PRINCIPLES OF AREA-WIDE INTEGRATED TSETSE FLY CONTROL USING THE STERILE INSECT TECHNIQUE

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ABSTRACT • The tsetse fly and the disease trypanosomosis it transmits, is one of the most severe medical and veterinary problems in Africa, infecting around 50,000 people every year and preventing the development of sustainable and productive agricultural systems. The most efficient way to contain the disease is by the management of entire populations of the vector (area-wide approach) using a combination of several control methods in an integrated pest management campaign. A very powerful method for integration in these programmes as a final eradication component is the sterile insect technique (SIT). The technique relies on the rearing of the target insect in large numbers in specialised production centres, the sterilisation with ionising radiation of one of the sexes and the sustained sequential release of the sterilised insects over the target area. Contrary to conventional control methods, the sterile insect technique becomes more efficient with decreasing density of the target population. Hence, the technique fits well within the concept of integrated pest management, as its complementary use in a phased approach with other suppression techniques, results in maximum efficiency. The five main prerequisites required to use the sterile insect technique against a target insect have been achieved for tsetse flies: 1. adequate information on the ecology of the insect is available, 2. the mass-production of the target insect is economically feasible, 3. efficient suppression techniques are available to reduce the population density of the target insect, 4. sufficient sterile males are available for release and their competitiveness is optimal, 5. the gamma treated sperm is competitive with the wild sperm. This paper gives a detailed review of the five implementation phases of the sterile insect technique based area-wide integrated pest management campaign against *Glossina austeni* on the island of Unguja, Zanzibar. The potential future prospects and requirements of using the sterile insect technique against tsetse populations are likewise presented.

KEY-WORDS • Human African trypanosomiasis -Tsetse fly - Integrated pest management - Sterile insect technique -Tsetse free zones.

LES PRINCIPES DE LA LUTTE INTEGREE PAR DES LACHERS DE MALES STERILES CONTRE DES POPULATIONS ENTIERES DE GLOSSINES

RESUME •La mouche tsétsé est le vecteur des trypanosomes, protozoaires uni-cellulaires qui causent la trypanosomose animale chez le bétail et la maladie de sommeil chez l'homme. Chaque année, environ 50 000 personnes contractent la maladie du sommeil. En plus, le développement de systèmes agricoles productifs et durables est sérieusement perturbé. Les problèmes causés par la maladie et le vecteur sont donc importants et ne peuvent être négligés. La lutte contre des populations entières de glossines (area-wide approach) en utilisant plusieurs techniques dans une campagne de lutte integrée, semble être la méthode la plus efficace pour lutter contre la trypanosomose. Les lâchers de mâles stériles est une méthode de lutte très efficace qu'on peut utiliser dans les stades finales d'une campagne de lutte integrée. La méthode de lâcher de mâles stériles requiert l'élevage de l'insecte à éradiquer en grand nombre dans des centres de productions spécialisés, la stérilisation par irradiation ionisée d'un des sexes et le lâcher de mâles stériles à intervalles réguliers dans les zones de lutte. Contrairement aux méthodes de lutte plus conventionelles, la méthode de lâcher de mâles stériles devient de plus en plus efficace avec des densités plus en plus faibles. C'est donc une méthode idéale à utiliser avec d'autres méthodes de lutte. Les cinq conditions indispensables pour l'utilisation de la méthode des mâles stériles sont présentes pour la mouche tsétsé : des données écologiques de l'insecte sont disponibles ; l'élevage des mouches est faisable économiquement ; des techniques de suppression existent pour réduire la densité de l'insecte ; des mâles stériles, compétitifs avec les mâles indigènes, peuvent être lâchés en quantité suffisante et le sperme irradié est compétitif avec le sperme des insectes sauvages. Cet article donne un résumé détaillé des 5 étapes consécutives d'une campagne de lutte intégrée dont le lâcher de mâles stériles est une des méthodes utilisée contre *Glossina austeni* sur l'île d'Unguja, Zanzibar. Les possibilités dans le futur de l'utilisation de la technique contre la mouche tsétsé sont également presentées.

MOTS-CLES • Trypanosomose -Glossine - Lutte intégrée - Lâcher de mâles stériles - Zones éradiquées.

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Tsetse flies (*Glossina* spp.) can be ranked among the word'st most destructive pests and are the vectors of the causative agents for sleeping sickness in humans and African Animal Trypanosomosis (AAT) or Nagana in livestock. Ten million km^2 of the continent of Africa are infested with tsetse flies and, according to the World Health Organisation, more

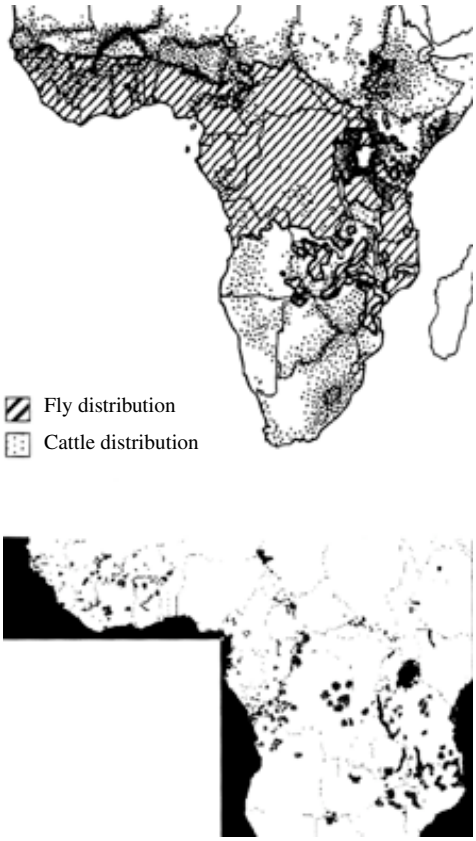

Figure 1 - The distribution of cattle and the tsetse fly (top diagram) and of the Human African Trypanosomosis foci (bottom diagram) in sub-Sahara Africa (Modified after Feldmann and Hendrichs, 1999 (top) and Feldmann and Jannin, 2001 (bottom)).

than 60 million people are permanently at risk from becoming infected with the disease. The detection of Human African Trypanosomosis (HAT) cases relies on the screening of humans and a drug treatment is only available at the early stages. The estimated number of infected people is between 300,000 and 500,000 but due to increased civil unrest in many African countries, the disease prevalence is dramatically increasing with 45,000 new cases reported in 1999 (1). HAT surveillance is insufficient and the drugs available for treatment are old and/or difficult to administer in poor treatment conditions due to the intra-muscular or intra-venous administration and the required long hospitalisation time (2). In addition, there are more than 60 million head of cattle and tens of millions of small ruminants living in the tsetse belt of sub-Saharan Africa and vulnerable to the disease (Fig. 1). The annual direct production losses in cattle due to the disease are estimated at US$ 0.6 - 1.2 billion (3). The presence of tsetse flies is in addition, responsible for the separation of crop farming and livestock production, preventing the development of sustainable agricultural systems in most of Africa (4). There is no vaccine available against animal trypanosomosis and most attempts to contain the disease have relied on controlling the parasite by chemotherapy. Only 3 prophylactic and therapeutic drugs are available for the treatment of animals (diminazene, isometamidium, homidium) of which an estimated 25 - 35 million doses are used every year (5, 6). These drugs are commonly available on the African market and their indiscriminate, unsupervised administration usually in an under-dose, have given rise to increased levels of drug resistance of the parasite (6,7). The promotion of trypanotolerant cattle, which show a certain degree of resistance to the disease, may work in areas of low trypanosomosis challenge, but their distribution is mostly restricted to West Africa and due to their small size and lack of strength to provide adequate draught power, not very popular with livestock keepers (3, 8).

It is obvious that eradicating the tsetse fly is theoretically the most desirable way of containing and preventing the disease. A recent economic study has estimated that the elimination of the tsetse fly from the continent of Africa would cost US$ 1 billion per year, but the annual benefit for overall agricultural production would amount to US$ 4.5 billion (9). In addition, the lives of tens of thousand of people would be saved. There are several tsetse intervention techniques available, each with their specific limitations, and only their integrated use in an area-wide approach can result in the permanent elimination of AAT and, eventually HAT and in the development of sustainable agricultural systems. A powerful technique for integration in tsetse campaigns is the Sterile Insect Technique (SIT) and this paper reviews the concept of SIT, the requirements for using the SIT in area-wide integrated pest management programmes and the role it can play in future tsetse control efforts in Africa.

ESTABLISHED METHODS OF TSETSE CONTROL : LIMITATIONS AND ADVANTAGES

The reproduction of tsetse flies is unique among insects and their peculiar life cycle has important implications for control or eradication efforts. Tsetse reproduce by adenotrophic viviparity i.e. the egg contains sufficient yolk to sustain the entire embryonic development and the larva is nourished in the female by special maternal organs (10). The absence of eggs and a free larval stage in nature and the fact that the pupal development occurs in the soil makes the adult fly the only phase easily accessible for control purposes. Early methods to control the tsetse fly such as the removal of vegetation or the destruction of game animals may have been very effective (as underlined by the rinderpest panzootic of 1895, which destroyed most of the existing game animals and domestic livestock and resulted in the disappearance of the tsetse fly throughout the Limpopo and Zambesi basins), but have become environmentally unacceptable (11, 12). The discovery of DDT and other organochlorides in the 1940's was hailed as a major breakthrough in the battle against the tsetse fly. The selective spraying of residual insecticides on resting sites of tsetse from the ground or with helicopters in the dry season was used to eliminate tsetse from 200 000 km^2 in Northern Nigeria (13). It remains to date the only successful and sustainable large-scale tsetse eradication campaign (8). The abundant use of persistent insecticides over large areas in often, fragile eco-systems had several negative effects: 1. the potential development of resistance to the insec-

ticide, 2. the killing of non-target beneficial insects, 3. the possibility of outbreaks of other pests due to the elimination of predators, 4. the general pollution of the environment (e. g. DDT accumulates in the food chain) and 5. the health hazard it poses to the staff of the spray-teams. In the 1970's and 1980's, the application of persistent insecticides was gradually replaced by the aerial spraying of non-residual ultra-low volume insecticides with fixed wing aircraft or helicopters i.e. the sequential aerosol technique (SAT). The goal is to kill adult tsetse flies in the first spraying cycle by direct contact and then kill emerging flies in five subsequent application cycles before the emerged flies can deposit a larva (5). The SAT has been used to clear tsetse from 48,000 km^2 of savannah areas in Zimbabwe (14). The implementation of SAT spraying operations is delicate and has to occur between sunset and sunrise during periods of temperature inversion. Any delay in the timing of the spraying may result in numerous flies depositing a larva. The spraying is in addition, difficult to apply in mountainous areas, demands skilled pilots, large ground teams to deploy beacons for aircraft navigation (this is meanwhile replaced by the use of the Global Positioning System (GPS)) and carefully planned and controlled application.

In the last two decades, the use of traps and targets has largely replaced the spraying of insecticides. The goal is to exert a modest daily mortality of 2-3 % on the female tsetse fly population by attracting them to a device and inducing a landing response. The flies are killed by the contact with a lethal dose of insecticides applied to the surface of the target or by heat or starvation after being guided to a non-return cage of a trap (15, 16, 17). The attractiveness of the devices can be enhanced for certain tsetse species by the use of potent odour attractants and these bait methods can reduce the original tsetse fly population effectively in a few months (17, 18, 19, 20). Because of the relatively low cost of the materials and the apparently unsophisticated technology, the use of traps and targets has been promoted in the last decades as the most sustainable method of tsetse control, especially in the context of community participation (8). In many instances, the involvement of the local communities has even become an essential prerequisite for donor funding (21). There are however, several technical aspects which are essential for the efficient application of the bait technology but sometimes difficult to grasp by the livestock holder i.e. the importance of trap/target siting (22), the maintenance requirements of traps and targets and their periodic replacement when the cloth material becomes faded, the periodic replenishment of the odours, the use of cloth material with an appropriate reflectivity pattern (23), the problem of insecticide deposits degradation by UV light and the use of the most suitable trap/target in relation to tsetse species and geographic distribution (24). The successful implementation of the target technology is in addition, hampered by several socio-economic aspects of the farmer community: 1. the problem of sustaining the interest of the farmer over time, especially when the fly catches have dropped dramatically or when targets are deployed (unlike traps, the farmer does not see the flies being killed, when targets are used), 2. the differential interest within the farmer community and the different perception of individual farmers of the problem influencing their willingness to contribute e. g. difficulties in assessing the communal labour contribution of an older versus a younger farmer, of a farmer with many cattle versus a farmer with few cattle, of a farmer living in the centre of the controlled area versus a farmer living in the periphery (8), 3. the problem of farmer participation in sparsely populated areas due to the increased travel time for trap deployment and maintenance combined with increased risk for theft and vandalism (21). Theft, inaccessibility of riparian vegetation during the rainy season combined with the absence of odour baits for some species and the high target density required per km^2 in certain dense forest eco-systems, are other factors affecting the efficiency of the bait technology (25, 26).

The application of a persistent insecticide in a pour-on formulation on livestock (live bait technology) has been used successfully in those areas with high cattle density and with adequate expert support (27, 28). The technique has several advantages over traps and targets in terms of theft and maintenance, but several important issues require further research i.e. the required cattle density, the required proportion of the herd to be treated, host preference of different tsetse species etc. (8). Disadvantages are the high treatment frequency, the high cost of the insecticides, motivation and participation of farmers and the development of resistance to the insecticides in both tsetse and ticks.

INTEGRATED PEST MANAGEMENT (IPM)

The growing concerns related to the massive use of insecticides resulted in increased demands for alternative methods of insect control and the development of the concept of integrated pest management (IPM). According to the Council on Environmental Quality, IPM is defined as 'the selection, integration and implementation of pest control methods based on predicted economic, ecological and sociological consequences' (29). Integrating several control methods using the specific advantages of each method in an environmentally and ecologically sound way while limiting their disadvantages, seems to be the most efficient way of tsetse intervention. IPM programmes can be implemented with emphasis on field-by-field management (local IPM) or by the management of entire insect populations in potentially large geographical zones with emphasis on eradication (area-wide IPM). In localised IPM programmes, tsetse fly control is restricted to certain areas of interest of the local farmer community i.e. coffee plantations, villages and watering points. These programmes usually involve the application of low cost technologies to be provided by the local communities, who are not only responsible for the implementation of the programme but also play a key role in programme development and management (bottom to top approach). The experience at Nguruman, Kenya, has shown that community based tsetse control operations can be successful in small areas (300 km^2) provided that 'the farmers have access to expertise and initial seed money' (12). Economic analysis has

Table I - Hypothetical example of the sterile insect technique (after E. Knipling).

Generation	N° of insects	N° of sterile insects released	The sterile to wild insect ratio	Percent sterility	N° of insects remaining fertile`	Growth rate
P	1 000 000	9 000 000	9 : 1	90,0	100 000	Fivefold
F1	500 000	9 000 000	18 : 1	94,7	26 316	Fivefold
F2	131 579	9 000 000	68 : 1	98,6	1 896	Fivefold
F3	9 480	9 000 000	949 : 1	99,9	10	Fivefold
F4	50		180 000 : 1	99,99	1	Fivefold

shown that the costs of such programmes are limited to US$ 30 per year per km^2 (with 2 traps/km^2 at Nguruman, Kenya). This figure is however deceiving as it excludes costs for labour, transport for trap deployment/maintenance and expert services to provide the required supervision and training. When all related expenditures are included, the recurrent cost of tsetse control using insecticide-impregnated targets ranges between US$ 220 and 385 per year/km^2 (9, 30). Moreover, tsetse fly populations extend far beyond these focal interest points (adjacent forests, abandoned plantations, game reserves etc.) and to sustain the degree of control achieved, efficient barrier systems have to be established and maintained indefinitely to prevent re-invasion. This re-invasion pressure is often underestimated and can mount to 100,000 females per month during the long rains in the case of *Glossina pallidipes* in Kenya (31). Small project areas and un-sustained tsetse control activities favour a quick re-establishment of tsetse populations to pre-intervention population densities (32). In addition, these barriers are usually located in uninhabited areas, complicating their maintenance by the local communities (21). It is obvious that these localised tsetse control programmes can give benefits to the farmers very rapidly, but they have to be implemented indefinitely and are therefore inefficient and uneconomical in the long run.

Area-wide IPM programmes, implemented with a certain degree of participation of the local communities, are a more efficient way of insect pest intervention. Area-wide IPM programmes can be implemented in a dynamic and phased approach over potentially large geographical areas, even covering several countries. As entire insect populations are tackled, the issue of barrier systems is less pertinent and required only temporarily during the implementation of the different phases. These programmes require a central decision making body or an institution which is not market oriented, a centralised implementation organisation (a top to bottom approach) and a larger source of funding. One of the most effective tools to integrate in these IPM programmes for tsetse intervention is the sterile insect technique (SIT).

THE STERILE INSECT TECHNIQUE (SIT)

The concept.

The sterile insect technique is one area-wide insect pest management method where the insect pest is controlled or eradicated by affecting its reproductive capacity. The concept was conceived and developed in the US in the 1950's by an American entomologist, E.F. Knipling. The technique relies on the production in large numbers of the target insect in mass-rearing facilities, sterilisation of one (i.e. in tsetse) or both sexes (i.e. in screwworm) and the release in sustained numbers in the natural habitat large enough to outnumber the wild pest population (33, 34). The feasibility of the technology was first demonstrated with the eradication of the screwworm *Cochliomyia hominivorax* (Coquerel) from the island of Curaçao, Netherlands Antilles in 1954 (35). The eradication of the screwworm fly by the massive release of sterile flies from the Southern USA, Mexico, Central America and Libya are undoubtedly the most successful eradication campaigns of an important pest insect in the world (36, 37, 38). The technique has been used to successfully eradicate or control other important insect pests such as Lepidoptera (39), fruit flies (40) and tsetse flies (41, 42, 43). In addition, the release of sterile insects has been successfully used in quarantine operations along the USA-Mexican border to prevent migration of the Mexican fruit fly *(Anastrepha ludens)* from Mexico into Texas and California (44).

Simple mathematical models were developed by Knipling (33) to demonstrate the principles of SIT. One model assumes a natural insect population of 1 million insects, which has the capacity to increase five fold with each generation (Table I). It also assumes complete competitiveness and sterility of the released insects and no practical problems as migration into the target area. This population is subjected to a release of 9 million sterile males, which will limit the reproduction of the natural population to the ratio of sterile to wild insects, i.e. 9 to 1 in this case. As the males are equally competitive, 90% of the native females would mate with a sterile male, resulting in only 100,000 reproducing insects, subject to a five fold natural increase or 500,000 fertile insects in the next generation. The original population is therefore reduced by 50% in the first generation. Due to a sustained release rate of 9 million sterile males, the native female insect population will be outnumbered by a ratio of 18 to 1, resulting in 131,580 fertile second-generation insects (after the fivefold natural increase). In the fourth generation, the ratio of sterile to fertile insect will have reached 180,000 to 1, leading to the extinction of the native insects population. The SIT has several advantages : 1. only the target insect is attacked and the technique is therefore species specific, 2. there is no development of resistance to the effects of the sterile males provided that adequate quality assurance is practised in the production process, 3. the sterile insects cannot get established

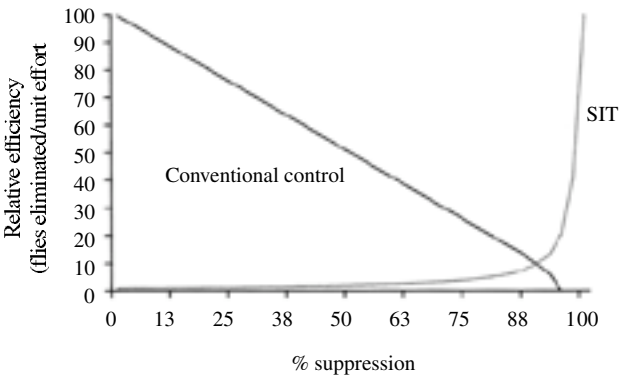

Figure 2 - The efficiency of conventional tsetse control methods (screens, targets, traps, insecticides) and the Sterile Insect Technique (SIT) used in area-wide integrated pest management programmes.

in the released areas as with other biological control programmes, 4. the technique is environmentally friendly without any contamination of the habitat.

The technique has also its limitations : i.e. it is not cost-efficient with high population densities and requires therefore prior population suppression in those cases and it has a delayed effect on the numbers of wild insects present. Specifically in the case of tsetse flies, the low reproductive capacity of tsetse makes the rearing in large numbers cumbersome and there is a potential danger of disease transmission in case the sterile male insects are released as pupae. The SIT is an ideal mechanism to be combined with other methods of control and it fits well within the concept of IPM. One of the major advantages of the SIT is demonstrated by the theoretical model of Knipling i.e. the control effort becomes more economical and efficient as the natural population declines and increasing ratios of sterile to wild males are achieved (45). This is in contrast with conventional methods of killing insects, e.g. with insecticides. Here, the continued use of the same treatment will result in the same percentage effect regardless of population density (46) and the technique will become therefore less efficient in terms of numbers killed as the natural population declines. The complementary use of both conventional techniques and SIT in a phased approach would therefore result in maximum efficiency throughout the intervention phase (Fig. 2).

Major requirements for the successful implementation of SIT programmes.

Not all insects are suitable for control with SIT and the main prerequisites are here examined in the case of tsetse flies.

• A comprehensive knowledge of the ecology and behaviour of the insect is required

Especially for the area-wide approach of pest control or eradication, an in-depth knowledge of the insect's biology is required to develop appropriate control strategies and to enable accurate evaluation of the progress made. Contrary to the strategy used in conventional IPM (only action is taken after the target pest population exceeds a predetermined economic threshold level), sterile males are released in SIT-based area-wide IPM when the target pest population reaches its lowest level, either naturally or after population suppression. Absolute tsetse fly population densities fluctuate in space and time and data on population dynamics, the mating behaviour, breeding areas, distribution and movement patterns of the insects will be needed. Analysis of these data will determine the spatial distribution and deployment density of the suppression tools, required application time, the optimal release rates of the sterile males in the different seasons and vegetation types and the establishment of efficient barrier systems. Special attention should be given to the temporal and spatial variations in the age structure and reproductive status of the target population as these constitute key parameters in the assessment of the success of the sterile male release programme. Knowledge on host preferences will determine the possibility of using insecticide pour-on formulations on livestock for population suppression.

• The colonisation and mass-production of the target insect should be feasible at reasonable cost

The slow reproductive rate of tsetse flies makes the growth of a tsetse colony slow with an estimated doubling time of 3 months under optimal conditions. However, special rearing conditions are required only for the pupae and adult stages, making tsetse fly rearing relatively easy as compared to other insects. Both sexes of the tsetse fly are obligatory haematophagous and flies were maintained on live hosts during early colonisation attempts (47). The development of an artificial silicone membrane and the use of blood, collected from animals in slaughterhouses and processed in the laboratory, made it feasible to colonise up to 1 million female tsetse flies (48, 49). The current rearing techniques make it possible to tackle suppressed tsetse populations in geographical areas of 5,000 - 10,000 km^2 but more efficient and refined rearing techniques will be required for the treatment of larger geographical zones. Progress is currently made in 1. the sexing of the immature stages or of young adults and development of self stocking systems in adult holding containers, 2. semi- or full automation of the feeding systems of adult tsetse flies (50), 3. commercialisation of the blood supply and eventually, the development of a standard artificial diet.

• The population density of the target insect must be inherently low or be reduced by economically feasible suppression techniques

In view of their slow reproductive capacity, natural tsetse population densities are in general low and estimates of population size may vary from 40 individuals to several thousands per km^2 (51, 52). Tsetse fly populations can be reduced very efficiently by aerial spraying of insecticides or with traps and targets (42, 53, 54). The numbers of sterile males required to outnumber the remaining indigenous male

fly population, is therefore very low i.e. 20 - 35 sterile *Glossina tachinoides* and *Glossina palpalis gambiensis* males per linear km of galleryforest in Burkina Faso (55), 135 sterile *Glossina morsitans morsitans* pupae per km^2 on a commercial ranch in Tanzania (56) and 25 to 400 sterile *Glossina austeni* males per km^2 on Unguja Island (43). This compares very favourably with densities of sterile insects required for other insects i.e. 1,200 - 1,500 sterile screwworm flies per km^2 (57) and 100,000 to 400,000 sterile fruit flies km^2 (58).

• The competitiveness of the reared and released sterile insects should be optimal

SIT programmes can only be successful if the artificially produced and released insects are sufficiently similar in behaviour, vigour, host location, dispersal and mating ability to compete with the native insect population in a natural environment. Male sterile flies should in addition, live sufficiently long to transfer their sterile sperm to as many virgin females as possible. Several factors inherent to the artificial colonisation, sterilisation and distribution of sterile insects will undoubtedly reduce the quality and competitiveness of the reared flies, i.e. physical manipulation of the flies, chilling for the irradiation, stress in the holding and release containers, insufficient feeding, etc. (59). Rigorous quality control procedures are therefore incorporated at all levels of the rearing and distribution process to assess the quality of the produced flies at any time.

The most significant quality-reducing factor is most likely the radiation treatment administered to sterilise the flies. The ionising radiation will result in sterility based upon the induction of dominant lethal mutations i.e. a nuclear change in the germ cells without affecting their maturation but killing the zygote during its development (60). The entire process of spermatogenesis occurs in the tsetse pupae and consequently, emerging male tsetse flies contain their entire supply of mature sperm (61). Male tsetse flies become fully potent 4-6 days post-emergence and can inseminate a female fly successfully every 2-3 days up to 6 times in the laboratory. A radiation dose of 60 - 120 Gy induces 95 % dominant lethals in the sperm of adult male tsetse without affecting the male's mating behaviour, ability to produce a spermatophore, ability to transfer sperm and its activity and dispersal patterns after release (62-67). Inevitably, the radiation treatment also inflicts damage to the flies' somatic cells, which is manifested most clearly in the reduction of the mean longevity of the male flies. In the laboratory, the sterilising radiation treatment reduced the life expectancy of male tsetse with 22-35 % as compared to untreated males (67). Field studies however, indicated that released sterile male tsetse survive long enough to find a host and virgin females i.e. a population half-life of 7 days for the first six weeks and a maximum survival of more than 40 days (53, 55, 68). Male tsetse flies can also be sterilised in the pupal phase, which has several advantages : 1. pupae are easier to handle, 2. pupae are less susceptible to damage, 3. pupae can be irradiated in bulk without chilling and 4. the radiation dose can be administered in a protecting nitrogen atmosphere, resulting in less somatic cell damage and hence, better quality flies (45, 69, 70). In the absence of a sexing mechanism of tsetse pupae, SIT programmes using pupal irradiation have relied on the small difference in male and female pupal period to isolate 40 % of the female flies before the onset of the male emergence flush. The remaining pupae were chilled to stop the eclosion process and then irradiated in a nitrogen atmosphere (71). Some progress has recently been made in this area and preliminary investigations have shown the potential to recognise the hypopygium structure automatically in late male pupae by measurement of their dielectric properties (72). A less sophisticated method for automated sex separation is being developed for self stocking of colony flies, whereby a temporary incubation at slightly increased temperatures is used to get the right number of males and females emerging into fly holding cages. Another problem with the release of sterile males as pupae, is the enhanced ability of un-fed flies to develop infections of the subgenus Trypanozoon after feeding on infected hosts within 24 hours after emergence (73). The vectorial capacity of male tsetse is not affected by the radiation treatment, making the release of flies as pupae problematic, especially in foci of human sleeping sickness (73, 74). The screening for factors enhancing refractoriness followed by the selection of appropriate strains is among the challenges of methods development for future tsetse SIT operations (75).

• The sperm of sterilised males should be as competitive as the sperm of wild males

Virgin female flies of most tsetse species become receptive to mating on day 1-2 post-emergence. During mating, sperm is transferred to the female fly by means of a spermatophore, produced by secretion of the male's accessory glands (76). The spermatozoa will migrate to the spermathecae of the female where the sperm is stored for the rest of the female's adult life (77). Small quantities of sperm are released during each ovulation and the oocyte is fertilised in the uterus. Similarly, after the mating with a sterile male, the sterile sperm will be stored in the spermathecae and as a consequence, no offspring will be produced (65). Contrary to what is commonly accepted, multiple mating behaviour of female flies, frequently observed in the laboratory and in the field (62, 78) is not an obstacle to the success of a SIT programme, provided that the sterile sperm has good motility and viability (immobile sterile sperm has no migration capacity and the empty spermathecae will be filled up with fertile sperm after a subsequent mating with a wild male, destroying the effect of the first sterile mating) and the first mating was one with a sterile male. A successful mating with a sterile male will usually fill up completely the spermathecae of the female and any subsequent mating with fertile males does not influence the female's sterility due to the mechanical barrier imposed by the filled spermathecae. Even with spermathecae filled with 90 % sterile sperm (of the first mating) and 10 % fertile sperm (of the second mating), the female will be sterile for 90 %, provided the sterile sperm is as competitive as the fertile sperm.

THE ERADICATION OF *GLOSSINA AUSTENI* NEWSTEAD FROM THE ISLAND OF UNGUJA (ZANZIBAR) : THE SUCCESSFUL APPLICATION OF A « SIT-BASED AREA-WIDE ERADICATION CAMPAIGN »

The island of Unguja (Zanzibar) has a size of 1,650 km^2 and is situated 35 km of the east - coast of Tanzania. *Glossina austeni* Newstead was the only species of tsetse present and solely responsible for the cyclical transmission of trypanosomosis. The overall disease prevalence in cattle was 19 %, but localised infection rates could be as high as 60% (79). According to a livestock census of 1993, the island contained 45,750 cattle and 27,000 small ruminants and direct losses of the disease to the livestock industry were estimated at US$ 2 million per year (80). In addition, 4,000 head of cattle had to be imported every year in the last decades to satisfy the demand in meat (81). An early eradication effort (1986 to 1993) using synthetic pyrethroid applications on livestock, failed to eradicate the tsetse fly and highlighted the limitations of a field-by-field approach. The area-wide concept was adopted in 1994 with the release of sterile males as the final eradication component (43). The fly population was suppressed with the live-bait technology in the agricultural zones of the northern half of the island and by the deployment of insecticide treated blue cotton screens in the dense forested areas (26, 82). Sterile male flies were dispersed in a phased approach over the southern half of the island from 1994 to mid-1996, while the fly population in the northern half of the island was kept under suppression with pour-on applications and cattle dips in strategic areas. From mid-1996 to December 1997, the release zone was expanded over the entire surface area of Unguja Island, including 12 small off-shore islands.

There are five distinct phases in a SIT-based area-wide IPM programme, illustrated here for the eradication of *Glossina austeni* on the island of Unguja.

Assessment of the technical, operational and economic feasibility of the technique on the island.

Laboratory and field tests, investigating aspects related to the quality of male *Glossina austeni,* indicated that : 1. a radiation dose of 120 Gy was sufficient to sterilise adult *Glossina austeni* males with acceptable survival rates, 2. the competitiveness of the male flies was not affected by the irradiation treatment, by the marking, by a packing density in the release containers at 1 fly per 5-10 cm^3 of cage space or by a 3-hour transport, 3. released sterile males contained sufficient fat reserves to find a host after release as indicated by survival tests without food, 4. the released sterile males showed an adequate dispersal of 600 m in the dense primary forest two days after release from the ground and 5. released sterile males were able to locate virgin indigenous females and to transfer the sterile sperm. These studies, complemented with the testing of several operational components, predicted an average requirement of 100-150 sterile males/km^2 to achieve the goal of eradication. The budget was estimated at US$ 5.5 million over a 4-year period, including a complete refurbishment of the existing insectaries at the Tsetse and Trypanosomosis Research Institute (TTRI), Tanga, Tanzania. With the estimated losses of US$ 2 million per year, the initial investment of the eradication effort would be returned after less than 3 years.

Collection of base-line data on tsetse ecology and disease transmission.

The collection of data on the ecology of tsetse flies requires the availability of appropriate trapping devices. The elusive *Glossina austeni* flies could however, not be sampled in adequate numbers with conventional tsetse traps and sticky panels were proposed and tested as an alternative (83-86). Surveys revealed that *Glossina austeni* was present at high densities in the Jozani forest (a primary forest), but population densities were much lower in the secondary forests and in the agricultural zones of the northern half of the island (82). Ecological studies were carried out in the primary tsetse focus and provided the required base-line data on the spatial and seasonal variations in apparent densities, sex ratios, population structure, reproductive status and natural abortion rates (22).

Trypanosomosis surveys were already conducted in the 1980's and revealed that the disease was widespread on the island but concentrated in three foci : Mangapwani in the North - West, Bambi in the Middle - East and Jozani - Muungoni in the South -West. Two species of trypanosomes were identified being predominantly *Trypanosoma congolense* Broden and to a lesser extent *Trypanosoma vivax* Ziemann (79)

Mass-production of the sterile flies in special factories.

The flies were produced at the mass-rearing facility of the Tsetse and Trypanosomosis Research Institute, Tanga, Tanzania. The rearing facility consisted of 3 separate modules, each with a holding capacity of 350,000 female flies. This approach has the advantage that in case of a problem in one module, rearing can continue and production increased in the other modules, without jeopardising the SIT field programme. The flies were kept in holding cages (diameter of 20 cm and width of 5 cm) at a density of 100-120 flies per cage, with netting on top and bottom for feeding and collection of the larvae. Flies were maintained at a temperature of 22-24 °C, a relative humidity of 75-85 % and a 12 hours scotophase. Mating was done at a 1:5 male:female ratio, in a self stocking system reducing labour considerably without affecting the quality of the flies. The flies were offered a meal of fresh-frozen blood 5-6 times a week. The blood was originally collected from locally slaughtered animals, but due to high bacterial contamination and variable nutritional quality the local blood was later replaced by tested and decontaminated (1.5 kGy gamma irradiation) blood collected in Vienna. Each batch of blood was subjected to a 25-day quality control bioassay to assess its nutritional value. In addition, routine bacteriological screenings were conducted. The performance of the colony was monitored in terms of fecun-

dity (daily pupae collection) and mortality (checks every 14 days). The daily mortality remained below the 1% standard in most weeks and fecundity fluctuated usually around 0.5 - 0.6 pupae per female every 10 days (68). The average weekly colony size increased from 40,705 in 1994 to 224,881, 628,781 and 639,972 in 1995, 1996 and 1997, respectively. The largest colony size of 954,445 female flies was attained in week 42 of 1996, producing 306,552 pupae a week. The mean numbers of pupae produced per week increased from 8,979 per week in 1994 to more than 170,000 per week in 1996 and 1997.

Development of appropriate fly handling methods and release systems.

To distinguish sterile from wild flies, the excess male flies were marked 'en masse' using fluorescent Day Glo® powder. The tsetse puparia were covered with a 0.5% mixture of Day Glo® powder and sterile sand before the onset of the emergence. The emerging flies crawled through the sand and the ptilinum and the frontal suture picked up small quantities of the fluorescent powder. After recapture in the field, the head of the recaptured fly was examined under an U.V. microscope for fluorescence, enabling a clear distinction between released and wild males. This highly accurate marking technique had no detrimental effect on the quality of the released flies, as it required no additional chilling or physical manipulation.

The emerged male flies, earmarked for release, were maintained under standard holding conditions for 4-6 days and were offered several blood meals containing 12.5 mg of Samorin® per litre of blood to prevent cyclical development of trypanosomes in the released flies (68, 87). The day before the release, the male flies were immobilised at 4 °C, irradiated in bulk in a pre-chilled vacuum flask with 120 Gy in a ^{60}Co or ^{137}Ce source and transferred to carton release containers at densities up to 200 flies/box(59). During the trial releases, the sterile flies were released from fixed release points on the ground (41, 42), but this required large logistic support in terms of personnel and vehicles, making the operation expensive. In addition, the flies were released in clusters, making this release method rather inefficient. Therefore and also because of the inaccessibility of large areas on Unguja Island, the sterile *Glossina austeni* males were dispersed by light aircraft 2 times a week along specific release lines separated by 1-2 km (Fig. 3). The Global Positioning System was used by the pilot for accurate flight navigation (59). Aside from the obvious logistic and economic advantages, aerial release procedures assured optimal dispersal and distribution of the flies enabling the released flies to economise drastically their energy reserves. The flies were released over all microhabitats without having to fly potential long distances to find a virgin fly as is the case when flies are released from fixed points on the ground. The number of sterile males released on each dispersal line was adjusted weekly based on feed - back information received from the fly monitoring programme. Depending on the suitability of the habitat, the male flies were released at densities of less than 25 sterile males/km^2/week in the unsuitable habitats to more than 300

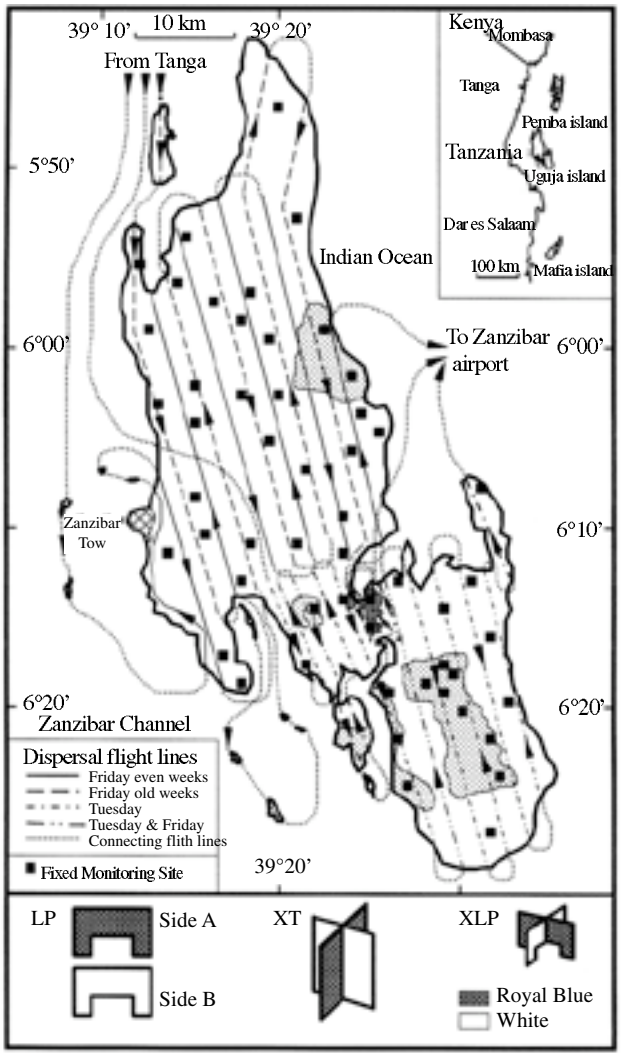

Figure 3 - The Island of Unguja (Zanzibar) indicating the forested areas (shaded), the 55 Fixed Monitoring Sites, the flight lines for the dispersal of the sterile male flies and the different types of sticky panels used in the fly monitoring programme (LP - legged panel; XT - cross shaped XT panel; XLP - cross shaped legged panel).

sterile males/km^2/week in the primary Jozani forest and surrounding secondary forests. In total, more than 8.5 million sterile males were dispersed during the 3.5 year aerial release programme at average weekly densities of 12,381, 35,180, 71,405 and 53,249 sterile flies in 1994, 1995, 1996 and 1997 respectively (43).

The quality of the sterilised male flies, earmarked for release was monitored constantly for each release flight. One or two release cartons were selected at random at the airport in Tanga before the departure of the release aircraft and during each release flight. In the laboratory (both at TTRI and on Unguja), the quality control boxes were opened in a specially designed release container to assess male fly mortality (on average 4.8 %), the proportion of non-flyers (on average 13.6 %), sexing errors and feeding status (on average 93 % partially or fully engorged). Comparison of quality control

data of the male flies before transport at the TTRI with those on Unguja after the release, revealed that only 1% of the mortality could be attributed to the transport (59). It was also shown that the average temperature in the aircraft during the releases was a critical factor affecting fly quality. Significantly more male flies died with increasing temperature when the temperature ranged between 26 and 33 °C (59). During the hottest seasons, the carton release boxes were therefore packed in styrofoam boxes with blue ice-packs to stabilise the temperature in the aircraft.

Monitoring the progress of the release programme and the impact on the wild fly population.

The monitoring of the progress made during the releases of the sterile males is one of the most critical aspects in any SIT operation. There are two important issues, which require attention and which will give essential information to the programme managers: 1. the monitoring of the sterile male releases (distribution patterns, the ratio of sterile to wild males, adequate survival of the sterile males) and 2. the monitoring of the impact of the sterile male releases on the wild fly population i.e. an evaluation of the progress made at any given time through an assessment of the rate of induced sterility in the wild target female population.

• *Trapping devices, fixed monitoring sites and monitoring strategy*

Suitable trapping devices are needed to monitor the efficiency of any sterile male release programme and to assess the impact on the female target population. Each tsetse trapping device is biased in one way or the other and this bias should be known to evaluate sampling data properly (84, 85, 88). The fly samples with the royal blue - white legged sticky panel (Fig. 3) were significantly biased for trapping *Glossina austeni* male flies (62.8%) making the panel an excellent tool to monitor the dispersal, distribution patterns and the ratios of the sterile to wild male flies (43). The crossed XT and XLP panels (Fig. 3) were more efficient for trapping female flies and were deployed in large numbers especially at the end of the programme, when very few wild females were trapped (85). It is not feasible logistically and economically to deploy trapping devices everywhere in the target zone and 55 representative areas (Fixed Monitoring Sites (FMS)) were therefore selected over the entire island based on vegetation cover and other factors affecting fly distribution and abundance (Fig. 3). The number of sticky panels deployed in each FMS was adjusted depending on the importance of the fly foci. The frequency of collecting the fly samples from the trapping devices in each FMS depended on the importance of the trap catch and the probability of trapping female flies. The sticky panels were checked from once a week in the unfavourable tsetse vegetation zones to once every week-day in the Jozani forest fly focus allowing the collection of fresh female flies for dissection.

All flies sampled in a given day were transferred to the laboratory and the head capsules examined under the UV microscope for fluorescence. Female flies were dissected under a dissection microscope and their reproductive system examined (insemination rate, uterine content and ovarian age). The collected data on the relative abundance of indigenous female and male flies, the ratio of sterile to wild males, the frequency distribution of the physiological age of the female target population and the rate of sterility induced were compiled each week.

• *Monitoring of the sterile male release programme and the impact on the wild fly population*

The efficiency and success of any sterile male release programme will depend on the males' survival, their dispersal rate, their spatial occupation of all suitable microhabitats and an adequate over-flooding ratio of sterile to wild males, sufficient to induce the required rate of sterility in the target population. Release-recapture studies of sterile male *Glossina austeni* released by air over the primary forest habitat showed survival rates comparable with other tsetse species released from the ground (56, 68, 89). Sterile males were trapped in all FMS both in the northern and southern half of the island, indicating their good dispersal and occupation of the different habitat types (43).

The most direct indication of the success of a sterile male tsetse release programme is the rate of induced sterility in the target female fly population. With constant numbers of sterile males released, the proportion of virgin female flies mated with a sterile male will increase with each fly generation as the ratio of sterile to wild males increases. This parameter is especially important with tsetse flies, as a drop in tsetse catches does not always reflect a true reduction in the absolute density of the fly population. Recapture data of known numbers of released male *Glossina austeni* on Unguja Island have indicated that the response of the flies towards the trapping devices changed with the seasons and fluctuated with a factor of > 10 (Vreysen, unpublished data). These fluctuations in the responses of the flies towards trapping devices and hence, the variations in sampling size could seriously cloud the interpretation of trapping data for the programme managers. Tsetse flies present an unique system to measure this rate of induced sterility. Female tsetse flies have two ovaries each containing two polytrophic ovarioles, which are always at different stages of development (90). The maturation of the ovarioles occurs sequentially and takes about 9-10 days. The growth curves of the follicle next in ovulation sequence (FNOS) correlates well with the different development stages *in utero*. The sequential development of the ovarioles, ovulation and the fertilisation of the oocyte *in utero* is not affected by the mating with a sterile male, provided the sterile sperm has retained its motility and viability (67). However, the development of the embryo is arrested, which is manifested visually by a contraction of the dying embryo, usually followed by its expulsion (abortion) from the uterus. Examination under a dissection microscope of the reproductive system of indigenous female flies which have mated with a sterile male, will reveal aberrations between the size of the FNOS and the development stage *in utero* (dead embryo or empty uterus). Knowledge of the seasonal fluctuations in 'natural' reproductive abnormalities (i.e. before

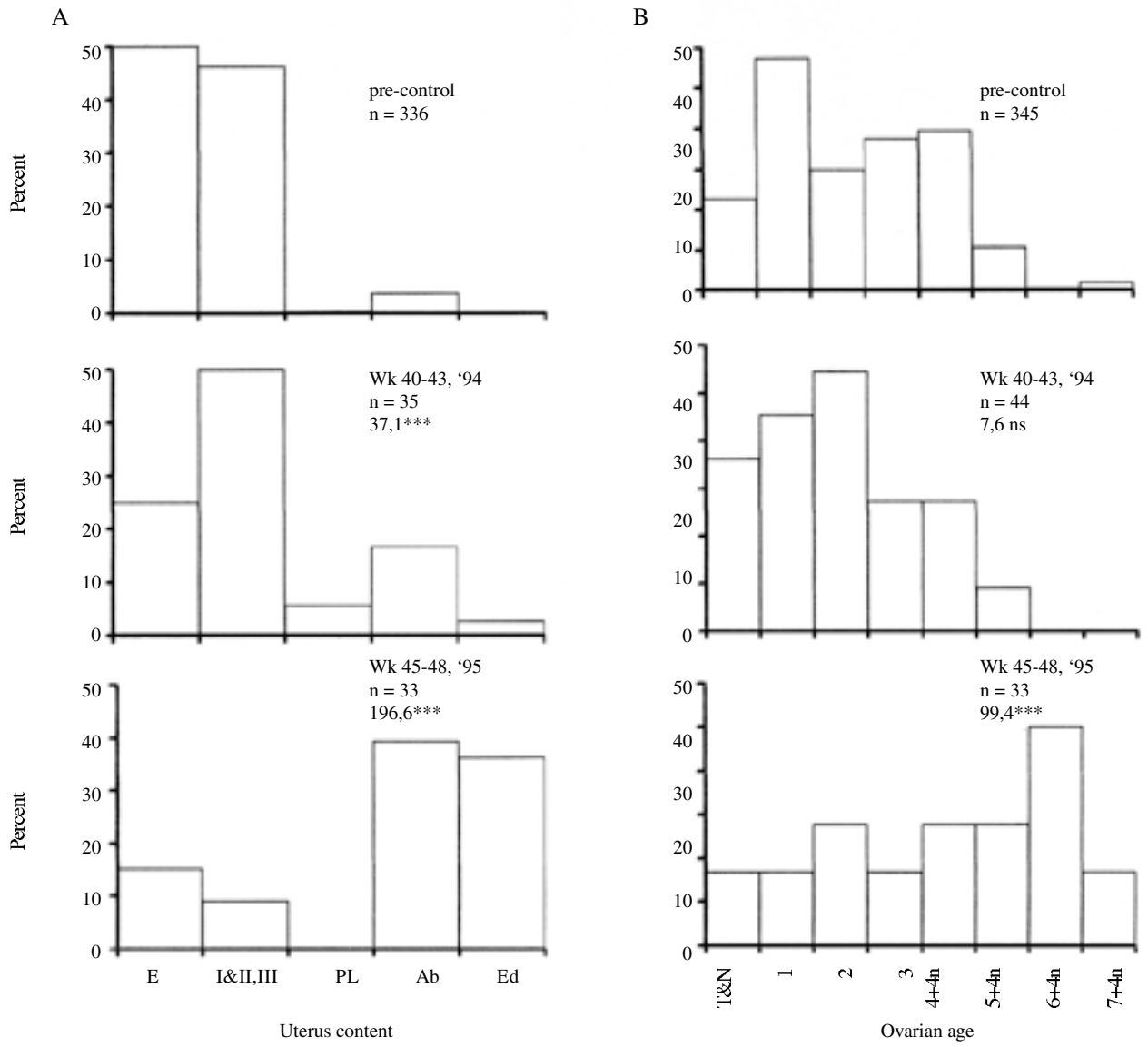

*Figure 4 - (A) The frequency distribution of the uterus content and (B) the ovarian age categories of the G. austeni females sampled during the pre-control phase (top graph), during the early release phase (middle graph) and the late release phase (bottom graph). (E = egg, I, II, III = first, second and third instar larva, PL = post larviposition, Ab = abortion, Ed = degenerating egg) (T = teneral, N=nulliparous, 1-7 = number of ovulations (for more details see Challier, 1965)). Number indicates chi-square value of comparison of the frequency distribution of the uterus content (left) and the ovarian age (right) with that of the pre-control sample (*** p < 0.001, NS = not significant).*

the release of sterile males) and dissection of a reasonably sized sample of wild females, enables an accurate determination of the proportion of indigenous female flies which have mated with a sterile male i.e. the rate of sterility induced.

Pre-control dissection data of the *Glossina austeni* population on the Island of Unguja revealed that 96.1 % of the female fly sample had a viable egg or a developing larva *in utero* and the natural abortion rate was established at 3.1 % (22). During the early phases of the release programme on the Island of Unguja, the numbers of sterile males released did not exceed 10,000 per week and the sterile to wild male ratio remained below 10:1 (Fig. 5). This ratio was however sufficient to induce 20 % sterility in the female target population (17.1 % and 2.8 % of the dissected females showed an empty uterus due to abortion and an egg in embryonic arrest, respectively) (43). As of week 13 1995 (last week of March), more than 25,000 sterile males were released every week and the sterile to wild male ratio increased to > 50:1 after week 34 1995. As a result, the rate of induced sterility in the female fly population increased gradually and in the last weeks of 1995, 75 % of the female flies showed evidence of having mated with a sterile male (Fig. 4).

Secondly, important information on the impact of the release programme is provided by the analysis of the age structure of the target population. The physiological age distribution of any tsetse population can be assessed based on the sequential development of the 4 ovarioles in female tsetse

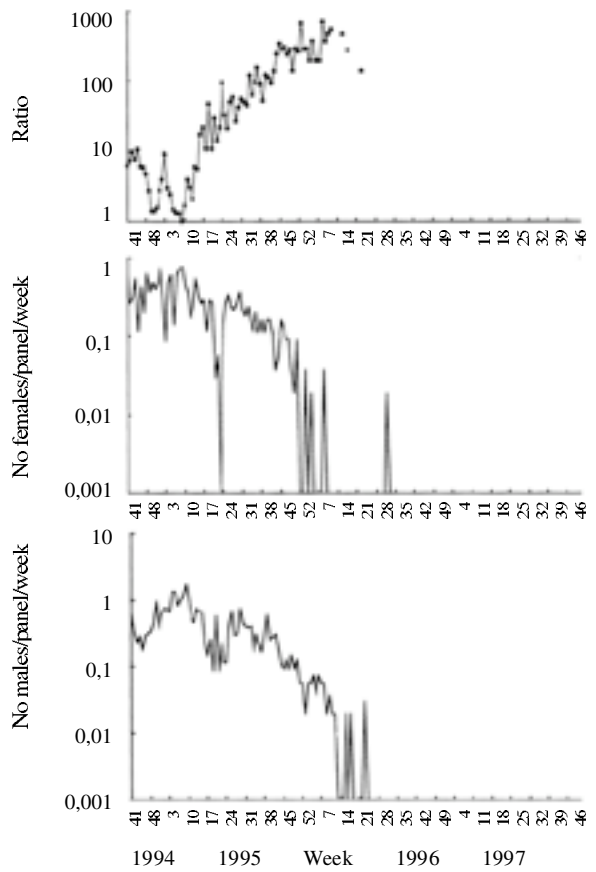

Figure 5 - The sterile to indigenous male ratio (top graph), the apparent density (+ 0.001) of indigenous female (middle graph) and indigenous male (bottom graph) G. austeni in the primary forest (Jozani) and surrounding secondary forests.

flies (91). Any increase or decrease in the mortality rate of the tsetse population will be translated in a significant shift towards a younger or older fly population. Dissection data of the *Glossina austeni* population showed that before any control was imposed, the female population contained 11.3% Teneral and Nulliparous (i.e. young) flies and 26.3% females with 4 ovulations (i.e. old flies) (Fig. 4). Although the age distribution of the female fly population remained similar during the initial stages of the release programme, the frequency distribution became significantly skewed towards older females (61.1% with 4 ovulations) by the end of 1995. The ageing of the female fly population due to a reduction in the replenishment rate of young female flies was again a clear indication of the success of the sterile male programme.

Finally, the gradual reduction in apparent density of the target fly population is the third important indicator for success. Despite the observed fluctuations in the response of the flies towards the trapping devices, the gradual loss of fertility in the female target population will unequivocally result in a decline in the absolute density of the target population (Fig. 5). On the Island of Unguja, the last indigenous fly was trapped in week 36 of 1996 (43). After the fly population crash of early 1996, the transmission of *Trypanosoma congolense* was completely halted and the disease incidence of *Trypanosoma vivax* remained below 0.1 % in 1997 (92).

After the completion of the release programme in December 1997, an intensive follow-up parasitological and entomological monitoring programme was conducted in 1998-1999. Surveillance for the presence of tsetse was carried out with > 200 sticky panels for more than 150 trapping days in areas which used to harbour high densities of tsetse flies. No tsetse flies were trapped. In addition, more than 3,000 head of cattle, aged between 6 months and 2 years, were screened in random selected sampling sites covering the entire island. No animals were found infected with trypanosomes with the Buffy Coat/MHCT technique (93).

FUTURE PROSPECTS AND REQUIREMENTS TO CREATE TSETSE FREE ZONES BY INTEGRATING DIFFERENT TSETSE CONTROL METHODS WITH THE RELEASE OF STERILE MALES

Taking into consideration current tsetse population suppression techniques, fly rearing methods, sterile male release technologies and other tools now available for assessing the confinement or isolation of a target tsetse population, there is an increased potential for the creation of sustainable tsetse free zones using an area-wide IPM approach with a SIT component (2). Areas with high potential for livestock and agricultural development containing biologically or geographically isolated tsetse populations should be considered as prime targets, especially when located at the geographical limit of the tsetse distribution allowing for a phased expansion of the target area. Available tsetse distribution maps indicate a fragmented fly population, rather than a continuous tsetse belt in East Africa. Unfortunately, these distribution maps are based on outdated field data, making extensive surveys in a chosen target area a prerequisite before embarking on any control operation. Remote Sensing (RS) techniques could complement the paucity of field data of certain geographical areas. All these RS and field collected data can be transferred to structured layers of Geographical Information Systems (GIS) to assist in the development of appropriate control strategies (94). Modern molecular genetic techniques can be used to assess gene flow between populations or sub-populations and can give critical indications on the degree of isolation of these populations (95, 96).

Some examples of 'population islands or peninsula like areas' that have high development potential and where the respective authorities and their partners schedule to launch area-wide tsetse campaigns with a SIT component include : 1. isolated valley systems in South - West Ethiopia (*Glossina tachinoides* Westwood, *Glossina fuscipes fuscipes* Newstead and *Glossina pallidipes* Austen), 2. the isolated *Glossina morsitans* centralis Machado belt in the Okavango delta in Botswana and Caprivi strip in Namibia and 3. peri-urban fly populations in riverine systems in West Africa. There are in addition, certain opportunity areas with sufficiently isolated tsetse populations that could be removed such

as : 1. the fragmented «island like» *Glossina pallidipes* Austen belt in East Africa, 2. the *Glossina austeni* Newstead-*Glossina brevipalpis* Newstead pocket in KwaZulu Natal, South Africa and 3. the «peninsula-like» distribution of *Glossina fuscipes fuscipes* Newstead around lake Victoria.

For each of these areas, appropriate SIT based IPM strategies need to be developed, integrating different suppression techniques with the release of sterile males depending on the specific situation and the tsetse species. The deployment of traps and targets might be considered in those situations where the operational area is small and the local communities overlap well with the tsetse fly distribution (e.g. peri-domestic habitats of *Glossina palpalis gambiensis* Vanderplank in West Africa). The participation of the local communities in the integrated programme will be limited to the suppression phase (usually not more than 1 year), avoiding the risk of 'participation fatigue' of the farmers. The live-bait technology (pour-on application of insecticides on livestock - cattle dips in strategic areas) can complement the trap and target methodology in areas of adequate cattle densities, provided that a significant proportion of the tsetse population feeds on cattle (97). The area-wide approach implies tackling an entire fly population and this inevitably includes tsetse populations in un-inhabited, isolated areas which are usually large. Aerial spraying of non-persistent insecticides could be the suppression technique of choice there, as all available evidence suggests that the SAT shows no lasting detrimental effects on the environment (98). In areas where fisheries are important, deltamethrin might be used in preference of endosulfan. Moreover, aerial spraying could possibly be substituted in areas with abundant river systems and on the shores of lakes with disposable targets deployed by helicopters or fixed wing aircraft (58). The applicability of this novel idea will depend on results of future research to assess the responses of different tsetse species to these targets and the technical and operational feasibility of deployment by air. These suppression activities are then followed by 'mop-up' operations using the sequential aerial release of large numbersof sterile males. The aerial dispersal technique can release sterile males easily in uninhabited and inaccessible areas, in potential dangerous areas of political unrest and in fragile ecosystems such as national parks where SIT will minimise the detrimental effects to the environment. One of the key bottlenecks will be the 'timely' delivery of large numbers of sterile males when the suppression phase has reduced the fly population sufficiently. This could be done by the creation of regional tsetse production centres in West, East and Southern Africa, which could supply the SIT package i.e. the delivery upon demand with some advance notice of adequate numbers of sterile males of different species of tsetse flies and aerial releases. In case tsetse species have to be produced, which are not naturally present in the area of the regional centre, fly proof systems will have to be developed and installed to prevent escape and establishment of new tsetse populations in the area. These regional centres will require an international mandate, support by regional and international experts, international funding and a location in politically stable countries ■

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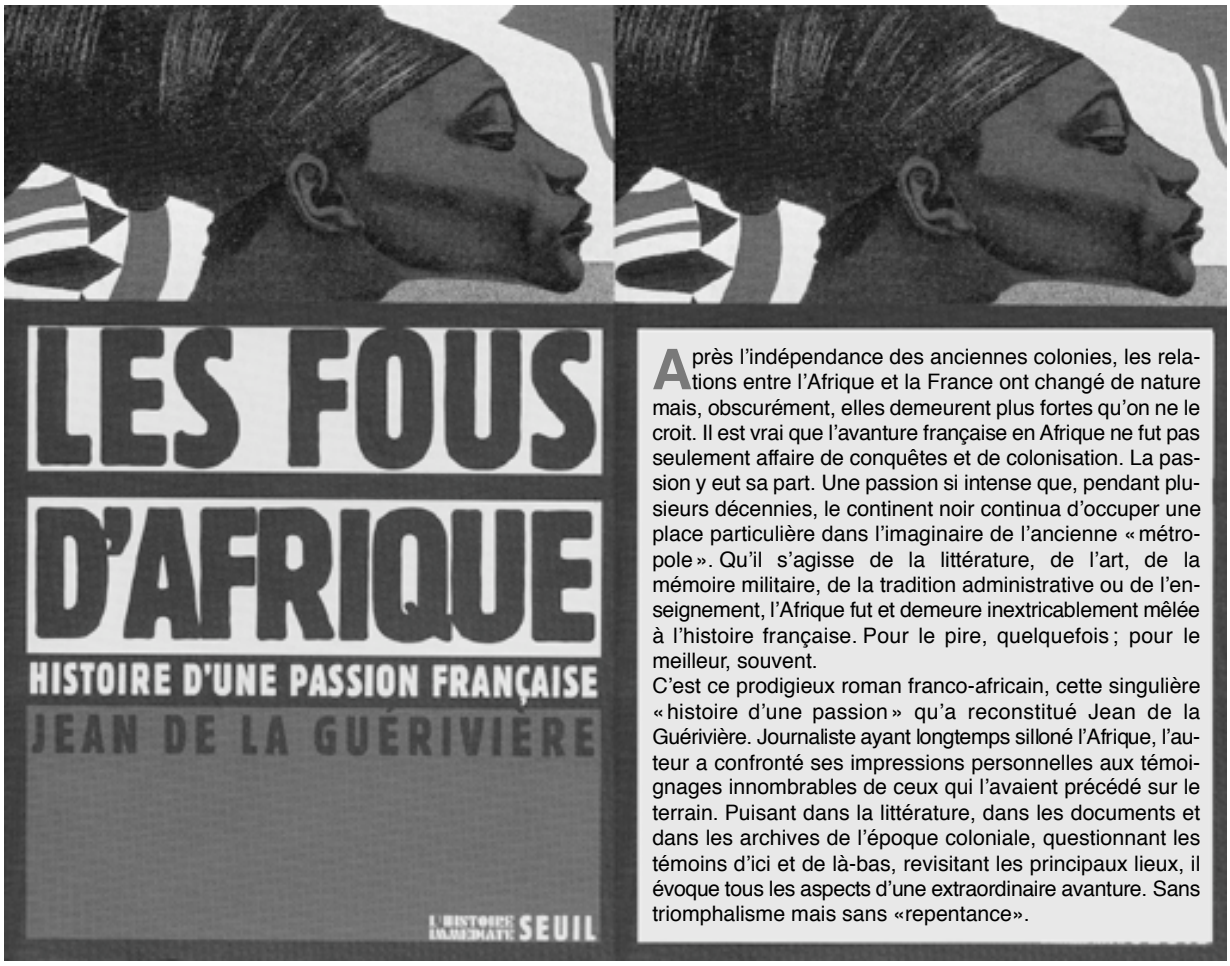

Après l'indépendance des anciennes colonies, les relations entre l'Afrique et la France ont changé de nature mais, obscurément, elles demeurent plus fortes qu'on ne le croit. Il est vrai que l'avanture française en Afrique ne fut pas seulement affaire de conquêtes et de colonisation. La passion y eut sa part. Une passion si intense que, pendant plusieurs décennies, le continent noir continua d'occuper une place particulière dans l'imaginaire de l'ancienne « métropole ». Qu'il s'agisse de la littérature, de l'art, de la mémoire militaire, de la tradition administrative ou de l'enseignement, l'Afrique fut et demeure inextricablement mêlée à l'histoire française. Pour le pire, quelquefois ; pour le meilleur, souvent.

C'est ce prodigieux roman franco-africain, cette singulière « histoire d'une passion » qu'a reconstitué Jean de la Guérivière. Journaliste ayant longtemps silloné l'Afrique, l'auteur a confronté ses impressions personnelles aux témoignages innombrables de ceux qui l'avaient précédé sur le terrain. Puisant dans la littérature, dans les documents et dans les archives de l'époque coloniale, questionnant les témoins d'ici et de là-bas, revisitant les principaux lieux, il évoque tous les aspects d'une extraordinaire avanture. Sans triomphalisme mais sans «repentance».