CHAPTER 5.2.

ENVIRONMENT AND THE STERILE INSECT TECHNIQUE

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SUMMARY

The sterile insect technique (SIT) is an exceptionally promising pest control method in terms of efficacy and environmental compatibility. Assessments of environmental risks vary according to the status and origin of the target pests. The suppression or eradication of non-native pest populations with the sit raises few environmental concerns, and these are related mainly to some pre-release suppression techniques. However, the elimination of native species, or at least populations of native species, requires more detailed and complex assessments of ecological effects and consequences for biodiversity conservation. Eradication programmes provide opportunities to study these topics within the scope of both environmental impact assessments and operational monitoring programmes.

1. INTRODUCTION

The sterile insect technique (SIT) is a species-specific control method that may be applied in the area-wide integrated pest management (AW-IPM) of insect pests of medical, veterinary, and agricultural importance. Contrary to chemical or other products that are intrusive, toxic, pathogenic or otherwise destructive entities, or to most other biological agents whose establishment is irreversible once they are released, sterile insects are non-invasive agents that leave no “ecological footprint” because they cannot become established due to their sterility. Consequently, sterile insects have been recognized among *beneficial organisms* by the International Plant Protection Convention to which most countries are parties (IPPC 2017). Therefore, the SIT alone poses *a priori* an exceptionally low risk to the environment (Müller and Nagel 1994). Ecologically, the release of sterile insects represents an input into ecosystems of allochthonous, living yet non-reproductive biomass readily integrated into and processed within food webs. Thus, if there are any direct adverse impacts of sterile insects on non-target biota, they are most likely related to changes in interactions among species.

The SIT is not a stand-alone technique, however, and in most situations, to be effective and economically viable, the SIT requires pre-release suppression of the pest population with conventional control techniques. These encompass simple devices such as sticky traps, as well as large-scale aerial treatments with insecticides. Therefore, environmental hazards range from negligible to high, depending on the actual type and combination of suppression agents and tactics. When target population densities are low, less hazardous control techniques can be employed to reduce target populations. For example, the initial population densities of the tsetse fly *Glossina austeni* Newstead in Unguja Island, Zanzibar, were already low due to previous habitat destruction by farmers. Thus, suppression was achieved with pour-on pyrethroids sprayed on cattle (living targets) in pastoral areas, and with insecticide-impregnated blue cotton screens (targets) deployed in areas where cattle were scarce (Vreysen et al. 2000), posing a low risk to the environment (Nagel 1995). An even lower risk is estimated from the use of chemical larvicides to control the New World screwworm *Cochliomyia hominivorax* (Coquerel); they are applied directly to the wounds of infested livestock, posing no hazard to treated animals or components of the environment (USDA 2001a).

Area-wide control targets the entire population of a specific pest in a particular area (Lindquist 2000; Hendrichs et al. 2007; Klassen and Vreysen, this volume). Therefore, it is more cost-effective than local control which only targets a portion of

the pest population and permits continuous pest movement from non-treated neighbouring areas into the treated areas (Klassen 2000; Hendrichs et al. 2007).

Most suppression or eradication programmes with an SIT component were directed against populations of introduced (non-indigenous) species, and did not aim explicitly at eradicating a pest species from its entire natural range. The risk assessment of full eradication strategies requires in-depth investigation of the ecological role of target indigenous pests in ecosystems and food webs, and the possible consequences of their disappearance.

This chapter discusses environmental issues related to different steps in the SIT strategy and process, from sterile insect production to release, and from direct to indirect ecological effects. Given that suppression and/or eradication programmes may eventually extend from area-wide to range-wide, in other words from population eradication to species extinction in the wild, trophic and other ecological interactions among target insects and non-target fauna and flora will also be addressed. While evaluating environmental risks associated with the SIT in a more general sense, particular emphasis is placed on the environmental effects of tsetse fly *Glossina* spp. control in Africa.

2. MASS-REARING AND STERILIZATION

2.1. Mass-Rearing

Insect-rearing facilities pose a low environmental risk if designed using current biosafety principles, and if managed according to best practices and standard operating procedures (FAO/IAEA 2008; Parker, Mamai et al., this volume). However, given that large numbers of insects are reared at a single site, they are a potential source of unintentional release of fertile insects into the environment. This might cause limited damage if facilities are located within the natural range of the native pest species, but potentially more serious hazard if environmental conditions are suitable for the establishment of an invasive species, although such a situation could immediately be mitigated by releases of sterile insects of that same species. Therefore, setting up facilities within the potential habitats of the target insect requires adherence to strict quarantine and security guidelines during all steps of insect production and shipping. To reduce this risk, sterile fruit fly production in the United States is only allowed in areas where the respective species is established or where environmental conditions are not suitable for establishment (USDA 2001b). Thus, production facilities may be located far away from the release area, but in many programmes that release sterile insects, mass-production takes place in their vicinity to minimize shipping costs.

Insect mass-rearing facilities can pose occupational health risks. Exposure to frass, hair, and scales may induce allergenic responses in humans (Parker, Mamai et al., this volume). Another risk arises from exposure to microbials (fungi, bacteria). Therefore, rearing facilities must be equipped with effective air filtration systems to minimize the aerial concentration of allergenic particles and potential pathogens, and staff frequently exposed to these agents should wear protective clothing and masks.

This may be problematic in countries with insufficient occupational health standards and capacities for industrial processes in general.

Another problem is the disposal of large quantities of liquid and solid organic wastes (Parker, Mamai et al., this volume), which can carry immature stages of the insect as well as various microbial species, e.g. *Escherichia coli* (Migula). Effective waste-treatment facilities are needed to prevent the release of insects and pathogens into the environment, and to prevent the direct infection of livestock if solid waste is processed further into animal feed.

RIDL (release of insects carrying a dominant lethal), a genetic control method based on modern biotechnology, is being applied using transgenic strains that require tetracycline in their larval diet to suppress lethality during mass-rearing (Alphey 2014). The disposal of such diet will require special procedures to prevent this broad-spectrum antibiotic from ending up in animal feed or the environment. Also, the potential effects of continuous exposure of mass-rearing staff to such antibiotics in the production facility needs to be assessed. Moreover, according to Leftwich et al. (2016), the permanent exposure of mass-reared colonies of RIDL strains to antibiotics is likely to (1) alter the composition of gut bacterial communities through a reduction in gut bacterial diversity, and (2) select for tetracycline-resistant gut bacteria. The effects on sterile insect fitness of gut bacterial communities that are altered in these ways, or their environmental impact, are not yet known (Augustinos et al., this volume).

Insects mass-produced for the SIT are reared on natural or artificial diets. For most species, no problems arise from using these techniques and diet ingredients. However, in the early days of tsetse mass-rearing, living mammals were used as hosts to feed the flies. This procedure was neither practical nor compatible with animal welfare. It was eventually replaced with a silicone-membrane feeding system simulating the skin of a host, and using warmed blood collected from abattoirs (Bauer and Wetzel 1976).

2.2. Irradiation

The radioactive isotope Co-60 is the most commonly used isotope for the sterilization of pupae or adults of target insects (Bakri et al., this volume). In the past, some radiation sources used Cs-137; this is problematic because Cs-137 in nature can move easily due to the high water-solubility of caesium's most common chemical compounds. Therefore, its use has been discouraged for insect sterilization. Nevertheless, also facilities containing Co-60 sources have to be earthquake-safe and operated according to nuclear safety standards. These are part of the standard operating procedures for sterile insect production (FAO/IAEA 2008). Further guidance is given by the International Atomic Energy Agency (IAEA), which supports many AW-IPM programmes that use the SIT. Thus, in countries with a proven record of the safe use and correct disposal of hazardous substances, a risk associated with the regular use of irradiation sources is not anticipated. According to IAEA norms, irradiation facilities cannot be set up in countries with insufficient nuclear safety legislation and infrastructure. In situations of political instability,

contingency plans must foresee that irradiators and associated technology are secured.

Recently, the development of X-ray machines for insect sterilization is being encouraged because they have the advantage of requiring access only to electricity, and do not involve the complex and costly shipment of radioactive sources across international borders, as well as their eventual problematic disposal (IAEA 2012, 2017).

2.3. Autosterilization

Autosterilization in the field has been proposed as a complement to the release of reared sterile insects. This technique relies on attracting target insects to baits or trapping devices and exposing them to chemosterilants which they then spread to other individuals of the target population. Various chemosterilants have been tested for tsetse control, including metepa, bisazir and insect growth regulators (IGRs) such as triflumuron, a chitin synthesis inhibitor, and pyriproxyfen, a juvenile hormone mimic. They aim at female flies, leading to the sterilization of females and a gradual suppression of the tsetse population (Knipling 1999; Oloo et al. 2000). Metepa and bisazir are carcinogenic, and may pose a risk to operators and trespassers. Therefore, these chemosterilants have never been used in operational control programmes. The other agents are less harmful, but lack clear evidence of efficacy. The environmental risk of chemosterilants such as IGRs is similar to the risk associated with stationary attractive devices (section 3.3.). Field work in Spain has indicated some potential for this technique (Navarro-Llopis et al. 2004).

3. SUPPRESSION OF TARGET POPULATION

3.1. Overview

Although large numbers of sterile insects can be produced in modern rearing facilities, achieving adequate overflooding ratios with competitive sterile insects is essential for effective SIT application. Depending on the target species, minimum ratios of sterile to wild fertile insects during the first release cycle vary from 2:1 to 15:1 (Feldmann and Hendrichs 2001), but may reach 100:1 (Drew et al. 1982). Therefore, applying additional suppression measures against the wild population remains a prerequisite for many AW-IPM programmes that release sterile insects. However, not all such programmes need to be preceded by sprays of synthetic insecticides to suppress the target population. Integrating pest management strategies by combining different techniques, both before and during sterile insect releases, can optimize control efficacy and minimize adverse environmental effects (Mangan and Bouyer, this volume).

One approach is to make releases when the target wild population is naturally low, as generally occurs in winter or dry seasons in sub-tropical and temperate climates, or during periods of low natural host availability. Such strategies often include using non-insecticidal suppression methods such as those based on cultural and mechanical controls, but can also include mating disruption, augmentative

release of natural enemies and pathogens, baits and biopesticides, or even genetically modified crop plants that express a toxin (Suckling et al. 2012).

Sometimes, insecticide-based methods are applied to suppress target populations before SIT application; they fall into two broad categories: insecticide spraying and artificial attractive devices. Other methods are employed against particular insects, e.g. insecticide treatment of livestock (pour-ons) against tsetse flies, wound treatment against screwworms, and soil-drench treatment against fruit flies.

3.2. *Insecticide Spraying*

Insecticides are applied with ground sprayers or aircraft, depending on the type, accessibility, and size of the target area. Aircraft are often used to apply larvicides to bodies of water to control mosquitoes and black flies. Ground applications include spot as well as small-scale, full-cover treatments, and are more focused than aerial applications. Many AW-IPM programmes, however, extend over large areas where ground access is very limited or even impossible, and reliance has then to be placed on aerial spraying as the main tool to reduce a population. Chemical pesticides are selected mainly based of their efficacy and friendliness to the environment. Furthermore, spraying techniques and cycles are adapted to specific behavioural and life-history traits of the target. Thus, environmental effects depend not only on the type of insecticide but also on the actual use pattern. Two examples of the environmental impact of aerial spraying for population suppression are given below.

3.2.1. *Fruit Flies*

Aerial bait-spray applications have been an effective tool as part of eradication campaigns against large outbreaks of non-native fruit flies (USDA 1993, 2001b), although their use is increasingly avoided in view of growing public opposition. The spray is used alone, or in advance of SIT application, to suppress or eradicate fruit flies. In the past, the sprays consisted mainly of the organophosphorous insecticide malathion mixed with a protein hydrolysate acting as an attractant and feeding stimulant. The bait, applied in larger droplets, improves efficacy because the insecticide uptake by attracted flies is then higher (via ingestion and the integument). Therefore, aerial sprays can be applied at ultra-low volume dose rates, lower than necessary for contact applications. Malathion is highly toxic to terrestrial and aquatic non-target invertebrates. Aquatic fauna are exposed via direct over-spray of water bodies or via run-off. Terrestrial insects, which are also attracted to the bait, are particularly at risk, including ground beetles (Carabidae) and many other beneficial organisms. In fact, a malathion bait spray may disrupt a substantial portion of natural biological control agents (USDA 1993, 2001b). Native fruit flies may also be adversely affected, resulting in shifts in community structure and perturbations of ecological services (section 5.5.). Possible hazards further up the food chain include secondary poisoning or food deprivation of insectivorous vertebrates.

Fortunately, malathion has been largely replaced by new and more environment-friendly insecticides in the bait, in particular spinosad (naturally produced bacterial (actinomycete) compounds) and SureDye® (xanthene dye) (Vargas et al. 2002; Mangan 2014; Mangan and Bouyer, this volume). The toxicity of these agents to non-target biota is much lower than that of malathion, and fewer adverse effects have been recorded (USDA/APHIS 2003). Acceptable spinosad formulations, certified as organic, have been developed and are being used extensively, e.g. in pest hot spots in the Mediterranean fruit fly programme in Guatemala and Mexico, before sterile male releases (USDA/APHIS/PPQ 2000; Enkerlin et al. 2017).

3.2.2. *Tsetse Flies*

The second example is from tsetse fly control. The pre-release suppression of tsetse, in some cases, has involved sophisticated aerial spraying techniques. Sequential aerosol drift application with fixed-wing aircraft, which previously relied on endosulfan with sometimes negative ecological impact especially on fish in shallow water, is now based on pyrethroids, in particular deltamethrin. This insecticide is one or two orders of magnitude more toxic to tsetse than to house flies and honey bees, respectively (SWRC 2001). Therefore, field rates are exceptionally low, posing a low risk to terrestrial non-target invertebrates. Furthermore, application parameters such as height, time and sequence of spraying are adapted specifically to behavioural and life-history traits of tsetse flies, reducing the risk to terrestrial organisms even further. Finally, as deltamethrin has low persistence, it does not accumulate in food chains. Nevertheless, adverse effects may occur temporarily in terrestrial environments, e.g. effects on certain spiders, and in particular in aquatic environments (Peveling and Nagel 2001). For example, diving beetles and decapod crustaceans are highly susceptible to pyrethroids. A reduction of aquatic and semi-aquatic macroinvertebrates may translate into food shortages for fish and reduce the survival of fry, which in turn may adversely affect local fisheries.

Another possible risk arising from broad-scale sequential applications of low-dose pyrethroids is that the selection for resistance in other insect pests may be enhanced. For example, bednets impregnated with pyrethroids are widely used for mosquito control to prevent malaria in tropical areas. Selection for resistance in malaria vectors, enhanced through insecticide use in AW-IPM programmes that release sterile insects against agricultural pests, would reduce the efficacy of this important control method. This externalized consequence of population suppression for the SIT would be expected mainly in rural areas with a high human population density, where pesticides are used for domestic and/or agricultural purposes.

Treatments with deltamethrin, using the sequential aerosol technique (SAT), have been used mainly in combination with trapping and baiting devices for tsetse suppression (section 3.3.). In a tsetse eradication programme in the Okavango Delta, Botswana, the technique was successfully applied for eradication (Allsopp and Phillemon-Motsu 2002; Feldmann et al., this volume). Preliminary assessments showed that adverse effects on terrestrial invertebrates were minimal (Biotrack 2003). Another insecticide widely used for sequential aerosol applications in the past is endosulfan, a chlorinated hydrocarbon. Tsetse flies are three orders of magnitude more sensitive to this chemical than honey bees (SWRC 2001). However,

endosulfan is highly toxic to fish and other non-targets, including the *Salvinia* weevil *Cyrtobagous salviniae* Calder and Sands, a classical biological control agent introduced successfully to contain the invasive aquatic fern *Salvinia molesta* Mitchell (SWRC 2001). In view of these risks, the endosulfan option for Okavango was discarded in favour of deltamethrin.

All available evidence suggests that the effects of the SAT with deltamethrin on most terrestrial non-target arthropods are of short duration. Nevertheless, environmental monitoring in Zimbabwe revealed long-term adverse effects on populations of certain lycosid spiders, *Hippasa* sp. (SEMG 1993). Given that little is known about the resilience of affected populations in natural or semi-natural ecosystems, the SAT should be used only temporarily for pre-release suppression. More selective techniques, such as stationary targets (section 3.3.), should be given priority unless they are logistically too demanding for large-scale operations or do not yield sufficient pest population suppression. Using a four-scale risk classification scheme (negligible, minor, serious, severe), Grant (2001) classified the environmental impact of sequential aerosol spraying as “minor”. In principle, this classification is acceptable, but should be taken with caution. The resilience of small and often highly fragmented non-target populations, to tolerate incremental insecticide stress in a multiple stressor environment, declines (Peveling 2001). Therefore, environmental impact assessments should be conducted with respect to site-specific features, such as the prevailing land-use patterns or the presence of vulnerable species. As one measure to mitigate adverse effects, Nagel (1995) proposed patchwork applications of different insecticides. This tactic would also reduce the above-mentioned risk of resistance development in other pests (Hoy 1998).

Low-flying spray aircraft may disturb domestic animals and wildlife, visually and by noise. Nesting birds are particularly vulnerable to this combination of disturbances. Although adverse effects such as increased susceptibility to predation should be temporary, nest abandonment may occur in the more sensitive species (USDA 2001b). A critical situation may arise in tsetse spraying, which relies on nocturnal treatments for optimal efficacy, using low-flying aircraft equipped with bright spotlights. Scared birds are unlikely to recover their nests during the night, leading to increased egg or nestling mortality. In Botswana, for example, there was concern that the wattled crane *Grus carunculatus* (Gmelin), an endangered species breeding in seasonally flooded marshes in the Okavango Delta, might experience reduced breeding success following perturbations by spray aircraft and insecticide-induced food shortages. A pilot study found high levels of nest attrition due to predation and other factors in both sprayed and unsprayed areas, but no indication of breeding failure due to tsetse spraying (Allsopp and Phillemon-Motsu 2002; BBCWG 2002). However, pre-spray observations were lacking, and follow-up studies are necessary before final conclusions can be drawn.

3.3. Artificial Attractive Devices

A variety of traps and targets (devices attracting insects without necessarily trapping them) have been developed for the detection, monitoring or control of insects. Tsetse

flies are attracted by odours (ketones, octenols, phenols, acetone, carbon dioxide) and by visual cues (colour, shape). Some odours induce host searching behaviour while others promote landing on the device or entering the trap (Vale 1993). Fruit flies and screwworms respond to olfactory cues, such as pheromones, parapheromones, host odours or food baits. Devices such as odour-baited targets for tsetse flies, and coloured baited traps or bait stations for fruit flies, combine visual and olfactory stimuli to enhance trapping efficacy (Piñero et al. 2014; FAO/IAEA 2018). Insects lured to traps or targets become stuck to glue (sticky traps), or are exposed to insecticides applied to the material. Traps or sticky panels for fruit fly suppression use synthetic lures (trimedlure, ceralure, cuelure) applied directly to the panels or to wicks attached to the traps or panels (USDA 2001b). These devices are deployed from the ground by placing on host trees, or nailing to posts. Alternatively, insecticide-treated baited blocks (wood chips) or wicks (so-called cordelitos) are released from aircraft for population suppression. The parapheromone methyl eugenol is particularly attractive to males of some species of *Bactrocera* fruit flies (Shelly et al. 2014), and is used in male-annihilation technique (MAT) programmes, either alone, or prior to or simultaneous with the release of sterile males (Barclay et al. 2014; Vargas et al. 2014). Baited traps for screwworm flies are employed only for detection and monitoring purposes (USDA 2001a); population suppression is achieved effectively by treating livestock.

The densities of traps or targets deployed for suppression vary depending on the insect species and its potential growth rate (Weidhaas and Haile 1978), the type of device, and features of the landscape. In the case of fruit fly suppression, trap densities must be very high to be effective, and mass-trapping is, therefore, not practicable over larger areas (USDA 2001b; Navarro-Llopis and Vacas 2014). For example, more than 1000 traps per square kilometre were deployed in an oriental fruit fly *Bactrocera dorsalis* (Hendel) eradication programme in Mauritius (Seewooruthan et al. 1997). In contrast, suppression of certain tsetse fly populations can be achieved with as few as 2–4 targets per square kilometre (Dransfield and Brightwell 1992).

The deployment and maintenance of trapping devices requires a network of tracks and roads. Servicing activities may disturb wildlife, especially in wilderness and/or sensitive areas. Thus, two issues have to be addressed with respect to the risk assessment of insect trapping techniques, particularly when deployed at higher densities for population suppression: (1) direct effects on non-target animals, and (2) indirect effects related to trap placement and servicing.

3.3.1. Direct Effects on Non-Target Animals

Traps using species-specific pheromones pose a low risk to non-target organisms. Certain species may be attracted coincidentally, especially potential predators and scavengers of target insects. However, local populations are unlikely to be affected. Ecologically relevant adverse effects are most likely to occur with non-target animals from the same genus or family as the target insects, even though other non-target species may sometimes be collected in high numbers. For example, mass-trapping of fruit flies, using parapheromones as attractants, may also have an effect on non-pest fruit flies. Some species are pollinators, thus, there may be a risk of

reduced pollination and hence fruit-set of certain plants at high trap densities (Tan 2000) (section 5.5.). Obviously, the risk to non-target organisms rises with increasing trap density, yet the risk is expected to be lower than that associated with aerial bait spray or with the application of insecticide-treated cordelitos dispensed in high numbers from aircraft (USDA 2001b). Suda and Cunningham (1970) reported that lacewings (beneficial predators) were caught unintentionally in methyl eugenol-baited traps or sources (fibreboard blocks, cotton strings or viscous slow-release paste) applied by ground or air in some MAT programmes against *Bactrocera* spp. fruit flies (Koyama et al. 1984; Vargas et al. 2014). However, Vayssières et al. (2007) provided evidence that the area-wide release of methyl eugenol-impregnated blocks had no greater impact on non-target insect populations than the non-impregnated blocks.

Contrary to fruit flies, tsetse fly trap densities are much lower, and the chances of incidental encounters of non-target organisms with stationary targets deployed for tsetse suppression are scarce. The degree of species-specificity depends on the combination of visual traits (shape, colour) and odours (octenols, phenols), as well as on the mode of placement. Blue and white targets attract more insects, including pollinators, than odour-baited black screens, which attract mainly stable flies (*Stomoxys* spp.), non-biting Muscidae, and horse flies (*Tabanidae*). Some of these flies are possible vectors of livestock and human diseases, including trypanosomiasis (Sumba et al. 1998), and can be considered as pests, but others such as male tabanids are beneficial flower-visitors and pollinators. Even though the number of studies is limited, there is as yet no clear indication that these taxa are adversely affected at the population level (SEMG 1993; SWRC 2001; Ciss et al. 2019). Likewise, insecticides such as deltamethrin and α -cypermethrin, used to impregnate the fabric of targets, pose a low risk. During the rainy season, some active ingredient may be washed off, but the contamination is negligible compared with full-cover spraying in agriculture and vector control, and the effects are restricted locally (Cuisance et al. 1984; Müller et al. 1984).

3.3.2. Indirect Effects on Non-Target Animals

The deployment and servicing of large numbers of traps and targets are logistically feasible and environmentally sound in agricultural areas with existing road networks. These conditions prevail in some areas subjected to fruit fly suppression or eradication. Therefore, disturbances of wildlife through the placement and maintenance of traps are expected to be minimal when compared with those induced by other agricultural activities such as planting, irrigation, and harvesting. However, disturbances may become more critical in landscapes composed of mosaics of agricultural and natural land.

This is particularly true for tsetse control, which is often conducted in protected and/or wilderness areas. Opening vehicle tracks for the deployment and maintenance of stationary targets can cause erosion, and provide access, not only to control operators and park rangers, but also to poachers (Grant 2001). It also facilitates unauthorized logging activities and firewood collection. Such illegal activities may disturb wildlife. A study in Kasungu National Park, Malawi, found significantly reduced numbers of small antelopes and certain birds on transects with odour-baited targets (Cheke et al. 1997; De Garine-Witchatitsky et al. 2001). For birds, the effect

was linked to the possible decline in the number of horse flies, affecting the insectivorous little bee-eater *Merops pusillus* Muller, and, as a consequence, reduced pollination and fruit-set of flowering plants, affecting nectarivorous sunbirds and the frugivorous bulbul *Pycnonotus barbatus* (Desfontaines). However, as no pre-treatment observations were made, follow-up studies are needed to validate these results. In West African gallery forests, insecticide-impregnated blue screens along river courses are sometimes deployed at distances of only 100 m. Studies in West Africa on invertebrates and insecticide residues in soil and wildlife showed at most negligible ecological effects (P. Müller et al., unpublished data). It is not known if there are further studies on indirect ecological effects resulting from such high screen densities, but assumedly the effects are of minor importance compared with other anthropogenic disturbances encountered in West African river systems.

3.4. Other Methods

A range of alternative methods to suppress fruit fly populations in AW-IPM programmes has been reviewed in environmental impact assessments, including mechanical, cultural, biological and biotechnological methods (USDA 2001b). A detailed discussion of these methods is beyond the scope of this chapter, but one method, soil treatment with organophosphorous insecticide, deserves mention because it may cause serious hazards. It consists of drench treatments within the dripline of infested host plants to control larvae entering the soil and adults emerging from the soil. Soil drenches with organophosphates, such as chlorpyrifos, fenthion and diazinon, are highly toxic to soil fauna, and may adversely affect key ecological processes, such as the breakdown of organic matter and nutrient cycling. Individual vertebrates are also at risk, even though the limited use of soil drenches (usually less than 1% of the total surface), as a whole, provides protection of populations.

Pour-on treatments of livestock (living targets) with insecticide, for population suppression of tsetse flies and other parasites, are widely used in Africa. Livestock are treated in dip tanks or by applying pour-on formulations. Pyrethroids, such as deltamethrin, α -cypermethrin and flumethrin, are used for this purpose. Originally, pyrethroids were applied mainly to control ticks, but it was found that they were equally effective against tsetse flies.

Dip and pour-on techniques may have adverse effects on non-target insects, including blood- and dung-feeders, as well as on livestock-associated insect-eating birds. Insect species attracted to livestock are often the same as those attracted to stationary targets, but there is an elevated risk since livestock densities are often much higher than stationary target densities. Adverse effects to other dipteran pests are highly desirable, from an animal health perspective. However, a risk to birds cannot be dismissed. For example, the decline or local extinction of the oxpecker *Buphagus africanus* L. in South African rangelands has been associated with the use of arsenic pesticides and organophosphates in cattle dips for tick control (Mundy 1991). These compounds were eventually replaced with insecticides posing a low risk of acute poisoning in birds. Nonetheless, little is known about sub-lethal effects or indirect effects due to food deprivation.

Dung beetles (Scarabaeidae) are important decomposers of animal dung, and benefit soils and plants by improving soil fertility. They are also important food items for a wide range of invertebrate and vertebrate predators. Similar to parasiticides such as avermectin (Petney 1997; Steel and Wardhaugh 2002), faecal residues of pyrethroids are toxic to dung beetles and other dung fauna such as muscoid larvae (Krüger et al. 1999; Grant 2001; Vale 2002), thereby impeding the decomposition of pats and depriving predators of their prey.

Inappropriate disposal of used pesticides is another serious risk of the insecticide-dipping technique. Dips are often disposed of on open ground, resulting in soil contamination. In other cases, dips are dumped in pits and covered with soil; this may lead to the contamination of groundwater.

3.5. Environmental Effects of Some Suppression Techniques — Conclusion

Each population suppression technique incorporated into AW-IPM programmes is associated with particular environmental risks. The optimum combinations of control methods, that result in the lowest cumulative risk but achieve the highest possible effect on target populations, vary among species, regions and ecosystems. Therefore, environmental assessments may come to different conclusions in different environmental settings. Nevertheless, some general conclusions can be drawn. Aerial spraying, depending on the form of application, is usually more harmful to non-target biota than ground spraying (which is often more focused and limited in scale) or attraction techniques using traps, bait stations or targets. One exception is residual ground application against tsetse flies; due to relatively high insecticide doses and persistence, it may be more harmful than aerial sequential aerosol applications as shown by the environmental recovery monitoring in Botswana, which indicated that most non-target species recovered to pre-spraying levels (Perkins and Ramberg 2004). Stationary attractive devices are normally the least harmful method (Nagel 1995, 1996), but the direct and indirect impact of generating and maintaining access (tracks or transects) to service them over large areas is usually underestimated.

In general, treatments in protected and/or wilderness areas require more careful approaches and risk mitigation measures than those conducted in croplands. This is because protected/wilderness areas are more complex in terms of biodiversity and interactions among biota, and hence less predictable in their responses to disturbances. Also, natural systems lack the adaptation of agroecosystems to human impact manifested in the dominance of ubiquitous or euryoecious species.

4. STERILE INSECT RELEASE

In AW-IPM programmes integrating the SIT, sterile insects are released from vehicles or aircraft (Dowell et al., this volume). Ground release requires appropriate road networks. This may be critical in sensitive areas, posing similar risks to non-target organisms as trap or target deployment and maintenance (section 3.3.2.) (Vreysen, this volume). Likewise, sensitive species, or life stages such as nesting birds, may be disturbed by the sight of, and noise from, aircraft dispensing sterile

insects (USDA 2000b; SWRC 2001). However, such disturbances are expected to be lower than those caused by low-flying spray aircraft because sterile insects are released at higher altitudes, e.g. greater than 200 m for tsetse flies (Vreysen et al. 2000) and about 600 m for Mexican fruit flies *Anastrepha ludens* (Loew) (SIRF 2001; FAO/IAEA 2017).

Aerially applied sterile insects are released directly into the air from temperature-controlled containers (chilled flies) or indirectly from cardboard boxes or paper bags that open once thrown out of the aircraft (FAO/IAEA 2017). In the latter cases, debris from the releases may be a visual disturbance, but such disturbance is transient since the materials used are biodegradable.

Sterile insects released in large numbers may become a nuisance to potential host animals, or may damage plants or fruit. Moreover, natural trophic interactions within communities, such as host or prey detection, may be disturbed by the sheer abundance of sterile insects. However, this is unrealistic, as in the case of the Mediterranean fruit fly, the insect with the highest release rates, approximately only one sterile male is released per 10 m². Nevertheless, little research has been done on this subject. In the case of tsetse control, sterile males are released at the lowest rates (approximately 20–100 sterile insects per km²). Since this may increase the vector load in the target area, leading to a temporary increased risk of trypanosomosis transmission, only sterile males that have been pre-fed with a trypanocide-treated blood meal are released (Dyck et al. 2000).

Biosecurity concerns may arise in the case of releases of sterile insects of species outside their natural range (section 2.1.). Nevertheless, unlike classic biological control, where released non-native agents are fertile and become established with sometimes irreversible negative consequences (Simberloff and Stiling 1996; Follett and Duan 2000), any adverse effects of released sterile insects are short-lived because of their high natural mortality, and because they cannot reproduce. No such concerns exist if AW-IPM programmes using the SIT are directed against native species. In this case, the SIT can be compared with augmentative biological control, in which native species are mass-produced and released in their natural range.

5. ECOLOGICAL CONSEQUENCES OF ERADICATION

Many area-wide SIT applications aim at suppression, containment or prevention, not eradication (Simmons et al., this volume; Enkerlin, this volume; Hendrichs, Vreysen et al., this volume; Klassen et al., this volume). However, if eradication is the goal (Feldmann et al., this volume; Vargas-Terán et al., this volume), the following issues are relevant.

5.1. Risks and Benefits

Populations living on remote islands are more vulnerable to extinction than those living on continents. This also holds for pest species targeted by area-wide control programmes. For example, the coconut moth *Levuana iridescens* Bethune-Baker, a widespread local pest in Fiji, is thought to have been eradicated by the tachinid fly *Bessa remota* (Aldrich) during a classical biological control programme in the 1920s

(Howarth 1991). However, in the history of economic entomology, there is only one known case of a continental agricultural insect pest becoming extinct. The Rocky Mountain grasshopper *Melanoplus spretus* (Walsh) was a major pest of crops in North America in the nineteenth century. The demise of this species was the result of the anthropogenic destruction of breeding habitats in river valleys (Lockwood and Debrey 1990). This shows that numerical abundance alone does not assure survival (Lockwood 2002). On the other hand, even the most intensive use of chemical insecticides has not threatened the survival of any major insect pest. Only area-wide control strategies incorporating the SIT or modern biotechnologies offer the opportunity to eradicate entire pest populations from selected areas. Eradication is most effective when directed against isolated populations on islands and in isolated habitats separated by natural barriers from the main range. However, the eradication of the New World screwworm populations in North and Central America shows that a pest can be eliminated even from continuous continental areas (Vargas-Terán et al., this volume).

Thus, the extinction of whole pest species from the wild seems possible in the longer term. It follows that ecological consequences must be evaluated thoroughly and impartially. What are the benefits and risks associated with the area-wide elimination of major pests? As for the benefits, these are beyond dispute. An immediate economic as well as environmental benefit is the enormous reduction in pesticide use (Kinley 1998; CDFA 2001). For example, to contain and mitigate permanent Mediterranean fruit fly establishment in California with conventional methods, more than 2 million kg of active ingredient would be needed annually (CDFA 2001; Enkerlin, this volume). The benefits arising from the eradication in 1991 of the New World screwworm in Libya are immeasurable (Reichard 2002; Vargas-Terán et al., this volume). Its spread over the entire African continent and Mediterranean region would have been an environmental, social and economic disaster, possibly comparable with the impact of rinderpest in the 19th century.

The environmental risks of eradicating indigenous populations are much more controversial (Allsopp 2001; Feldmann and Hendrichs 2001; Grant 2001; Vargas-Terán et al., this volume). In view of the devastating economic and/or medical impacts of the prime targets of the SIT, most notably the huge economic losses caused by fruit flies, mosquitoes, moths, screwworms and tsetse flies (Mumford 2000; Enkerlin, this volume; Vargas-Terán et al., this volume), the suffering of people and livestock from tsetse-transmitted trypanosomosis in Africa (Grant 2001), and the threat to the biodiversity of island faunas by non-indigenous invasive species which could be effectively controlled with the SIT (Suckling 2003), one might even question the justification for raising the risk issue at all. Nonetheless, it is important that possible risks, however low, be brought into perspective too, irrespective of the overwhelming environmental, economic and health benefits; only then can risks be managed adequately. The specific goal of this section is to elucidate ecological roles of certain target insects in their respective ecosystems, and to identify research themes and topics that should be addressed when embarking on future eradication programmes.

5.2. *Loss in Genetic Diversity of Target Species*

An area-wide programme that targets the eradication of populations of the pest insect leads inevitably to a decline in the genetic diversity of that pest species. For various reasons (section 5.3.) this may not be generally acceptable. Therefore, in the unlikely case of eradication from the whole range, a certain level of genetic diversity of the target insect can be maintained in laboratory colonies. These could be used, and their genomes explored, for future research in the biological and life sciences. It would be impractical, of course, to rear strains from all populations representing discrete demes within metapopulations. Yet, as a minimum requirement, voucher specimens from all target populations must be deposited in scientific collections, including all development stages and both sexes. One part should be mounted, and others preserved deep-frozen and in alcohol (various concentrations between 60–100%). The preservation of insects will be greatly facilitated by using the cryopreservation techniques for embryos (long-term storage at liquid-nitrogen temperatures), which are already available for a number of insects (Leopold 2000; Parker, Mamai et al., this volume).

5.3. *Eradication versus Conservation*

The prospect of the eradication of native species from their complete natural range is largely theoretical at this point. Nevertheless, it raises some general questions with respect to conservation. On the one hand, the planned extinction of a limited number of pests appears to be a negligible issue in view of the scale and dynamics of the speciation and extinction processes in the evolutionary history of the earth. However, in modern times, human activities have become the major cause of extinction, leading to a strong imbalance of speciation/extinction rates towards extinction. Given the dramatic decline of species worldwide, biodiversity conservation — as outlined in the Convention on Biological Diversity (CBD) — has become a global priority. This was motivated partly by the prospect that biodiversity will provide enormous resources for future uses, as well as by fears that ecosystems might be destabilized if extinction continues unabatedly. The latter notion leads to the introduction of the *precautionary principle* into decision-making (Cartagena Protocol on Biosafety (CBD 2018). Precautions must be taken whenever we are uncertain about the ecological consequences of our activities. This principle, however tentatively, also applies to pathogens and pests. Only if ecological consequences could be assessed and predicted conclusively would we dare to signal the deliberate elimination of a species. Such safety of judgement did not even exist for the smallpox virus, which is still being preserved for possible future medical research, including drug development (Joklik et al. 1993).

In view of our limited knowledge about the consequences of eradication, strategies that suppress populations of native pests, without necessarily eradicating them from their entire natural range, are preferred. Suppressing a key insect pest population by the integration of the SIT with other environment-friendly methods often also leads to decreases in secondary pest populations once overall insecticide treatments are minimized, which in turn allows even further reductions in insecticide

use. For example, as a result of the codling moth sterile insect release (SIR) programme in Canada, leafroller populations (*Spilonota ocellana* (Denis and Schifferrmüller), *Choristoneura rosaceana* (Harris) and others) appear to be on the decline (Nelson et al. 2021). This is similar to what organic growers have experienced when natural enemy populations are allowed to increase once insecticide use is reduced (Leach and Mumford 2008). Furthermore, alternative approaches, such as transgenic technologies introducing and expressing foreign genes with antipathogenic properties that interfere with pathogen viability, development or transmission, rather than vector population elimination, should not be ignored (Hao et al. 2001; Van Den Abbeele et al. 2013; Gilbert et al. 2016). These options obviously require that genetic resources be preserved in a viable state.

The precautionary approach does not apply, in the same way, to the elimination of populations of invasive species that have invaded areas outside their native range (Hendrichs, Enkerlin et al., this volume). Application here of the precautionary principle implies the imperative that outbreaks of non-indigenous pests be eliminated to prevent adverse effects on native communities (CBD 2000, 2001). Even then, care should be taken to minimize destabilizing impacts on other species as the non-native one is progressively removed.

It is beyond the scope of this chapter to discuss these hypothetical possibilities in more detail; doing so would involve ethical, philosophical, biological, and ecological discourses. Nevertheless, it is important to point out that these aspects should be considered when designing strategies that attempt the eradication of native species throughout their whole range.

5.4. Release of Wildlife from Disease

Diseases induced by tsetse flies, screwworms, and other insect vectors can adversely affect the health of wildlife, and reduce their survival rates. Conversely, free-ranging wild animals may benefit from the eradication of disease vectors and/or parasites, and increase the size of their populations.

If tsetse flies were eliminated, the immediate benefit to wild mammals would be only moderate, since African wildlife is trypanotolerant to at least those trypanosomes to which they are continuously exposed (Reichard 2002). Yet wildlife could benefit indirectly by spending more time in habitats previously avoided when fly densities were high. For example, the presence of tsetse can deter elephants from riverine forests (Bond 1993). These habitats would become fully available after tsetse eradication, but to the possible detriment of the woody vegetation. Nevertheless, experience has shown that forests are exploited and devastated whenever elephant populations exceed the carrying capacity, irrespective of the presence or absence of tsetse flies (Nagel 1995).

The impact of screwworms on wildlife can be much more pronounced. Prior to the eradication of the New World screwworm from the southern United States, a wide range of mammals was attacked by this parasite. White-tailed deer *Odocoileus virginianus* (Boddaert) populations were highly susceptible to myiasis, with fawn mortality reaching 80% (Reichard 2002; USDA/APHIS 2017). White-tailed deer are hosts to more than 100 disease agents (Schaefer and Main 2001). While these agents

are seldom, by themselves, fatal to deer, interactive effects may, in periods of stress and malnutrition, weaken animals and cause substantial mortality. After the eradication of the screwworm, a dramatic surge in deer numbers was observed, and this was welcomed by hunters and the game-ranching industry (Reichard 2002). However, it caused a new problem for cattle — they became heavily infested with the deer-parasitizing Gulf Coast tick *Amblyomma maculatum* Koch (Kettle 1993). Moreover, in marginal production areas, increased numbers of deer increased competition for pasture. Overall, however, both domestic and wild animals benefited tremendously from screwworm eradication. This includes the endangered Florida or dwarf key deer subspecies *Odocoileus virginianus clavium* Barbour and G. M. Allen. Its population has stabilized to several hundred animals from a low of fifty in the 1930s (Schaefer and Main 2001). Likewise, the endangered Florida panther *Puma concolor coryi* (Bangs), the bobcat *Lynx rufus* (Schreber), and other predators profited from the increase in the numbers of deer and wild boar *Sus scrofa* L.

Similar effects may occur in other areas subjected to screwworm eradication, yet with different ecological consequences and management implications. The endemic Jamaican hutia or cony *Geocapromys brownii* (J. Fischer) is highly endangered due to predation by the invasive small Indian mongoose *Herpestes javanicus* (E. Geoffroy Saint-Hilaire), as well as stray domestic cats and dogs. Stray dogs, with a screwworm infestation rate of 40% (Hoelscher 1999), are to some extent kept in check by this pest. Releasing cats and dogs (mongoose seems to be less susceptible) from the disease may translate into increased predation on conies, and, unless predator control measures are intensified, upset conservation efforts. Likewise, free-ranging introduced deer, pigs, and goats can be expected to increase in numbers in the absence of myiasis, threatening crops and remnants of natural vegetation. These examples show that the risk of area-wide control differs among ecosystems. Island ecosystems are highly susceptible to the addition or elimination of elements of native food webs. Pest management solutions must, therefore, be adjusted to recognize these specific risks.

5.5. Pollinator-Plant Interaction

Pollination is the most important ecological service provided by insects to flowering plants. Pollinator assemblages comprise a wide range of insects, including blow flies (Calliphoridae) and fruit flies (Tephritidae) (section 3.3.1. regarding male horse flies). Most species in these families are opportunistic, non-specific pollinators. Therefore, the removal of the population of a single species is unlikely to impede pollination. Among the main dipteran pests targeted by the SIT, only some fruit flies comprise obligate pollinators. A mutualistic relationship has coevolved between species of *Bulbophyllum* orchids and a guild of *Bactrocera* spp. fruit fly species, including pest and non-pest species (Tan 2000). Male *Bactrocera* are attracted to orchid flowers by synomones, i.e. chemicals benefiting both the plant and the fly. These are consumed (pharmacophagy), and used further by the males as aggregation and sex pheromones to attract females. Apart from orchids, some species of the Araceae and Lecythidaceae are also pollinated by male fruit flies. It is evident that perturbation of species-specific flower-pollinator systems may result in reproductive

failure of the plant. In this case, applying the SIT against pollinator fruit flies within their natural range may not be an environmentally acceptable control option. However, apparently, no specific flower-pollinator relationships exist for the principal SIT targets. Furthermore, the Mediterranean fruit fly, the oriental fruit fly, the Solanum fruit fly *Bactrocera latifrons* (Hendel), and the melon fly *Zeugodacus cucurbitae* (Coquillett) are often controlled as non-native pests mainly outside of their natural range.

5.6. Predator-Prey and Host-Parasitoid Interaction

There are apparently no obligate predators of insects targeted by the SIT (Laird 1977; Nagel 1988, 1995). In fact, most predators have opportunistic feeding habits. Therefore, ecologically relevant effects on predator populations are unlikely. The role of parasitoids, however, is much more specific, and needs to be discussed in more detail.

Many hymenopteran larval and egg parasitoids attack fruit flies. Their potential as biocontrol agents has been explored on various scales in several classical and augmentative biological control programmes (Montoya and Liedo 2000). The host range of parasitoids among tephritids varies, but none seems to be host-specific. Therefore, a risk to parasitoids from fruit fly eradication, resulting from an AW-IPM programme using the SIT, is not anticipated.

Contrary to the species-rich Tephritidae and Calliphoridae, the Glossinidae comprise only 23 species. The most frequent parasitoids of tsetse puparia are *Chrestomutilla* spp. (Mutillidae) and *Exhyalanthrax* spp. (Bombyliidae). In tsetse flies, about 40 parasitoid species have been reported, some of which appear to be hyperparasitoids (Greathead 1980). *Exhyalanthrax* spp. have a wide host range among tsetse flies and other dipterans. Some species have been reared from only one tsetse species (Greathead 1980). *Chrestomutilla glossinae* (Turner) appears to be restricted to *Glossina* spp., while *Nesolynx glossinae* (Waterston) (Eulophidae) is believed to have hosts other than tsetse (Greathead 1980). The rate of natural parasitism rarely exceeds 20%, and often is considerably lower. Although some speculation remains with regard to host specificity, experience from other taxa suggests that several parasitoids are specific to certain tsetse fly species (but only about 5–7 tsetse species are of economic importance). Therefore, the possibility remains that parasitoid species would be eliminated along with their hosts resulting in a loss of biodiversity and, possibly, in a diminution of natural control in case of tsetse fly reinvasions.

Females of *C. glossinae* are long-lived, and have exceptional host-finding ability. These traits can be used in biological control approaches. Knipling (1999) proposed tsetse eradication tactics that combine augmentative releases of *C. glossinae* with the SIT. The logical end, however, should the eradication of all hosts from their whole range be achieved, would be the demise of the parasitoid. Even though, at this stage, this scenario is merely hypothetical, measures to conserve mutillid parasitoids should be components of full-range eradication programmes. Conservation can be achieved by establishing and maintaining combined tsetse/parasitoid rearing facilities. This would also provide insurance against the possibility that mutillids or

other parasitoids are eliminated but not their hosts. Such undesirable effects have been observed in previous tsetse programmes targeting eradication at the population level (Fiedler et al. 1954). In this case, parasitoids could be released to re-establish natural biological control.

5.7. *Host-Vector Interaction*

Tsetse flies are the main vectors of African trypanosomes. Metacyclic (infective) forms of the parasites colonize the salivary glands, and are transmitted during blood meals. Apart from trypanosomes, saliva may also contain viruses (Sang et al. 1999), bacterial symbionts (Beard et al. 1998), and rickettsia-like organisms (Weyda et al. 1995). This suggests that tsetse could also transmit pathogenic bacteria and viruses, or antigenic fragments of them, to their hosts, evoking concomitant immunoresponses. Therefore, wildlife immunization against bacterial or viral diseases may be enhanced by exposure to pathogens and/or antigens transmitted by tsetse (and other blood-sucking insects), thereby improving the health and fitness of wildlife. However, there is as yet no evidence on which to base such a hypothesis. Some salivary viruses are known to be pathogenic to tsetse flies (Sang et al. 1997; Abd-Alla et al., this volume), but their pathogenicity in vertebrates is unknown. Even if wildlife pathogens and/or antigens were transmitted by tsetse, their contribution to the overall load of transmission would probably be low compared with more abundant blood-sucking species such as horse flies or stable flies *Stomoxys* spp. (Muscidae). So “vaccination services” provided by tsetse may be seen as an odd and far-fetched scenario. Nevertheless, as long as epidemiological data are insufficient to unambiguously dismiss this hypothesis, this topic should be put on the research agenda.

Pre-release immunizations against viral and bacterial diseases are important steps in programmes of wildlife translocation and release. If the animals are to be released in high-density tsetse areas (Woodford 2000), existing protocols even suggest moderate pre-release exposure to vectors of trypanosomes and other parasites to enhance immunization. Allsopp and Phillemon-Motsu (2000) predicted that the eradication of a tsetse population in a given area may cause a temporary rise in endemicity of trypanosomosis. If tsetse disappear from areas in which trypanotolerant breeds were reared, the more productive trypanosusceptible Zebu cattle might be introduced and the genetic trait of trypanotolerance lost. In the event of a reintroduction of tsetse, this loss would seriously disrupt livestock production. These examples show that host-vector interactions should be evaluated beyond established views.

This is substantiated by experiences in the temperate zone, showing that management traditions may be ill-founded. In areas in the UK, with high bovine tuberculosis infection rates, it has been a long-standing practice to cull Eurasian badgers *Meles meles* (L.), the main non-bovine reservoir of *Mycobacterium bovis* Karlson and Lessel. Surprisingly, field trials revealed that culling increases rather than controls the incidence of bovine tuberculosis in cattle, indicating that transmission pathways and dynamics are highly complex and not fully understood (Donnelly et al. 2003).

These arguments are not raised against livestock-insect pest eradication programmes. Instead they aim to encourage and extend epidemiological research to non-haemoparasitic diseases in eradication zones, and to emphasize the importance of trypanotolerance in wildlife populations and livestock breeds.

5.8. Effects of Tsetse Eradication on Land Use

The area-wide control of disease vectors and parasites may cause a strong increase in the number of domestic and wild herbivores, resulting in significant changes in land-use dynamics and patterns. This issue is particularly controversial with respect to tsetse flies (Grant 2001; Peveling and Nagel 2001). On the one hand, it has been suggested that tsetse flies provide insurance against human encroachment of wilderness areas (Jordan 1986; Chater 2003), and against environmental degradation caused by cattle overgrazing in the ecologically vulnerable Sahel zone (Ormerod 1990). Grzimek and Grzimek (1960) wrote about the tsetse fly:

It is the only true friend the elephants and zebras have left, for it makes their homeland uninhabitable for men.

Other authors dismiss these notions on the grounds that it is the enforcement of regulations and not tsetse that protects wildlife areas (including gallery forests and dense woodland), and that new areas are opened up to cultivation as a result of human population pressure, independent of tsetse presence or absence (Nagel 1994; Kinley 1998; Feldmann and Hendrichs 2001). Furthermore, African landscapes now plagued with tsetse were thriving pastoral lands rather than wildlife havens until the rinderpest pandemic swept over the continent in the 19th century, depriving once prosperous pastoral societies of their livelihood (Pearce 2000; Feldmann and Hendrichs 2001). From this perspective, fighting tsetse flies means reclaiming land that had already been used by humans for thousands of years. Arguments can be raised in favour of either standpoint (Feldmann et al., this volume).

Pearce (2000) holds rinderpest responsible for the spread of tsetse flies in the 19th century — the demise of cattle led to the transformation of pastures into savannah woodland, providing new habitats for tsetse flies. This mechanism, however, is hypothetical. Typically, cattle promote bush encroachment by selectively exploiting the grass biomass, which in turn favours the growth of tree seedlings and shrubs. Furthermore, because the fuel load of the standing grass crop in heavily grazed savannahs is low, seasonal bushfires are less destructive to the woody vegetation. This idea, that tsetse flies benefited from land-use changes, was already put forward by Ford (1971). In his view, these changes resulted from activities of cultivators and pastoralists who transformed forests into savannah woodland long before trypanosomosis and rinderpest struck the area.

Historical evidence suggests that tsetse flies prevented the migration of early pastoralists into the tsetse “belt” of Africa. Surely tsetse flies and trypanosomosis were a constraint to the colonization of African landscapes for animal husbandry and agriculture, but their presence did not halt this process. For example, a study in Côte d’Ivoire found no indications that recent land-use changes and deforestation were governed by tsetse control (Erdelen et al. 1994; Nagel 1994). Studies in Ethiopia

found expanding agriculture in areas where tsetse suppression was successful, but overall changes in vegetation cover and structure were low (Reid et al. 1997; Wilson et al. 1997). In other parts of Africa, tsetse suppression may have had a greater impact on rural development (Jordan 1986; Stevenson 1988; Bourn et al. 2001). Conversely, rural development may affect the distribution of tsetse flies. Some species have disappeared due to the expansion of cropland, and the destruction of woodland and riverine forest habitats. Others have adapted to rural landscapes, where they feed mainly on domestic animals (Jordan 1986; Dye 1992).

It has been proposed that the eradication of economically important species of tsetse flies may enable a more-even distribution of livestock, thereby reducing overgrazing and erosion in the labile Sahel and highlands, and may also reduce the poaching intensity in national parks and wilderness areas since eliminating wildlife reservoirs of trypanosomes would no longer be practiced (Feldmann and Hendrichs 2001). This is a desirable but unlikely scenario. The following issues are considered to be equally important determinants of resource allocation and exploitation: food supply and security, land tenure, access to regional and global markets, and political and socio-economic stability. Decisions by people are based on the specific combination of these factors (Jordan 1986, 1992). The key to the sustainable use of natural resources is strategic land-use planning and implementation that mitigate deleterious changes (Grant 2001). This is true irrespective of the severity and extent of tsetse infestations.

In conclusion, it is true that wilderness and protected areas in Africa may harbour dense populations of tsetse flies. However, the conservation of many of these areas is also due to the fact that they are unsuitable as arable land. Moreover, some tsetse species have become resident in rural agricultural areas. Thus, the notion that tsetse flies are key protectors of wilderness areas cannot, as a general rule, be maintained. Finally, human/livestock health and wildlife conservation should not be traded against each other. Both are objectives in their own right, and they require concerted efforts to realize one without hampering the other.

6. CONCLUSIONS

In this chapter the principal environmental risks of SIT application and related activities have been reviewed. Some of them have been substantiated by reliable scientific evidence, while others are merely hypothetical and warrant further investigation.

SIT-related activities *sensu stricto* comprise the mass-rearing, sterilization, and release of sterile insects. Few environmental risks are associated with these activities, as long as safety standards and good field practices are guaranteed. However, SIT implementation also involves other supporting activities, and some of these may have adverse effects on ecosystems.

The first relates to pre-release population suppression. Insecticide applications may be harmful to the environment. In many situations, suppression can be achieved with more selective insecticides, some of which have been certified as organic, as well as ecologically sound techniques, such as traps and targets. These can be used alone or in combination, and may provide an environmentally acceptable alternative

or supplement to spraying non-persistent insecticides. However, adverse effects on selected biota or ecological processes and interactions cannot be ruled out for either method.

Secondly, area-wide control leading to the suppression or eradication of pest populations may have adverse indirect effects. These are often related to insufficient land-use planning and/or the lack of appropriate means of implementation, which in turn may lead to the unsustainable use of natural resources.

The third aspect is of particular importance if native species are targeted. Eradication of a species throughout its range may lead to a loss in species diversity of target and non-target species, including parasitoids and hyperparasitoids. Thus, the SIT can adversely affect host-parasitoid systems. Another aspect refers to the risk to pollinators, which has to be taken into account in all AW-IPM programmes that integrate the SIT. Finally, the immunological and epidemiological consequences of the transmission of non-haemoparasitic disease agents by vector insects, and the consequences of a loss of trypanotolerance in wildlife and livestock populations in tsetse infested areas, are open questions.

Optimum combinations of different control methods, resulting in the lowest cumulative risk, while achieving the highest possible effect on target populations, vary among species, regions and ecosystems. Thus, environmental assessments may reach different conclusions in different environmental situations, and pest management solutions must be adjusted accordingly.

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