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Management of Tsetse Fly Using Insecticides in Northern Botswana

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1. Introduction

The tsetse fly (*Glossina* spp.) is only found in Africa and carries trypanosomes (the disease agents causing human sleeping sickness and animal trypanosomosis- *Nagana*), reaching their southern limits (particularly the *morsitans* group) in Botswana and Kwazulu Natal in South Africa. The tsetse fly transmitted disease is a serious problem in Sub-Saharan Africa and it is estimated that the removal of this disease could double livestock production and markedly increase cultivation levels. It is estimated that potential distribution of tsetse fly in Africa is 300,000 km² (Mathiessen & douthwaite, 1985).

Generally, the economic and social impacts of *nagana* and sleeping sickness on animal production and human health are severe, estimates put annual cattle production losses at US$2.7 billion and >55, 000 people dying from sleeping sickness annually (Budd, 1999). The disease is usually of chronic and debilitating form. It is essentially a problem in rural areas, where the threat and burden of such is a significant contributor to rural poverty and malnutrition.

In Botswana, the tsetse infested area covered ≤ 5% but has had significant impact on livestock and human populations, particularly in Ngamiland and Chobe regions, largely because of the wet areas in an otherwise dry country. Prior to the rinderpest pandemic of 1896 which significantly reduced tsetse populations in much of east and southern Africa as a result of the critical loss of food source, the distribution of tsetse fly in Botswana had reached its historical limits of approximately >20,000 km² (Ford, 1971; Jordon, 1986). As the tsetse populations recovered from the rinderpest epizootic the incidence of trypanosomosis increased. For instance, between 1949 and 1960, the cattle populations in Chobe District declined by ≤ 95% (Lambrecht, 1972). Ploughing along the flood plains is a common local practice in these areas, and whilst beneficial in the sense of optimal exploitation of soil moisture, this practice carries the risk of potential exposure of farm workers to tsetse fly bites. An average of 50 (geometric mean range = 13-272) trypanosomosis cases was recorded between 1957 and 1977 in Maun Hospital each year. Today the Okavango Delta, Kwando-Linyanti-Chobe areas are the most important destinations for international tourists and one of the major sources of revenue for the country. The risk of sleeping sickness within these areas is perceived as potential threat to the tourism industry, both locally and nationally (RTTCP, 1995).

However, at the end of the rinderpest epidemic, a rebound of the tsetse population in northern Botswana and the subsequent disease challenges led to the introduction of intensified control efforts in the mid-twentieth century using conventional and improved insecticide based methods. This chapter therefore reviews the history of management of tsetse fly control in Botswana, with specific focus on the factors that influence tsetse fly distribution in Botswana, methods of insecticide applications to control tsetse fly, effectiveness of the control methods, and monitored environmental impacts.

2. History, distribution, control and management of tsetse fly in Botswana

Comprehensive historical review of tsetse distribution in Botswana up to the 1980s is provided by Davies (1980). Early records largely from European explorers suggest that tsetse occurred in a continuous belt from Angola, through Caprivi Strip (Namibia) and then the Kwando-Linyanti and Chobe River systems, then via the Selinda Spillway to cover most of northern Botswana's Okavango Delta and its immediate surroundings including Nxai Pan N. P (Figure 1). The history of control and management of tsetse in Botswana is detailed below.

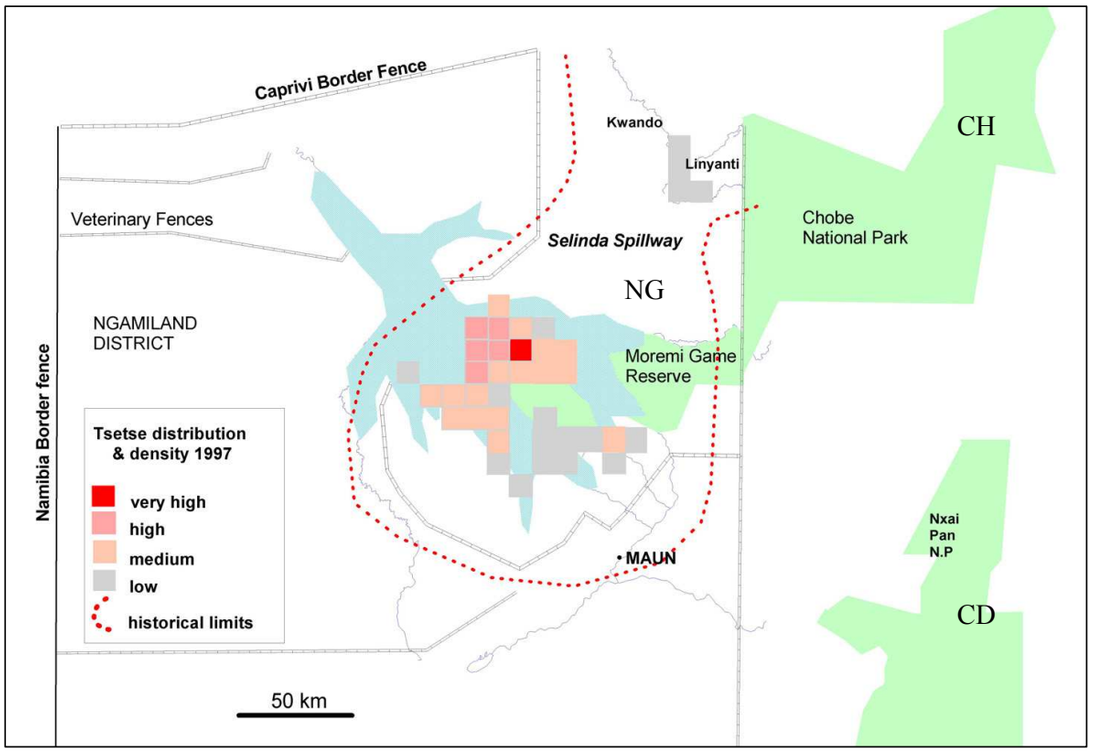


Fig. 1. Distribution of tsetse flies in Botswana (NG = Ngamiland District – Okavango Delta, Maun, Kwando Linyanti; CH = Chobe District – Chobe and Kasane; and CD = Central District – Nxai Pan N. P)

2.1 1940-1960 early methods of tsetse control

The disease Trypanosomosis (sleeping sickness and *Nagana*) is the primary reason for controlling tsetse fly in Botswana. In the early 1940s, cattle *Nagana* in parts of Ngamiland was so bad that a government tsetse control department was formed to combat the disease.

The earliest methods used for reducing tsetse numbers in Botswana (and throughout Africa), were large-scale clearing of bush and vegetation where tsetse fly rested, thus denying them shelter, and elimination of wild game animals which provided the natural food source of the fly. However, both these methods had huge environmental implications and were gradually phased out when alternative methods became available. Nonetheless, bush clearing continued as a complementary method until the mid 1960's (Davis, 1980). Game fencing also emerged as alternative, especially to limit the incursion of game animals into the settled areas of the Okavango Delta fringes.

2.2 1960-1972 residual ground spraying

The method of controlling tsetse using chemicals became common in the 1940s following the discovery of chlorinated hydrocarbon insecticides. In Botswana, residual insecticides such as DDT were introduced in 1967 by applying it to selected tsetse resting sites using knapsack spraying machines. This technique, known as *selective ground spraying*, targeted only about 20% of all potential tsetse resting sites in the woodland, including tree trunks, lower large branches, rot holes and holes on the ground such as ant-bear holes, springhare and hyena dens (Davies, 1980). The residual insecticides would remain available (even after spraying) to tsetse which emerged from underground pupal sites for 2 to 3 months after spray treatment. Given the accessibility challenges within the Okavango Delta, the ground spraying method of control got restricted only to the peripheral areas around the western Delta, the 'Maun Front' or along the Savuti Channel, and it was found to be unsuited to the swamps and island mosaics of the delta interior.

2.3 1970-1990 non-residual aerial spraying

Following preliminary trials carried out in 1971, Botswana's tsetse control strategy switched almost entirely to aerial spraying of insecticide using the Sequential Aerosol Technique (SAT). Very low dosages of endosulfan, and later a cocktail of endosulfan and synthetic pyrethroid insecticide were applied several times over the tsetse habitat to cover all the emerging tsetse pupal period. At best, the early SAT campaign by aerial spraying (Davies, 1979) reduced the tsetse distribution limits from 20,000km^2 to 5,000km^2 but still tsetse could not be eliminated completely despite that being the primary objective from the onset.

2.4 1990-2000 traps and targets

In 1992 Botswana (following other African countries) adopted the use of chemically-impregnated tsetse screens or targets and traps known as the *odour-bait technique* (Vale and Torr, 2004). The system was pioneered in Zimbabwe in the 1980s and became wildly used due to its perceived environmental sensitivity. Targets were treated with synthetic pyrethroid insecticides, particularly deltamethrin suspension concentrate formulation of 0.6% (w/v) following the treatment procedure (Kgori et al., 2006). In the technique the insecticide is applied only to the target screens and not the surrounding vegetation. All traces of the insecticide would therefore disappear once the targets are removed. The concept was well received and particularly suited for the Okavango's pristine wilderness.

Overall, the effectiveness of targets depended on the management and institutional capacity of the government's Tsetse Control Department. Effective distribution of targets and their regular maintenance in the Okavango Delta became a problem as the access was severely impeded by vegetation and terrain. However, a long period of drought ending in 1999 allowed some 25,000

targets to be deployed throughout much of the usually inaccessible parts of the Okavango Delta. These gains were to be reversed when good rains returned in 1999/2000, thus again putting the effectiveness of this tsetse control measure at question. With the above average rainfall, the tsetse fly was able to recover and disperse beyond the confines of the Okavango Delta, taking the threat of trypanosomosis once again back to the people and livestock. Cattle deaths resulting from *Nagana* increased during this period (Sharma et al., 2001).

2.5 2000 onwards - aerial spraying; a reversal in strategy

In the year 2000, the Botswana government initiated a new programme to control tsetse fly and trypanosomosis in and around the Okavango Delta. However, the primary objective remained unchanged; to eliminate tsetse and trypanosomosis from the Okavango Delta and the adjacent Kwando and Linyanti. Tsetse surveys in 2001 showed that the tsetse distribution limits had extended from 5,000 km^2 to about 12,000 km^2. Some 30,000 cattle within the villages surrounding the Okavango delta were clearly at risk of *Nagana* and they were subsequently treated with prophylactic trypanocides.

Reintroduction of aerial spraying became the cornerstone of the new campaign, but this time around targets were used as protective barriers between successive operations to stop tsetse fly from reinvading treated areas. Two aerial spraying operations were planned and executed in succession (in 2001 and 2002) to cover all the infestation in the Okavango Delta (Kgori et al., 2006; Allsopp & Phillemon-Motsu, 2002). In 2001, about 7,000 km^2 (upper box Figure 2) of the northern part of the Delta was aerial sprayed, followed in 2002 by 8,650km^2 (Lower Box Figure 2) of all the remaining infestation in the south (Figure 2). The insecticide of choice was deltamethrin (0.35% (w/v) ulv formulation applied at night using four turbo thrush fixed-wing aircraft. The aircraft were all guided by previously unavailable advanced navigation guidance system (Kgori et al., 2009).

3. Effectiveness of control measures

Apart from limited ground spraying in accessible peripheral areas such as Savuti Channel in the Chobe District, aerial spraying using ulv applications of endosulfan was the only method used to control tsetse fly in Botswana in the 1970s and 80s. Unfortunately for Botswana, since tsetse fly control was conducted largely in aquatic and pristine environment, endosulfan concentrations had to be kept lower than usual; it was applied at maximum of 12 g ha^{-1} compared to operations in other countries where higher levels of 16 to 20 g ha^{-1} were used to achieve comparatively good results (Douthwaite et al., 1981).

Typically, a series of aerial spray treatments were applied at night-time in winter with stable air and temperature inversion conditions in place, and using Piper Aztec or Cessna 310 aircraft from a height of about 15 m above the tree canopy. Under such inversion conditions, the tiny insecticide droplets would drift through the tsetse habitat in order to effectively kill adult tsetse fly. The insecticide was dispersed through a micronair atomizer set to give droplets in the range of 30–40 microns. This ensured that only small quantities of the insecticide were applied to the tsetse habitat. During these early years of aerial spraying, SAT operations were flown without the benefit of advanced aircraft guiding systems which are available today. Therefore spray distribution relied upon far less sophisticated methods of guidance such as ground marker parties with hand held miniflares positioned at each end of the spray run in order to guide the pilots. Also the formulation was non-residual in

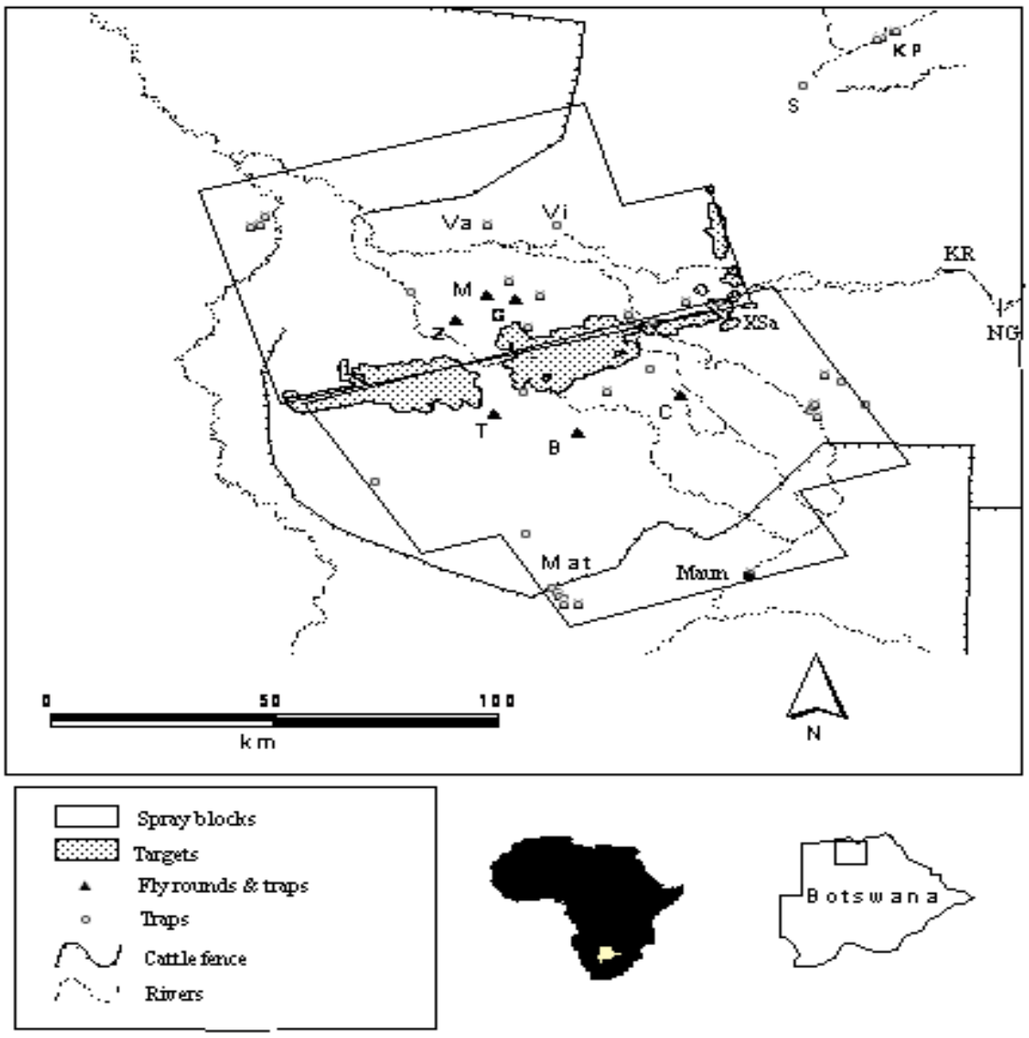


Fig. 2. Operations to control tsetse in the Okavango Delta region of Botswana conducted between 2001 and 2002, and the locations of tsetse and other non-target agents' monitoring sites. Sites indicated by solid triangles indicate the permanent sites at Zimbiri (Z), Mombo (M), Guai (G), Thapagadi (T), Bobo (B) and Chief's Island (C). Open circles indicate occasional monitoring sites used at various times during the spraying operations, including Kings Pool (KP), Selinda (S), Vumbura (Va), Vundumxiki (Vi), and Matsibe (Mat). Source: Kgori et al (2006). Xakanaxa Salvinia monitoring sites (XSa), Khwai River (KR) and North Gate (NR) – Source: Kurugundla and Serumola (2007).

nature; the insecticide deposition remained in the environment only for a short period of time and therefore was non-persistent.

Large-scale trials (1,000 – 4,000 km²) of aerial spraying with endosulfan in Botswana began in 1973 as a pilot programme to assess the feasibility of even bigger operations to eliminate tsetse fly from the whole of the Okavango Delta (Davies, 1979). By the mid 80s, the scale of the annual operations had increased to about 6,000 – 9,000 km² and very good control was achieved. The distribution limit was reduced significantly from 20,000 km² to 5,000 km² and

the threat of both *Nagana* and human sleeping sickness was effectively controlled due to sequential aerial spraying of insecticide, reduced water levels with less flooded areas and increased drought conditions in Botswana. Sequential spraying was necessary because the tsetse (i.e., young adults) would continue to emerge from the underground pupal stage for several days after each preceding cycle.

However, despite repeated applications complete eradication was not possible. Several possible reasons may have contributed to the failure by early SAT operations to achieve eradication in Botswana - including; low dosages used, lack of boundary protection since odour baited targets were unavailable then, poor navigation and random rather than systematic treatments. The navigation challenges observed often resulted with localized over-spraying which raised environmental concerns, notably fish kill (Merron & Bruton, 1991), but the low dosages used ensured that only limited off-target effects were possible.

4. Deltamethrin

When endosulfan-based tsetse aerial spraying campaign was ended in 1992, targets almost immediately became the next and only preferred option for tsetse fly control in Botswana. At the time, pyrethroid insecticides were also becoming firmly established in the insecticide market and Deltamethrin was the preferred choice for use in the treatment of odour-baited targets (Vale & Torr, 2004). For the next ten years, targets remained the only method used for controlling tsetse in northern Botswana's Okavango Delta, Kwando-Linyanti-Chobe River systems. A new integrated strategy involving the reintroduction of sequential aerial spraying was later introduced in 2001 when targets were proving difficult to effectively implement in Northern Botswana due to accessibility problems.

Prior to commencement of spraying in May 2001, tsetse surveys indicated that tsetse distribution had increased significantly to about 12,000 km² from the previous 5,000 km² since the end of the last aerial spraying campaign in the 1980s. Increased spread of tsetse fly could be attributed to a long period of no effective control and above average rainfall coupled with increased flood inflows in the Okavango Delta. Also the use of motorized boats as well as airplanes used to transport tourists in and out of the Delta contributed to the spreading of tsetse flies. This was evidenced by the occasional sighting of the tsetse flies in Maun which became a real concern to authorities, and hence the need for concerted effort to reverse the situation.

A two year aerial spraying operation (2001 and 2002, Figure 2) for the north and south of the Okavango Delta using Turbo Thrush Aircraft was planned and implemented in succession to cover the entire Okavango Delta. At the interface of the two spray blocks a target barrier was deployed to prevent tsetse crossing from one unsprayed area to another sprayed area between the successive spray operations. The revised strategy also included a component of the sterile insect technique (SIT) as technical backstop, should SAT fail to eliminate tsetse as was previously the case in the 1980s (Feldmann, 2004).

Improvement in the reintroduction of aerial spraying in 2001, 2002 and 2006 was the availability of latest navigation systems which could ensure precision placement of spraying material and eliminate overdosing or even under-dosing through erratic track guidance. For instance all aircraft were fitted with GPS-guided SATLOC navigation and spray management equipment accurate to about 1m. The system therefore had control on the distribution of the spray application and automatically cut off the spray if the aircraft wondered out of the spray block and indeed the prescribed flight path. The aircraft insecticide dispersal units involved

two boom-mounted micronair AU 4000 rotary atomizers operated at cage speeds of 10,800 rpm and flowrate of 7.6-8.6 l/km². Such technology development used in recent SAT operations had positive implications on the distribution and deposition of formulated insecticide droplets and, ultimately on the efficiency and effectiveness of the spray application. During 2001 and 2002 operations, and later in 2006 at Kwando and Linyanti, deltamethrin insecticide (0.35% (w/w) ulv formulation was applied at 0.26 -0.30 g active ingredient (a.i.) ha^{-1}. The higher dose rate of 0.3 g a.i. ha^{-1} was used for the first two cycles when tsetse fly population would normally be at its highest density (Saunders, 1962).

Initially, two successive spray treatments were conducted in 2001 and 2002 to cover approximately 16,000 km² in the Okavango Delta (Figure 2). A similar and follow up operation took place in 2006 covering an additional 10,000 km² of the Kwando and Linyanti border area, north of the Okavango Delta which also extended across Namibia's eastern Caprivi border into Southern Angola (Figure 3) in order to guarantee complete removal of all the remaining tsetse fly infestation in northern Botswana. This approach ensured that the northern tsetse infestation along the Kwando and Linyanti Rivers did not re-infest the Okavango Delta.

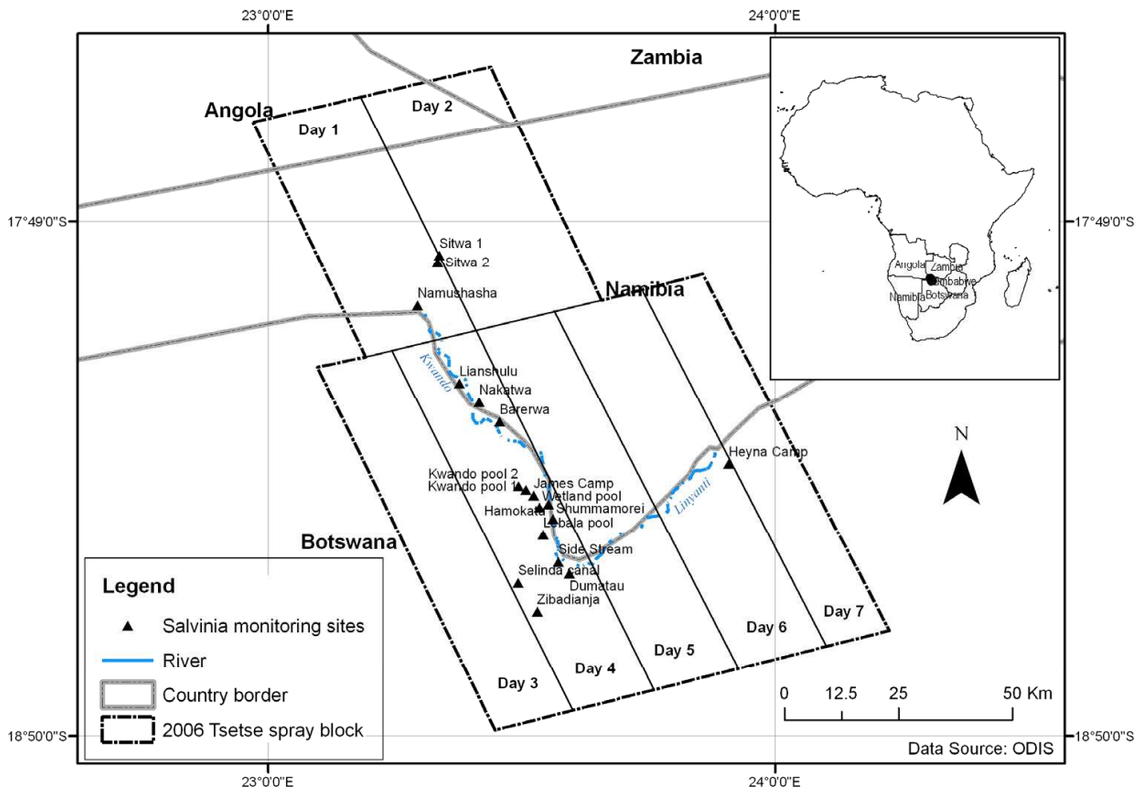


Fig. 3. Area of deltamethrin spraying in 2006. Sites of bioassay experiments and field monitoring areas to assess the impacts of deltamethrin spray on salvinia weevils and other aquatic invertebrates in Kwando-Linyanti River System.

Spraying of the block (7000 km^2) commenced on 3 June 2001. Figure 4 shows the mean daily catch from the five fly-rounds (Figure 4A) and 18 traps within the spray block (4C), and the fly-rounds outside it (Figure 4B). The results from the fly-rounds within the block show that the mean tsetse catch up to the first day of spraying was 44.6 tsetse day^{-1}. Immediately after each cycle the daily catch declined to zero, but then recovered to peaks of 12.8 tsetse day^{-1} after the 1st cycle and 20.6 tsetse day^{-1} after the 2nd cycle. Thereafter recovery was less marked, peaking at 6.3 tsetse day^{-1} after the 3rd cycle, 1.2 tsetse day^{-1} after the 4th cycle and finally no tsetse was found after the 5th cycle. By contrast, the daily catches from fly-rounds outside the spray block (Figure 4B) increased significantly over the period of spray operation.

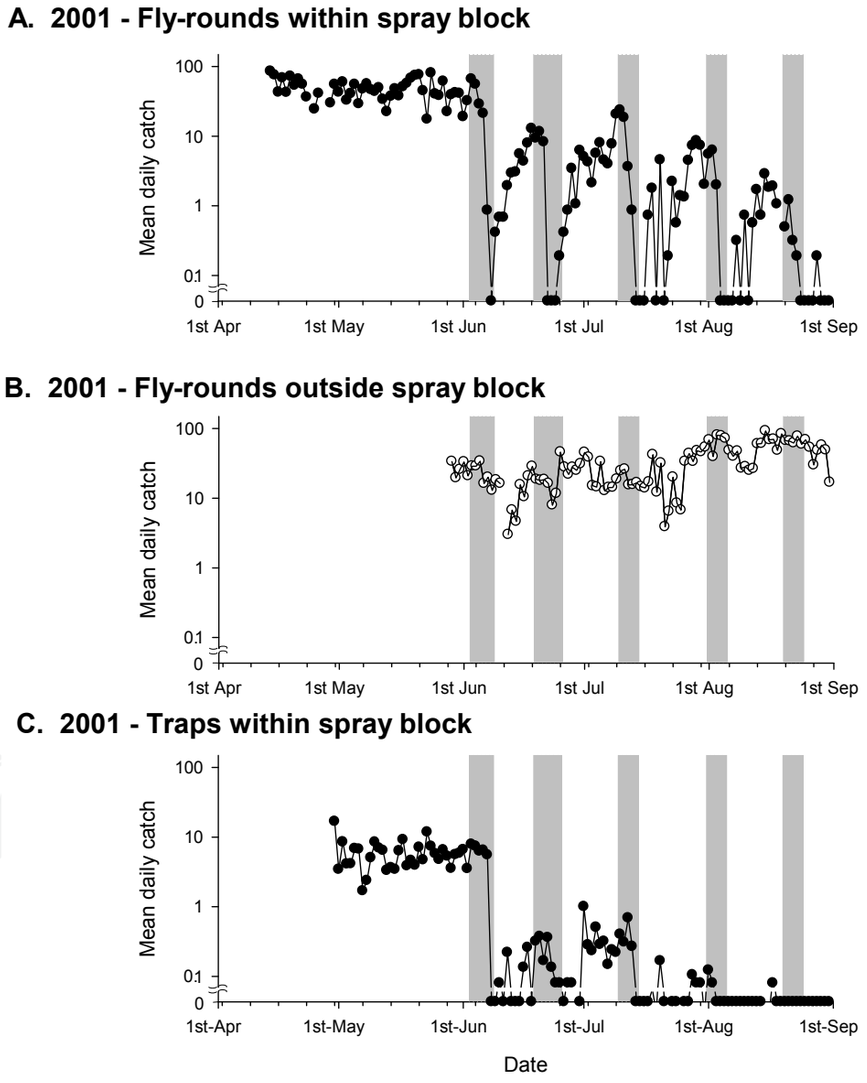


Fig. 4. Detransformed mean daily catch of tsetse from fly rounds and traps within (Mombo, Guai and Zimbiri) or outside (Chief's Island, fly rounds only) the area sprayed during the 2001 control operation. Vertical grey bars indicate the timing of the five spray cycles. Source: Kgori et al., (2006).

Spraying commenced in the south block (8650 km^2) on 16 May 2002. Following the start of spraying, the catches declined dramatically (Figure 5). For instance, the mean daily catch from fly-rounds was 101.7 (±0.026, *n*=148) for the period 10 April - 16 May compared to 0.23 (±0.019, *n*=66) for the period 24 May - 3 June, this being the period between the end of 1st spraying cycle and the beginning of the second cycle (Figure 5A) and after the 4th cycle no tsetse were found. The catches from traps showed a similar decline (Figure 5B). During 2006 campaign, the tsetse surveys started on 13th May 2006 (Day 1 = 13 May 2006. Figure 6 shows that the abundance of tsetse was higher than 100 with fluctuations in Kwando-Linyanti prior to spraying and it reduced to zero after 2nd, 3rd, 4th and zero catches after the 5th spraying cycle (Kgori et al., 2006, Kgori et al., 2009, VEEU-TCD/DAHP 1998).

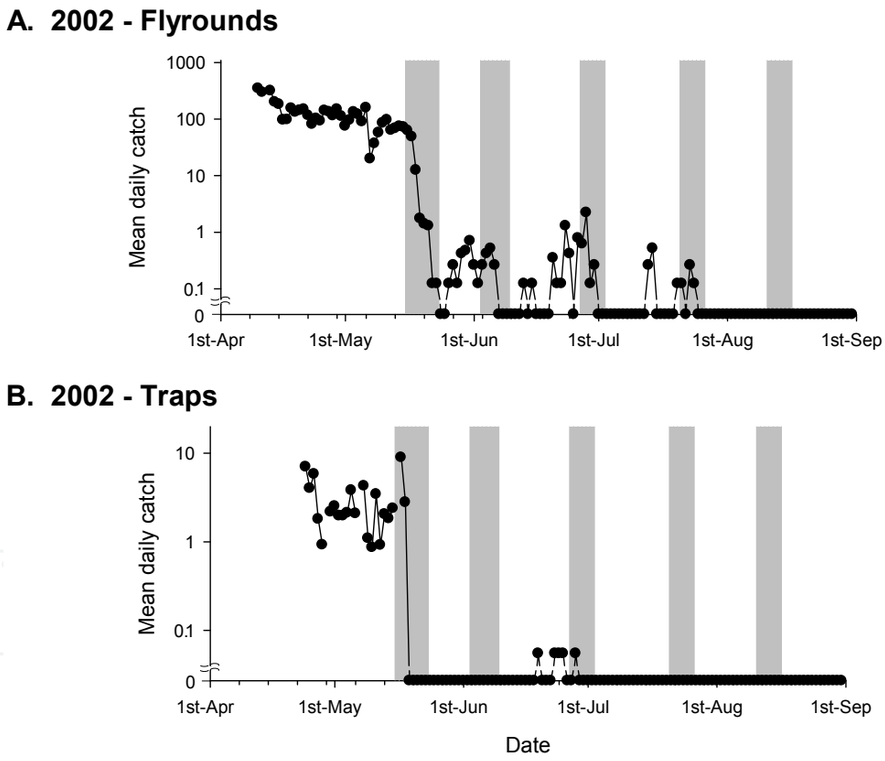


Fig. 5. Detransformed mean daily catch of tsetse from fly rounds and traps within (Bobo Island, Thapaghadi and Chief's Island) the area sprayed during the 2002 control operation. Vertical grey bars indicate the timing of the five spray cycles. Source: Kgori et al., (2006).

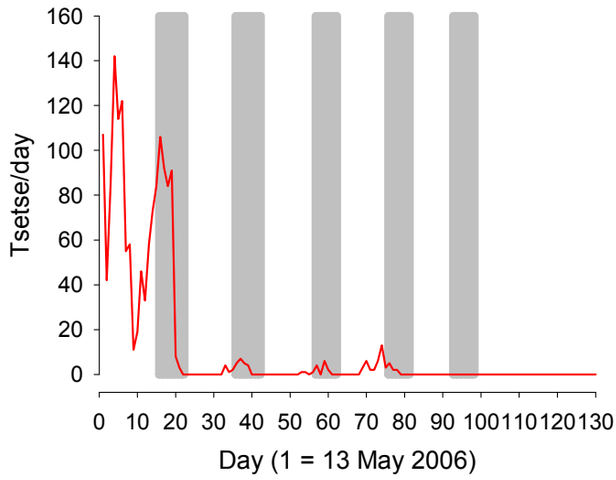


Fig. 6. Tsetse survey results at Kwando/Linyanti 2006 in five spray cycles.

5. Environmental implications

5.1 DDT

'Silent Spring' (Carson, 1962) described the environmental impacts of the indiscriminate spraying of DDT (Dichloro-diphenyl-trichloroethane) in the world and its effects on ecology or human health. It has high potential to bioaccumualte especially in predatory birds and magnify through food; and still highly effective against disease vectors such as malaria parasite (Thomas, 1981). DDT was banned for agricultural use worldwide under the Stockholm Convention but its limited use in disease vector control still continues in some parts of the world to this day and remains controversial (Connel, 1999). Its persistence ranges from 22 days to 30 years depending on the conditions of the ecosystem. It is insoluble in water, less biodegradable and degrades by means of aerobic, anaerobic and photolysis (Thomas, 1981). No specific monitoring of impacts of DDT spraying in Botswana was ever carried out.

5.2 Dieldrin

Deldrin was used world-wide to control locusts and tropical disease vectors, such as tsetse fly and mosquitoes prior to the 1970s, and has persistence of 5-25 years. It has similar characteristics to DDT (Hunter & Robinson, 1968). Botswana was one of the first countries in Africa to monitor the side-effects of chemical control of tsetse fly. In 1964 riverine forests were sprayed with Dieldrin against *G. morsitans* in an area near Maun in the Okavango Delta, Botswana. The effects of the motorized spraying (mist blower) on non-target organisms were observed for a period of 10 days following spraying (Allsopp, 1978). Among the animals found dead were many birds, mammals, reptiles and fish (Graham, 1964). Casual observations of the aerial spray showed no difference between the wildlife populations between the sprayed and unsprayed areas (Davies & Bowles, 1979).

5.3 Endosulfan

Endosulfan degrades more rapidly than DDT and dieldrin; 9% degradation in water between 5-25 days, 15-30 days from vegetation surface, but remains more than 100 days to

one year in soil as residue (Maier-Bode, 1968). It is being phased out globally and a global ban on the manufacture and use of endosulfan was initiated under the Stockholm Convention in April 2011. The ban will take effect in mid 2012 and more than 80 countries became part of the ban (http://en.wikipedia.org/wike/endosulfan). Chemical control methods have been used in anti-tsetse campaigns in at least 20 countries in Africa. Side-effects on non-target organisms have been studied to a greater or lesser extent in only about half of the 20 countries (Table 1).

Country	Year (s)	Type of insecticide + method of application	Reference
Botswana	1964 1975-78 2001-02 2006	Dieldrin - Ground spray (Mist blower) Endosulfan ULV Fixed-wing Deltamethrin – Aerial spray Deltamethrin - Aerial spray	Graham, 1964 Ali, 1978; Fox et al., 1979 Perkins and Ramberg, 2004; 2004a Bonyongo & Mazvimavi, 2007; 2008
Cameroon	1979	Dieldrin – Helicopter	Muller et al., 1980
Chad	1972-1974	DDT- Ground spray	Tibayrence and Gruvel, 1977
Ivory Coat	1979 1968-69	Dieldrin – Ground spray Endosulfan and Decamethrin – Helicopter	Koeman and Pennings, 1970 Everts, 1979
Kenya	1970-72	Dieldrin – Fixed wing	Allsopp, 1978
Namibia	2006	Deltamethrin – Aerial spray	Bonyongo & Mazvimavi, 2007; 2008
Niger	1968 1969-70 1974-76 1977	DDT – Ground spray Dieldrin –Ground spray Dieldrin – ULV Helicopter Endosulfan – Helicopter	Koeman & Pennings, 1970 Koeman et al., 1971 Koeman et al., 1978 Dortland et al., 1977
Nigeria	1975-76 1976 1976 1977-78	Dieldrin/Endosulfan ULV helicopter DDT/Endosulfan – Ground spray Endosulfan – ULV fixed-wing Pyrethroids –Ground and Helicopter spray	Dortland et al., 1977 Koeman et al., 1978 Takken et al., 1976 Smies et al., 1980
Tanzania	1961-71 1979	Dieldrin – Ground spray DNOC (2 methyle-4, 6-dinitro-ortho-oresol), Bush clearing	Sserunjoji & Tjell 1971 Tarimo & Palloti, 1979
Uganda	1963-73	Endosulfan-pyrethroids – Helicopter	Wilson, 1972
Zambia	1968	Endosulfan – ULV fixed-wing	Magadza, 1979
Zimbabwe	1978	Endosulfan – ULV aerial	Cockbill. 1979

Table 1. Anti-tesetse fly campaigns in Africa and impacts studied on the non-target agents.

Deposition

The insecticide deposition in the various habitats in the Okavango Delta is presented in Table 2. However, the range and frequency of individual values are insignificant between them (Douthwaite et al., 1981). Endosulfan concentration in different types of aquatic habitats nine hours after spraying at 9.5 g ha^{-1} varied with depths and the values were insignificant between the various habitats: In marshes ≤ 0.5 m = 0.81 µg l^{-1}; in main river between 1-2 m depth = 1.16 µg l^{-1} and in open pool at ≤ 0.5 m depth = 1.54 µg l^{-1} where as persistence of the insecticide in pools of water declined from 1.42 µg l^{-1} nine hours after spraying and undetectable levels within five days (Douthwaite et al., 1981). Its half life in aquatic environment is between one and five days (Moulton, 1973).

	Open water	Water in grass swamp	Open grassland	Grassland under tree canopy
Mean (Range) Variance	20.7 (1.4-42.9) 116.1	17.7 (3.6-45.9) 193.8	21.1 (4.5-43.8) 188.3	14.3 (2.4-24.5) 54.2

Table 2. Quantities of endosulfan (µg) drift found on aluminum sheets placed in different habitats and analyzed one hour after spraying 9.5 g ha^{-1} (4 µg per sheet = 1 g ha^{-1}). Source: Douthwaite et al., (1981).

5.3.1 Fish

Bioaccumulation

The major route of uptake in aquatic invertebrates is probably via the digestive system (Roberts, 1975), whereas fish absorb most endosulfan directly from the surrounding water injuring gills, thus reducing the oxygen consumption and disrupting the osmoregulatory function of aquatic organisms (Saravana & Geraldine, 2000). Dortland et al., (1977) have shown that endosulfan applied at 900 g ha^{-1} for tsetse control near West African Rivers produced residue levels of 1.4 and 37.3 µg g^{-1} fish muscle and liver respectively. Experimental applications of endosulafan to fish in paddy fields (Moulton, 1973) showed that gouramis, *Tricho gaster pectoralis* could accumulate the pesticide in abdominal organs to concentrations over 1000 times those in surrounding water. It was found that the absorbed endosulfan in fish was rapidly metabolized to the endosulfan sulphate (Ali, 1978).

The edible fish species tested for bioaccumulation during the endosulfan spraying in Botswana include species of *Clarias, Serranochromis, Schilbe, Haplochromis, Tilapia, Marcusenius*. Endosulfan mean residue concentration with respect to percentage lipid 5 days after the spraying was 0.19 µg g^{-1} wet tissue in muscle, while the maximum found in whole dead small fish was 1.5 µg g^{-1} wet tissue. These values refer to the combined concentration of alpha+beta + endosulfan sulfate - all three compounds are equally toxic to the fish (Anon, 1973). The USA has set a tolerance limit for endosulfan in meat of 0.2 µg g^{-1} fresh weight; this therefore means muscle tissue from living fish in the Okavango would be considered safe (Douthwaite et al., 1981).

Fatty species tend to accumulate the most endosulfan (Douthwaite et al., 1981), and one might perhaps expect these groups would show greater mortality in the field. Such

relationship was however, not apparent in the study because the very fatty insectivore *Marcusenius macrolepidotus* was never found dead after spraying as they accumulated higher residue concentration of 1.002 µg g^{-1} wet weight in its viscera lipid. So the bioaccumulated insecticide can do little damage to vital metabolic processes. Indeed, the laboratory experiments with *Hepsetus* suggest that the fatty lean fish is susceptible and succumb most readily to poisoning to endosulfan and thus fish weight is probably the dominant factor determining the survival, i.e. fry and small individuals are at greater risk. Tests with the predators of fish such as crocodile *Crocodilus niloticus*, fish eagle *Heliaeetus vocifer*, Kingfisher *Ceryle rudis* accumulated endosulfan residues, although these never exceeded 0.2 µg g^{-1} wet weight, except in the visceral fat of the crocodile with 0.783 µg g^{-1} wet weight suggesting again that fatty organs tended to accumulate the highest residue concentrations (Douthwaite et al., 1981).

Mortality

During ultra-low-volume aerial applications of endosulfan at 14g ha^{-1} for control of tsetse fly in savanna woodland, Zimbabwe, no deleterious effect of the insecticide was demonstrated, other than fish (*Tilapia* spp.) in shallow water (Cockbill, 1979). In general, endosulfan killed small fish first, (*Alestes lateralis)* although almost all species were ultimately affected by the 10 g ha^{-1} spray. An endosulfan spray done in the Okavango Delta in 1978 showed that the fish mortality extended over a period of 3 days after spraying in four cycles (Table 3). Fish species affected included *Tilapia, Hemichromis, Haplochromis, Pseudocrenilabrus, Serranochromis, Clarias, Barbus, Schilbe and Hepsetus.* Among them, *Tilapia* was the dominant species affected with 65% poisoning followed by *Pseudocrenilabrus* with 13% (Douthwaite et al., 1981).

Fish mortality per hectare (n = 9 sites)			
Cycle 1	Cycle 2	Cycle 3	Cycle 4
12 g ha^{-1}	12 g ha^{-1}	9 g ha^{-2}	6 g ha^{-2}
542.7 ±339.6 (0-3250)	544.9 ±266.5 (0-2344)	672.1 ±336.5 (0-2531)	2.0 ±1.6 (0-16)

Table 3. Fish mortality resulting from endosulfan spray in Khwai River in the Okavango Delta. (SE ± = sd/$\sqrt{n}$). Figures in the parantheses indicate minimum and maximum mortality (Source: Douthwaite et al., 1981).

The general symptoms of endosulfan or other pesticides' poisoning in fish are epithelial lifting (Bucke et al., 1996, Choudary et al., 2003), Hyperplasia (Munshi et al., 1996), muscle hypertrophy and aedema, liver necrosis (Bucher & Hofer, 1993). Samples of liver and brain were tested from *Hepsetus odoe, Tilapia sparrmanii, T. rendalli and Sarotherodon andersoni* throughout the 1978 spraying and during the ensuing 7 months. Whereas liver samples alone were collected from *Clarias ngamensis and C. gariepinus*. In general endosulfan spray induced liver focal (peripheral) necrosis, brain aedema leading to encephalitis, lining in cephalic tissue during the spray periods as well as 15 days after cycle 6 in the species tested. However, the fish showed healing areas of focal necrosis in liver, absence of aedema in brain in the post spray periods after 7 months. Among the species, *Hepsetus odoe* was tolerant to endosulfan showing only slight change in the fatty liver few days after the spray (Douthwaite et al., 1981).

5.3.2 Aquatic invertebrates

Among the Oligochaeta, Chironomidae, Trichoptera and Ephemeroptera groups the numbers of Chironomid larvae reduced significantly (P≥ 0.001), Oligochaets and Ephemeroptera reduced in abundance while Trichoptera showed fluctuations during the 1978 spray. The decrease in Chironomid larvae in the sprayed lagoon was unexpected as the reported LC50 values for the larvae were considerably higher than the residue levels recorded in the study indicating a normal seasonal change. The Ephemeroptera, Oligochaeta and Chironomidae remained almost constant in pre spray, mid spray while in post spray they increased significantly reflecting positive response to the falling water levels rather than related to the endosulfan effects. With the exception of *Hexarthra* sp. the species namely *Filina, Brachionus, Keratella* and *Polyarthra* perecentage representation was considerably lower in the lagoons following the spraying season (Douthwaite et al., 1981).

5.3.3 Terrestrial invertebrates

The abundance of terrestrial invertebrates in floodplains, grassland and in dry land under tree canopies, *Colophospermamum mopane* canopies in the sprayed and unsprayed areas was determined in the Okavango Delta. The major groups in the studies included Chironomidae, Cicadellidae, Diptera, Hymenoptera, Orthoptera, Araneae, Formicidae, Coleoptera. Only in the case of adult *Chironomids* was there a large reduction in numbers in the sprayed site. However their abundance was almost identical in the post spray periods with the 'control sample' attributing doubts over the spray effects. Three of the major groups namely Formicidae, Tenebrionidae and Diptera showed reduction in activity and the most affected genus was the *Pheidole* in Formicidae following the spray. There was a significant decrease in numbers (P≥ 0.05) of spiders in the sprayed site which correspond to the significant increase (P≥ 0.001) in the sprayed site in the 3rd cycle (Douthwaite et al., 1981).

5.3.4 Flying insects

The behaviour of nocturnal insects during the spraying in the Okavango Delta was caught in the water trays in the grassland along the margins of the permanent swamps before and after each spray application in both sprayed and unsprayed areas. In the first spray cycle a sharp peak in mortality was observed in the adult *Chironomid* insects trapped in the sprayed site. However similar results were not obtained during subsequent spray cycles. This could be due to the emergence of adults from the larvae as the adults have short life-span. Among other groups, only Culicidae, some *Nematocera* and *Diptera spp.* were abundant in water traps and fluctuated in numbers from night to night in both sprayed and control sites, thus showing that there was no consistent evidence for either decreases or increases following each spray cycle (Douthwaite et al., 1981).

5.3.5 Birds

Endosulfan is neither toxic nor cumulative in birds and therefore unlikely to be lethal to them. However, there could be indirect effects on the insectivorous and piscivorous birds through disruption of their food supplies. The occurrence of birds in *Acacia* woodland was monitored before and after spraying in 1978 using transects. Besides similarities in the species in four transects, each transect lost and gained some species between sampling

periods, but no species disappeared from both sprayed and unsprayed transects. A comparison of 39 species was grouped by diet, and by site and method of feeding. To determine the source of the heterogeneity comparisons were made within groups of insectivores, frugivores and granivores and birds with mixed diets. Significant heterogeneity occurred only in the granivores such as *Lamprotornis* starlings that increased in the unsprayed transects but declined in the sprayed transects, and the Grey Hornbill *Tockus nasutus* and Sengegal Coucal *Centropus senegalensis*, which did the opposite. The other insectivore species showed divergent occurrences include Meyer's Parrot *Poicephalus meyeri,* a granivore, Brubru *Nilaus afer* and Red-billed Wood-hoopoe *Phoeniculus purpureus*. These changes in occurrence could, in view of the varied habitats of the species concerned, be as well explained by rainfall, vegetation re-growth between sprayed and unsprayed transects as by the effect of spraying.

The major diet for kingfisher (*Ceryle rudis*) is fish ranging from 28-112 mm and 0.2 to19.1 g in weight. The diet consists mostly of *Tilapia, Haplochromis, Barbus and Pseudocrenilabrus*. These species accumulated the endosulfan in liver and brain and the feeding of these fish by kingfisher may have some concentrations of endosulfan. The study showed the total concentration of alpha and beta endosulfan and endosulfan sulfate in the pooled samples from three kingfisher birds as 0.012 µg g^{-1} wet weight in the liver and 0.205 µg g^{-1} weight in the brain. These concentrations are no higher than the levels found in fish and agree with earlier observations (Maier-Bode, 1968).

5.4 Deltamethrin

Deltamethrin is a broad spectrum insecticide, relatively stable but less persistent in the environment than the organochlorine pesticides (Grant & Crick, 1987). It has been in wide use in various crops, in gardens, indoors, outdoors for controlling pests such as mites, ants, weevils, beetles, leafhoppers the world over (Tomlin, 2006). Its persistence ranges from 8 to 48 hours (Erstfield, 1999) in water and 5.7 to 209 days (EFASP, 1999) in terrestrial habitats. Reported concentrations in water are rarely greater than 20 *ng* l^{-1} (Amweg et al., 2006) and were only found to be toxic to honey bees (*Apis* sp.) (Tomlin, 2006). The 2001 deltamethrin spraying over the upper Okavango Delta was done with very little systematic monitoring of the impacts/effects on the non-target organisms (Perkins & Ramberg, 2004). However, the subsequent spraying in 2002 period was done with adequate regular monitoring from the 1st to the 5th cycle. The analysis of data has been assessed by two methods.

i. Sampling was carried out just before each cycle spraying event and in the following day after the spraying. This assumed that significant changes in abundance of individuals in any taxa are likely to be caused by the spraying.
ii. Analysis of trends in numbers of any taxa is compared from cycle 1 to 5 to show the tolerance and susceptibility.

In 2002, the spray deposition as determined by rotating slides was between 23 and 867 drops cm^{-2} and varied considerably within and between sites (Wolski & Huntsman-Mapila, 2002), which could be due to habitat variation, wind, temperature and distance from the flight lines. The wool strands that were exposed to the spraying absorbed the insecticide and revealed that for tsetse fly lethal concentrations were likely to have lasted for four to five days after the spray event (Perkins & Ramberg, 2004). However deltamethrin deposition determined in water, sediments and soil in 2002 and 2006 yielded almost insignificant results except one sediment sample that had low levels of the insecticide (Bonyongo &

Mazvimavi, 2007). Nevertheless, the insecticide deposition as captured by spreading aluminium foil sheets during the monitoring of salvinia weevils gave between 0.2 µg m^{-2} and 6.9 µg m^{-2} in 2002 and 2006 spraying occasions (Kurugundla & Serumola. 2007; Kurugundla et al., 2010).

5.4.1 Aquatic Invertebrates

Impacts - 2002

It is well known that flowing and still water usually differ in biotype composition and hence aquatic macro invertebrate studies were undertaken in still water of pools and flowing channels in Xakanaxa. The results were compared with those of the control site of Khwai River at North Gate. A total of 695 macro invertebrate samples and 200 zooplankton samples were collected, and 64 macro invertebrate families were identified. In channels, abundance declined by 46% after five spray cycles (927 individuals to 520) and in lagoons it declined by 25% (1230 individuals to 917). However, in the reference control site in Khwai River at North Gate, the abundance increased slightly over five spray cycles (789 individuals to 839) (Palmer, 2002).

Samples fixed in 75% ethanol were identified to family in the field using Gerber & Gabrial, (2002) and Davies & Day, (1998). A total of 47 taxa were recorded in channels and 49 taxa in lagoons and in total 65 taxa were identified, of which 23 taxa commonly occurred consistently in samples before and after the spraying. Out of these common taxa 6 showed distinct rapid declines after the first spray cycle and had disappeared completely after the fifth cycle. This corresponds to a loss of 26% of common taxa and was likely caused by the deltamethrin spray deposition. Whereas at North Gate on the Khwai River control site, the number of taxa increased from 29 to 30 after five spray cycles.

It has been shown that the mortality differs between the channels and lagoons and also between the taxonomic groups. Among 64 taxa, more than 24 have been found to be susceptible while few taxa (11) were found to be resistant to the insecticide spraying. Mollusks are probably more physiologically resistant to spraying than insects for obvious shell protection. The other survivor insect families include Chironomidae (non-biting midges), Ceratopogonidae (biting midges), Libellulidae (hairy dragon flies) and Caenidae (crawling mayflies). All these entire insect families live in the sediment, which may function as a protection against the insecticide spray, which is less bioavailable as the pyrethroids could be partitioned and adsorbed to various organic sediments (Muir et al. 1985). On the other hand, the elimination rate recorded for the Hemiptera (water bugs) Carduliidae (dragonflies), for most Ephemeroptera (mayflies) families and some other families could be understood by their active behavior in free water surfaces, sediment and vegetation surfaces. In particular the air breathing behaviour exhibited by most Hemiptera and Coleoptera (beetles) force them to come into contact with deltamethrin and oil-based carrier, paraffin that accumulate on water surface as a thin film (Perkins & Ramberg, 2004; Bonyongo & Mazvimavi, 2007).

Recovery - 2003

The recovery monitoring was measured in 2003 at the same periods and similar sites to those used in 2002 in order to assess recovery at community, family and morphospecies levels. The total abundance after a year was still significantly lower: 39% in channels and

60% in lagoons. The spraying caused significant reductions in abundance of many sensitive taxa often specific for respective habitats like lagoons and channels. What remained in both habitats was a common group of resistant species. The distinct feature is that the reappearance of some of the sensitive taxa that was affected in 2002 spraying was found again during the 2003 recovery studies. At the family level, the most negatively affected families were Atyidae (shrimps) which are characteristic of areas of permanent flow, and Pleidae (pygmy backswimmers), that are found in more seasonal areas. The abundance of Naucoridae (creeping water bugs) was significantly lower than the benchmark as well. Out of 39 identified morphospecies four (10%) were classified as sensitive as they did not reappear during the 2003 recovery study. Three species belonged to the family Notonectidae (Backswimmers) and one to Naucoridae (creeping water bugs), which might reflect a loss from the system. It is however difficult to assign this to persistent post-spray impacts of deltamethrin as the natural variation and abundance in aquatic invertebrates from year to year in the Delta is unknown (Palmer & Davies-Coleman, 2003)

Impact – 2006

Samples were collected at 21 sites in the main Kwando- Linyanti Rivers, Zibadianja and Dumatau lagoons, floodplains and on the vegetation of *Phragmites*, papyrus (*Cyperus papyrus*), hippo grass (*Vossia cuspidata*) and water lilies, (*Nymphaea* spp.) using kick nets (Picker et al 2002). The abundance of macro-invertebrates reduced between 10 and 90% in all the sample sites and affected marginally in the rivers, lagoons and the floodplains. About 70% macro-invertebrates were reduced in numbers from the vegetation types. Abundance of the invertebrate taxa reduced between 40 and 90% except *Chironomids* which appeared to increase during the spraying period. Twenty-four families of macro invertebrates were knocked down almost completely when compared between pre-spray and at the end of spray. About 11 of the total families survived the five spraying cycles (Masundire & Mosepele, 2006).

Recovery – 2007

An average of about 25% of the macroinvertebrates in 24 taxa (Table 4) that were present before spraying did not reappear one year after spraying. Perkins & Ramberg (2004a) reported 26% loss in taxa following spraying in the Okavango Delta in 2002. The mean abundance of all macro-invertebrates was only 11% in Kwando River while more than 100% in Linyanti River, Floodplains, Zibadianja and Dumatau lagoon areas. The *Phragmites* – and hippo grass dominated habitats had still below 50% of pre-spray levels of abundance and in other sites the invertebrates recovered well. Families such as Atydae and Dytiscidae were still well below pre-spray levels while Corixidae, Hirudinea and Chironomidae exceeded their pre spray levels of abundance. Planorbinae appear to have been little affected by the spraying (Masundire, 2007).

5.4.2 Terrestrial invertebrates

Impact – 2002 and 2006

In 2002, sampling was done by collecting the terrestrial invertebrates that had been knocked down by the aerial spray, under tree crowns of *Kigelia Africana, Lonchocarpus capassa* and *Combretum imberbe* on plastic sheets with an area of 3 m^2 in the riparian zone and under *Colophospermum mopane* in the drier land (Dangerfield, 2002). In 2006, similar studies were

conducted in Kwando during the spraying in the woodland dominated by *Croton megalobotrys, Colophospermum mopane, Combretum imberbe, Lonchocarpus nelsii* and in open vegetation dominated by *Pechuel-loeshea leubnitziae* and *Cynodon dactylon* (riparian grass land).The results were compared to the control sites in unsprayed Khwai River at North Gate. Percent declines in terrestrial invertebrate abundance in combined woodland types in 2002 (Dangerfield, 2002) and 2006 were 64% and 63% respectively. All other common taxa showed significant declines as well with the exception of Flies (Diptera Families, Chironomidae and Ceratopogonidae) that have their larval stages in water and therefore produced mass swarming during spring and early summer.

During 2006, 21 taxa groups belonging to 14 families were identified to species level compared to 31 families of flies identified to morphospecies during 2002 spraying. There was marked decrease (50%) in arthropod species richness in the spray block among the woodlands as compared to pre-spray and after spray cycle 5. Significant difference in the composition of families of flies was recorded between the 2002 and 2006 monitoring. The most common families of flies during the 2002 and 2006 monitoring were Tabanidae, Tipulidae, Muscidae, Calliphoridae, Anthomyiidae, Syrphidae, Tephritidae. Spider families sampled in 2002 and 2006 were the same with the exception of family Theraphosidae which was first recorded during 2006. Family Heteropodidae was recorded in 2006 but not in 2002. Family Oxyopidae disappeared after 5th cycle of spraying in both 2002 and 2006. The crickets, particularly *Gryllus bimaculatus* was lost after the 1st cycle and was not captured throughout the remaining spraying cycles. Grasshoppers, *Lithdiopsis carinatus, Truxaloides* sp., *Ailopus thalassinus* and *Eucoptacara exguae* disappeared from the riparian grasslands (Chikwenhere & Shereni, 2006)

Common name	Taxa order	% Reduction – 2002	% Reduction – 2006
Ants	Hymenoptera	11	74
Flies	Diptera	41	60
Mosquitoes	Diptera	71	80
Beetles	Coleoptera	84	43
Wasps	Hymenoptera	23	65
Leaf hoppers & bugs	Hemiptera	46	45
Spiders	Arachnida	30	24

Table 4. Effects of deltamethrin on terrestrial arthropods dwelling in woodland types after spray cycle 2 in 2002 and 2006 (Source: Bonyongo and Mazvimavi, 2007).

In 2006, mosquitoes suffered the highest reduction of 80% followed by ants with 74%, the wasps had 65% reduction, while flies reduced by 60%. The rest of the groups listed declined below 50% and the least reduced was spiders at 24%. Conversely, ants were the least abundant while maximum reductions were found in beetles at 84% followed by mosquitoes with 71% reduction in 2002 (Table 4).

Recovery - 2003 and 2007

In May and August 2003 and 2007 sampling of terrestrial invertebrates in the selected woodland tree types yielded interesting results in the Okavango and Kwando respectively. In the key insect groups, the spider abundance recovered in all cases to pre-spray levels; beetle abundance had not recovered on *K. africana*, but recovered on other tree species; there

was no change in fly or ant abundance between 2002 and 2003 while Hemeptera abundance was significantly greater in 2003 than before the spray events. Fifty-seven morphospecies were found for the first time in 2003 indicating that the species that were lost from 2002 had started to recover in 2003. This shows that there is great variation between years in the composition of invertebrates (Dangerfield & McCulloch, 2003). There was sharp increase in the flies and mosquitoes in Kwando/Linyanti areas in the recovery periods of 2007. Beetle abundance was highest at above 60% and wasps and ants increased more than 100% a year after the spraying. However crickets, *Gryllus bimaculatus* were not detected in 2007 where as Grasshoppers *Lithdiopsis carinatus, Truxaloides sp., Ailopus thalassinus* and *Eucoptacara exguae* that had disappeared from the riparian grasslands started to recover in 2007 (Chikwenhere, 2007)

5.4.3 Flying insects

About 7,500 individuals, mostly flies, were sampled in 2002. Within each cycle catches were lower in the days after the spray event but increased between the spray cycles and much greater in the subsequent pre-cycle catches. Increase in the abundance of flies over the cycles was most likely due to increasing temperatures and the arrival of the annual flood in the sampled areas.

5.4.4 Fish

Using gill nets, the abundance of fish in the Kwando and Linyanti Rivers were studied. In general, a comparison of relative abundance before and after the five spray cycles remained stable. Relative abundance in fish in a given water body reflects the seasonal events, water levels, feeding and breeding behaviour (Mosepele, 2006). However there was decrease in species diversity from the pre spray period until cycle 2 and diversity remained stable after cycle 5. Being an opportunistic predator (Teferra et al., 2003, Mosepele et al., 2005) slight decrease in *Schilbe intermedius* is caused by feeding of knocked down terrestrial and aquatic invertebrates. Increased competition for food between the species does occur. *Hepsetus odoe* and *S. intermedius* were pscivorous predators (Merron & Bruton, 1991) and deltamethrin would have increased inter-specific competition for food between these two species as the feeding rate of *S. intermedius* progressively decreased from the pre spray periods until cycle 5. *Brycinus lateralis* and *B. poechii* feed on small aquatic invertebrates and therefore it was possible that their abundance decreased in the river systems due to decreased food supply caused by deltamethrin spray. The lack of significant change in the feeding behavior of *Marcusenius macrolepidotus* during the spraying suggests that its dominant prey item (Chironomids) were not significantly affected by deltamethrin.

5.4.5 Birds

Using circular point counts for monitoring forest birds, transects for *Acacia* thorn-veld species, and boat surveys for water dependent species, sampling was carried out on three occasions in the Okavango Delta. In summary, there were some local changes in bird populations during the spraying, but these changes could not be attributed to effects of deltamethrin (Pendleton, 2002; Perkins & Ramberg, 2004). The spraying of deltamethrin over the Kwando-Linyanti areas in 2006 did not have discernible negative effects on any of the bird species monitored (Slaty Egret, Arnot's Chat, raptors and

vultures). The only significant effect recorded was increased feeding success of Slaty Egrets during spraying due to the negative effect of the deltamethrin on its prey. This was short-lived and the temporarily depressed fish stocks did not cause the Slaty Egrets to vacate the area.

6. Aquatic plants (*Salvinia molesta*) and biological control weevil *Cyrtobagous salviniae*

The distribution of salvinia and weevil populations varies widely under field conditions. Therefore, using field and static short-term toxicity bioassay methods (Reish & Cshida, 1987) in the Okavango (Figure 2) and iron cages representing open conditions in Kwando (Figure 3), the impacts of the insecticide on the weevil were determined during the five sequential aerial spray cycles. The controls were maintained in unsprayed area of Khwai River at North Gate. Assessments of the impacts were carried out at 12, 36 and 60 hours after the spray in each cycle from basins and cages as well as in field conditions before and after each spraying cycle (Kurugundla & Serumola, 2007, Kurugundla et al., 2010).

Mean survival of the 50 adult salvinia weevils extracted using Berlese funnels (Boland & Room, 1983) in the controls was generally in the range of 45.5 (mortality = 09.0%) to 48.4 (mortality = 03.2%) in number. The range of weevils' survival in closed basins exposed to deltamethrin in 2002 was between 25.0 (mortality = 47.0%) and 44.7 (mortality = 04.9%) while it was 33.7 (mortality = 27.2%) and 39.3 (mortality = 16.4%) in cages in 2006 with respect to controls (Table 5). However, in the 4th cycle of 2006 spray, the weevil mortality was 52.5% (live weevils = 22.0 ±1.8) (Table 5), which was obviously due to the formation of ice crystals and the cold conditions in the weevil extraction cups (≤ 50C) increasing the weevil mortality significantly ($P \leq 0.05$), but not necessarily as a result of deltamethrin spray drift. Cesida (1980) found that pyrethroid toxicity increased at low temperatures.

The percentage deltamethrin collected on the aluminium foil sheets was in the range of 0.2% to 6.9% of the applied rate and the insecticide drift is varied depending on the inversion, wind direction and temperature (Perkins & Ramberg, 2002; Bonyongo & Mazvimavi, 2007). Significant difference in weevil mortality was observed between 2.3% and 6.9% (Table 5) deltamethrin deposition and did not show significant mortality at less than 2% deposition as determined from the aluminium foils (Kurugundla & Serumola, 2007; Kurugundla et al., 2010).

The fluctuations in the abundance of weevils in the field Salvinia infestations at the sites of Xakanaxa (Figure 2) and Kwando (Figure 3) after praying was due to the spatial distribution of weevils and to less breeding during winter (Forno et al., 1983; Naidu et al., 2000) despite some spray effects. In all five cycles the abundance of weevils in 20 standard plants was higher than one (Forno, 1987) showing that weevils maintained their equilibrium at Shummamori, Hamokata, Lebala and Selinda (Figure 3) during the spray programme.

Although deltamethrin deposition caused significant weevil mortalities, the insecticide did not affect the weevil ability to control salvinia. It might be difficult to relate the declines of weevils in the field to the deltamethrin toxicity, as toxicity is influenced by factors such as temperature, season of spraying, habitat conditions and a protective mechanism possessed by the life stages of weevils (Schlettwein & Giliomee, 1990). In aquatic habitat conditions deltamethrin aerosols could be diluted, partitioned and adsorbed onto various organic sediments (Muir et al., 1985), which would reduce the toxicity not only to the weevils but several aquatic invertebrates. It is also suggested that the vegetation might act as a limiting factor for insecticide deposition on target surfaces, unlike in the open areas. On cold nights

the weevils normally hide in buds, roots and beneath the leaves. They deposit their eggs in buds and underneath leaves, and emerging larvae normally feed inside the rhizome (Forno et al 1983). Therefore adults and larvae would often be protected from contact with the insecticide (Schlettwein & Giliomee, 1990).

	Okavango Delta - Basins – 2002				Kwando-Linyanti - Cages- 2006			
Cycle	Control	12 hours	36 hours	60 hours	Control	12 hours	36 hours	60 hours
1	47.2 ±1.2 (5.6%)	*32.0 ±1.3 (32.3%)	*30.5 ±1.4 (35.4%)	*25.0 ±1.0 (47.0%	47.0 ±1.6 (06.0%)	39.3 ±2.4 (16.4%)	37.4 ±4.5 (20.4)	35.7 ±1.8 (24.0%)
2	48.4 ±0.5 (03.2%)	31.7 ±0.9 (34.5%)	38.2 ±1.0 (21.1%)	38.8 ±1.3 (19.9%)	46.5 ±0.6 (07.0%)	39.1 ±2.5 (16.0%)	*35.2 ±3.3 (24.3%)	*35.8 ±2.0 (23.0%)
3	46.0 ±0.6 (08.0%)	42.3 ±0.6 (08.1%)	33.5 ±0.9 (27.2%)	31.0 ±1.4 (32.6%	45.5 ±0.6 (09.0%)	37.7 ±3.3 (17.2%)	*34.4 1.4 (24.6%)	*35.0 ±1.9 (23.1%)
4	47.0 ±0.6 (06.0%)	37.0 ±1.1 (21.3%)	44.7 ±1.3 (04.9%)	37.0 ±1.4 (21.3%	46.3 ±0.9 (07.1%)	*35.9 ±3.1 (22.5%)	*33.7 ±1.7 (27.2%)	*22.0 ±1.8 (52.5%)
5	45.4 ±0.5 (09.2%)	*30.3 ±0.7 (33.3%)	*30.5 ±0.9 (32.8%)	*32.2 ±1.5 (29.1%)	46.3 ±1.3 (07.4%)	*36.1 ±1.7 (22.0%)	36.7 ±1.8 (20.7%)	*34.3 ±3.1 (26.0%)
	Okavango Delta- mean of 5 cycles				Kwando-Linyanti - Mean of 5 cycles			
	Deltamethrin deposition (% m^{-2})		Weevil mortality (%)		Deltamethrin deposition (% m^{-2})		Weevil mortality (%)	
Average	2.7 ±0.5		26.5 ±1.0		4.1 ±0.8		29.7 ±5.1	

Table 5. Mean survival of 50 weevils (SE = sd√n) in the Okavango Delta and Kwando-Linyanti in response to deltamethrin spray deposition (% m^{-2}). Figures in parentheses indicate corrected percent mortality with respect to controls in each cycle. * Probability ≤0.05 with reference to controls.

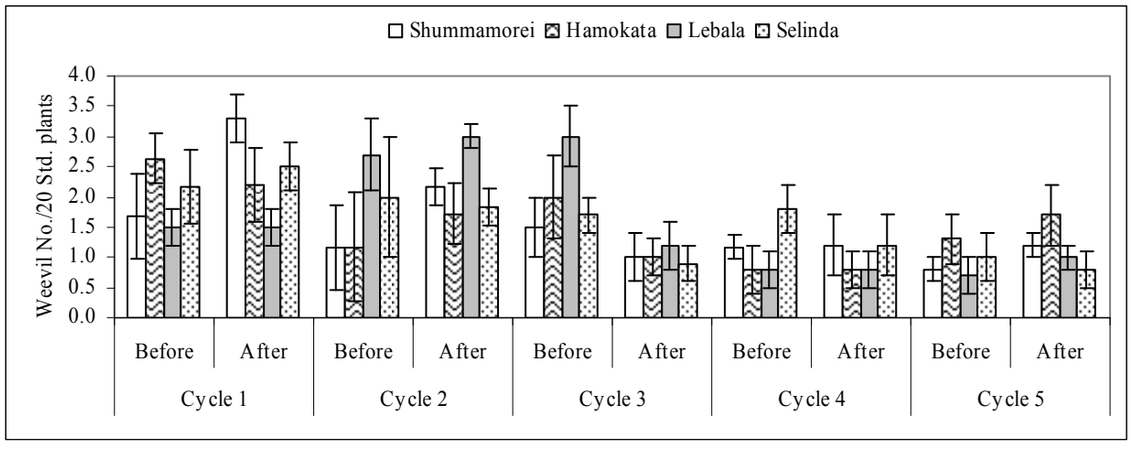


Fig. 7. Number of weevils in 20 plants by standard plant method before and after the spray in five cycles.

Average weevil mortalities are typically 26.5% in 2002 and 29.7% in 2006 at 2.7% and 4.1% deltamethrin respectively (Kurugundla& Serumola 2007; Kurugundla et al., 2010). It was also observed that Paradise pool and Lebala pool were completely covered with the salvinia two months after the end of spraying, yet the weevils controlled the infestation after 7 to 8 months. Aerial spraying of deltamethrin for controlling tsetse fly in any given area is not a continuous process and it is applied only in winter, when the breeding rate of the weevils

generally low. The two important monitoring studies conducted in 2002 and 2006 confirm that, although *C. salviniae* was affected negatively by the aerial spraying of deltamethrin, it recovered thereafter as shown by the subsequent effective control of salvinia in Paradise and Lebala pools in the Okavango delta and Kwando River respectively.

7. Socio-economic implications

No side effects on human health was reported and people expressed their appreciation about the programme. However, there were sporadic reports of irritation to eyes during the spraying as reported by the humans. During the spraying campaign, people continued utilizing crops, fish and wild veld products. No short-term land use changes were observed and no disturbances to domestic live stock (Bendsen et al., 2006). People who moved from the core of tsetse infested areas during 1960s and 1970s have now settled permanently in Caprivi region. The changes in land use did not become apparent during the spraying and in the post spray periods. Botswana is one of the prime wilderness tourism destinations and there were no direct or indirect impacts on the tourism inflow as the result of spraying. The successful eradication of the flies has created an enabling environment for livestock development. No stock losses due to *nagana* have occurred after the spray of 2001, 2002 and 2006 and the carrying capacity of the rangelands has increased. Eighty-two commercial livestock farms, at a size of 2000 ha each, have already been sanctioned by the Namibian Government in the western section of the Spray Block area in Caprivi. Only 8% of the lodges were against the spraying and 92% of the tour operators appreciated the tsetse eradication. The successful eradication of tsetse fly would save the Botswana Government the recurrent costs that were invested annually for the control of flies through the maintenance of 10,000 odour baited targets in the tsetse dominated areas (Bonyongo & Mazvimavi, 2008).

8. Conclusions

The incidence of *nagana* in northern Botswana as a result of tsetse fly spread increased between 1950 and 1960. Besides large scale clearing of bush and vegetation, ground sprays using insecticides such as DDT, Dieldrin, endosulfan and deltamethrin have been used to control the spread of tsetse fly. Application of non-residual spraying of endosulfan in the Okavango Delta, coupled with odour bait technique in the northern wetlands in 1992, reduced the tsetse fly distribution from 20,000 km^2 to 5000 km^2. By exploiting the improved aerial spraying techniques (fitted with GPS-guided spray equipment fixed to the aircraft), Botswana Government sprayed deltamthrin in 2001 and 2002 in the Okavango Delta and in 2006 in the Kwando-Linyanti systems. Almost 10 years following the end of spraying in the Okavango Delta, tsetse fly have still not been found and the threat of cattle trypanosomosis has been quelled. Furthermore, the tsetse frontiers involving the northern tsetse fly distribution along the Kwando and Linyanti Rivers bordering Caprivi region in Namibia – which is part of the continental common tsetse fly-belt has been effectively pushed back into Southern Angola. As such, the threat of reintroduction of tsetse fly back into northern Botswana has been greatly reduced.

Endosulfan aerial spraying did not produce serious harm to terrestrial invertebrates and no significant difference between seasonal and spraying effects was found in aquatic invertebrates at 12 g ha^{-1} of endosulfan applications. Possible exceptions included adult Chironomidae and Hymenoptera other than ants, both of which showed some declines in

the spraying season. Endosulfan had possible influence on migration of fish and *Tilapia rendalli* abundance declines in shallow vegetated areas. Residue of endosulfan was highest in *Schilbe mystus* at 0.04 ppm in muscle and 0.28 ppm in viscera in gram wet weight. The spraying influenced the feeding in king fisher due to behavioural changes. However, physiological studies in fish showed that surviving fish became significantly debilitated although recovery followed cessation of spraying. However, several groups of invertebrates, especially arthropods, are susceptible to the deltamethrin and deltamethrin spraying caused significant reductions in abundance of sensitive aquatic and terrestrial taxa. The results indicate that the surface dwelling arthorpods were affected in great deal rather than the groups such as leaches, snails, pond damsels and others that live in sediments. High elimination rate recorded for the order Hemiptera (water fly), Ephemeroptera (may flies) and Coleoptera (beetles) as they are active in free water and on vegetation surfaces. However deltamethrin did not affect the fish and birds as the result of deltamethrin spraying.

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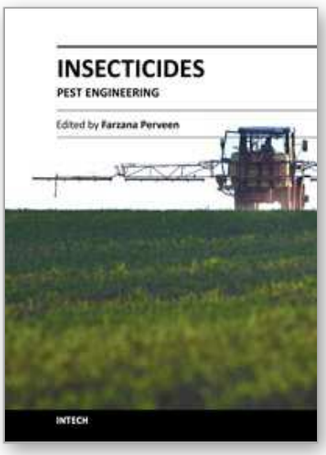
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Insecticides - Pest Engineering

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This book is compiled of 24 Chapters divided into 4 Sections. Section A focuses on toxicity of organic and inorganic insecticides, organophosphorus insecticides, toxicity of fenitrothion and permethrin, and dichlorodiphenyltrichloroethane (DDT). Section B is dedicated to vector control using insecticides, biological control of mosquito larvae by Bacillus thuringiensis, metabolism of pyrethroids by mosquito cytochrome P40 susceptibility status of Aedes aegypti, etc. Section C describes bioactive natural products from sapindacea, management of potato pests, flower thrips, mango mealy bug, pear psylla, grapes pests, small fruit production, boll weevil and tsetse fly using insecticides. Section D provides information on insecticide resistance in natural population of malaria vector, role of Anopheles gambiae P450 cytochrome, genetic toxicological profile of carbofuran and pirimicarp carbamic insecticides, etc. The subject matter in this book should attract the reader's concern to support rational decisions regarding the use of pesticides.

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