Effects on Non-Target Organisms of Insecticides Used to Control Desert Locust, *Schistocerca gregaria*

Environmental Impact in Ecologically Sensitive Areas

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Abstract

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Concern for environmental impact of chemical insecticides used for desert locust control has increased and improved knowledge about insecticide impact on faunal non-target organisms (NTOs) in the natural environments of the desert locust is needed.

In this thesis, I investigated the impact of chlorpyrifos and carbosulfan on NTOs. I aimed at identifying species that were vulnerable to insecticides under natural conditions in a desert locust breeding area; the Red Sea Coast of Sudan. Survival rate, abundance, activity, density and species richness in a treated and an untreated area were compared using pre- and post-spray monitoring periods. Suitable reaction indicators and methodologies, which had potential for environmental monitoring of control operations, were sought.

Juvenile prawns of *Metapenaeus monoceros,* (Penaeidae), in the mangrove lagoon were affected negatively by an aerial application of chlorpyrifos. Adverse effects were also detected on antlions, *Cueta sp.,* (Myrmeleontidae), and hoopoe larks, *Alaemon alaudipes,* (Alaudidae), counted along transects. Negative effects, considered attributable to the insecticide application, were found using pitfall trapping for i) the beetle *Mesostena angustata*, (Tenebrionidae), ii) crickets both at the species level, *Gryllus bimaculatus,* and family level, Gryllidae, and iii) arachnids.

Dung beetles (Scarabaeidae: Scarabaeinae and Aphodiinae) sampled in dung pats placed in the field showed a response to carbosulfan within 24 h after application against desert locusts. Abundance of *Onthophagus margaritifer* (Scarabaeinae) declined after spraying. Numbers of *Aphodius lucidus* (Aphodiinae) and Aphodiinae beetles at the subfamily level increased. There was a marked difference in dung beetle abundance and species richness between two biotopes; *Acacia tortilis* shrubland and cultivated wetland.

The results suggest that the studied organisms and the applied methodologies (simple, robust and low-cost) could be useful for environmental monitoring of desert locust control. Follow-up studies and refinements of the methodologies are suggested.

Keywords: Penaeidae, Alaudidae, Myrmeleontidae, Scarabaeidae, Tenebrionidae, Gryllidae, arachnids, mangrove, arid, breeding area, monitoring, pest.

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Effekter på icke-målorganismer av insekticid-användning för bekämpning av vandrings-gräshoppan (*Schistocerca gregaria*)

Miljöpåverkan i ekologiskt känsliga områden

Oron för miljöpåverkan av insekticider som används för bekämpning av vandringsgräshoppan har ökat och mer kunskap om insekticidernas inverkan på andra organismer i vandringsgräshoppans naturliga miljö har efterlysts.

I denna avhandling har jag undersökt påverkan av klorpyrifos och karbosulfan på icke-målorganismer. Syftet var att identifiera arter som kan vara känsliga för insekticider i ett av vandringsgräshoppans förökningsområden; Rödahavskusten i Sudan. Överlevnadsgrad, aktivitet, täthet och artrikedom av huvudsakligen artropoder i ett behandlat och ett obehandlat område under en tid före och efter besprutning jämfördes. Målet var att hitta reaktionsindikatorer och metoder som är adekvata för miljöuppföljning av insekticid-bekämpningar. Juvenila räkor av *Metapenaeus monoceros,* (Penaeidae), i en mangrovelagun påverkades negativt av en experimentell flygbekämpning med klorpyrifos. Sidoeffekter upptäcktes också på myrlejon, *Cuaeta sp.*, (Myrmeleontidae), och på härfågellärka, *Alaemon alaudipes*, (Alaudidae), som räknades längs transekter. Negativa effekter som ansågs kopplade till insekticidbehandlingen påvisades också med fallfällefångster av i) skalbaggen *Mesostena angustata*, (Tenebrionidae), ii) syrsor, på både art-, *Gryllus bimaculatus*, och familjenivå, Gryllidae, och iii) spindeldjur.

Medelfångsten av dyngbaggar (Scarabaeidae: Scarabaeinae och Aphodiinae) som insamlades med utlagda dynghögar förändrades inom 24 tim efter gräshoppsbekämpning med karbosulfan. Fångsterna av *Onthophagus margaritifer,* (Scarabaeinae), minskade efter besprutning. Antalet *Aphodius lucidus*, (Aphodiinae), och skalbaggar i underfamiljen Aphodiinae ökade. Det var en markant skillnad i abundans och artrikedom av dyngskalbaggar mellan biotoperna *Acacia*-buskmark och odlad våtmark.

Resultaten visar att de studerade organismerna och de använda metoderna (enkla, robusta och billiga) skulle kunna vara lämpliga för miljöuppföljning av bekämpningar av vandringsgräshoppor. Uppföljande studier och metodutveckling föreslås.

Contents

Appendix

Papers I-II.

The present thesis is based on the following papers, which will be referred to by their Roman numerals:

I. Eriksson, H. & Wiktelius, S. Impact of chlorpyrifos used for desert locust control on non-target organisms in mangrove, an ecologically sensitive area. (Submitted)

II. Eriksson, H. & Isaksson, D. Short term assessment of dung beetle response to insecticide treatment against desert locust. (Submitted)

Introduction

The desert locust, *Schistocerca gregaria* (Forsskål, 1775), (Orthoptera: Acrididae) is a migratory plant pest that threatens crops and pasture in arid and semi-arid countries in Africa, the Near East and Southwest Asia (Uvarov, 1957, 1977; Popov, 1958). The risks to agricultural production and livelihoods are greatest in subsistence farming areas especially when other constraining factors exist, such as drought. The evaluation mission of the latest desert locust emergency (2003-2005) reported on widespread food insecurity affecting eight million people who had lost all or part of their food crops due to a combination of drought and desert locusts (Brader *et al*., 2006). The harvest losses due to several factors, including desert locust, were estimated at up to US$ 2.5 billion. Even if the scale of desert locust impact has been debated, *e.g.* it has been argued that the pest seldom has an economic effect nationally, but affects local socio-economics (Joffe 1995, 1998), the species is generally regarded as a pest of significant economic status that needs to be controlled or managed (see *Control strategy and methods*). An explanation of its severe impact is that several countries in the desert locust-affected area are already some of the poorest agricultural economies. Poor trade, processing and storage, inadequate infrastructure, and weak regulatory and financial intuitions, are common constraints (Joffe, 1995).

Coordinated control efforts using chemical insecticides are still perceived as the main means of reducing desert locust populations and were extensively used in the latest campaigns (2003-2005) that occurred mainly in Northwest and West Africa. The immediate beneficiaries of control operations are the local people as the control campaign reduces the threat of food insecurity. Early, effective control of locust populations in one area or country also benefits people in other parts of the locust breeding and invasion zones as it reduces the development of swarms and further breeding. However, it remains unclear if the plague in 1986-89 and the upsurge in 2003-2005 were ended by unfavourable weather conditions, control operations or a combination of both.

Control operations are characterized by the need for rapid decisions to prevent further spread of the desert locust population. Detection of the population may occur in remote areas with long transport routes for survey and control teams, and their equipment. Especially during emergency, sufficiently trained staff may not be available and recommended insecticides and appropriate equipment may not be at hand, or used. The same applies to protective clothing and other personal gear. There is often insufficient warning to the local population, who remain unaware of any risks connected to the insecticide applications. Under these conditions, it becomes difficult to comply with the principles of Good Agriculture Practice that are aimed at producing safe and healthy food and non-food agricultural products while taking into account of the need for economic, social and environmental sustainability (FAO, 2003a). Even if the risk of environmental side-effects is known, priority is often given to secure crops.

Since the 1980ies, concern for environmental side-effects of insecticides used for desert locust control has increased. Today it is recognised that environmental risk assessment and human health aspects ought to be a standard element of planning, executing and financing desert locust campaigns (TAMS Consultants, 1989; Joffe, 1995; FAO, 2000, 2001c, 2006a). Monitoring of the insecticide treatments have been regarded as a key activity in desert locust management (Peveling, 2001; FAO, 2003b). The monitoring results should be applied in the planning and operational phase of future locust control campaigns to avoid repetition of any damaging operations. Another aspect of monitoring and risk assessment as a whole is to revalidate authorized control product and methodologies, and to test new insecticides and alternatives under operational conditions.

This thesis focuses on the impact of insecticides on aspects of the natural environment, rather than on the safety of humans and their livestock.

Aims of the thesis

The main aim of this thesis was to identify faunal organisms that are vulnerable under natural conditions to conventional insecticides used for controlling desert locust. The faunal groups found in or close to Ecologically Sensitive Areas (ESAs), described in this thesis, were of special interest as these areas should not be contaminated by insecticides.

If possible, a selection of taxa could be proposed for monitoring of insecticide impact. A related objective was to perform field tests of methodologies for monitoring the effect of chemical control on chosen taxa.

Because of the unpredictable occurrence of desert locusts, field studies on insecticide impacts on non-target organisms (NTOs) involving experimental spray treatments were planned on the Red Sea Coast of Sudan, a well known desert locust winter breeding area (Maxwell-Darling, 1936; Pedgley, 1981). The 2003-2005 desert locust emergency affected the coast. The locust control operations by the plant protection services consequently enabled environmental monitoring of activities under real scenarios.

Desert locust control

Adverse environmental impacts of insecticides used for pest control is a concern world-wide and for a range of organisms of pest status. The environmental risks associated with desert locust control are strongly influenced by the behaviour of the species, the geographical range and means of control. Therefore, before proceeding to environmental impact assessment, which is the focus of the thesis, desert locust population dynamics, scope of control campaigns, and strategies used in desert locust management are described.

Desert locust distribution and population dynamics

Locusts, which encompass twenty species, differ from grasshoppers in their ability to change from a solitarious phase to a gregarious phase. Morphology (*e.g.* colour and shape), number of instars, feeding preferences, and especially, dispersal capacity are altered. In the gregarious phase, instead of moving as a single nymph or adult, individuals congregate and move as a cohesive group known as a hopper band during the juvenile (nymphal) stages, and a swarm during the adult stage. The intermediate phase is known as transient (FAO, 2001a). Change from the solitary phase to gregarious phase is triggered by a combination of factors such as rainfall, vegetation density and composition, and the crowding of the population itself. The size and density of hopper bands and swarms vary. The size of a band can be a few square meters or several square kilometres. A swarm containing 50 million locusts per km^2 is regarded as a medium-density swarm (Steedman, 1990).

During recessions, desert locusts are present in low densities as solitarious, or transiens locusts. They breed in low densities and pose no immediate threat to crops or pasture. Almost 16 million km^2 between 12ºN and 35Nº is covered by this recession zone and includes more than 30 countries (Waloff, 1966). Rainfall in this area is erratic and unpredictable, but rainfall is necessary to create favourable conditions for breeding. Traditional breeding areas are known in most of the affected countries, but the dependency on rainfall means that breeding might take place almost anywhere in the vast areas that have received rain, and population increases are difficult to predict and detect. In the summer (July-September), breeding takes place in Sudan, Eritrea, Ethiopia, Yemen, the Sahel, West Africa and along the Indo-Pakistan border, while in winter (October-March) it occurs in three main areas: south-west Asia, the coasts of Red Sea and Gulf of Aden, and Somalia peninsula and East Africa (Maxwell-Darling, 1936; Popov, 1997; Roffey & Magor, 2003).

The total area at risk from infestation is estimated at 29 million km^2 across almost 60 countries, between 12ºN and 40Nº, and in East Africa extended southwards to 8ºS (Waloff, 1966; Pedgley, 1981).

In a recent review (van Huis, Cressman & Magor, 2007) the terminology concerning population stages is discussed. Generally, an *outbreak* is registered when gregarisation takes place, resulting in localised hopper bands and swarms. An *upsurge* involves widespread outbreaks followed by two or more successive seasons of transient-gregarious breeding in complementary breeding areas, and a *plague* is the stage when all locusts are in the gregarious phase and affect extensive areas outside the recession zone. If outbreaks are not inhibited by drought, emigration to unsuitable habitats or human intervention, further rainfall will allow the populations to develop into an upsurge and eventually into a plague (Waloff, 1966). It is believed that the desert locust has been known as a significant agricultural pest for at least 3 000 years (Waloff, 1966). Recent plagues occurred in 1926-1934, 1940-1948, 1949-1963, 1967-69 and 1986-1989, with several upsurges in-between (Steedman, 1990). The latest upsurge lasted from October 2003 to December 2005.

Control strategy and methods

A transboundary pest

The desert locust is a transboundary pest with high mobility. Therefore cooperation between countries and at regional and international level is essential for effective control. In the literature *managing* the pest is often used in favour of *controlling* the pest as the purpose is not only to kill the gregarious phase of the desert locust, but to stress the importance of monitoring and forecasting to keep the species at an acceptable level. A preventive strategy that involves regular surveys in the key breeding areas to detect any build-up of populations, and instigate control at an early stage, *i.e.* an early warning system, has been adopted as the most cost-effective and environmentally friendly way to manage the desert locust. Operations are usually carried out by the national plant protection services under the Ministry of Agriculture within the affected countries or by specialised organisations such as the Desert Locust Control Organization for Eastern Africa. Ideally, all field teams should be trained in survey and control methodologies and safe handling of insecticides. This is a part of national training initiatives as well as regional and international cooperation programmes. The international monitoring and overall coordination mandate of desert locust, among affected countries, donor countries, bilateral and multilateral organizations research institutes, universities and the chemical industry, lies within the mandate of the Food and Agricultural Organization (FAO), as confirmed by the United Nations (UN) (Joffe, 1995).

Costs of control

The costs of control campaigns are immense, for example the 1986-1989 and 2003-2005 campaigns are estimated to have cost US$ 274 million[1] and US$ 400 million, respectively (Skaf, Popov & Roffe, 1990; Brader *et al.*, 2006). There are not only the direct costs of control products, staff and operations, but also indirect costs. These are difficult to quantify and may include poisoning incidents, soil and water contamination, impacts on ESAs, detrimental effects on NTOs and the costs of clean-up *e.g.* collection of empty containers, assessing the quality and remaining shelf life of the insecticides left-over and disposal of obsolete stocks of insecticides.

Control methods and developments

Before the introduction of insecticides for desert locust control, farmers protected their crops from locusts by destruction of eggs, beating with sticks, burning and digging trenches. Farmers still relay on these means of mechanical control as well as indigenous knowledge of natural products, *e.g.* extracts from neem, *Azadirachta indica* (Meliaceae). The use of chemical insecticides for desert locust control started in the 1930ies (Uvarov, 1928). One of the first experiments took place in Amani in Tanzania where desert locust hoppers were dusted with calcium cyanide, ‘cyanogas’, and offered bran poisoned with sodium arsenate (Williams, 1933). In the 1940s the persistent organochlorines were introduced. Aerial spraying in barriers was a new applicable technique. Due to the bioaccumulation and adverse

[1] The figure includes costs for locusts and grasshoppers (Magor, pers. comm.).

effects of these compounds, organochlorine insecticides were banned in the mid-80s and replaced with organophosphates, carbamates and pyrethroids. This was also the time when bioinsecticide development began (Roffey & Magor, 2003; Wiktelius, Ardö & Fransson, 2003).

There is a growing demand for environmentally-friendly products, but chemical insecticides still dominate. For example, between October 2003 and December 2005, about 13.5 million litres of control products were used to treat 12.9 million ha of the Sahel region, mainly in West and Northwest Africa, affected by the most recent upsurge of desert locust. Applications of conventional insecticides were undertaken in more than 20 countries. Data which are available for almost half of the reported products (5.8 million litres) show that about 67% of these were chlorpyrifos and 29% malathion, both organophosphates, with the remainder unspecified (Mullié, 2006). Some bioinsecticides (see below) were applied for testing and evaluation purposes.

The Pesticide Referee Group (PRG) was established in 1984 to assess insecticides and dose rates for control of locusts and grasshoppers. The PRG is an advisory body of independent experts who evaluates efficacy and potential risks to humans and the environment. The latest list of dose rates verified for the desert locust, belong to the classes organophosphates, carbamates, pyrethroids and benzyolurea (FAO, 2004a). The toxic effects of the insecticides include knock-down and cessation of feeding of the locusts. They are broad-spectrum in activity, which means that not only the desert locust is affected, but other organisms as well, so called non-target organisms (NTO).

A bioinsecticide that developed during the 1990ies was Green Muscle®, which contains *Metarhizium anisopliae* var. *acridum* (Dueteromycotina: Hyphomycetes). This entomopathogenic fungus affects nymphs of grasshoppers and locusts, but side-effects on other organisms have not been detected (Lomer *et al.,* 2001). Other promising alternatives include the pheromone phenyl-aceto-nitrile (PAN); a semio-chemical that affects the gregarisation behaviour of desert locusts; and benzoyl-urea insect growth regulators (IGRs), which stop the moulting process of the nymphs. The latter is a chemical with a fairly narrow spectrum of action but unsuitable for application close to water bodies due to its adverse effect on crustaceans (FAO, 2004a). Ways of integrating these environmentally-friendly options into locust management are being evaluated (FAO, 2007a). For example, the practical use of *Metarhizium* in the field and the required dose of IGR are under investigation. The potential of PAN is still at the research stage.

Natural enemies, parasitic and predatory organisms, that attack the desert locust at various stages, are probably unable to prevent outbreaks, but these organisms are believed to slow down the rate of locust population increase (Greathead, 1966, 1992; Cheke, Mullié & Ibrahim, 2006).

The most commonly used application technique is to apply small concentrated doses of ultra low volume (ULV) formulations that are ready to spray and based on oil. Occasionally emulsifiable concentrates (EC) are used, but these need to be mixed with water, which is scarce in the desert locust environments. Depending on resources and distance to target and its size, the applications are made by vehiclemounted-, airborne-, knapsack-, or handheld-sprayer equipment. Full land cover applications are most common. An alternative control technique effective against marching hoppers that reduces the amount of insecticide applied is to create widely-spaced barriers of persistent insecticide. The vegetation is sprayed and the nymphs march through the sprayed barrier where they ingest the insecticide. The insecticide dieldrin, which is now banned, was particularly effective. Of today's products, this approach is particularly appropriate for IGR and fipronil (a phenylpyrazole) as they are relatively persistent. The use of Global Positioning Systems (GPS) and introduction of track guiding systems of differentiated GPS in spray vehicles and aircrafts allow for better navigation and the avoidance of applications in areas that should not be sprayed (FAO, 1991; Ottesen *et al*., 1999).

Environmental impact

Protection of biodiversity

The need to protect biodiversity is recognised in Principle 4 of the Rio Declaration on Environment and Development (UNCED, 1992), which states: *'In order to achieve sustainable development, environmental protection shall constitute an integral part of development process and cannot be considered in isolation from it'*. The importance of monitoring of activities that may have adverse impact on the environment is stated in Principle 17, *i.e. 'Environmental impact assessment, as a national instrument, shall be undertaken for proposed activities that are likely to have a significant adverse impact on the environment and are subject to a decision of a competent national authority'*. The declaration stresses the importance of identifying processes and activities that can have an adverse effect on the conservation and sustainable use of biological diversity. Chapter 19 of Toxic Chemicals Management (UNCED, 1992) emphasises the need to reduce environmental risks of insecticides by using products that are target-specific and degrade quickly, and promotes the use of biocontrol agents. This UN Declaration, affirmed by all member states, applies also to desert locust control management.

Ecologically sensitive areas

The large geographic range of the desert locust means that a variety of ecosystems with different sensitivity to insecticides can be affected by control operations. For example, in 1986 when 240 000 ha was treated on the coastal plains of Eritrea, the sprayed area most certainly included habitats of NTOs with different degrees of susceptibility to the insecticides (Wiktelius, Ardö & Fransson, 2003).

Ecologically sensitive areas (ESAs) as defined by the World Conservation Union (IUCN) and the World Conservation Monitoring Centre (WCMC) have specific ecological attributes such as key natural processes, unique features, rare flora and fauna, high biodiversity or critical habitats for breeding and feeding of wildlife (WCMC, 1993). Some ESAs are natural, while others have been significantly altered by human activities such as agriculture, aquaculture or forestry practices. ESAs with regard to desert locust control have been described by Wiktelius, Ardö & Fransson (2003) based on McNeely *et al.* (1990) and Hughes & Hughes (1992), and the definition set forth by the World Conservation Monitoring Centre (WCMC, 1993). The identified ESAs include wetlands according to the Ramsar Convention on Wetlands (Ramsar, 1971) such as oases and marine shorelines, legal protected areas, areas with a regular concentration of migratory birds, areas with a high or unique biodiversity and human settlements. In arid environments, especially, any wetlands including oasis, temporary rivers (khors or wadis), and coastal zones are important for the fauna and flora, and for use by people and livestock. The freshwater ESAs in the desert locust environments are often small, ephemeral and isolated making non-mobile fauna vulnerable to local extinction.

Environment at risk

Two foci of research to reduce environmental impact of locust control operations were initiated in the 1980ies (van der Valk, 1998). The first involved development of environmentally friendly means of control, for example through the Lubilosa project[2]. The second focus was to evaluate the environmental impacts of locust control products. Studies in the Sahel, especially in Senegal, covering arthropod taxa in soil, water and crop systems, were initiated in 1989 through the Locustox project[3] (Everts, Mbaye & Barry, 1997; Everts *et al.,* 1998a, 1998b, 2002). Other side-effect studies on terrestrial arthropods include Ottesen & Somme (1987), Ottesen *et al.* (1989), Everts (1990), Johanessen (1991), Murphy, Jepson & Croff (1994), Keith *et al.* (1995), van der Valk, Diakhaté & Seck (1996), Balanca & de Visscher (1997), Peveling *et al.* (1997a, 1997b, 1999a, 1999b), and Mamadou, Mazih, & Inezdane, (2005), to mention a few.

The latest biography of literature on the ecotoxicology of locust and grasshopper control that encompasses studies of both human and environmental side-effect includes 218 references (van der Valk, 2004). They consist of 76 studies focusing on terrestrial invertebrates, 23 on aquatic organisms (mainly in West Africa and associated with the Locustox project), 20 on vertebrates (five on birds, six on reptiles, six on livestock and three miscellaneous), and eight on environmental impacts occurring during operational conditions. The remaining 91 papers include reviews and multi-disciplinary studies covering several taxonomic groups, environmental chemistry, human toxicology and environmental impact studies of biological control methods. The most frequently studied insecticides are of chlorpyrifos and fenitrothion (organophosphates), deltamethrin (pyrethroid), fipronil (phenyl pyrazole) and the IGRs diflubenzuron and triflumuron.

An explanation for the preponderance of invertebrate NTO studies is because of the physiological similarity of target insects to non-target invertebrates. The fact

[2] The project 'Lutte Biologique Contre les Locustes et Sautereaux' (Centre for Biological Control of Locusts and Grasshoppers) started in 1989 and ended in 2002.

[3] The Locustox project (1989-2004) became the CERES/Locustox Foundation in 2002.

that invertebrates, especially insects, often occur in large numbers and have short life-cycles also facilitates insecticide impact assessments within a reasonable timeframe. The focus has been narrowed by studying beneficial arthropods including pollinators and natural enemies of locusts. Other studies include organisms important for ecosystem functioning, for example for recycling of soil organic matter, or microorganisms involved in the detoxification and decomposition of insecticide residues. Dung beetles (Coleoptera; Scarabaeidae), which are beneficial as manure and nutrient recyclers in arid environments, has not been studied in a desert locust control context.

There are aquatic studies including freshwater organisms vital for temporary ponds (Lahr & Diallo, 1997; Lahr, 1998; Lahr *et al*. 2000, 2001), but impact studies along shorelines and of marine organisms appear to be non-existent. Studies on vertebrates include mammals (*e.g.* tenrecs, livestock), (Touré, Mullié & Ba, 1998; Rakotondravelo, 2001), birds (Mullié & Keith, 1993; Mullié & Mineau, 2004; Cheke, Mullié & Ibrahim, 2006; Story *et al.,* 2007 - a review), and reptiles (*e.g.* lizards) (Randimbison, 2001; Peveling & Demba, 2003).

Studies that assess the risks to NTOs under operational conditions are relatively few. Adverse effects of the insecticides have been ad-hoc observations upon revisits by the control teams to treated sites for efficacy inspection or orally reports by local inhabitants. This information does not appear in the scientific literature. For example there were cases of bird and lizard mortality (Mullié, FAO consultant, pers. comm.), and some unconfirmed cases of alleged effects on domestic animals in 2003-2005 (FAO, 2006a). In general, monitoring and reporting about NTOs have not yet become standard operational practices in the affected countries, although there are initiatives in that direction (See *Environmental monitoring of control operations*).

Any potential change of a control strategy, method or product acceptance by decision makers and by legislation needs to be based on studies that demonstrate quantitative and qualitative effects on human and environmental safety (van der Valk & Peveling, 1997). The PRG recommendations on dose rates for insecticides for desert locust control, based on reports from the manufacturers of insecticides, research organisation and plant protection services in the affected countries, partly contain extrapolations from laboratory tests on other pest organisms and on NTOs and environments others than typical for the concerned grasshoppers and locust species. Nonetheless, in recent years, field data on environmental side-effects in desert locust environments have been increasing. The latest list of risk classifications by the PRG (FAO, 2004a) of eight non-target organism groups including aquatic organisms, terrestrial vertebrates and terrestrial non-target arthropods, for thirteen different insecticides at verified dose against desert locust were based on the following studies/data; i) 'laboratory and registration data on taxa which do not occur in locust area' - 22% of the risk data, ii) 'classification based on laboratory data or small scale field trials with indigenous species from desert locust areas' - 12% of the risk data, and iii) 'classification based on medium to large scale field trials and operational data from locust areas' - 49% of the risk data. (There is no information for the remaining 17% of the 104 classifications). The highest risks were associated with aquatic organisms, bees and natural enemies, and were based on a mixture of testing categories. The report states that the proportion of tests (laboratory and field) on NTOs originating in desert locust environments, and outcomes from monitoring during operational conditions need to be increased.

Environmental monitoring of control operations

Environmental monitoring of field operations is necessary to validate the findings of toxicological studies made in the laboratory and ecotoxicological semi-/field studies done under experimental conditions. Another aspect of monitoring is to apply the results in the planning and operational phase of future locust control campaigns to adjust for the environmentally damaging operations that were detected, thus avoiding them to be repeated.

Until the latest emergency, there had been little environmental monitoring of desert locust during control operations, but independent field teams for quality and environmental surveys of treatments (QUEST) were trained in several of the countries that were affected during 2003-2005. The teams were trained to oversee the efficacy of control and use of good agricultural practice, to monitor effects on human health, to ensure protective clothing was worn, to monitor the impact of spraying on NTOs and to sample for insecticide residues. The activation of these teams during coming control campaign will be one way of ensuring health and environmental monitoring of the operations, and will probably result in an increased and documented knowledge on adverse side-effects under operation conditions. The QUEST concept of FAO shares the objectives of several other national initiatives and projects by the international community, *e.g.* the Africa Emergency Locust Project of the World Bank, *i.e.* to minimise unwanted insecticide effects and to establish a system which facilitates corrective actions in a timely manner (World Bank, 2004).

Types of environmental monitoring

Three levels of monitoring have been distinguished; rapid assessment (1 hr - 1 day), dedicated operational monitoring (1 day - 1 week) and in-depth monitoring (weeks - months) (FAO, 2003b). In this thesis, the definition of assessment that has been set forth for wetland conservation (Ramsar Convention Secretariat, 2005) is applied; an assessment is an identification of status of and threats to the environment as a basis for the collection of more specific information through monitoring activities and does not necessary account for temporal variance, such as seasonality, in ecosystems. Rapid assessments are carried out where insecticide applications are reported by preferably comparing the treated area with one untreated area (or more areas) nearby. If adverse impacts of insecticides are found, adjustments and improvements of the application procedure including choice of insecticide can immediately follow.

The dedicated and the in-depth monitoring procedures should include comparison of pre- and post-treatment observations in treated and untreated areas with replicates to enable random population changes associated with the site to be distinguished from the effects of spraying. Study areas should preferably be located near each other, but with enough distance to avoid cross-contamination of organisms. Although replicates are crucial for statistical reliance, monitoring of population fluctuations in birds and flying insects, for example, require large plots and this makes spatial replication difficult as well as time and resource demanding. Over long time periods, the use of replications in time as pseudo-replicates for a pre-treatment period and a post-treatment period has been a suggested approach for these types of large field trial when spatial replicates are not feasible (Stewart-Oaten, Murdoch & Parker, 1986).

Embarking on an in-depth monitoring scheme at a site is challenging because even if desert locusts are present or are expected to arrive, they are likely to move on. Furthermore, as control operations are carried out rapidly by the plant protection services once locusts are detected, pre-spray studies are only possible when it is agreed that time and area can be set aside for these activities. Good communication between the monitoring and control teams will be crucial as the monitoring team depends on information from the control (and survey) teams for location, site characteristics and insecticide parameters of the spray operation. The control teams in turn will benefit from monitoring outcomes through recommendations of potential adjustment of spray procedure and insecticide choice for a certain habitat, for example.

Use of indicators in monitoring

It would be optimal to use bio-indicators in desert locust monitoring programs, *i.e.* key organisms with specific roles in the structure/function of an ecosystem that can serve as a direct indicator of the state of an ecosystem (Römbke & Moltmann, 1996). Useful organisms for desert locust control monitoring are believed to be the ones which meet the criteria of: i) being present at the same time as the desert locust, ii) being abundant and representative of the certain ecosystem, *and/or* iii) being chosen for their particular sensitivity to a specified insecticide. The fidelity of a taxon, *i.e.* its frequency and occurrence within a habitat, has been described as one of the key requirement for a bio-indicator (McGeoch, van Rensburg & Botes, 2002). Within the scope of this thesis, it was not feasible to select bio-indicators. Evaluation of bio-indicators requires comprehensive data bases based on temporal and spatial repetitions. Instead organisms susceptible to insecticide applications, *i.e.* reaction indicators, were sought. These indicators are not necessarily closely correlated with certain ecological factors, but are explained as indicators of an overall state of stress often by a notable change in abundance, and can be linked to an action (Römbke & Moltmann, 1996; UNEP, 2005). If these susceptible taxa are further studied, these may fill the requirements for bio-indicators and likewise be upgraded as such in desert locust monitoring programmes.

Red Sea Coast of Sudan - a case study

A desert locust breeding area

Sudan has both a winter and a summer breeding area of desert locust (Maxwell-Darling, 1936). Occurrence of rainfall from September to April on the Red Sea Coast, the winter breeding area, greatly influences the coastal desert locust breeding, which in turn has an impact on the summer breeding areas. The Red Sea Hills mark the boundary between the summer and winter breeding areas of the desert locust (Woldewahid, 2003). The coastal plains, which stretch 750 km in a north-south direction, offer preferable conditions for the desert locusts such as irregular rainfall, high temperature, bare soil with habitats of mosaic vegetation or ecotones, where two or more types of plants are in contact (Uvarov, 1957; Dampster, 1963), and areas with preferred host plants *e.g. Heliotropium spp. Tribulus longipetalus*, *Pennisetum spp.*, *Crotalaria microphylla* and *Dipterygium glaucum* (Maxwell-Darling, 1936; van der Werf *et al.*, 2005). The patchy vegetation leads to locust concentrations which in turn can result in phase changes from solitarious to gregarious locusts. The common plant communities have been described in Woldewahid *et al.* (2007) and are used in this thesis (*Paper II*). Apart from the humidity and vegetation of the valleys and khors the *Heliotropium* plant community has been found frequently inhabited by solitarious desert locusts and therefore also considered as high-risk sites for gregarious populations. In contrast, desert locusts are less frequently detected at the shoreline, where the plains are hard and saline.

Coastal agriculture, which includes small-scale farming systems on rain-fed land and the comparatively wide-ranging farming in the Tokar Delta, located in the south, is at risk for desert locust infestation. Even in periods of drought, the 630 000 ha Tokar Delta annually hosts locusts due to irrigation schemes and the green natural vegetation of the wetland, thus control operations are frequent. For example, Wiktelius, Ardö & Fransson (2003) reported 478 spray operations conducted between 1986 and 1998.

The sites on the coast of reported control operations from the period 1986-2005 by the Locust Control and Research Centre (LCRC), Plant Protection Directorate, Ministry of Agriculture and Forestry, which is responsible for desert locust management in Sudan, are indicated in Figure 1. During the period 638 insecticide applications were carried out on the Red Sea Coast (17º-22ºN, 35º30′-38º30′E) (Fig. 1). (Wiktelius, Ardö & Fransson, 2003; FAO, 2004b, 2006b). The applied insecticides were mainly organophosphates and carbamates with the following proportion of reported insecticides; malathion (34%), carbosulfan (28%), fenitrothion (11%) and the rest (27%) of diazinon, propoxur, bendiocarb and chlorpyrifos, each less than 10%.

Coastal sensitive areas

The coast has sparse vegetation apart from the Tokar Delta and along wadis and khors. The coast is characterized by hot summers (min. 28°C and max. 41°C) and warm winters (min. 20°C and max. 33°C) (Satakopan, 1965), with the north part of Port Sudan defined as desert and the south part as semi-desert (Fig. 1). The environment has developed in the harsh climate of high temperatures, unpredictable rainfall, sandstorms and considerable yearly and seasonal weather fluctuations. In these arid environments water is necessary for vegetation, animals, and humans, thus the most important ESAs are found in association with water. The Red Sea Hills feed the khors, *i.e.* temporary rivers, that run westwards inland, and eastwards providing water to the coastal plain, a 20-50 km wide strip of land. Fresh water bodies include shallow water ponds when sufficient rain has fallen, and the Tokar Delta. Beds of sea grasses grow along the marsa (bay) contours. Coral reefs, both fringing and barrier reefs, are well developed. Fragmented mangrove forests are found from the Eritrean border to the Egyptian border in the north. The mangroves, temporary rivers and ponds, the delta, coral reefs and sites of large assemblages of migratory birds all meet the criteria of an ESA. Among the protected areas, or areas that are proposed for legal protection status and therefore ESAs, are the 12 km^2 Sanganeb Marine National Park, Dongonab Bay, Mukkawar Island, Suakin Archipelago, Tokar Delta, Erkawit-Sinkat Wildlife Sanctuaries, Jebel Elba and Jebel Gurgei Massif (UNEP/WCMC, 2006) (Fig. 1).

Mangrove

Mangrove habitats were identified as important ESAs on the Red Sea Coast due to their ecological significance, the increasing risks of becoming extinct and because of the risk of being affected by desert locust treatments. Mangroves are among the most threatened ecosystems in the world (Valielea, Bowen & York, 2001) and the economic and ecological importance of the habitats have been widely described (*e.g.* Tomlinson, 1986; Spaninks & van Beukering, 1997; Hogarth, 1999). The Sudanese mangroves are on the bird migration route between breeding sites in the western Palaearctic and wintering areas south of the Sahara thus attracting high concentration and diversity of birds (Wiktelius, Ardö & Fransson, 2003; personal obs.). The narrow mangrove stands in Sudan and Egypt comprise the northern limits of the Indo-Pacific-East African mangrove realm (Hogarth, 1999). The 'black mangrove', *Avicennia marina* (Forssk.) Vierh. 1907, (Acanthaceae), is the dominant species of the fragmented habitats along the Sudanese coast. Other species, *Bruguiera gymnorhiza* and *Rhizophora mucronata,* have been reported from the areas south of Suakin, and the latter also north of Halaib (Wilkie, 1995). The largest habitats are found at the mouths of the major khors and in the typical marsas in the flat coastal plains, for example at Ashat, Hoshiri and Gowb (Wilkie, 1995; pers. obs.) (Fig. 1).

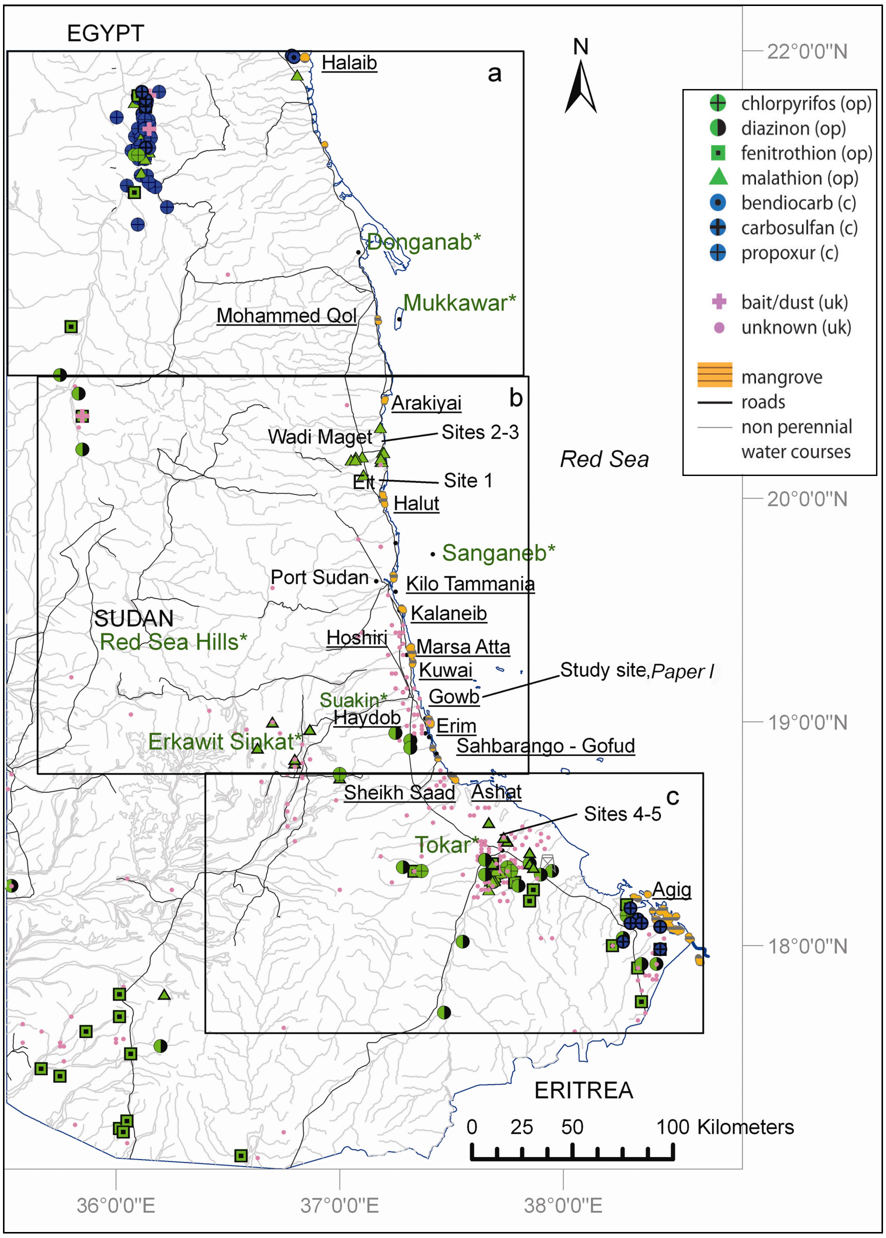

Fig. 1. The Red Sea Coast of Sudan. The study described in *Paper I* took place at Gowb and the assessments described in *Paper II* at Wadi Maget, Eit and Tokar (five sites). Ecologically sensitive areas include the mangrove (names of locations are underlined) and protected areas, or areas identified for legislation (names in green with an asterix, *). The reported control operations of desert locust from the period 1986-2005 are indicated. (op=organophosphate; c=carbamate). The delineation into the squares a, b and c refers to the figures in Appendix A, see also *Results and discussion*. (ArcGIS9, ArcView®).

The topography of the northern area of the coast has a hilly landscape and narrow coastal plain which result in small mangrove stands without the otherwise typical growth pattern and zonal delineation, *e.g.* Mohammed Qol. Today 500 ha in total are left of a mangrove belt which was believed to cover the whole coastline in the 1870ies (Wilkie, 1995; FAO, 2007b). A combination of both human-induced and biological factors is believed to be responsible for these diminishing mangroves. The low annual rainfall, the scarcity of permanent streams and the low-level fluctuations of seawater result in thin stands (Hogarth, 1999). Human-induced impacts include tree-felling for charcoal and building material, camel browsing, coastal developments such as dredging and land filling, and pollution, possibly including the use of agrochemicals (*Paper I;* Babiker, 1984; Abdellatif, 1993; PERSGA, 2000; Bashir, 2001).

In 1993, the Sudanese Environment Conservation Society expressed a need to study the extent of pollution, including insecticides used for desert locust control, in the mangroves, coral reefs and marsas of the Red Sea Coast of Sudan (Abdellatif, 1993). Urgent attention and inventories to establish the quantities, types and residue levels of insecticides being sprayed in the area were requested. Later, also UNEP/PERSGA (1997), PERSGA (2000), Bashir (2001), Wiktelius, Ardö & Fransson (2003) and the World Bank (2004) identified potential threats to the coast by desert locust control operations.

Material and methods

Papers I and *II* report studies undertaken during the winter months of 2002 and 2004, respectively, on the Red Sea Coast of Sudan.

Paper I describes an experiment designed to monitor side-effects of one insecticide on selected non-target fauna in, and in the vicinity of an ESA. The study site was located 30 km south of Suakin (Fig. 1). The area includes one of the major khors, Gowb, which is temporarily filled with water during heavy rains and has an adjacent mangrove habitat. An illustration of the experimental layout with the vegetation zonation from shore line westwards into the crop areas is found in the paper. The landward zonation, typical for mangrove, was described in detail, as the mangrove represents an ESA of high significance. Susceptibility to insec-ticide and monitoring methods were tested for prawns (Crustacea; Penaeidae), hoopoe lark, *Alaemon alaudipes*, Alaudidae, and epigeal arthropods including antlions (Neuroptera; Myrmeleontidae) (Fig. 2a-c). Prawns that were caught by cast net were placed in cages in the mangrove lagoon and were monitored with regard to survival rate. The hoopoe lark and antlion pits were counted along transects and arthropods were sampled with pitfall traps. Two separate areas (treated and untreated), 88 ha each, with a buffer zone between, were monitored during a pre-spraying period of 16 weeks and a post-spraying period of 10 weeks, by a four-person field team. Effects of the organophosphate chlorpyrifos (Dursban®, ULV, 324 g a.i. ha^{-1}) applied by air (11 February 2002) were monitored. Desert locusts were not present, but the application resembled a real control situation and was undertaken by staff from the LCRC. The mangrove itself was not sprayed. Recommendations on calibration, dose and application procedures followed FAO (2001b).

2a). Prawn cages in mangrove lagoon.

2b). Antlion larval pit.

2c). Pitfall trap.

2d). Floatation of cow dung.

Figure 2. Examples of applied environmental monitoring methods of non-target organisms in desert locust environments on the Red Sea Coast of Sudan; 2a-c: Insecticide experiment at mangrove, Gowb (*Paper I*), 2d: Operational monitoring of desert locust control operations at Eit, Wadi Maget and Tokar Delta (*Paper II*). (Photos: H. Eriksson).

The drift of insecticide droplets from the aerial application was assessed as it implies a contamination risk for the mangrove even in situations when treatments take place further inland. The drift was measured by oil sensitive papers attached on poles that were placed perpendicular to the wind direction from the first spray line into the mangrove habitat.

Paper II reports on a rapid assessment of desert locust control operations on the coast. An environmental monitoring team of two persons was formed who accompanied the teams from the LCRC during January-February 2004. Five treated sites at Eit, Wadi Maget and Tokar Delta, representing two main biotopes, *Acacia tortilis* shrubland (Woldewahid *et al.*, 2007) and cultivated wetland, were included in the study (Fig. 1). Immediate impact of insecticide treatments with the carbamate carbosulfan (Marshal®, ULV, 100 g a.i. ha^{-1}) by ground application was assessed for dung beetles (Coleoptera; Scarabaeidae). Dung beetles are known for using dung for feeding and brood sites (Hanski & Cambefort, 1991), thus dung pats from Zebu cows were placed in sites of desert locusts that were targeted for desert locust control. At each site, dung was placed in an area to be controlled and in an area that upon approval from LCRC could remain free from insecticide.

Fresh dung was placed in three plots in each area of approximately 100 m^2 for 24 hr periods before and after application. The dung beetles were extracted by floatation and abundance and species richness were compared between the time periods in the areas (Fig. 2d).

Statistics

The 'Before and After Control Impact' (BACI) design (Stewart-Oaten, Murdoch & Parker, 1986) was applied in the field experiment (*Paper I*). In the BACI approach the difference in a response variable between treated and untreated areas before treatment (here the insecticide) is tested against the difference between the two areas after treatment. Certain prerequisites were decided on for the use of BACI. These criteria are explained in *Paper I* and based on Stewart-Oaten, Murdoch & Parker (1986). Probability of survival (Norman & Streiner, 1994) was assessed to monitor the insecticide impact on the prawns.

In the second study (*Paper II*), the insecticide effect was analysed by a Wilcoxon matched pairs signed rank test (Siegel, 1956). Each pair consisted of the numbers of beetles in the plot before treatment and the corresponding number in the same plot after treatment. The differences in dung beetle abundance between the pre-spray period and the post-spray periods were compared. The treated and untreated areas were analysed separately. To test for any differences in abundance between areas before insecticide applications a t-test was performed. A difference in dung beetle diversity between the two major biotopes was obvious during the sampling, but was tested by a paired t-test.

Statistical analyses and calculations of descriptive statistics were performed using Minitab 15® and Microsoft Excel 2000® for Windows. Values were transformed by lg(n+1). A 95 %-confidence significance limit was applied to analyses.

Results and discussion

The studies described in this thesis contribute to our knowledge of environmental impacts of insecticides on a selection of non-target organisms (NTO) in a key breeding area of the desert locust, with special attention to ecologically sensitive areas (ESAs).

The results of the two studies (*Papers I* and *II*), site locations, insecticide parameters, monitored NTOs, methods and statistics are summarized in Table 1.

Table 1. *Summary of the studied habitats, non-target-organisms (NTOs), monitoring methods and types and significant results as reported in Papers I and II. Ta=Treated area, Uta=Untreated area. Significant symbols: *=P<0.1; **=P<0.05; ***=P<0.01.*

Location, time, insecticide, formulation and dose	**NTO**	**Habitat**	**Monitoring method**	**Monit. type**[1]		**Statistical test**	**Results** - = decrease, + = increase in numbers in Ta compared to Uta when comparing periods before and after application.
				Rapid assess -ment	In-depth		
Gowb (1 site), Nov - April 2002; chlorpyrifos, ULV 324 g a.i. ha^{-1} *(Paper I)*	Prawns	Lagoon Mangrove	Caged prawns, (mortality rate)	x	x	Probability of survival (Norman & Streiner, 1994)	Mortality of juvenile prawns of *Metapenaeus monoceros* began earlier in Ta compared to Uta (***)
	Antlion (larvae)	Cropland	Transect counts (abundance)		x	BACI (Stewart-Oaten, Murdoch & Parker, 1986)	Antlion pits of *Cueta sp*. (Myrmeleontidae) (- **)
	Epigeal arthropods	Mudflat Salt marsh Cropland	Pitfall trapping (activity density)		x	–" –	*Mesostena angustata* (Tenebrionidae) (- **) *Gryllus bimaculatus* (- *), and family Gryllidae (- *) *Pachytychius setosus* (Curculionidae)(- *)[2] Spiders and solifugids (Arachnids) (- **)
	Resident bird	Salt marsh Cropland	Transect counts (abundance)	x	x	–" –	Hoopoe lark *Alaemon alaudipes* (Alaudidae) (- **)
	n.a.	Mudflat Lagoon Mangrove	Measuring drift of insecticide droplets	x		n.a.	A north-western wind (310°), a direction from land towards the mangrove, carried the insecticide droplets at least 1 000 m
Eit, Wadi Maget, Tokar Delta (5 sites), Jan - Feb 2004; carbolsulfan, ULV 100 g a.i. ha^{-1} *(Paper II)*	Dung beetles (and hister beetles)	*Acacia tortilis* shrubland, Cultivated wetland	Beetles extracted from cow dung placed in field (abundance)	x		Wilcoxon matched pairs signed rank test (Siegel, 1956)	*Onthophagus margaritifer* (Scarabaeinae) (- **) *Aphodius lucidus* and subfamily Aphodiinae (+**) Histeridae *spp.* (-**)

1 Types of monitoring are explained in *Environmental monitoring of control operations.*

2 A decrease in the weevil *Pachytychius setosus* (Curculionidae) in untreated area was mainly due to one unusually large pitfall catch during pre-spray period, thus not discussed further.

Susceptible non-target organisms

Caged juvenile prawns of *Metapenaeus monoceros* in the treated area died more quickly following the chlorpyrifos application than the juveniles in the untreated area, and also compared to subadult prawns (*Paper I*). The result supports earlier studies on crustacean sensitiveness to chlorpyrifos (*e.g.* Johnson & Finley, 1980; Barron & Woodburn, 1995). There was a significant difference in the mean abundance of pits of antlions, *Cueta sp.* (Myrmeleontidae) in treated and untreated areas for the pre-and post spray periods. The numbers decreased in treated area compared to untreated area after application. Hoopoe larks also decreased in the treated area after insecticide application. The arthropod taxa that were sampled by pitfall traps and met the set of BACI-criteria, revealed a decrease in abundance, or rather activity density (Topping & Sunderland, 1992), for i) the tenebrionid beetle *Mesostena angusta* (Fabricius, 1775), ii) crickets both at the species level, *Gryllus bimaculatus,* De Geer, 1773, and family level (Gryllidae), and for iii) arachnids. The mean numbers were lower in treated area compared to untreated area, comparing the pre- and post-spray periods. In contrast to the caged prawns and antlion pits, the results of the more mobile organisms, the hoopoe lark and arthropods, were somewhat difficult to interpret as the populations showed temporal fluctuation both before and after application in both areas. However, as the mean of transect counts and number of trapped individuals were used, the significant differences between the means in treated and untreated areas before and after application were regarded as valid and linked to the insecticide application. Visible observations of insecticide impact, an immediate effect, were high numbers of dead insects found throughout the zones in the treated area.

The second study (*Paper II*) on potential immediate effects of carbosulfan on dung beetles (Scarabaeidae: Scarabaeinae and Aphodiinae) showed difference in beetle abundance between pre-and post-spray periods in the treated area, but no differences were found in untreated areas. All significant results apply to the biotope *Acacia tortilis* shrubland because the number of colleted beetles was low in the cultivated wetland. Scarabaeinae beetles tended to decrease after insecticide treatment. The decrease was statistically significant for the dark colour morph of the species *Onthophagus margaritifer,* D´Orbigny, 1907. (The abundance of the light morph decreased also, but not significantly). In contrast, Aphodiinae beetles, especially the species *Aphodius lucidus* (Olivier 1789), increased significantly after treatment. There might have been a repellent effect of the treated dung to Scarabaeinae beetles, and especially to the species *Onthophagus margaritifer.* Aphodiinae beetles may be less susceptible to the insecticide, but the increase could also be a result of inter-specific competition with the Scarabaeinae beetles. The Scarabaeinae species were probably the first colonisers of the dung, and when these beetles were absent, the Aphodiinae beetles had better access to the resource. Histeridae beetles, non-scarabs, were significantly reduced in numbers following application. This result may be a direct effect of the insecticide or an indirect effect of fewer prey items in the dung for these predacious beetles.

There was a marked difference in dung beetle abundance and species richness between the two biotopes; the *Acacia tortilis* shrubland with many beetle individuals and species, and the cultivated wetland (Tokar Delta) with few. The artificially placed dung could have been an increased resource in the meagre desert environment in the *Acacia tortilis* shrubland where land use was low and people and animals were mainly nomadic households. In contrast, dung was a more readily available resource in the fertile delta with sedentary livestock and an active land use. Therefore the experimental dung in this biotope (cultivated wetland) was presumably less attractive, and consequently fewer dung beetles and species were found. Davis (1996a) showed that higher species richness was found in un-shaded vegetation compared to shaded, which also applied to this result. The *Acacia tortilis* shrubland had fewer thickets, especially compared to Site 4 in the wetland. Furthermore, Davis (1996b) pointed out that soil type influences the associated beetle assemblages. In this study, the hard clay layer in the cultivated wetland was perhaps less suitable for activities by dung beetles, in particular the paracoprid dung beetles (tunnelers), which dig brood chambers beneath the pats. The loose sand in *Acacia tortilis* shrubland seemed more suitable. The recent rainfall in the desert environment (*Acacia tortilis* shrubland) which triggered desert locust breeding, probably also lead to increased dung beetle activity. Since animal husbandry is relatively extensive in Tokar Delta, the risk that the tested dung from cows in this biotope included chemicals was believed to be higher than in the dung collected for the study in *Acacia tortilis* shrubland. It is a plausible additional explanation for the low numbers of individuals and species found in the dung in the cultivated wetland.

During the inventory, two new species of Scarabaeinae and three new species for Aphodiinae for Sudan were found.

Many factors are believed to influence the degree of NTO susceptibility to insecticides, for example the activity, density, vegetation inhabitation, diurnal rhythm, foraging patterns and interactions (intra- and interspecies). These factors were included in the analyses as far as possible (*Papers I* and *II*). To appraise the value of the organisms as indicators for environmental monitoring of desert locust control operations (See *Environmental monitoring of control operations*), the geographic distribution in the desert locust affected countries, temporal overlap with likely desert locust occurrence, beneficial status, robustness, ease of sampling and identification, and their economic and conservation importance were taken into account. For example, the penaeid prawns are of economic value for human consumption world wide. Contamination of their nursery grounds may involve risks to local people and animals that use the prawns as a food resource and could also lead to economic implications. The penaeid prawn *Metapenaues monoceros,* the tenebrionid beetle *Mesostena angustata*, the crickets *Gryllus bimaculatus* (and Gryllidae species), the dung beetles *Onthophagus margaritifer* and *Aphodius lucidus* and the antlions *Cueta sp*. stand out among the tested taxa because they meet the main criteria for indicator species as described in this thesis. It is premature to suggest the taxa as bio-indicators or even reaction indicators for environmental monitoring of chlorpyrifos and carbosulfan. However, the results suggest more detailed studies of these organisms.

Methodology evaluation

The tested methods of i) caged prawns, ii) pitfall trapping of epigal arthropods, iii) transects counts of hoopoe larks and antlion larval pits, and iv) assessment of dung beetles in artificially made dung pats, were all simple and low cost methods that did not need sophisticated equipment, and yet provided useful data. A downside of the pitfall sampling of the arthropods inhabiting the zone close to the shoreline was the low sample size per species which weakened the analysis (*Paper I*). As described (See *Environmental monitoring of control operations*), a high fidelity, *i.e.* occurrence, is important for indicators. A further constraint at the initial stage of both studies (*Papers I* and *II*) was the limited access to documentation on the species that potentially could be encountered. It applied particularly to arthropods. The species information presented here could facilitate further research.

The results from the rapid assessment of dung beetles are of special value for inventories. The discovery of five new species of dung beetles for Sudan in the fairly limited spatial and temporal assessment, using one sampling methodology, indicates that the dung beetle fauna on the coast, or/and in the country as a whole, is poorly known.

The first study (*Paper I*) was an example of a relatively in-depth and long term monitoring exercise, compared to the second study (*Paper II*). For both studies, increased temporal and spatial replicates would improve the statistic analyses. Longer monitoring periods could probably reveal other insecticide impacts, both lethal and sublethal, such as behaviour changes, reduced fecundity and reduced number of offsprings. Longer study periods could also give a picture of recovery patterns for the organisms that decreased in the sites, including re-colonisation from the surroundings.

Wind drift risk and precaution close to ESAs

The common occurrence of land breezes from land towards the sea in the morning (Liljequist, 1970) was also the case at Gowb (*Paper I*). The drift study showed that the north-western wind direction of a wind speed of 2.7 m s^{-1} caused droplets from the aerial application of chlorpyrifos to move at least 1 000 m eastwards, to the mangrove stand. The smell of Dursban®, described as ‘mercaptan (WHO, 1975), was noticed as far as the sand banks on the seaward part of the off-shore mangrove. Because desert locust control operations often occur in the early hours of the day when weather conditions are suitable for ULV spraying and the target insects are settled (Steedman, 1990), the result indicates a risk of insecticide drift to the shoreline and into mangroves, ESAs, even if the spray target is further inland. As an indicative recommendation ULV compounds should not be applied by air closer than 1 500 meters from a mangrove site as well as from the shoreline. This buffer zone complies with the size that has been recommended for water bodies (FAO, 2003b) and estimations made by Lahr, Gadji & Dia (2002) based on drift studies close to fresh water ponds. The buffer will offer some protection even during accidentally incorrect applications. In Appendix A, maps of the northern, central and southern parts of the Sudanese Red Sea Coast illustrate the sites of mangroves and the suggested buffer zones.

With regard to ESAs in the other study sites (*Paper II)*, the Tokar Delta is an area of high biological importance. The wetland was declared a Game Reserve in 1939 and has the protection category VI, which by definition is an area that should be managed to ensure long term protection and maintenance of biological diversity UNEP/WCMC, 2008). The frequent desert locust treatments in the delta are a matter of concern because long-lasting detrimental effects from the insecticide applications are probably highest in areas frequently treated.

Conclusion and recommendations

With the growing concern for side-effects of insecticides, desert locust management is probably going towards a compulsory integration (and implementation) of an environmental risk assessment component. Enhanced knowledge of the environments, selection of appropriate study organisms and development of monitoring methodologies are essential for assessing potential impacts associated with insecticide treatments against the desert locust. The results of this thesis contribute to this growing body of knowledge.

The results of this thesis point to some worthwhile avenues for more detailed follow-up studies. Several NTOs showed measurable responses to insecticide treatments in this study and therefore have potential as indicators. Monitoring techniques were shown to be appropriate for use in the field for rapid and long term assessment. These methods should be tested in other desert locust locations and also at different time of the winter breeding period.

Some of the results are also applicable to other countries around the Red Sea and Gulf of Aden, and to similar environments in the desert locust distribution area as a whole. The outlined safety measurements in the vicinity of mangrove habitats apply also to Djibouti, Egypt, Eritrea, Mauritania, Oman, Saudi Arabia, Senegal, Somalia and Yemen, as well as desert locust invasion countries where mangroves are found, such as the Gambia. More precise studies of wind patterns close to the sea are recommended.

Environmental monitoring is a challenge because of the certain characteristics of the desert locust; their ability to quickly increase in numbers, migrate across vast areas and be detected unexpectedly; that give rise to the need for rapid control operations. Monitoring will need to be undertaken on both short and long term time scales. The environment will vary and so will the non-target fauna. Furthermore, it is not uncommon that baseline data and resources are limited in the affected country.

In order to meet these challenges it is recommended that *National Environmental Guidelines* with regard to desert locust control be developed. This supports similar recommendations by TAMS Consultants (1989) and Ritchie & Dobson (1995). Important documents for the development of these *National Environmental Guidelines* include international guidelines and protocols related to the environmental effects of insecticides (*e.g.* EPA, 1985; Hassan & Oomen, 1985; Hassan *et al.*, 1988a, 1988b; IOBC/OILB, 2000; EPPO, 2003; OECD, 2006; IOBC/WRPS, 2007), monitoring methodology descriptions (*e.g.* Dent & Walton, 1997; Southwood & Henderson, 2000; Grant & Tingle, 2002) and studies and guidelines especially related to desert locust management (FAO, 2003b; Locustox literature[1]).

The *National Environmental Guidelines* should contain the following information:

- Lists of different anticipated environmental problems;
- Maps of ESAs;
- Descriptions of common ecosystems in the zones most often affected by desert locusts;
- Lists of relevant key NTOs for each ecosystem that may be at risk, *and*
- Specification of monitoring methods categorised by habitat, NTO of interest for monitoring purposes, and insecticide in use.

The information in this thesis, for example, the review of ESAs on the Red Sea Coast, suggestions of valuable taxa for environmental monitoring and the dung beetle inventory, will be of use for the environmental component of the desert locust management in Sudan.

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[1] See *Environment at risk.*

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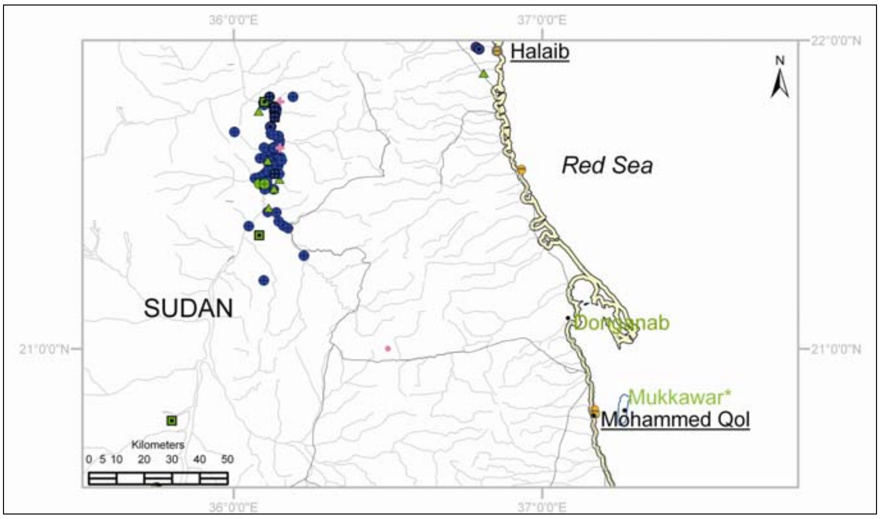
Abbreviations and acronyms

a.i.	active ingredient
BACI	before and after control impact
CERES	'Centre de Recherches Ecotoxicologiques dans le Sahel' (Centre for Exotoxicological Research in the Sahel)
EC	emulsifiable concentration
EMPRES	Emergency Prevention System (for Transboundary Animal and Plants Pests and Diseases)
EPA	Environment Protection Agency
EPPO	European and Mediterranean Plant Protection Organization
ESA	ecologically sensitive area
FAO	Food and Agriculture Organization
GPS	global positioning systems
GTZ	'Deutsche Gesellschaft für Technische Zusammenarbeit' (German Technical Cooperation)
ICIPE	International Centre for Insect Physiology and Ecology
IGR	insect growth regulator
IOBC	International Organisation for Biological and Integrated Control of Noxious Animals and Plants
IUCN	World Conservation Union
Locustox	(Not an acronym; the full name of FAO project)
LCRC	Locust Control and Research Centre

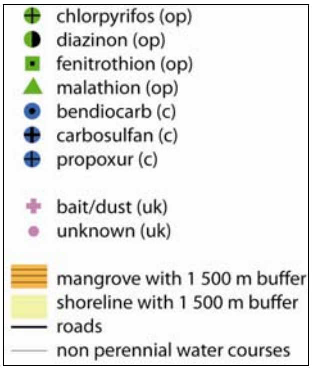
LUBILOSA	'Lutte Biologique Contre les Locustes et Sautereaux' (Centre for Biological Control of Locusts and Grasshoppers)
NTO	non-target organism
PAN	phenyl-aceto-nitrile
PERSGA	Regional Organisation for the Conservation of the Environment of the Red Sea and Gulf of Aden
PRG	Pesticide Referee Group
QUEST	quality and environmental surveys of treatments
RAMSES	Reconnaissance and Management System of the Environment of *Schistocerca*
SLU	'Sveriges Lantbruksuniversitet' (Swedish University of Agricultural Science)
ULV	ultra low volume
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environmental Programme
USAID	United States Agency for International Development
VAR	volume application rate
WCMC	World Conservation Monitoring Centre

APPENDIX A.

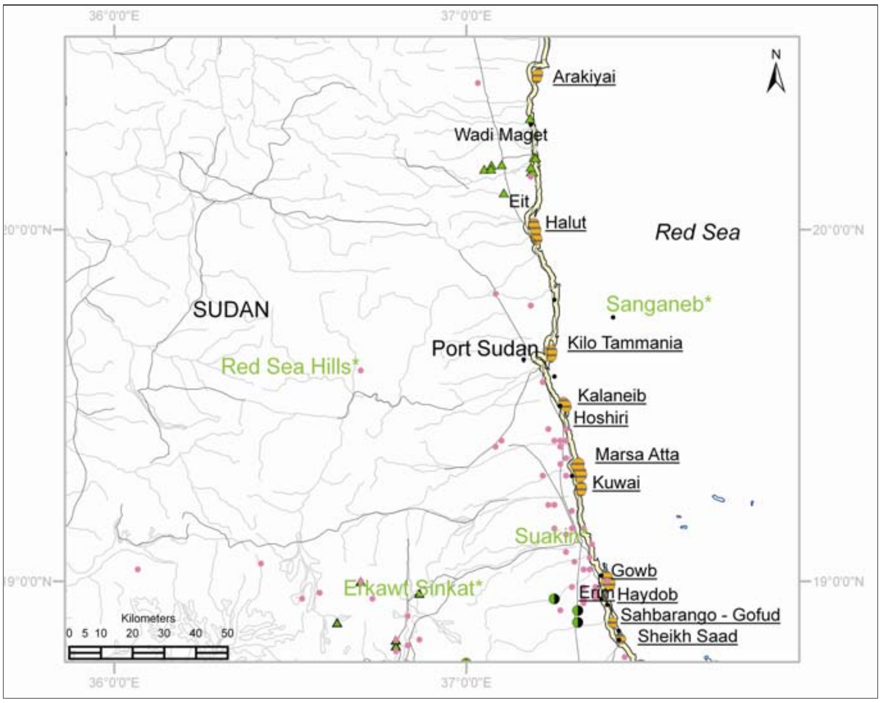
The Red Sea Coast of Sudan divided into three parts; a northern, middle and south. Buffer zones of 1 500 along the coast and around the mangroves are indicated. Names of mangrove locations are underlined and sites shown in orange. Ecologically sensitive areas also include the protected areas, or areas identified for protection (names marked in green with an asterix, *). Control operations from 1986 to 2005 are shown. (op=organophosphate, c=carbamate). See also Fig. 1.



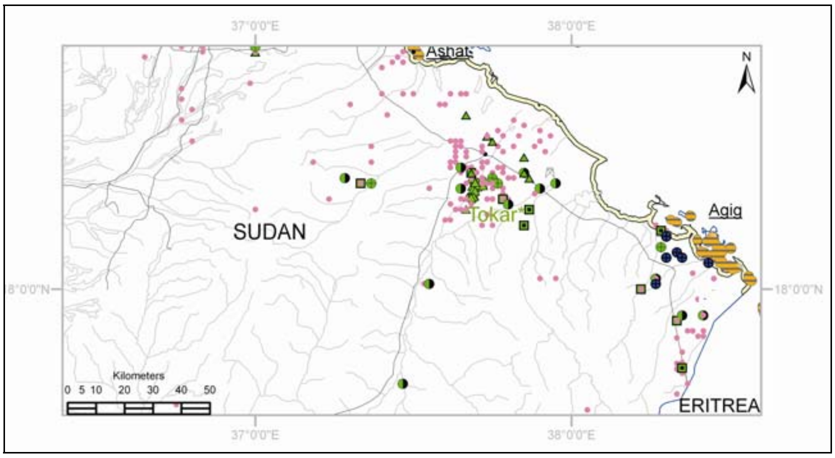
a). North part of the Red Sea Coast of Sudan (20º33′ - 22º00′N).



(ArcGIS9, ArcView®).



b). Central part of the Red Sea Coast of Sudan (18º42′ - 20º27′N).



c). South part of the Red Sea Coast of Sudan (17º36′ - 18º46′N).