of this exposure route (Peveling & Demba unpublished, Mullié *et al.* 1998).

There are only a few data on effects of locust control agents other than OPs and carbamates on reptiles. Small lizards feeding on brown locusts treated with deltamethrin may accumulate sublethal toxic levels (Stewart & Seesink 1996), but hazards of deltamethrin in the field could not be substantiated (Pauli & Money 2000, Peveling *et al.*, in prep.). Relatively high residues of fipronil were found in carcasses of *Furcifer oustaleti* (Mocquard) (Chamaeleonidae) collected from migratory locust spray blocks in Madagascar (ONE 1999). However, an unequivocal relationship between pesticide residues and mortality could not be established. The examples clearly underline the need of further investigations, both with respect to direct (lethal and sublethal) effects and indirect effects through food chains (see below).

In some places such as wetlands and temporary waters there may also be a high risk to amphibians. As with reptiles, actual reports of hazards due to locust control are scarce. Amphibian exposure can be greatly reduced if unsprayed buffers of sufficient width are maintained (Lahr *et al.* 2000, Story & Cox 2001). This option does not of course exist if locusts in wetlands are targeted.

Indirect effects.— Insecticide treatments affect some organisms more than others, depending not only on intrinsic exposure routes and toxicities, but also on the time of the treatment in relation to life-history traits. Unlike most crop-specific pests, acridids are typically controlled over several months within a single season. As a consequence, treatments may affect different fractions of both the acridid and the nontarget fauna at different times, and have different ecological implications with regard to intra- and interspecific interactions.

An example illustrating the complexity of trophic interactions among insects stems from Senegal (van der Valk *et al.* 1999). This study concluded that fenitrothion, applied early in the season against early-hatching grasshoppers, reduced natural enemies of late-hatching grasshoppers which therefore laid more egg-pods than their conspecifics in untreated plots. On the other hand, predation on egg-pods by tenebrionid larvae was also enhanced, probably due to reductions of hyperpredators or parasitoids of these larvae. The predicted outcome was a net increase in hatching of late-hatching grasshoppers in treatment plots during the following season. In other words, late-hatching grasshoppers gained advantage from a treatment directed against early-hatching grasshoppers. It is obvious that a treatment later in the season would have evoked completely different responses. Other studies found indications of release of lepidopterans from natural control due to insecticide-induced suppression of parasitoids and predators (van der Valk & Kamara 1997, Kamara & van der Valk 1998, Peveling *et al.* 1999b).

A limited number of studies examined trophic effects further up the food chain. Most were concerned with the problem of food shortages and reproductive failure in birds (Mullié & Keith 1993, de Visscher & Balança 1993, Norelius & Lockwood 1999, Tingle & McWilliam 2001). These studies suggest that nonbreeding birds may readily adapt to food shortages by foraging in untreated areas. Thus, the risk of food-deprivation for nonbreeding birds appears to be low. However, one study found evidence of impaired reproductive success in breeding birds (Mullié & Keith 1993). Food-chain effects on mammals and reptiles were investigated in two recent studies in Madagascar. Barrier treatments of fipronil and triflumuron had no effect, despite indications of different foraging activity within and between spray bar-

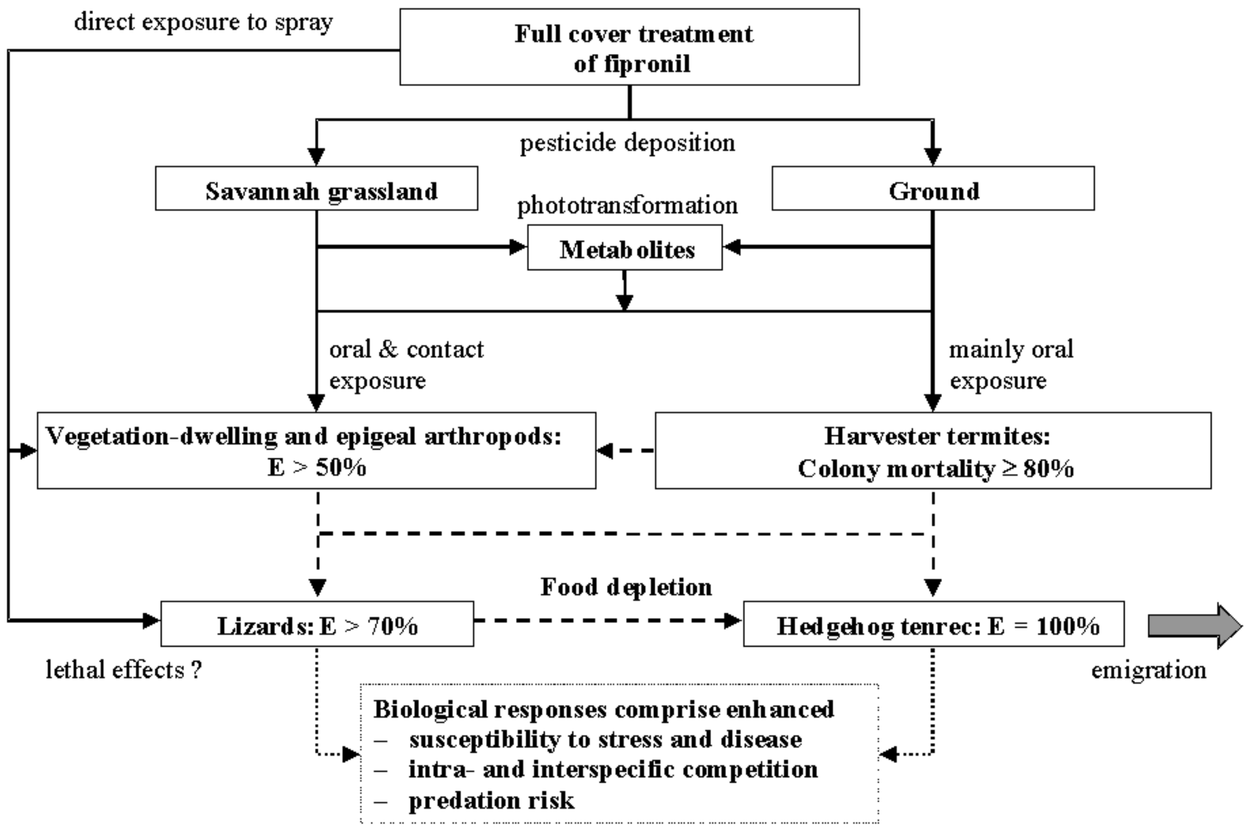

Fig. 2. Exposure routes (solid lines), food-chain links (broken line) and biological response mechanisms (dotted line) in a savannah food web exposed to fipronil. Effects (E) are for 6 mo post-spray. Lizards were directly exposed to the spray, contrary to the lesser hedgehog tenrec, which was in aestivation at this time. Emigration due to depletion of the invertebrate food stock, in particular termites, was held responsible for the reduced abundance of insectivores. Note that the hedgehog tenrec was affected both by a depletion of its regular prey (termites) and its occasional prey (skinks). Modified after Peveling *et al.* (2001).

riers (Tingle & McWilliam 2001). In contrast, severe food-chain perturbations were observed in sites treated with early dry season, full-cover sprays of fipronil (Peveling *et al.*, in prep.). These treatments caused a collapse of epigeal and grass-dwelling arthropods and harvester termites, depriving insectivorous vertebrates of their principal prey (Fig. 2). This led to the decline (lizards) or complete disappearance (lesser hedgehog tenrec) of several species, probably due to emigration.

In arid and semiarid areas, reliance on termites and ants is highest during the dry season when many other insects are in diapause or persist in very low densities (James 1991). Therefore, treatments in the late rainy, early dry, season seem to be particularly harmful to insectivorous vertebrates. Food shortages increase intra- and interspecific competition, susceptibility to stress and disease and predation risk, and may eventually lead to population declines. Moreover, in fragmented landscapes, food-impoverished areas may act as barriers and aggravate the isolation of populations and reduce gene flow. Such mechanisms, while founded on common knowledge in conservation biology, have never been investigated in the context of grasshopper and locust control.

The examples show that indirect effects express themselves via a network of interactions on different trophic levels, and that seasonality is an important covariable in the exposure-effect equation. The ecological significance of indirect effects is probably greater than that of direct effects, as is, however, the uncertainty.

Ecosystem level effects.— Ecosystem level effects are the least studied, not only in locust but also in vector and forest pest control. Several ecological key functions are maintained by organisms which are susceptible to insecticides. Pollination and nutrient cycling are the most important.

In many locust and grasshopper habitats, grasses provide the highest biomass but contribute little to overall floral diversity, which mainly derives from flowering plants. Grasses depend on pollination services provided by pollinator assemblages which, in natural and seminatural landscapes, have wider diversity than in agricultural settings and are particularly vulnerable to insecticides. For example, fenitrothion sprayed against spruce budworm in Canada induced devastating declines of wild pollinators and led to reduced fruit and seed set in blueberries and some native flora (Kevan 1999). Pollinator limitation can reduce seed output by 50-60% in plants (Allen-Wardell *et al.* 1998), invoking long-term community changes. Thus, concern has been expressed that areas of high floral diversity such as the Karoo hotspot, which is already under severe pressure from overgrazing and habitat fragmentation (Kevan 1999), might further suffer from insecticide-induced pollinator declines (Samways 2000). Reduced floral diversity in turn may have negative effects on nonpollinating anthophiles such as sphecid wasps. Many are antagonists of pests and require florally derived food to mate, find hosts or oviposit. Therefore, side-effects on pollinators may restrain several ecosystem services at a time. Furthermore, such hazards are difficult to predict on the basis of bee toxicity data, since honeybees are regarded as poor indicators for effects on other pollinators, including other bees (Kevan 1999).

Nutrient cycling is a process of similar importance. A landmark study on the productivity of temperate grasslands in North America demonstrated that grasshoppers may increase net primary production by speeding up the cycling of nitrogen, the limiting nutrient for plant growth in many grasslands (Belovsky 2000, in process). Thus, consumption by grasshoppers, even though reducing livestock forage in some years, maintains more productive grasslands in the longer term and enables, rather than hinders, their sustainable use. To what extent similar feedback mechanisms hold for other grassland, steppe and savannah habitats of acridids is not known.

In arid and semiarid ecosystems in the tropics, productivity is significantly linked with termite activity. Termites improve, in most but not all cases, soil fertility, soil porosity and water infiltration, and increase patch scale heterogeneity (Lavelle *et al.* 1997, Webb *et al.* 2000). Many species are associated with symbiotic nitrogen-fixing bacteria. Therefore, termites are particularly successful and competitive when foraging on nitrogen-poor vegetation or litter which have little nutritional value for other herbivores and detritivores (Morton & James 1988). It follows that insecticide-induced decreases of termites — through mechanisms similar to those described above for grasshoppers — can be detrimental to the productivity and stability of these ecosystems. This risk adds with that of food shortages to termite-feeding invertebrates and vertebrates, and may translate into long-term changes in community structure and function. To be sure, this disturbance scenario lacks sufficient field evidence, and some plant protection practitioners may intuitively consider the demise of termites due to locust control a gain rather than a loss to the environment. However, it is exactly this notion which demonstrates the need to elucidate this important issue in future research.

Traditionally, environmental impact studies are particularly concerned with direct effects. Notwithstanding the importance of this approach, in particular with respect to species conservation issues, it is evident that an understanding of indirect or ecosystem level effects may have much greater bearing on the management of pests and associated risks. Therefore, the focus should gradually shift from organisms to the interactions among them and the processes these interactions mediate. Food-chain effects and ecosystem services such as pollination and nutrient cycling are important endpoints in this research.

Mismatches in locust control

Previous paragraphs have shown that the environmental impact of locust and grasshopper control has many different facets and possible outcomes, depending on prevailing control strategies, biological receptors and environmental endpoints of concern, and it is clear that generality is difficult to achieve. Similar agents may evoke different responses in different environmental settings, and their use be acceptable in one setting, but not in another. Thus, it is important to open up and deepen the dialogue among acridologists and other stakeholders concerned with or affected by acridid pest control, in order to exchange views and experiences from different parts of the world and co-ordinate future research. This requires access to global networks and platforms, as well as adequate support from donors and funding agencies. The 8th meeting of the Orthopterists' Society provided testimony that this dialogue is taking place successfully and vividly. Here, achievements match up with obligations. However, when moving from the global to the regional and local scale, and inspecting current grasshopper and locust control practices, several mismatches become apparent that will be addressed in the following.

Environmental endpoints and test organisms.— Our knowledge about the ecotoxicity of pesticides derives, for the most part, from studies conducted in mesic ecosystems which differ in many respects from typical arid and semiarid grasshopper and locust habitats (Everts 1997). These dissimilarities are related to different life-history traits, physiological adaptations and food web structures and dynamics (van der Valk 1997). As a consequence, projections based on data from mesic ecosystems have limited validity for other areas. Naturally, principal modes of action do not change along geographical gradients, but exposure regimes and susceptibilities of receptor tissues, organisms and communities do.

Moreover, test organisms (*e.g.*, Japanese quail) used in pesticide regulatory testing are often inappropriate to predict risks to native species or other taxonomic groups (*e.g.*, lizards). This mismatch has not only been demonstrated for fringe-toed lizards (see above), but also for invertebrates. For example, long-term effects of fenitrothion (Peveling *et al.* 1999b) and fipronil (Danfa *et al.* 1999, Tingle & McWilliam 2001) on springtails and termites, respectively, would not be expected on the basis of earthworm toxicity data. Likewise, a risk of fipronil to decapod crustaceans (Peveling *et al.* 2001) would not be predicted from tests with branchiopod species such as water flea, *Daphnia magna* L., or fairy shrimp, *Streptocephalus sudanicus* Daday (Lahr 1998, Lahr *et al.* 2001). Such mismatches may have significant environmental and economic consequences. For example, commercial shrimp farmers in Madagascar experienced massive kills in their farms during migratory locust control operations (Coste 1999). These kills were not only attributed to deltamethrin, an agent known to be toxic to aquatic fauna, but also to fipronil which — at recommended field rates — has been classified as one of the insecticides least toxic to aquatic macro-invertebrates (Lahr 1998). As a consequence, fipronil may have been sprayed too close to the farms on the false assumption of low shrimp toxicity. Irrespective of the type of insecticide, accidental poisoning of aquatic fauna can of course be avoided if buffer zones are respected.

Ecosystem characterization.— Ecosystem characterization is part of the ERA exposure analysis and requires information on the function as well as spatial and temporal distribution of ecological components (EPA 1998). However, in many locust-affected countries we know as yet very little about the natural resources and their spatial and temporal distribution. Inventories of habitat types and the fauna exposed to locust control are rare, let alone studies on their vulnerability. Given the lack of information, associated risks cannot be adequately managed. It is therefore of utmost importance to characterize and delineate sensitive areas, especially, but not only, those located in hotspots and endangered ecoregions. This undertaking goes beyond mapping *a priori* sensitive areas such as wetlands and protected or candidate-protected areas. A much finer scale of ecological classification will be needed to reflect and give name to the diversity and complexity of the target areas, thereby opening the field for ecosystem-specific acridid pest management.

Control strategies.— There is a tendency among acridologists to proclaim universal solutions to acridid pest problems. This tendency is nourished by the demand of end-users, usually governmental organizations, for general recommendations on control agents and strategies. In the field of desert locust control, such guidance is given by the Pesticide Referee Group on issues such as dose rates, use patterns and environmental risk (FAO 2000). However, recommendations provide a framework rather than a recipe for locust control. For example, at a given dose rate, the same agent may have different efficacy and side effects in different climatic conditions. Likewise, optimal barrier spacing in barrier treatment may differ in relation to the vegetation structure and the behavior of the locust species, and have a different impact on nontarget fauna. Thus, the responsibility to translate general recommendations into the specific context of the respective country cannot be delegated to external bodies, but rests with national authorities and their collaborators. In the words of Showler (1997): "Specific strategies should be selected on a situational basis."

Timing.— All too often, emergency control operations start before adequate environmental monitoring programs are launched. Thus, environmental studies, if conducted at all, often lag behind or are confined to postcampaign field experiments whose results may have scientific value and long term managerial implications, but no immediate bearing on actual decision making and campaign steering. This schism between control and environmental monitoring is also reflected on the institutional and financial level: operations are managed and executed by government plant protection services and intergovernment or regional institutions, whereas environmental studies are usually entrusted to universities or environmental agencies. An advantage of this dual system is that it guarantees some degree of independence of judgement, an important aspect in the extremely politicized locust sector; but do *post hoc* environmental assessments address relevant endpoints over adequate (= long term) time scales? In my opinion, opportunities of operational monitoring have been grossly underexplored. Operational control provides temporal and spatial scales which cannot be achieved in field experiments, and the disadvantage of limited control over operational conditions is compensated by the gain in replication and realism. It seems that this approach has been successfully implemented by the Australian Plague Locust Commission (APLC). APLC connects environmental assessments to control operations, not as an alternative but as an important complement to field experimentation (Hamilton, pers. com).

Decision making.— The new paradigm of decentralization has not yet found its equivalent in locust and grasshopper control. In governmentally executed campaigns in particular, beneficiaries are seldom involved in taking the decisions from which they are supposed to benefit; nor are those groups involved that may be disadvantaged, harmed or merely concerned. While it is acknowledged that participatory procedures are difficult to follow in emergency situations, they can hardly be omitted in normal years, provided there is the political will. Stakeholder participation provides an opportunity to make decision-making processes more transparent — a central postulation of previous appraisals (*e.g.*, Joffe 1995) — and to tailor management solutions to the specific economic, societal and environmental context of the country or target area.

A list of mismatches should eventually be translated into a list of opportunities. Some have already been mentioned or alluded to, others will be brought into perspective below.

Management in lieu of control

Environmental risks have different levels of uncertainty, and one level is linked to risk perception which, a risk in itself, is often influenced by personal attitude, political background or economic interest (Buekens *et al.* 1993). This also holds for the perception of risks associated with acridid pest control. On the side of environmental activists, risks are sometimes overemphasized on the basis of singular, non-validated observations. This rationale may be accompanied by a tendency to play down the potential damage of acridids and question the need to control them. On the other hand, an implicit and equally ill-founded no-risk assumption pertains among control practitioners who believe that, since the pests they combat cannot be lastingly suppressed, non-target organisms should be equally robust to insecticide treatments. This ignores that a pest is a pest because it performs better than most of its competitors and predators, at least temporarily, and that it is therefore an inadequate model for nontarget effects. That said, it is obvious that, in a dialogue without prejudice, perception-based risk or no-risk assumptions should be gradually replaced by information-based risk assessments. The first step towards bridging the schism would then be mutual recognition of two basic principles: the genuine human right of people to save their crops and the inherent value of other life-forms beyond their potential as a resource.

What regulations and instruments are at hand to safeguard environmentally sound locust and grasshopper control? First and foremost, strict adherence to the voluntary "International Code of Conduct" on pesticide use provides reasonable environmental safeguards under the registered conditions of use (FAO 1990). Nevertheless, unforeseen hazards may arise during operational use, due to weaknesses and limits of the predictive systems or, in the absence of formal verification regimes, violations of good practices. This is why EPA (1998) has incorporated "monitoring" into the risk assessment framework. Likewise, the FAO (1988) proposes "post-registration surveillance and monitoring" of pesticide effects to validate predictions made during registration and take appropriate regulatory action if unacceptable risks are confirmed. This comprises modifying use patterns as well as restricting or cancelling registered uses.

In other sectors such as forestry and marine fisheries, voluntary procedures have been established that encourage discussion and seek consensus among stakeholders on environmental management issues. Here, as in locust control, the supply of humans with resources is weighed against the risk that the resource base is exploited in an unsustainable manner or otherwise harmed. Views about how to define this balance inevitably differ, but there is increasing agreement on appropriate procedures and platforms guiding the consensus-finding process. Examples are environmental audits (*e.g.*, the EU Eco-Audit) and stewardship councils (*e.g.*, the Forest Stewardship Council). Environmental audits aim to facilitate management control of environmental practices and to assess compliance with regulatory requirements (ICC 1989). Stewardship councils aim to create consensus between environmental and economic interests on the management of natural resources. This is achieved by setting up common principles and criteria and verifying voluntary compliance with them in an independent certification process. Council members are from industry, governments and environmental organizations. The scope for stakeholder participation is much wider than that envisioned in the "Code of Conduct", which specifically addresses parties directly involved in the development, procurement, distribution and use of pesticides.

Even though the aforementioned tools may not be readily applicable to locust control, they are certainly an option in the medium term. In a "decentralizing world", some sort of entry point for local concerns and knowledge needs to be incorporated into the bottom of the decision-making tree. Whether this is achieved by staging roundtables with stakeholders or creating Locust Stewardship Councils as steering instruments is of minor importance.

It has been argued that an extinction episode, unseen in evolutionary history, will occur in the twenty-first century (*e.g.*, Mittermeier *et al.* 2000). This caveat of itself underlines the importance of the precautionary principle in environmental management. Other arguments lack this apocalyptic connotation but are equally compelling. In the first place, we simply need more time to understand the nature of the problem and to explore and extend the scope of management options. For example, the decline of farmland birds in England due to changes in farming practices, including pesticide use, was only detectable after 5-6 y (Chamberlain *et al.* 2000). Similar lessons were learned from analyses of agricultural practices in the northern prairies (McLaughlin & Mineau 1995), whole-lake experimental perturbations in Canada (Schindler 1990), and from multiple-stressor studies on fish which, however remote from pest control, confirm what appears to be a widespread phenomenon in disturbance ecology: "Stressors that act indirectly. . . typically have their effect lagged in time" (Power 1997). These examples, as well as food web theory (*e.g.*, Polis & Strong 1996) suggest that risk predictions are generally tested over long time scales. Applying the precautionary principle provides extra time to collect and evaluate new data, validate predictions, and take timely, information-based risk-mitigating action if necessary.

Conclusions

This article has taken a rather broad perspective on environmental issues related to the control of acridids. This was deemed necessary because risk assessment in this particular field of crop protection extends well into — and is strongly influenced by — the societal and political sphere. The available information sums to the conclusion that ecologically significant risks may arise, in particular in ecosystems exposed to multiple stressors.

Several arguments have been put forward in support of the risk hypothesis. First, there is limited yet clear field evidence of population-level effects on non target biota due to locust and grasshopper control. Second, in many locust-affected countries, we know little about the biodiversity resources, their spatial and temporal distribution, and their vulnerability. Third, the rationale of preventive control implies concentrated operations in outbreak areas, thereby increasing the frequency and intensity of insecticide exposure. These areas often support high biodiversity and are priorities for conservation. Fourth, other, probably stronger environmental disturbances, both chemical and physical in nature, increase in magnitude and scale world-wide and may compromise the capacity and resilience of ecosystems to accommodate incremental insecticide stress.

It follows that these topics should be adequately addressed in environmental assessments. This requires a commitment of scientists, decision-makers and donors to the following tasks: 1) delimitation and characterization of sensitive areas within locust and grasshopper habitats, 2) ecosystem-specific, long-term field studies and operational monitoring, 3) real-time stewardship of control campaigns, with adequate participation of stakeholders, and 4) incorporation of the precautionary principle into decision-making and risk management.

Proactive locust control has been described as a strategy that aims to intervene early against localized outbreaks before plague status is reached (Showler 1997). I propose to extend Showler's definition to include the aim of risk mitigation. Thus, proactive locust control is also a strategy that aims to intervene early, at the first sign of negative environmental effects, before hazard status is reached.

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