CHAPTER 7.4.

IMPACT OF TSETSE FLY ERADICATION PROGRAMMES USING THE STERILE INSECT TECHNIQUE

U. FELDMANN¹, V. A. DYCK¹, R. C. MATTIOLI², J. JANNIN³ AND
M. J. B. VREYSEN¹

¹*Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture,
International Atomic Energy Agency, A-1400 Vienna, Austria*

Email: M.Vreysen@iaea.org

²*Animal Production and Health Division, Food and Agriculture Organization of
the United Nations, 00100 Rome, Italy*

³*Communicable Diseases, Control, Prevention and Eradication, World Health
Organization, 1211 Geneva 27, Switzerland*

TABLE OF CONTENTS

1. INTRODUCTION.....	1052
2. POVERTY AND HUNGER	1054
3. LIVESTOCK AND CROP PRODUCTION.....	1056
4. TSETSE AND TRYPANOSOMOSIS (T AND T) PROBLEM	1057
4.1. Human African Trypanosomosis (HAT) (Sleeping Sickness).....	1057
4.2. African Animal Trypanosomosis (AAT) (Nagana).....	1058
4.2.1. Problem of African Animal Trypanosomosis.....	1058
4.2.2. Benefits of Controlling African Animal Trypanosomosis	1059
Livestock Production.....	1059
Crop Production and Mixed Farming	1061
4.2.3. Causal Relationship between T and T, Hunger, and Poverty	1061
4.2.4. Why is the T and T Problem so Hard to Solve?.....	1061
4.2.5. T and T, and Sustainable Agriculture and Rural Development (SARD)	1063
4.2.6. PATTEC.....	1064
5. TSETSE- AND TRYPANOSOMOSIS-FREE ZONES.....	1064
5.1. Concept.....	1064
5.1.1. African Animal Trypanosomosis	1065
5.1.2. Human African Trypanosomosis	1066
5.2. Potential Role of the SIT	1066

Pages 1051–1080

*V. A. Dyck, J. Hendrichs and A. S. Robinson (eds.), Sterile Insect Technique. Principles and Practice in
Area-Wide Integrated Pest Management. Second Edition.*

© 2021 IAEA. CRC Press, Boca Raton, Florida, USA.

6.	BENEFITS FROM TSETSE ERADICATION	1068
6.1.	<i>Benefits from Eradicating Glossina austeni in Unguja Island, Zanzibar, Tanzania</i>	1068
6.1.1.	<i>Benefits to Livestock Keepers</i>	1069
	<i>Livestock Keeping</i>	1069
	<i>Milk Production</i>	1070
	<i>Livestock-Crop Integration</i>	1071
	<i>Household Income</i>	1071
6.1.2.	<i>Red Colobus Monkey</i>	1072
6.1.3.	<i>Challenges – Constraints</i>	1072
6.2.	<i>Benefits from Eradicating Glossina palpalis gambiensis in the Niayes of Senegal</i>	1073
6.3.	<i>Prediction for the Ethiopian Southern Rift Valley</i>	1073
6.4.	<i>Benefits from a Planned Programme to Eradicate Glossina austeni and Glossina brevipalpis in KwaZulu Natal, South Africa</i>	1074
7.	CONCLUSIONS	1074
8.	REFERENCES	1075

SUMMARY

Hunger and poverty persist in rural sub-Saharan Africa. Many affected communities could produce enough food for themselves, and even for sale, if they had the basics — livestock and crops. In most of these communities, the presence of tsetse flies and the disease they vector, trypanosomosis, prevents optimal productive livestock-keeping and mixed farming, resulting in inadequate local food production. Since a vast majority of the rural communities depends on agriculture, the removal of a key development problem like tsetse and trypanosomosis (T and T) would permit increased local agricultural production, socio-economic and market development, and alleviate hunger and poverty. A sustained alleviation, if possible a complete lasting removal of the T and T problem, is therefore considered a prerequisite to rural self-sufficient agriculture, in which productive livestock can provide milk, meat, draught power to cultivate the land, and eventually generate higher income and market opportunities. Hence the removal of such a key problem would catalyse overall development in rural areas. However, the poverty and food security status of communities in Africa is rather heterogeneous, and reflects the impact of various constraining factors, including T and T, on the current agricultural production process and human well-being, as well as on the overall development potential. Correspondingly, the benefits to sustainable agriculture and rural development (SARD), resulting from an elimination of the T and T problem, will also vary from area to area. In view of the substantial funding required over the next decades to address this key problem, and the need for early “success stories” that show tangible benefits, it is important that the initial T and T control areas are carefully selected according to technical feasibility, and to the predicted potential of increasing agricultural productivity in the context of SARD. Trypanosomosis is a major, but technically solvable, development problem, and the effectiveness of the sterile insect technique (SIT), as a component of area-wide integrated pest management (AW-IPM) programmes, to create tsetse-free zones, has been demonstrated in Unguja Island, Zanzibar, and other locations. This chapter (1) outlines the causal relationship between the T and T problem and food insecurity, malnutrition, poverty, and related disease and development constraints, (2) describes the impact of the problem on African rural communities and the overall economy, and (3) indicates the benefits of a reduced T and T burden, or even of its zonal elimination from selected priority areas in support of sustainable rural development.

1. INTRODUCTION

Tsetse flies are the cyclical vectors of trypanosomosis, a disease occurring mostly in rural areas of sub-Saharan Africa where it gravely affects agro-pastoral activities. The fly infests an estimated area of 8.7 million km² where it transmits human African trypanosomosis (HAT) or “sleeping sickness” in humans and African animal trypanosomosis (AAT) or “nagana” in livestock. While human suffering and deaths from sleeping sickness have been declining and are confined to certain areas, livestock production in rural areas continues to be severely constrained by nagana. The resulting

food insecurity and the limitations on health, food production, and even survival, imposed by these vectors and transmitted diseases, make the tsetse and trypanosomiasis (T and T) constraint one of the most underestimated and severe problems for sub-Saharan rural communities.

In 1997, sleeping sickness was a potential threat to 60 million people living in the infected areas, and up to 350 000 people were assumed to be infected. However, the number of reported cases decreased from >25 000 in 2000 to 7106 cases in 2012, and the areas at high or very high risk were reduced by 60% (Simarro et al. 2015; Franco et al. 2017). In 2017, less than 1600 new cases of sleeping sickness were reported to the WHO, which represents the lowest number of sleeping sickness cases ever recorded (WHO 2017; Jose Ramon Franco, personal communication). However, there appears to be a general consensus that active and passive surveillance of the human population alone will not be enough to reduce further the number of reported cases. Therefore, vector control needs to be embraced as a requirement to keep reducing the incidence of sleeping sickness (recommendation of the third WHO stakeholders meeting (Geneva, April 2018) on *gambiense* human African trypanosomiasis (g-HAT) elimination).

Considering the overall impact (large direct and indirect losses), and the causal relationship among poverty, food insecurity, and the tsetse-related rural development constraints, it is inevitable that, in the long term, the suppression of vector populations, and better yet the creation of tsetse-free zones, are both economical and moral imperatives. If the T and T constraint were removed in an area, thereby making it feasible for rural people in subtropical and tropical Africa to produce more food than for their subsistence through mixed livestock-crop farms, they will obtain better nutrition and higher incomes, and the poorest region of the world will experience improved economic and social development.

Although some livestock producers apply methods of suppressing tsetse flies and trypanosomiasis with reasonable success, the benefits are partial and usually last only a short time (Vreysen 2006). The rural poor cannot generally afford and sustain enduring T- and T-control efforts. Therefore, it appears more appropriate to identify those T- and T-infested areas that have a high rural-development potential and contain isolated or at least geographically confined target tsetse fly populations, and then implement programmes aiming at removing vector populations in a phased, integrated, and sustainable manner by applying — where feasible and justifiable — the sterile insect technique (SIT) as part of an area-wide integrated pest management (AW-IPM) programme (Feldmann 2004; Vreysen et al. 2013a; Feldmann et al. 2018). The SIT lends itself to be the final component of an integrated programme for the creation of sustainable tsetse-free zones in some, e.g. humid riparian forests and moist savannah areas in West Africa, but not all, e.g. open savannah woodland in East Africa, ecosystems. The potential to eliminate the disease in a sustainable manner may open a new dimension of benefits, derived from introducing upgraded livestock breeds and cross-breeds, resulting in more productive agricultural farming practices (Bouyer et al. 2014).

Although important for economic development and conservation of the environment (Ford 1973; Reichard 2002; Nagel and Peveling, this volume), the potential for changes in land use resulting from tsetse control is not discussed here.

2. POVERTY AND HUNGER

The International Fund for Agricultural Development (IFAD) stated in its 2016 rural development report that, although rural poverty declined in all regions, the Asia and the Pacific region, Latin America and Near East, North Africa, Europe, and Central Asia cut by half their rates of extreme poverty, whereas extreme poverty fell by only 10 per cent over the 1990–2010 period for eastern, southern, western, and central Africa (IFAD 2016). The annual growth of the gross domestic product (GDP) per capita in sub-Saharan Africa was reduced from 3.6% in 2000 to 1.2% in 2016 (WB 2016).

Reducing poverty in poor countries, especially in sub-Saharan Africa, is now the primary objective of development programmes. In 1990, 35% of the world's population lived in extreme poverty (USD <1.9 per day), but by 2013 this had declined to 10.7%. However, half of the extreme poor live in sub-Saharan Africa. During this same time period the number of poor in the region fell by only 4 million; in 2013 there were 389 million people living on less than USD 1.90 a day, more people than in all the other regions combined (WB 2018).

An initiative by the World Bank (WB) and the International Monetary Fund (IMF) to help the Least Developed Countries (LDC) (34 of 49 are in Africa), and especially the Heavily Indebted Poor Countries (HIPC) (34 of 42 are in Africa), to obtain debt relief, led to these countries preparing Poverty Reduction Strategy Papers (PRSPs) (UN 2000b, 2001). Significant debt relief was granted, which would, it was hoped, enhance food security and agriculture (FAO 2001a; IMF 2018). FAO has provided recent estimates; the number of chronically undernourished people in the world stands at 815 million. Most of the hungry live in low-income and lower middle-income countries, many of which have yet to make the necessary headway towards the structural transformation of their economies (FAO 2017). Although the prevalence of undernourishment in sub-Saharan Africa has decreased from 33.3% in 1991 to 18.6% in 2015, it is still higher when compared with the other regions, i.e. 16.3% in South Asia, 10.2% in East Asia and the Pacific, and 7.6% in Latin America (Roser and Ritchie 2018).

Sub-Saharan Africa remains the poorest region of the world. In 2010, average real per capita income was USD 688 compared with USD 1717 in the rest of the developing world. Over the past 30 years, GDP growth per capita in sub-Saharan Africa has averaged 0.16% per year (Chauvin et al. 2012). The World Bank estimates that the share of Africans who are poor fell from 56% in 1990 to 43% in 2012. Although the poverty rate may have declined, many more people are poor because of population growth, i.e. 330 million poor in 2012, up from about 280 million in 1990. Poverty reduction has been slowest in fragile countries, and rural areas remain much poorer, although the urban-rural gap has narrowed (Beegle et al. 2016). Poverty rates have declined only slightly in most sub-Saharan African countries, and have actually increased in Kenya and Zambia (FAO 2017).

In 2013, 6.3 million African children under the age of five died, i.e. almost 17 000 every day, and the risk of a child dying before completing five years of age is highest in Africa (90 per 1000 live births), about 7 times higher than in Europe (12 per 1000 live births). Approximately 3.1 million children die from hunger each year. In 2011 poor nutrition caused nearly half (45%) of deaths in children under five. Children who

are poorly nourished suffer up to 160 days of illness each year, and undernutrition magnifies the effect of every disease, including measles and malaria (Hunger Notes 2018).

Boosting poor-country agriculture is critical to reducing hunger (Economist 2002), and the sustainable removal of this key development problem appears to be a prerequisite for tackling poverty and food insecurity.

A sharper focus on hunger and agricultural development is needed within the broader objective of poverty reduction (FAO 2001b).

Hunger leads to reduced productivity, to environmental degradation, and to conflict at national and international levels (FAO 2002a; Sachs 2004; Diamond 2005). It also increases sickness, which reduces productivity, quantifiable through the Disability-Adjusted Life Year (DALY) Index (Murray 1994; Murray and Lopez 1994). Every year, across the developing world, 66 million primary school-age children (with 23 million in Africa alone) attend classes hungry, which greatly impacts their ability to learn (Hunger Notes 2018).

At the 1996 World Food Summit, a goal was set to eradicate hunger in all countries, and to halve the number of chronically undernourished people in the world (from about 840 to 420 million) by the year 2015 (FAO 1996). The target, later called one of the United Nations' Millennium Development Goals (MDG), was to achieve sustainable food production and security for all. According to the Food and Agriculture Organization of the United Nations (FAO), in 2015, sub-Saharan Africa was the region furthest from reaching the MDGs, with the actual number of hungry people increasing rather than decreasing (FAO 2017).

As part of a new sustainable development agenda, in September 2015 countries adopted a new set of goals to end poverty, protect the planet, and ensure prosperity for all. These 17 global Sustainable Development Goals (SDGs) were set by the United Nations with specific targets to be achieved over the next 15 years. The SDGs cover a broad range of social and economic development issues, including poverty, hunger, health, education, climate change, etc. Although the SDGs replaced the MDGs, unlike the MDGs, they do not distinguish between "developed" and "developing" nations, and apply to all countries (UN 2015).

Programmes that feed the hungry with imported food, as important as they are at critical times, provide only temporary relief, and, if wrongly implemented, they can have a devastating effect on rural people whose livelihoods depend on the production and sale of staple crops (Clark 2001). The role of agriculture, in generating food supplies and incomes necessary for development and access to food, is paramount in developing countries, especially the Low-Income Food-Deficit Countries (LIFDCs) (FAO 2001d).

Agriculture employs on average 65% of Africa's labour force, but it accounts for only about 32% of gross domestic product, reflecting the relatively low productivity of the sector (Chauvin et al. 2012). Success in raising small-farmer productivity will lead to improvements in household food security, level of nutrition, and income. Efforts to eradicate hunger need to focus on empowering families to achieve inclusive food security, encouraging a maximum of self-reliance (FAO 2001c).

As incomes grow and diets diversify during structural transformation, the demand for food generally shifts from basic staples to horticultural and livestock products. This leads to a shift in the overall structure of agricultural production. But evidence from Africa suggests that while such a shift is occurring in some countries, it is not yet the norm across the continent. Agriculture shows healthy growth in terms of both output and productivity, but it is not diversifying its commodity mix much. The picture that emerges is of an expanding agricultural sector, but one with weak fundamentals that are preventing a broad-based reduction in poverty and inequality (IFAD 2016).

3. LIVESTOCK AND CROP PRODUCTION

A major barrier to significantly improving agriculture in sub-Saharan Africa is the lack of productive livestock. Productive livestock are the key to agricultural improvement because they: (1) provide food (milk and meat), (2) aid in crop production, especially of staples and cash crops, through draught power to cultivate the land for crops and manure for fertilizer, and they can live off crop residues as well as grazing, (3) provide manure for fuel, hides for leather and power for transport, (4) act as a form of savings, a “walking bank”, and thereby reduce risk, and (5) provide a vital, and often the only, source of income for the poorest and most marginal of the rural poor, such as pastoralists and those living on marginal land, sharecroppers and widows (Delgado et al. 1999). Livestock, for example a few cattle and goats, owned by each rural family are the means to food production on a continuing basis.

An estimated one-third of all children in developing countries, and perhaps a higher share of pregnant or lactating women, suffer from mild to moderate protein-energy malnutrition (FAO 2001d). People in developing countries typically consume annually only one-fifth to one-sixth the milk, and one-third to one-fourth the meat, of those in industrial countries (FAO 2000). In 1995–1997, people in developing countries obtained an average of only 11% of their calories, and 22% of their protein, from animal food products, compared with more than twice these figures (25% and 49%, respectively) in developed countries (FAO 2001d).

These low consumption levels in developing countries indicate the potential for growth in the consumption of animal food products without adverse consequences on human health. Increased consumption, of even a relatively small additional amount of meat and milk, would supply the necessary protein and micronutrients, as well as needed additional calories, especially for children (FAO 2001d).

Farming families with small holdings must be enabled, through mixed farming, to increase agricultural productivity for their own immediate benefit.

The integration of livestock and crop operations is the main avenue for sustainable intensification of agriculture in many regions of the developing world (FAO 2000). Zimbabwean smallholders, who combine livestock and crop production, have incomes twice as high as those with only crops (IFAD 2001).

Traditional agriculture in Africa is based on crops grown on land worked with a hand-hoe. According to the FAO, in sub-Saharan Africa, 89% of all primary cultivation is carried out by hand (Budd 1999). However, the hand-hoe is not enough to produce sufficient crops to feed rural Africa! Animal draught power enables a family to cultivate at least twice as much land as can be done by hand (2 hectares with a team of oxen compared with 1 hectare with a hoe) (Swallow 1999). Animal traction

has been shown to generate higher returns on land (25–45%) and labour (140%) than the hoe, partly from the advantage of using manure as a fertilizer (Swallow 1999).

If the land is not suitable for crops, then livestock can still be grazed on it. In the case of natural disasters, such as drought and floods, livestock provide longer-lasting food security, and more risk-free agriculture, than crops. Even landless people can own cattle or small livestock, which graze on communal-pasture land, or are kept indoors with feed brought to them (zero grazing).

4. TSETSE AND TRYPANOSOMOSIS (T AND T) PROBLEM

4.1. Human African Trypanosomosis (HAT) (Sleeping Sickness)

Tsetse-transmitted human African trypanosomosis, sleeping sickness, has been a major burden on African people in rural areas between northern Angola (Independent Online 2004) and southern Sudan. If left untreated, the disease is inevitably fatal; it has been estimated that, at the beginning of the last century, 50 000–100 000 people died every year from the disease (Shaw 2004). Although the number of persons dying from the disease drastically decreased between 1900 and 1960, since many African countries obtained their independence in the early 1960's the number of people succumbing to the disease increased again until the end of the last century. However, since then, enormous progress has been made in reducing the disease prevalence in Africa, from many thousand new HAT cases in 2000 to 977 cases in 2018 (Fig. 1).

Figure 1. Total number of reported cases of HAT (gambiense and rhodesiense) per year (2000–2018). The green line and the green bar show the milestones and target set in the WHO Roadmap for HAT elimination. (Reproduced from Franco et al. 2020.)

4.2. *African Animal Trypanosomosis (AAT) (Nagana)*

4.2.1. *Problem of African Animal Trypanosomosis*

Unlike HAT, the disease continues to be especially devastating to livestock, with 45–50 million animals at risk in T- and T-affected countries (Kamuanga 2003; Shaw 2004); in these countries, the vast majority of the animals are crowded into the few tsetse-free areas. In some areas, there is evidence that the problem is exacerbated by an expansion in the distribution of tsetse flies (Leak and Mulatu 1993; Stevenson 1998), even reaching, as in Ethiopia, higher altitudes than was previously recorded (Vreysen et al. 1999).

As stated in ILRI (1999),

Trypanosomosis is probably the single greatest health constraint to increased livestock productivity in sub-Saharan Africa,

and it significantly impairs agricultural development (Swallow 1999). When not lethal, trypanosomosis in livestock leads to a chronic debilitating condition that reduces fertility (calving rates), weight gain, meat and milk offtake by at least 50% (USD 2750 million per year), and the work efficiency of oxen used to cultivate the land (Budd 1999; Swallow 1999; DFID 2001; Shaw 2004). However, if left untreated, it is often fatal (especially for calves), with at least 3 million cattle and other domestic livestock dying each year (Hursey and Slingenbergh 1995). The problem is getting worse rather than better.

Besides the direct impact of the disease on livestock, there are also indirect negative effects. It discourages using more-productive exotic and cross-bred cattle, depresses the growth and affects the distribution of livestock populations, reduces the potential opportunities for livestock and crop production (mixed farming) through less draught power to cultivate land and less manure to fertilize (in an environment-friendly way) soils for better crop production, and affects human settlements (people tend to avoid areas with tsetse flies) (Shaw 2004).

T and T are enormous barriers to raising productive cattle in most of the humid and sub-humid zones of Africa (FAO 2000), especially exotic breeds and cross-bred cattle, which are much better milk and meat producers than local breeds but more susceptible to the disease. At present, cattle (especially cross-breds) can only be raised relatively satisfactorily outside (or around the periphery) of the tsetse zone, or by giving regular treatments of expensive trypanocidal drugs, in addition to other health care. Therapeutic chemical treatments are expensive and must be administered regularly. It has been estimated that as many as 35 million doses of trypanocides are used annually in sub-Saharan Africa alone (Holmes 2013), which represents a figure suitable to treat only about one-third of the cattle at risk (Swallow 2000). Inclusion of trypanocides sold informally in the African market may substantially increase the total number of doses sold annually, which may be as high as 70 million doses (Giordani et al. 2016). This practice elicits drug resistance in the trypanosomes, in combination with the sale of fake trypanocides drugs (Melaku and Birasa 2013). Consequently, treatments are no longer effective, and the future of cattle production in these areas may become problematic.

The use of trypanotolerant cattle in West Africa shows some promise as a way of coping with the disease threat, but these animals are rather small (DFID 2001) and thus are less suitable as draught animals. Shaw et al. (2004) compared trypanotolerant, Zebu and cross-bred (trypanotolerant x Zebu) cattle in herd models. Benefits with and without T and T, expressed per head of cattle over a 20-year period, were highest with cross-bred cattle.

Current methods of controlling tsetse, and the disease in humans and livestock, are by no means perfect. The current situation with respect to AAT is untenable, with risk to the environment arising from high pressure on natural resources in uninfested areas where livestock are being concentrated. The problem remains a major barrier to meeting the basic livelihood needs of the rural poor.

4.2.2. Benefits of Controlling African Animal Trypanosomosis

Everyone agrees that AAT

... is sufficiently important for virtually any intervention to be beneficial (Shaw 2003).

Livestock Production. The benefits of T and T control are reduced disease prevalence or even disease elimination, reduced mortality rates and treatment expenses, and improved health and agricultural productivity. These benefits can be estimated using a dynamic herd model, which includes animal traction among the herd outputs. The reduced livestock production cost (38% and 25% per tonne of milk and meat, respectively) would increase the amount of milk and meat supplied by farmers, and lower the price for consumers. For areas freed of tsetse, milk and meat production would almost double, increasing by 83% and 97%, respectively. Benefits from traction power and manure production have been estimated to be, on average, 34% of the total value of livestock production (Kristjanson et al. 1999). The monetary values of losses and benefits are summarized in Box 1.

The 36 countries (10 million km², population 260 million) that have some level of tsetse infestation have about 172 million cattle, but only 45 million of them are kept in tsetse-infested areas, while the remainder are forced to crowd around the periphery, leading in some instances to land degradation (Swallow 1999). The overcrowding of cattle and people in tsetse-free areas is a problem for both good land-use practices, in terms of sustainable utilization of natural resources, and long-term community development activities.

It is expected that enhanced trypanosomosis control will allow the replacement of low-productive cattle by high-productive cross-breeds that can be kept at a lower average density per unit of land (with more rural families owning cattle) which will in many instances bring relief to the often fragile ecosystems in sub-Saharan Africa (Vreysen et al. 2021).

Therefore, the creation of sustainable T- and T-free zones, and the resulting rural development and the opportunities for profitable investment into productive agricultural and livestock systems, are not expected only to be major contributions in the fight against food insecurity and poverty, but also to reduce the environmental risks of a potentially large increase in the number of cattle.

Box 1. Monetary Values — Estimates of Losses from the T and T Problem, and Potential Benefits of Controlling African Animal Trypanosomosis

Hursey and Slingenbergh (1995) valued the direct annual losses in cattle production due to AAT at USD 1000–1200 million.

Shaw et al. (2004) created maps that show the estimated potential benefits from T and T control in Benin, Burkina Faso, Ghana, Mali, and Togo. The research modelled cattle density, animal draught work, rate of herd growth, and rate of cattle spread. If the disease were removed, the total benefits after 20 years (in the form of a present value discounted over 20 years) ranged from less than USD 500 to well over 5000 per km² (Fig. below). Benefits included milk, meat, draught power, the extra cattle present, and the spread of cattle. The estimated benefits from the removal of the tsetse fly from the Niayes were much higher, amounting to about USD 3250 per km² per year, mainly by replacing indigenous breeds with cross-breeds or exotic breeds (Bouyer et al. 2014; section 6.2.).

The potential benefit of enhanced trypanosomosis control in livestock in Africa is USD 700 million per year, arising from increased milk and meat productivity (Kristjanson et al. 1999). If one includes other potential benefits that would accrue from trypanosomosis elimination, such as animal traction and manure,

...the total cost of the disease is likely to be well in excess of USD 1338 million per year (Kristjanson et al. 1999).

In 10 fully infested countries alone, the impact of T and T on the agricultural GDP was estimated to amount to 10% below a theoretical T- and T-free GDP level (Swallow 1999), which corresponds to USD 1000 million in monetary terms.

Estimates of the overall annual lost potential in livestock and crop production range from USD 1950 to 4500–4750 million (Budd 1999; DFID 2001; Shaw 2004; Gooding and Krafur 2005).

Total calculated potential benefit (USD per km²), after 20 years, of removing trypanosomosis (benefit range USD 0–500 [dark red] to 7000+ [dark green] per km²). (Modified from Shaw et al. (2004) and W. Wint for the countries Benin, Burkina Faso, Ghana, Mali, and Togo; reproduced with permission.)

Crop Production and Mixed Farming. In sub-Saharan Africa, livestock and crops are usually separated due to T and T, but there is a huge potential benefit if livestock and crop production can be integrated (Box 1).

In total, about 8.2 million km² in Africa are classed as cultivable land (but half of it is marginal) (Harrison 1996). Up to 6 million km², especially in Central and southern Africa, are not cultivated for various reasons (Ford 1973). The best potential for fodder production lies in the humid zones, 18% of Africa's land area, but only 6% of the livestock are found there (Harrison 1996). In some cases, tsetse flies deny access to fertile, arable land, and their removal makes it accessible to livestock-agricultural production.

African animal trypanosomiasis constrains agricultural production in the areas of Africa that hold the continent's greatest potential for expanded agricultural production (Swallow 1999).

4.2.3. *Causal Relationship between T and T, Hunger, and Poverty*

Evidence for the causal relationship between the T and T problem and the prevalence of hunger and poverty is presented in this section. It cannot simply be a coincidence that most of the 37 tsetse-infested countries of Africa are also poor, debt-ridden, and underdeveloped. A comparison between the tsetse-infested areas and the 34 Heavily Indebted Poor Countries in Africa (WB 2001) (32 of which have tsetse flies), reveals a striking overlap (Fig. 2); it is logical to conclude that the T and T problem is a major contributor to hunger and poverty.

Of course there are other problems creating food insecurity, such as limited water and fertilizer supply, severe human diseases, lack of credit, poor governance, civil unrest and wars, as well as other livestock diseases, and these are also important, and some are interconnected and interdependent. Solutions to these problems must be found as well. However, to achieve rather quickly the objective of reducing hunger and poverty in such a needy region as sub-Saharan Africa, it is vital first to adopt the solution that will bring about the biggest change in the fundamental problem, and for which strategies and technology packages already exist and need to be integrated into the overall context of sustainable agriculture and rural development (SARD). It is a matter of giving a high priority to a problem that is fundamental, and to a solution that will have a great impact in the near future. This approach is part of the comprehensive policy of the Programme Against African Trypanosomiasis (PAAT), an international alliance comprising the FAO, African Union/Inter African Bureau for Animal Resources (AU/IBAR), International Atomic Energy Agency (IAEA), and WHO. The removal of T and T is expected to have a catalytic effect on overall rural development initiatives aimed at food security and poverty reduction.

4.2.4. *Why is the T and T Problem so Hard to Solve?*

Why has the barrier of T and T remained so strong, and prevented a breakthrough in livestock and crop production? The T and T problem is a rural problem, and most political leaders, policy makers, and planners are probably already overwhelmed by various needs and deficiencies requiring immediate attention, ranging from water supply, infrastructure issues like roads and schools, to medical and other services.

Figure 2. Left map: Heavily Indebted Poor Countries (dark green – countries qualifying for full HIPC relief, light green – countries qualifying for partial HIPC relief, yellow – countries eligible for HIPC relief but have not met the conditions) (map by Christallleke (2016) - Own work, CC BY-SA 4.0); Right maps: Predicted areas of suitability (yellow – 10–40%, orange – 40–70%, red – 70–95%, brown – >95%) for the palpalis (riverine), morsitans (savannah), and fuscus (forest) groups of tsetse flies (FAO/DFID, reproduced with permission).

Actions against a problem like T and T are expected to result in benefits only in the medium to long term, and thus may receive a low or inadequate level of attention and political support. The attention of donors and the media tends to focus on acute, novel, or emerging problems such as the Ebola (WHO 2016) and Zika (CDC 2016) crises of 2015–2016, and not on chronic problems such as T and T. This is probably a contributing factor why the HAT and AAT are considered to be “neglected tropical diseases”. Since several efforts in the past to control the T and T problem did not lead to a sustainable improvement, it is difficult now to generate the necessary awareness and commitment among decision-makers.

Also, several influential scientists maintain the view that tsetse flies and the disease trypanosomiasis cannot be eradicated, and that there is no alternative except to “live with the problem” at the lowest possible level of disease transmission. Many people have spoken out against “eradication” of tsetse populations, and many are pessimistic, believing that the “curse of tsetse” must simply be endured. This prevailing fatalistic attitude has led to a submissive acceptance of the seemingly inevitable need to suffer hunger and poverty, with no hope of change. This attitude and approach to the T and T problem has prevented farmers, governments, and donors from trying to create, and consistently and gradually expand in a sustainable manner, zones that are free of the problem.

In past years, several community-based programmes to reduce fly populations were initiated enthusiastically, and relatively successfully suppressed tsetse populations and consequently the disease risk. However, enthusiasm waned, suppression was neglected, and the flies and disease returned (Jordan 1995; Barrett and Okali 1998). Unfortunately, even during phases of good tsetse suppression, the flies were still efficient vectors, and therefore continued to discourage the introduction of productive livestock breeds. This was recently demonstrated again in the Mouhoun area of Burkina Faso where, despite a reduction in apparent density of the tsetse fly population from >10 flies/trap/day to 0.43 flies/trap/day, there was no impact on the prevalence of AAT (Percoma et al. 2018).

4.2.5. T and T, and Sustainable Agriculture and Rural Development (SARD)

Large-scale AW-IPM programmes against T and T should focus on priority development areas in affected countries. The selection of such priority areas in the context of SARD, and in view of the need for substantial funding over the next decades, should focus on areas where the required investments are expected to result in maximum benefits. FAO provided some criteria and guidelines for the selection of initial priority intervention areas (FAO 2002b; Cecchi et al. 2014, 2015; Diall et al. 2017).

To generate impact and benefits for the affected communities, it is essential that control measures against the T and T problem be firmly embedded in overall development efforts towards SARD. A programme called Farming in Tsetse Controlled Areas (FITCA), which was completed in 2004, aimed to improve the welfare of people through sustainable rural development, and to increase livestock productivity by improving animal health through community-based T and T suppression. FITCA had anticipated that the generation of integrated crop/livestock production systems would increase food production (Daily Nation 2003;

AU/IBAR/FITCA 2004). However, the last 20 years have shown that sustaining such community-reliant methods of T and T suppression beyond the phase of funded institutional assistance has been challenging if not impossible (Vreysen 2001, 2006). It has been demonstrated numerous times that, after the successful introduction of community-based tsetse suppression and a discontinuation of donor support, very few farmers pursue the work and pay for the traps, insecticides, etc. Whenever an approach, that necessitates continued action, is not sustained, no breakthrough is possible. Under such scenarios, sub-Saharan Africa will likely remain a “green desert”, preventing sustainable self-sufficiency in food for the rural poor.

4.2.6. *PATTEC*

The African Heads of State and Government, at the 36th Ordinary Session of the Organization of African Unity (OAU) (now called African Union (AU)) summit meeting in Lomé, Togo, in July 2000, recognized the seriousness of the T and T problem and made an historic decision (OAU 2000). The year 2001 was declared as the “Year of the Control of Tsetse Fly” to mark the beginning of renewed efforts to suppress tsetse flies and trypanosomosis. This new effort, initiated by the OAU, is called the Pan-African Tsetse and Trypanosomosis Eradication Campaign (PATTEC) (PATTEC 2000; Pesticide Outlook 2002). The PATTEC Plan of Action to be implemented was approved at OAU’s Lusaka meeting in 2001 (OAU 2001). This decision was received with great enthusiasm by the T- and T-affected countries; they anticipated that this new African-owned and African-led initiative would result in a useful contribution to reducing rural hunger and poverty. Despite the initial euphoria and high expectations, the reality after almost 20 years is more sobering and, with a few exceptions, little overall progress can be reported.

5. TSETSE- AND TRYPANOSOMOSIS-FREE ZONES

5.1. *Concept*

To implement this approach of creating and progressively expanding T- and T-free zones in areas with great potential for livestock-agricultural development, properly developed plans and programme documents are needed. As the problem is complex, a major effort is required that necessitates full ownership, and a high, consistent commitment by the affected countries. Long-term partnerships with local, national, and international stakeholders, non-governmental organizations (NGOs), and the private sector will be instrumental in the gradual creation of zones free of the most important tsetse species in priority areas for rural development. The very large benefits of complete disease removal will only be realized if the disease threat is virtually non-existent, which would encourage poor producers to take the step of investing in productive cattle.

Whereas suppression of tsetse fly populations, to temporarily alleviate the burden of the disease, will remain important in many areas of sub-Saharan Africa, in certain ecological settings the creation and progressive expansion of sustainable T- and T-free

zones (Feldmann and Jannin 2001; UN 2001) will provide substantial benefits for the rural poor, enabling them to produce enough food (Feldmann 2004).

Given the current technologies available, it is not possible to apply this concept to the whole of tsetse-infested areas of sub-Saharan Africa. In addition, the use of the SIT against tsetse populations would only be justifiable in those ecological zones where the SIT would bring a comparative advantage. Successful examples, where the SIT was not used, include: 1) the combined use of insecticide applications by air and ground teams and habitat destruction, which resulted in long-lasting relief from the disease in northern Nigeria (Spielberger et al. 1977), and 2) the integrated use of the sequential aerosol technique (SAT) with trapping in the border areas, which resulted in the creation of a sustainable zone free of *Glossina morsitans centralis* Machado in the Okavango Delta of Botswana (Allsopp and Phillemon-Motsu 2002; Kgori et al. 2006). Both programmes followed, intentionally or not, the principles of AW-IPM, and capitalized on favourable agro-ecological or other relevant trends or developments.

5.1.1. African Animal Trypanosomosis

In animal trypanosomosis, tsetse suppression has an important role to play in immediate (but with long-term perspectives) problem alleviation in priority areas, and as a forerunner of creating tsetse-free zones (PAAT 2000).

The concept of creating and progressively expanding T- and T-free zones following AW-IPM approaches will require substantial funding over many decades (Vreysen et al. 2007). Initial resources must be focussed on a few selected priority areas — with strong demographic pressures, and high agricultural, livestock, and overall development potential — and must achieve good progress with early successes. An advantage that should be utilized is the fragmented distribution of some tsetse fly species, with discrete populations in isolated or well-confined habitats. In that respect, Bouyer et al. (2014) identified natural barriers that isolate populations of *Glossina palpalis gambiensis* Vanderplank in West Africa using a statistical model that assessed the genetic distance between 37 populations. Potentially isolated clusters of *G. p. gambiensis* habitat were identified based on a species distribution model and ranked according to their predicted genetic distance to the main tsetse population (Bouyer et al. 2014; Feldmann and Ready 2014; Vreysen, this volume).

The initially targeted areas will be those with such isolated or confined fly populations. Progressively, over time, the size of infested areas will be reduced. The transboundary nature of fly infestations requires a regional approach, based on the AW-IPM concept, to reduce substantially the risk of fly reinvasion.

The international T and T community has agreed that efforts to create and subsequently expand T- and T-free zones should be initiated in areas with a high potential for agricultural development, e.g. Southern Rift Valley in Ethiopia and the Niayes area in Senegal (Swallow 1999; Feldmann and Jannin 2001; FAO 2002b; PAAT 2002; Alemu et al. 2007; Zerihun 2017; Vreysen et al. 2021). Whereas the Moist Savannah Zone in West Africa has great potential for agricultural development, and the watersheds of the main river basins were initially considered as effective barriers to migration (Hendrickx et al. 2004), new data have indicated the potential of flies to cross these barriers, demonstrating the need for artificial barriers (Vreysen et

al. 2013b). In addition, the use of the SAT against *Glossina tachinoides* Westwood and *G. p. gambiensis* was shown to have its limitations in the Moist Savanna Zone of Ghana, West Africa. The SAT operations failed to achieve eradication in an area of $\approx 18\,000\text{ km}^2$, and both target species were still detected in the sprayed blocks, albeit at low densities (Adam et al. 2013). In view of the extreme low fly population densities obtained, the project in Ghana would most likely have been successful in creating a tsetse-free zone had the spraying operation been followed by the release of an adequate number of high-quality sterile males.

There may be opportunities to embark on projects for creating T- and T-free areas in several other countries, but further evaluations are needed, e.g. Chad (Mahamat et al. 2017), South Africa (Kappmeier et al. 2007), Kenya, Uganda, and the United Republic of Tanzania (IAEA 2001). In some of these areas, particularly where other vector suppression techniques face technical limitations, or for environmental or other reasons can only be applied as a temporary measure, the SIT may play a role.

To minimize ecological disturbances, and ensure environmentally appropriate utilization of natural resources, components of the environment, and land-use practices, must be monitored before and after removal of the vector population (Feldmann and Hendrichs 2001). Even though there is no factual basis for the fear that tsetse eradication will lead to ecological imbalance (AU 2002; Nagel and Peveling, this volume), it is wise to monitor continuously several components of the biological and physical environments to permit, at an early stage, the identification and correction of undesirable developments in the field.

5.1.2. Human African Trypanosomiasis

In addition to efforts to create T- and T-free zones in selected areas that have great potential for agricultural development, T and T suppression needs to be pursued in the remaining sleeping sickness foci (Fig. 3). The neglected tropical disease roadmap of the WHO calls for the elimination of *gambiense* HAT (g-HAT) as a public health problem by 2020, and complete elimination of transmission by 2030 (Franco et al. 2017). In 2017, there were 1370 centres that were equipped to screen for *gambiense* HAT, and more than 600 centres were equipped to provide treatment. As a result, the number of cases reported in 2017 was low (<1600). Even though 80% of all the new cases were reported from the Democratic Republic of the Congo, they were still distributed over 17 countries (J. R. Franco, WHO, personal communication). In view of the ever-decreasing number of new *gambiense* HAT cases detected each year, there is evidence that vector control will gain in importance in the overall human sleeping sickness elimination approach (Mahamat et al. 2017).

5.2. Potential Role of the SIT

The SIT has been demonstrated to be effective and efficient against tsetse flies under certain ecological conditions when integrated in a phased conditional manner with other suitable tsetse suppression methods (Cuisance et al. 1986; Clair et al. 1990; Oladunmade et al. 1990; Vreysen et al. 2000, 2021). The scientific principles of the technology against tsetse flies have been well studied in Africa, and have now been

proven (Offori 1993; Feldmann and Hendrichs 2001; Feldmann and Jannin 2001; Feldmann 2004; Vreysen 2006; Vreysen et al. 2021). When applied on an AW basis, the integrated approach benefits all segments of rural society, including poor farmers, because, instead of protecting selected animals or farms, entire economically important populations of tsetse flies are targeted (Klassen and Vreysen, this volume). Furthermore, because these programmes aim at a public good, local people would usually not be charged for the SIT component. This approach involves, in a first phase, the area-wide application of control tactics suited for tsetse suppression (e.g. insecticide impregnated traps/targets, pour-on for livestock, stationary bait technology, and the SAT) (Mangan and Bouyer, this volume), which, in certain ecological settings, are followed by a second phase – the release of sterile male insects to remove the remaining relic populations.

Figure 3. Remaining foci of gambiense (red circles) and rhodesiense (blue circles) HAT in sub-Saharan Africa for the period 2010–2014. Green circles: active screening in which no HAT case was detected. (From Franco et al. 2017.)

The SIT is one of the few control tactics that acts in an inverse density-dependent manner, and is therefore most efficient at low pest densities (Knippling 1979). Therefore, the SIT would best be applied when the pest density is naturally low or due to prior suppression. When the SIT is integrated as a final component into an area-wide pest management system, the treatment area can ultimately become a tsetse-free zone (Vreysen et al. 2000, 2021).

The insecticide-based and other suppression techniques, e.g. trapping, most often used in such integrated area-wide campaigns are environmentally acceptable, provided they are applied for a short time (Nagel and Peveling, this volume). The insecticide is applied in a localized way – on cloth targets, cloth traps, netting, or

livestock, and is therefore not dissipated in the environment. Even after the application of the SAT (repeated application of ultra-low-volume formulations of non-persistent insecticides, usually from aircraft) used to eradicate *G. m. centralis* from the Okavango Delta in Botswana (Kgori et al. 2006), Perkins and Ramberg (2004) showed that terrestrial and the vast majority of aquatic non-target invertebrates recovered within 1 year to the pre-spray composition and abundance. After the temporary use of such techniques to suppress efficiently the vector population to a very low level, the application of the SIT to remove the relic tsetse population involves using the only vector-control method that has no known side-effects on non-target organisms (Müller and Nagel 1994; Feldmann and Hendrichs 2001).

The weekly cost of tsetse SIT per km², i.e. USD 2.7–9.4, is in the range of, or lower than, the required expenditure (weekly, per km²) in AW-IPM programmes integrating the SIT against other insect pests of agricultural and veterinary importance, e.g. codling moth *Cydia pomonella* (L.) (USD 100), Mediterranean fruit fly *Ceratitis capitata* (Wiedemann) (USD 80), and the New World screwworm *Cochliomyia hominivorax* (Coquerel) (USD 3.5) (Hendrichs, Vreysen et al., this volume). Therefore, in those ecological settings where the SIT brings a comparative advantage, integrating the SIT into area-wide programmes, and sustainably removing a target tsetse fly population, will be cost effective. If programmes to create and expand T- and T-free zones are focused, and relatively small incremental steps are taken following the phased conditional approach (Vreysen et al. 2021), financing field projects in African countries should be feasible. Budd (1999) stated that an

... economic analysis indicates that the cost of controlling trypanosomosis through controlling the tsetse fly populations will be covered several times by the benefits of tsetse-free status.

6. BENEFITS FROM TSETSE ERADICATION

6.1. *Benefits from Eradicating Glossina austeni in Unguja Island, Zanzibar, Tanzania*

In 1994–1997 it was demonstrated that, after pest suppression with insecticides, the SIT completely eradicated the *Glossina austeni* Newstead population in Unguja Island of Zanzibar (Vreysen et al. 2000); subsequently, trypanosomosis in local cattle could no longer be found (Vreysen et al. 2014). This successful AW-IPM programme created significant opportunities to improve livestock and crop farming, although Unguja Island is not the best example of the agricultural benefits that would accrue from eliminating the T and T constraint compared with the African mainland. Unguja Island has poor soils, and hence the contribution of agriculture to the GDP on Unguja has been rather low and not consistent, i.e. it declined from 38% in 1997 to 24.7% in 2007, but increased again to 30.8% in 2013 (Mwaseba et al. 2015). According to a government census in 2007/2008, crop production dominated agricultural activity, and engaged 86 509 households (66%); this compares with 43 844 households (33%) that were engaged in both crops and livestock, and 1840 households (1%) that were engaged in livestock only. According to the socio-economic survey of 2014 (Mwaseba et al. 2015), 57.4% and 27% of respondents listed farming and livestock

keeping, respectively, as their major occupation. This is a significant reduction when compared with earlier studies that indicated 88 or 89% of the population was engaged in farming (Tambi et al. 1999; Mdoe 2003).

Socio-economic studies were carried out in Unguja Island in 1997, 2002, and 2014 (Tambi et al. 1999; Mdoe 2003; Mwaseba et al. 2015) using collected local data, interviews with farmers, and relevant socio-economic parameters. The data illustrate the range of agricultural and socio-economic benefits that can accrue after removing the T and T constraint. (Sleeping sickness did not occur in Unguja, so no direct human health benefits were assessed.) It is important to recognize that the benefits began accruing as soon as the tsetse fly population and disease transmission were reduced, in some areas starting in 1985, using insecticides, and continued until, and especially after, the target fly population collapsed in 1996 as a result of applying the SIT. For the past 20 years or more, the island of Unguja has remained free of *G. austeni* and AAT (Saleh et al. 1999; Vreysen and Dixit 2016).

The following summarizes some of the benefits, but also some of the constraints experienced after the removal of the T and T problem. An analysis is made as to why agricultural development on Unguja Island has not expanded to its full potential.

6.1.1. Benefits to Livestock Farmers

Although the contribution of the livestock sub-sector to the agricultural GDP increased from 12% in 1986 to 34% in 1997, in the following 15-year period (1999–2014) the percentage of the population engaged in global farming decreased, suggesting a significant shift to better paid employment opportunities other than farming. This is reflected in a reduction of the population engaged in farming as a principal and secondary occupation, i.e. from 88–89% in 1999–2002 to 57% in 2014 (as principal occupation), and from 40.7% in 2002 to 25% in 2014 (as secondary occupation).

Livestock Keeping

- Whereas the proportion of households raising improved cattle increased from 2% in 1985 to 18% in 1999 and to 24% in 2002, this percentage declined to 13% in 2014.
- Generally, there has been improvement in agriculture as evidenced by increases in crop and livestock numbers. Whereas from 1985 to 1999 the number of indigenous cattle increased by a factor of 1.5 and that of cross-bred cattle increased 7 fold, between 2009 and 2014 the number of improved cattle breeds increased by only 4%. However, during the same 5-year period, there was a significant increase in the numbers of improved chickens (82%), sheep and goats (69%), and donkeys (62%), and there was a decline in indigenous cattle (-21%), local chickens (-22%), and indigenous sheep and goats (-15%).
- Even though 38% of the farmers preferred local breeds of cattle, the majority (61%) preferred improved breeds, primarily because of their high productivity. Although the 2014 survey showed that farmers keep more local cattle breeds than improved ones, about 96% of those who preferred improved breeds said that they produced more milk than the indigenous ones. This is slightly higher than the 94%

reported in a similar study by Mdoe (2003). In 2014, a shortage of land and feeds was often mentioned as a constraint on increasing the number of livestock kept, especially dairy animals.

- Only about half (48.2%) of livestock keepers were using zero grazing in dairy production, down from 91.6% in 2002 (Mdoe 2003). The limited expansion and development of the dairy sector is largely explained by the constraints that the sector continues to face: low adoption of rearing improved cattle because of the high cost of improved heifers, low financial ability among poor farmers identified, and tick-borne diseases (especially East Coast Fever). There was limited use of by-products and supplements, perhaps because tethering rather than zero grazing is common in the area; as a result, farmers used grasses and legumes to feed their animals. These constraints have not been addressed properly, and as a result the potential of the dairy sector in Unguja has not been realized.
- The higher increase of improved breeds/cross-breeds of goats when compared with cattle may be explained by pressure on the land due to, among others, population growth, and therefore a limited availability of grazing land. In this context, it is easier to get enough feed for dairy goats than to meet the nutritional needs of dairy cattle.
- The 2014 study showed that among farmers who keep cattle, about 67% used local bulls for breeding, but about 20% used improved bulls, and only about 14% used artificial insemination. This is in contrast to 2002, when 72% of dairy farmers used artificial insemination while 68% of them used improved bulls [assuming that some farmers used both methods]. This might be related to the fact that farmers find keeping local cattle cheaper in terms of operational costs, and the fact that exotic breeds are easily attacked by diseases. The absence of artificial insemination projects might also have contributed to this situation.
- There was an increase in meat production. The proportion of domestic versus imported cattle slaughtered for meat doubled (29 to 66%) between 1978–1985 and 1986–1995, indicating an increase in slaughter cattle obtained domestically. Between 1999 and 2001, the production of beef increased by 7%.

Milk Production

- Average milk production increased for both indigenous and improved cattle – for indigenous cattle from 2.4 to 2.5 to 4.6 litres per cow per day in 1997, 2002, and 2014, respectively, and for improved cattle from 8.2 to 8.3 to 9.7 litres per cow per day in 1997, 2002, and 2014, respectively.
- There was an increase in the number of farmers selling milk, and the quantity of milk being sold. Milk processing is not well developed in Zanzibar; only 1% of dairy-cattle keepers participated in some form of milk processing in 2014. Most of the milk is marketed in its raw form, and therefore this has not improved since 2002. However, producers have little difficulty in finding buyers – street vendors and hawkers provide a market outlet for about 73% of the milk produced. About 12% of the milk produced is consumed by local households, 4.4% is sold through collection centres, and 3.9% is sold to hotels and restaurants. An increase in milk

production and consumption probably contributes to an improvement in the nutritional status of rural households.

Livestock-Crop Integration

- Crop productivity in mixed-farming systems increased, resulting from a greater capability to use animal power (stronger and healthier animals) for ploughing and transporting farm products. The use of animal traction for land preparation is, in general, rather low, but it increased from 3% in 1997 to 5% in 2002 and to 10% in 2014. In 2002 about 21% and 18% of farmers used animals to transport their own and commercial products, respectively. By 2014, the percentage of farmers using animals for their own transport increased further to about 64% of sample households, but decreased to 10% for those who used them for commercial transport.
- Livestock-crop integration increased because more farmers used manure for crop production. About 51% of farmers in 1999, and 54% in 2002, grew crops on fields fertilized with animal manure. From 1999 to 2002, the increase in productivity of cassava, rice, maize, coconut, and vegetables may be attributed to the use of improved seed varieties and manure for crop production. In 2014 similar figures were found – 58% of respondents used manure for crop production. In addition, more farmers are using crop by-products to feed their animals. In 1999 only 13% of farmers were feeding crop by-products to livestock, but in 2002 this figure had increased to 22%. Also, farmers are increasingly feeding improved fodder to their cattle. Some 92% of dairy farmers raising improved breeds zero-grazed their cattle. The 2014 study found a limited use of by-products and supplements. Most farmers were using grasses (62%) and legumes (50%) to feed their animals (probably because tethering rather than zero grazing is common in the area).
- In the 2014 survey, 68% of respondents indicated that cultivated land has remained the same, whereas 25% and 8% of the farmers reported an increase and decrease in cultivated land, respectively. This compares well with the data from the 2002 study where 52%, 35%, and 7% cultivated the same land, increased or decreased the land cultivated, respectively. These findings suggest that farmers have not been able to expand the area under cultivation.

Household Income. Household income increased over time – in 1999 the average household income per month was estimated at USD 51.5, in 2003 USD 53.5, and in 2014 USD 116. A strong correlation was observed between household income and milk yields, milk sales, and use of manure and animal power for cultivation and transport. However, given the reduction in recent years in the percentage of families engaged in farming, the increase in household income might also be attributed to additional family income coming from employment outside of the agricultural sector, e.g. the growing tourism industry. Nevertheless, the economic benefits to those who continue to keep livestock are higher now than they were before the eradication of T and T.

6.1.2. Red Colobus Monkey

The number of Zanzibar red colobus monkeys *Ptilocolobus kirkii*, an endangered and protected species found primarily in forests (also former major habitat of *G. austeni*), increased from 1000–1500 in 1991 to more than 2500 in 1999 (Masoud et al. 2003). In the period 2013–2014, a systematic assessment of the demography and distribution of the red colobus monkey indicated a total population of 5862 individuals in Unguja, of which 2907 were present in the Jozani-Chwaka Bay National Park (formerly the Jozani Forest Reserve) (Davenport et al. 2017). Therefore, subsequent to eradicating *G. austeni* in Zanzibar, there was no decline in the monkey population. This contradicts the opinion of several conservationists that eradication of tsetse flies would lead inevitably to habitat destruction followed by a reduction in wildlife.

6.1.3. Challenges – Constraints

Much of Unguja Island is coral rag, and consists of low-fertile soils that are not really suited for permanent agriculture (Hettige 1990). This in itself poses a constraint on the development of more sustainable and efficient agriculture systems in general, and livestock systems in particular. There are several reasons why agricultural development on Unguja Island, after the sustainable removal of the tsetse fly and AAT, has not been realized to its full potential. The following provides a non-exhaustive analysis:

- Before the eradication of *G. austeni* in Unguja Island in 1997, AAT was the major constraint to the development of more effective livestock systems and the intensification of the dairy sector. Clearly, eradication of the disease offered real opportunities for the intensification of livestock production in Unguja. These opportunities were most evident immediately after the eradication programme, with a rapid increase in the number of improved cattle, more use of improved seeds that resulted in increased use of crop by-products as animal feed, use of manure for crop production, and use of animal power for ploughing and transport activities. However, the numbers of pure breed and cross-breed cattle increased only slightly between 2009 and 2014, although the numbers of improved sheep and goats were more impressive. These data suggest that, although intensification is on-going, it has in the last decade not evolved at the same rapid pace as in the 1999–2003 period.
- Improvement of the livestock sector requires the availability of improved cattle breeds. The 2014 study showed clearly that only 46% of respondents indicated that improved livestock breeds were readily available. In addition, some farmers, despite changes and development of the dairy industry in Unguja, still preferred to keep local cattle breeds largely because it is easier to raise them (76%), and they are more resistant to other diseases (21%). Other constraints that can partially explain the low adoption of improved dairy cattle are the high cost of improved dairy heifers, the low financial ability of resource-poor farmers, limited access to credit facilities, poor quality of cattle feed that consists mainly of local grasses with low use of concentrates and mineral supplements, high costs of veterinary drugs for disease treatment compared with the milk and meat prices (animal drugs and feeds increased by 92–110% in the period 2005–2008 compared with a 43% increase in food commodities), and the absence of a good milk-marketing system.

- The creation of a tsetse- and AAT-free Unguja removed a significant constraint to agricultural development on the island. However, livestock keepers still had to cope with other debilitating animal diseases such as the tick-borne disease East Coast Fever. Although the disease prevalence declined from 84% in 2002 to 56.9% in 2014, it is still very important. Other diseases that cannot be neglected are lumpy-skin disease and helminthiasis.
- The importance of market functions in terms of economic development, and the stimulation of agricultural production and development, should not be underestimated. The 2014 study found that the marketing system on Unguja Island tends to be highly controlled by a network of intermediaries, resulting in a situation that does not give farmers equitable benefits for their commodities but allocates high margins to the middleman (Mwaseba et al. 2015).

6.2. *Benefits from Eradicating Glossina palpalis gambiensis in the Niayes of Senegal*

In the Niayes of Senegal, an area located north-east of the capital Dakar, three main cattle farming systems can be identified – a traditional system that uses trypanotolerant cattle, and two systems that use more productive cattle breeds for milk and meat production. Before the project started, herd size was 45% lower, and annual cattle sales >3 times higher, in the improved farming systems as compared with the traditional farming system (USD 290 per head versus USD 86 per head, respectively) (Bouyer et al. 2014). In the tsetse-infested areas only a small proportion (6%) of the farmers kept improved breeds, whereas almost half (43%) of the farmers living in the tsetse-free areas owned more productive cattle (Bouyer et al. 2014).

An ex-ante socio-economic study that assessed the potential benefits of the sustainable removal of *G. p. gambiensis*, the only tsetse species present, considered two possible scenarios with respect to potential increases in cattle sales to be expected after eradication. The first, a conservative scenario, assumed an annual replacement rate of 2% of traditional by improved systems, and the second assumed a higher replacement rate of 10% five years after the removal of the tsetse fly population. The final annual increase in cattle sales was estimated at USD 3250/km² versus a total cost of the eradication campaign of USD 7430/km² (Box 1). In spite of this relatively high cost, the benefit/cost analysis indicated that the project was highly cost-effective, with internal rates of return (IRR) of 9.8 and 19.1%, and payback periods of 18 and 13 years, for the two scenarios, respectively (Bouyer et al. 2014; Bouyer and Vreysen 2018). The replacement of traditional local cattle with more productive exotic animals is already apparent in the areas that have been cleared from tsetse (Block 1) or are close to eradication (Block 2) (Paquette 2019; Vreysen et al. 2021)

6.3. *Prediction for the Ethiopian Southern Rift Valley*

The anticipated benefits of removing the T and T problem in the Ethiopian Southern Rift Valley are substantial (Alemu et al. 2007; Zerihun 2017). At the request of the Ethiopian government, Knight (2001) conducted a preliminary benefit/cost analysis,

pointing out that there are significant benefits to be gained from sustainably removing tsetse flies by involving the SIT as part of an AW-IPM strategy. For investments made to create a tsetse-free zone in the Southern Rift Valley, the break-even point should be reached in year 5 or 6, and the net present value (NPV) over 12 years is estimated at between USD 36.6 and 52.7 million. This represents an internal rate of return of between 33 and 43%.

6.4. *Benefits from a Planned Programme to Eradicate Glossina austeni and Glossina brevipalpis in KwaZulu Natal, South Africa*

The province of KwaZulu Natal in South Africa harbours two species of tsetse flies, *Glossina austeni* and *Glossina brevipalpis* Newstead. These populations were responsible for a major outbreak of nagana in 1990, prompting the government to assess potential benefits from a sustained removal of these populations (Kappmeier et al. 1998)

Kappmeier Green et al. (2007) developed an AW-IPM strategy to remove sustainably the two tsetse populations. It included two cycles of the sequential aerosol technique (SAT) followed by the release of sterile males. A benefit/cost analysis indicated that such an approach would reach a break-even point after 8 years, with a cumulative total net benefit (net present value, taking into account a discount rate of 8%) of USD 51 million, and an overall benefit/cost ratio of 3.4, over a 15-year period. These figures do not take into account additional benefits, such as improved agricultural productivity because of healthier draft animals. Starting in year 9, the project would reach the maintenance phase, and benefits would be fully established; the annual benefit/cost ratio would fluctuate between USD 90 and 493 for each dollar invested (year 9 to year 15). Moreover, the project would have an internal rate of return of 23%, meaning that the discount rate could be almost three times higher than the estimated value of 8% and the project would still break even in a 15-year time frame (Kappmeier Green et al. 2007; Bouyer and Vreysen 2018).

7. CONCLUSIONS

Keeping livestock, and especially operating a mixed farm, is fundamental to the rural poor being able to produce their own food. There are many problems of food security that, even though they limit the availability of adequate food supplies, can be solved, step-by-step. However, if approached from the viewpoint of conventional pest suppression, the T and T problem remains an insurmountable barrier to productive agriculture. A partial or unsustainable solution is really no solution. Without breaking this barrier to enable the introduction of higher productive agriculture and livestock systems, and without the resulting development and profitable investment opportunities, there is no hope that the hungry in sub-Saharan Africa will become food self-sufficient within a reasonable time period. The poor farmers of Africa, because of where they live, are helpless in the face of a problem that, even though they may be able to alleviate it temporarily, on their own they cannot remove it in a sustainable manner.

8. REFERENCES

- Adam, Y., G. Cecchi, P. M. Kgori, T. Marcotty, C. I. Mahama, M. Abavana, B. Anderson, M. Paone, R. Mattioli, and J. Bouyer. 2013. The sequential aerosol technique: a major component in an integrated strategy of intervention against riverine tsetse in Ghana. *PLOS Neglected Tropical Diseases* 7(3): e2135. <https://doi.org/10.1371/journal.pntd.0002135>
- Alemu, T., B. Kapitano, S. Mekonnen, G. Aboset, M. Kiflom, B. Bancha, G. Woldeyes, K. Bekele, and U. Feldmann. 2007. Area-wide control of tsetse and trypanosomosis: Ethiopian experience in the Southern Rift Valley, pp. 325–335. *In* M. J. B. Vreysen, A. S. Robinson and J. Hendrichs (eds.), *Area-wide control of insect pests. From research to field implementation*. Springer, Dordrecht, The Netherlands. <https://www.iaea.org/sites/default/files/area-wide-control-insect-pests-book.pdf>
- Allsopp, R., and T. K. Phillemon-Motsu. 2002. Tsetse control in Botswana — a reversal in strategy. *Pesticide Outlook* 13: 73–76. <https://pubs.rsc.org/en/Content/ArticleLanding/PO/2002/B202993F#!divAbstract>
- (AU) African Union. 2002. Statement from the Commission of the African Union to the AHP/DFID Special Workshop on: “Tsetse Control — The Next 100 Years”, 10 September 2002, Edinburgh, UK. http://www.africa-union.org/Structure_of_the_Commission/depPattec.htm#
- (AU/IBAR/FITCA) African Union/Inter African Bureau for Animal Resources/Farming in Tsetse Controlled Areas. 2004. Overview of FITCA. <http://www.ibar-fitca.org/fitca-overview.htm>
- Barrett, K., and C. Okali. 1998. Partnerships for tsetse control — community participation and other options. *World Animal Review* 90 (1998/1): 39–46.
- Beegle, K., L. Christiaensen, A. Dabalén, and I. Gaddis. 2016. Poverty in a rising Africa. Washington, DC, USA. World Bank. <https://doi.org/10.1596/978-1-4648-0723-7>
- Bouyer, F., M. T. Seck, A. H. Dicko, B. Sall, M. Lo, M. J. B. Vreysen, E. Chia, J. Bouyer, and A. Wane. 2014. Ex-ante benefit-cost analysis of the elimination of a *Glossina palpalis gambiensis* population in the Niayes of Senegal. *PLOS Neglected Tropical Diseases* 8(8): e3112. <https://doi.org/10.1371/journal.pntd.0003112>
- Bouyer, F., and M. J. B. Vreysen. 2018. Vectors: tsetse flies. Part 1. *In* J. A. W. Coetzer and R. C. Tustin (eds.), *Infectious diseases of livestock*. <http://www.anipedia.org/resources/vectors-tsetse-flies/1109>
- Budd, L. T. 1999. DFID-funded tsetse and trypanosome research and development since 1980. Volume 2 — economic analysis. Department for International Development, UK.
- (CDC) Centers for Disease Control and Prevention. 2016. Zika virus spreads to new areas – region of the Americas, May 2015–January 2016. *Morbidity and Mortality Weekly Report* (29 January 2016) 65(3): 55–58. <https://www.cdc.gov/mmwr/volumes/65/wr/mm6503e1.htm>
- Cecchi, G., M. Paone, U. Feldmann, M. J. B. Vreysen, O. Dially, and R. C. Mattioli. 2014. Assembling a geospatial database of tsetse-transmitted animal trypanosomosis for Africa. *Parasites and Vectors* 7: 39. <https://doi.org/10.1186/1756-3305-7-39>
- Cecchi, G., M. Paone, R. Argilés Herrero, M. J. B. Vreysen, and R. C. Mattioli. 2015. Developing a continental atlas of the distribution and trypanosomal infection of tsetse flies (*Glossina* species). *Parasites and Vectors* 8: 284. <https://doi.org/10.1186/s13071-015-0898-y>
- Chauvin, N. D., F. Mulangu, and G. Porto. 2012. Food production and consumption trends in sub-Saharan Africa: prospects for the transformation of the agricultural sector. Working Paper 2012-011. United Nations Development Programme. Regional Bureau for Africa. NY, USA.
- Christallkeks. 2016. File: Heavily Indebted Poor Countries.svg. Wikimedia Commons. Data from the World Bank. <https://commons.wikimedia.org/w/index.php?curid=49344753>
- Clair, M., D. Cuisance, H. Politzar, P. Merot, and B. Bauer. 1990. Tsetse fly eradication in Burkina Faso and evaluation of traps and targets, pp. 31–43. *In* Proceedings: Sterile Insect Technique for Tsetse Control and Eradication. Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, Final Research Co-ordination Meeting, 6–10 June 1988, Vom, Nigeria. STI/PUB/830. IAEA, Vienna, Austria. <https://www.iaea.org/publications/3698/sterile-insect-technique-for-tsetse-control-and-eradication>
- Clark, C. S. 2001. Food aid in WTO agricultural trade policy. Canadian Foodgrains Bank, 22 November 2001. http://www.foodgrainsbank.ca/downloads/fjfa_foodaid.pdf
- Cuisance, D., H. Politzar, P. Merot, I. Fevrier Tamboura, B. Bauer, I. Kabore, and J. Fidelier. 1986. La campagne de lutte intégrée contre les glossines dans la zone pastorale d’accueil de Sideradougou (Republique de Burkina Faso), pp. 334–343. *In* Proceedings: 18th meeting of the International Scientific Council for Trypanosomiasis Research and Control (OAU/STRC, ISCTRC), Harare, Zimbabwe. Document Number 604. OAU/IBAR, Nairobi, Kenya.

- Daily Nation.** 2003. EU tsetse fly control plan in East Africa extended. 20 November 2003. <http://www.nationaudio.com/News/DailyNation/20112003/News/News2011200321.html>
- Davenport, T. R. B., S. A. Fakh, S. P. Kimiti, L. Kleine, L. U. Kleine, L. S. Foley, and D. W. De Luca.** 2017. Zanzibar's endemic red colobus *Piliocolobus kirkii*: first systematic and total assessment of population, demography and distribution. *Oryx* 1–9. <https://doi.org/10.1017/S003060531700148X>
- Delgado, C., M. Rosegrant, H. Steinfeld, S. Ehui, and C. Courbois.** 1999. Livestock to 2020. The next food revolution. Food, Agriculture, and the Environment Discussion Paper 28, IFPRI, FAO and ILRI. <ftp://ftp.fao.org/docrep/nonfao/lead/x6155e/x6155e00.pdf>
- (DFID) Department for International Development.** 2001. Trypanosomiasis, tsetse and Africa. The year 2001 report. DFID, UK. <http://ftp.vli.co.uk/lpp/publications/Tsetse%20yearbook.pdf>
- Diall, O., G. Cecchi, G. Wanda, R. Argilés-Herrero, M. J. B. Vreysen, G. Cattoli, G. J. Viljoen, R. Mattioli, and J. Bouyer.** 2017. Developing a progressive control pathway for African animal trypanosomiasis. *Trends in Parasitology* 33(7): 499–509. <https://doi.org/10.1016/j.pt.2017.02.005>
- Diamond, J.** 2005. Collapse: how societies choose to fail or succeed. Viking Adult, Columbus, OH, USA.
- Economist (The).** 2002. Hunger. Always with us. 15 June 2002. p. 81–82.
- (FAO) Food and Agriculture Organization of the United Nations.** 1996. Rome declaration on world food security and world food summit plan of action. World Food Summit, 13–17 November 1996, Rome, Italy.
- (FAO) Food and Agriculture Organization of the United Nations.** 2000. Livestock production, pp. 129–148. *In* The state of food and agriculture 2000. FAO Agriculture Series. FAO, Rome, Italy.
- (FAO) Food and Agriculture Organization of the United Nations.** 2001a. Statement of Jacques Diouf, Director General, FAO. FAO Panel on Agriculture and Sustainable Food Security in Africa: Meeting Basic Needs. Draft Statement (9 April 2001) in preparation for ECOSOC Substantive Session, 27 April 2001, New York, NY, USA.
- (FAO) Food and Agriculture Organization of the United Nations.** 2001b. FAO press release 01/24. 18 April 2001. FAO, Rome, Italy.
- (FAO) Food and Agriculture Organization of the United Nations.** 2001c. Fostering the political will to fight hunger. Draft paper of the Committee on World Food Security, 27th Session, 28 May–1 June 2001. FAO, Rome, Italy.
- (FAO) Food and Agriculture Organization of the United Nations.** 2001d. Mobilizing resources to fight hunger. Draft paper of the Committee on World Food Security, 27th Session, 28 May–1 June 2001. FAO, Rome, Italy.
- (FAO) Food and Agriculture Organization of the United Nations.** 2002a. The state of food insecurity in the world 2002. FAO, Rome, Italy.
- (FAO) Food and Agriculture Organization of the United Nations.** 2002b. Workshop on PAAT–PATTEC Harmonization. 2–3 May 2002. FAO, Rome, Italy. http://www.fao.org/ag/againfo/programmes/en/paat/documents/workshops/harmonization_workshop.pdf
- (FAO) Food and Agriculture Organization of the United Nations.** 2017. The state of food and agriculture 2017 - Leveraging food systems for inclusive rural transformation. FAO, Rome, Italy. <https://reliefweb.int/report/world/state-food-and-agriculture-2017-leveraging-food-systems-inclusive-rural-transformation>
- Feldmann, U.** 2004. The sterile insect technique as a component of area-wide integrated pest management of tsetse, pp. 565–582. *In* I. Maudlin, P. H. Holmes and M. A. Miles (eds.), The trypanosomiasis. CABI Publishing, Wallingford, U.K.
- Feldmann, U., and J. Hendrichs.** 2001. Integrating the sterile insect technique as a key component of area-wide tsetse and trypanosomiasis intervention. PAAT Technical and Scientific Series 3. FAO, Rome, Italy. <http://www.fao.org/DOCREP/004/Y2022E/Y2022E00.htm>
- Feldmann, U., and J. Jannin.** 2001. Tsetse fly free zones for disease prevention and poverty reduction. *Sustainable Development International* 4: 159–166.
- Feldmann, U., and P. D. Ready.** 2014. Applying GIS and population genetics for managing livestock insect pests: case studies of tsetse and screwworm flies. *Acta Tropica* 138(Suppl.): S1–S5. <https://doi.org/10.1016/j.actatropica.2014.03.025>
- Feldmann, U., S. G. A. Leak, and J. Hendrichs.** 2018. Assessing the feasibility of creating tsetse and trypanosomiasis-free zones. *International Journal of Tropical Insect Science* 38: 77–92. <https://doi.org/10.1017/S1742758417000285>
- Ford, J.** 1973. The consequences of control of African trypanosomiasis, pp. 141–144. *In* Proceedings, Panel: Computer Models and Application of the Sterile-Male Technique. Joint FAO/IAEA Division of

- Atomic Energy in Food and Agriculture, 13–17 December 1971, Vienna, Austria. STI/PUB/340. IAEA, Vienna, Austria. <https://www.iaea.org/publications/3096/computer-models-and-application-of-the-sterile-male-technique-vienna-13-17-dec-1971>
- Franco, J. R., G. Cecchi, G. Priotto, M. Paone, A. Diarra, L. Grout, R. C. Mattioli, and D. Argaw. 2017.** Monitoring the elimination of human African trypanosomiasis: update to 2014. *PLOS Neglected Tropical Diseases* 11(5): e0005585. <https://doi.org/10.1371/journal.pntd.0005585>
- Franco, J. R., G. Cecchi, G. Priotto, M. Paone, A. Diarra, L. Grout, P. P. Simarro, W. Zhao, and D. Argaw. 2020.** Monitoring the elimination of human African trypanosomiasis at continental and country level: update to 2018. *PLOS Neglected Tropical Diseases* 14(5): e0008261 <https://doi.org/10.1371/journal.pntd.0008261>
- Giordani, F., L. J. Morrison, T. G. Rowan, H. P. De Koning, and M. P. Barrett. 2016.** The animal trypanosomiasis and their chemotherapy: a review. *Parasitology* 143(14): 1862–1889. <https://doi.org/10.1017/S0031182016001268>
- Gooding, R. H., and E. S. Krafur. 2005.** Tsetse genetics: contributions to biology, systematics, and control of tsetse flies. *Annual Review of Entomology* 50: 101–123. <https://doi.org/10.1146/annurev.ento.50.071803.130443>
- Harrison, P. 1996.** The greening of Africa — breaking through in the battle for land and food. Academy Science Publishers, Nairobi, Kenya.
- Hendrickx, G., S. de la Rocque, and R. C. Mattioli. 2004.** Long-term tsetse and trypanosomiasis management options in West Africa. PAAT Technical and Scientific Series 6. FAO, Rome, Italy. <ftp://ftp.fao.org/docrep/fao/007/y5342e/y5342e00.pdf>
- Hettige, M. L. 1990.** Land evaluation and land suitability classification — Unguja and Pemba Island. Food and Agricultural Organization of the United Nations, Zanzibar, Tanzania.
- Holmes, P. 2013.** Tsetse-transmitted trypanosomes – their biology, disease impact and control. *Journal of Invertebrate Pathology* 112(Suppl. 1): S11–S14. <https://doi.org/10.1016/j.jip.2012.07.014>
- Hunger Notes. 2018.** World child hunger facts. <https://www.worldhunger.org/world-child-hunger-facts/>
- Hursey, B. S., and J. Slingenbergh. 1995.** The tsetse fly and its effects on agriculture in sub-Saharan Africa. *World Animal Review* 84/85(3–4): 67–73.
- (IAEA) International Atomic Energy Agency. 2001.** IAEA thematic planning meeting, 29 January–2 February 2001. Draft report. IAEA, Vienna, Austria.
- (IFAD) International Fund for Agricultural Development. 2001.** Rural poverty report 2001. The challenge of ending rural poverty. Published for IFAD by Oxford University Press, Oxford, UK.
- (IFAD) International Fund for Agricultural Development. 2016.** Rural Development Report 2016. Fostering inclusive rural transformation. IFAD, Rome, Italy. <https://reliefweb.int/report/world/rural-development-report-2016-fostering-inclusive-rural-transformation>
- (ILRI) International Livestock Research Institute. 1999.** Making the livestock revolution work for the poor. International Livestock Research Institute. Annual Report.
- (IMF) International Monetary Fund. 2018.** Debt relief under the heavily indebted poor countries (HIPC) initiative. <https://www.imf.org/en/About/Factsheets/Sheets/2016/08/01/16/11/Debt-Relief-Under-the-Heavily-Indebted-Poor-Countries-Initiative>
- Independent Online. 2004.** Death by tsetse fly: an Angolan epidemic. 03 February 2004. <http://www.iol.co.za>
- Jordan, A. M. 1995.** A review of the tsetse research programme of the International Centre of Insect Physiology and Ecology, 1971–1994. Wageningen University. Wageningen, The Netherlands.
- Kamuanga, M. 2003.** Socio-economic and cultural factors in the research and control of trypanosomiasis. PAAT Technical and Scientific Series 4. FAO, Rome, Italy. <ftp://ftp.fao.org/docrep/fao/005/y4619e/y4619e00.pdf>
- Kappmeier, K., E. M. Nevill, and R. Bagnall. 1998.** Review of tsetse flies and trypanosomiasis in South Africa. *Onderstepoort Journal of Veterinary Research* 65: 195–203.
- Kappmeier Green, K., F. T. Potgieter, and M. J. B. Vreysen. 2007.** A strategy for an area-wide control campaign with an SIT component to establish a tsetse-free South Africa, pp. 309–323. *In* M. J. B. Vreysen, A. S. Robinson and J. Hendrichs (eds.), Area-wide control of insect pests. From research to field implementation. Springer, Dordrecht, The Netherlands. <http://www-naweb.iaea.org/nafa/ipc/public/Area-Wide-Control-Insect-Pests-book.pdf>
- Kgori, P. M., S. Modo, and S. J. Torr. 2006.** The use of aerial spraying to eliminate tsetse from the Okavango Delta of Botswana. *Acta Tropica* 99: 184–199. <https://doi.org/10.1016/j.actatropica.2006.07.007>

- Knight, J. D. 2001.** Cost benefit analysis of tsetse fly eradication in the Southern Region of Ethiopia. Report to the IAEA. IAEA Technical Contract Number 9660/RO. IAEA, Vienna, Austria.
- Knipling, E. F. 1979.** The basic principles of insect population suppression and management. Agriculture Handbook, Number 512. SEA, USDA, Washington, DC, USA.
- Kristjanson, P. M., B. Swallow, G. J. Rowlands, R. L. Kruska, and P. N. de Leeuw. 1999.** Measuring the costs of African animal trypanosomosis, the potential benefits of control and returns to research. *Agricultural Systems* 59: 79–98.
[http://www.sciencedirect.com/science/article/pii/S0308-521X\(98\)00086-9](http://www.sciencedirect.com/science/article/pii/S0308-521X(98)00086-9)
- Leak, S. G. A., and W. Mulatu. 1993.** Advance of *Glossina morsitans submorsitans* and *G. pallidipes* along the Ghibe-river system in southwest Ethiopia. *Acta Tropica* 55: 91–95.
[https://doi.org/10.1016/0001-706X\(93\)90052-D](https://doi.org/10.1016/0001-706X(93)90052-D)
- Mahamat, H. M., M. Peka, J. B. Rayaisse, K. S. Rock, M. A. Toko, J. Darnas, G. M. Brahim, A. B. Alkatib, W. Yoni, I. Tirados, F. Courtin, S. P. C. Brand, C. Nersy, I. O. Alfaraoukh, S. J. Torr, M. J. Lehane, and P. Solano. 2017.** Adding tsetse control to medical activities contributes to decreasing transmission of sleeping sickness in the Mandoul focus (Chad). *PLOS Neglected Tropical Diseases* 11(7): e0005792. <https://doi.org/10.1371/journal.pntd.0005792>
- Masoud, T. S., D. Finnie, A. B Omar, A. U. Basha, and R. G. Wild. 2003.** Zanzibar red colobus conservation strategy. A long term strategy for the survival of the Zanzibar red colobus *Ptilocolobus kirkii*. Forestry Technical Paper 137. Department of Commercial Crops, Fruits and Forestry, and CARE Tanzania. Maruhubi, Zanzibar, Tanzania.
- Mdcoe, N. S. Y. 2003.** Livestock and agriculture development in Zanzibar, post-tsetse eradication: a follow-up socio-economic study. Report prepared for the International Atomic Energy Agency. IAEA, Vienna, Austria.
- Melaku, A., and B. Birasa. 2013.** Drugs and drug resistance in African Animal Trypanosomosis: a review. *European Journal of Applied Sciences* 5(3): 84–91. [https://idosi.org/ejas/5\(3\)13/4.pdf](https://idosi.org/ejas/5(3)13/4.pdf)
- Müller, P., and P. Nagel. 1994.** Tsetse fly eradication on Zanzibar Island — environmental surveys. End of Mission Report to the International Atomic Energy Agency. IAEA, Vienna, Austria.
- Murray, C. J. L. 1994.** Quantifying the burden of disease: the technical basis for disability-adjusted life years. *Bulletin of the World Health Organization* 72: 429–445.
- Murray, C. J. L., and A. D. Lopez. 1994.** Global and regional cause-of-death patterns in 1990. *Bulletin of the World Health Organization* 72: 447–480.
- Mwaseba, D. L., F. J. Mishili, and F. Mramba. 2015.** Socio-economic study on livestock and agriculture development. Unpublished report to the International Atomic Energy Agency, Vienna, Austria.
- (OAU) Organization of African Unity. 2000.** Decision AHG/Dec.156 (XXXVI). Decisions adopted by the 36th Ordinary Session of the Assembly of Heads of State and Government, and 4th Ordinary Session of the AEC. Official Documents, Decisions and Declarations. OAU, Addis Ababa, Ethiopia. <http://www.africa-union.org/home/Welcome.htm>
- (OAU) Organization of African Unity. 2001.** Decision on the implementation of the plan of action for the eradication of tsetse flies in Africa. AHG/Dec. 169 (XXXVII). Decisions and Declarations Adopted by the 37th Ordinary Session of the Assembly of Heads of State and Government, 5th Ordinary Session of the AEC, 9–11 July 2001, Lusaka, Zambia. Official Documents, Decisions and Declarations. OAU, Addis Ababa, Ethiopia. <http://www.africa-union.org/home/Welcome.htm>
- Offori, E. D. 1993.** Tsetse sterile insect technique programmes in Africa: review and analysis of future prospects, pp. 345–357. *In* Proceedings: Management of Insect Pests: Nuclear and Related Molecular and Genetic Techniques. FAO/IAEA International Symposium, 19–23 October 1992, Vienna, Austria. STI/PUB/909. IAEA, Vienna, Austria. <https://www.iaea.org/publications/3782/management-of-insect-pests-nuclear-and-related-molecular-and-genetic-techniques>
- Oladunmade, M. A., U. Feldmann, W. Takken, S. O. Tenabe, H. J. Hamann, J. Onah, L. Dengwat, A. M. V. Van der Vloedt, and R. E. Gingrich. 1990.** Eradication of *Glossina palpalis palpalis* (Robineau-Desvoidy) (Diptera: Glossinidae) from agropastoral land in central Nigeria by means of the sterile insect technique, pp. 5–23. *In* Proceedings: Sterile Insect Technique for Tsetse Control and Eradication. Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, Final Research Co-ordination Meeting, 6–10 June 1988, Vom, Nigeria. STI/PUB/830. IAEA, Vienna, Austria. <https://www.iaea.org/publications/3698/sterile-insect-technique-for-tsetse-control-and-eradication>
- (PAAT) Programme Against African Trypanosomiasis. 2000.** Newsletter 7. <http://www.fao.org/ag/againfo/programmes/en/paat/documents/newsletters/paatnl7.pdf>
- (PAAT) Programme Against African Trypanosomiasis. 2002.** The PAAT information system. http://www.fao.org/ag/aga/agah/pd/paat_l/html/home.htm

- Paquette, D. 2019.** Fly sterilization saves Senegal's cows. Article in The Washington Post, 1 June 2019.
- (PATTEC) Pan African Tsetse and Trypanosomosis Eradication Campaign. 2000.** Pan African Tsetse and Trypanosomosis Eradication Campaign (PATTEC). A continental plan of action for the eradication of tsetse and trypanosomosis.
http://www.africa-union.org/Structure_of_the_Commission/depPattec.htm#
- Percoma, L., A. Sow, S. Pagabeleguem, A. H. Dicko, O. Serdebéogo, M. Ouédraogo, J. B. Rayaissé, J. Bouyer, A. M. G. Belem, and I. Sidibé. 2018.** Impact of an integrated control campaign on tsetse populations in Burkina Faso. *Para. and Vectors* 11: 270. <https://doi.org/10.1186/s13071-017-2609-3>
- Perkins, J. S., and L. Ramberg. 2004.** Environmental recovery monitoring of tsetse fly spraying impacts in the Okavango Delta — 2003, final report. Okavango Report Series 3, May 2004.
- Pesticide Outlook. 2002.** Campaign launched to eliminate tsetse fly. *Pesticide Outlook* 13: 77–78.
- Reichard, R. E. 2002.** Area-wide biological control of disease vectors and agents affecting wildlife. *Revue Scientifique Technique, Office International des Epizooties* 21: 179–185.
- Roser, M., and H. Ritchie. 2018.** Hunger and undernourishment. *Our World in Data*.
<https://ourworldindata.org/hunger-and-undernourishment>
- Sachs, J. 2004.** Doing the sums on Africa. *The Economist*, 22 May 2004. p. 21–23.
- Saleh, K. M., W. A. Mussa, K. G. Juma, and M. J. B. Vreysen. 1999.** Eradication of *Glossina austeni* from the island of Unguja confirmed; results of 2 years of post-eradication monitoring activities, pp. 231–238. *In* Proceedings: 25th meeting of the International Scientific Council for Trypanosomiasis Research and Control, 27 September–1 October 1999, Mombasa, Kenya. OAU/IBAR, Nairobi, Kenya.
- Shaw, A. P. M. 2003.** Economic guidelines for strategic planning of tsetse and trypanosomiasis control in West Africa. PAAT Technical and Scientific Series 5. FAO, Rome, Italy.
<ftp://ftp.fao.org/docrep/fao/006/y4972e/y4972e00.pdf>
- Shaw, A. P. M. 2004.** Economics of African trypanosomiasis, pp. 369–402. *In* I. Maudlin, P. H. Holmes and M. A. Miles (eds.), *The trypanosomiasis*. CABI Publishing, Wallingford, U.K.
- Shaw, A., G. Hendrickx, M. Gilbert, R. Mattioli, and W. Wint. 2004.** Mapping the benefits: first steps in developing a new decision tool for tsetse and trypanosomiasis interventions. 27th Meeting of the International Scientific Council for Trypanosomiasis Research and Control (ISCTRC), South Africa, 2003. Abstract Nr 709. Revised paper. <http://ergodd.zoo.ox.ac.uk/download/drafts/mtbdraft3.htm>
<http://ergodd.zoo.ox.ac.uk/download/reports/ISCTRC-709.doc>
- Simarro, P. P., G. Cecchi, J. R. Franco, M. Paone, A. Diarra, G. Priotto, R. C. Mattioli, and J. G. Jannin. 2015.** Monitoring the progress towards the elimination of gambiense human African trypanosomiasis. *PLOS Neglected Tropical Diseases* 9(6): e0003785.
<https://doi.org/10.1371/journal.pntd.0003785>
- Spielberger, U., B. K. Na'isa, and U. Abdurrahim. 1977.** Tsetse (Diptera: Glossinidae) eradication by aerial (helicopter) spraying of persistent insecticides in Nigeria. *Bulletin of Entomological Research* 67(4): 589–598. <https://doi.org/10.1017/S0007485300006957>
- Stevenson, P. 1998.** DFID-funded tsetse and trypanosome research in Kenya, 1980–1997. A case study. *In* DFID-funded tsetse and trypanosome research and development since 1980. Volume 1 – Scientific Review. 2000. Department for International Development, UK.
- Swallow, B. M. 1999.** Impacts of trypanosomiasis on African agriculture. PAAT Technical and Scientific Series 2. FAO, Rome, Italy.
<http://www.fao.org/ag/againfo/programmes/en/paat/documents/papers/Pos2.pdf>
- Tambi, N. E., W. O. Maina, and N. S. Y. Mdoe. 1999.** Livestock and agriculture development in Zanzibar, pre- and post-tsetse eradication. Report prepared for the International Atomic Energy Agency, Project RAF5040. IAEA, Vienna, Austria.
- (UN) United Nations. 2000a.** Millennium report of the Secretary-General of the United Nations. 3 April 2000. New York, NY, USA.
- (UN) United Nations. 2000b.** Implementation of the first United Nations decade for the eradication of poverty (1997–2006). Report of the Secretary-General. 21 September 2000. New York, NY, USA.
- (UN) United Nations. 2001.** The role of the United Nations in support of the efforts of the African countries to achieve sustainable development. Report of the Secretary-General. High-level segment, substantive session of 2001, 2–27 July 2001, Geneva, Switzerland. Economic and Social Council of the United Nations (ECOSOC). Also: An overview of activities. E/2001/CRP.3.
- (UN) United Nations. 2015.** Sustainable development goals.
<https://www.un.org/sustainabledevelopment/sustainable-development-goals/>
- Vreysen, M. J. B. 2001.** Principles of area-wide integrated tsetse fly control using the sterile insect technique. *Médecine Tropicale* 61: 397–411.

- https://www.researchgate.net/publication/11554946_Principles_of_area-wide_integrated_tsetse_fly_control_using_the_sterile_insect_technique
- Vreysen, M. J. B.** 2006. Prospects for area-wide integrated management of tsetse flies (Diptera: Glossinidae) and trypanosomiasis in sub-Saharan Africa. *Revista de la Sociedad Entomologica Argentina* 65: 1–21. <http://www.scielo.org.ar/pdf/rsea/v65n1-2/v65n1-2a01.pdf>
- Vreysen, M., and A. Dixit.** 2016. Tsetse free for 20 years thanks to a nuclear technique: the island of Unguja, Zanzibar. <https://www.iaea.org/newscenter/news/tsetse-free-for-20-years-thanks-to-a-nuclear-technique-the-island-of-unguja-zanzibar>
- Vreysen, M. J. B., A. Mebrate, M. Menjeta, B. Bancha, G. Woldeyes, K. Musie, K. Bekele, and G. Aboset.** 1999. The distribution and relative abundance of tsetse flies in the Southern Rift Valley of Ethiopia: preliminary survey results, pp. 202–213. *In* Proceedings of the 25th Meeting of the International Scientific Council for Trypanosomiasis Research and Control, Mombasa, Kenya, 27 September–1 October, 1999. OAU/IBAR, Nairobi, Kenya.
- Vreysen, M. J. B., K. M. Saleh, M. Y. Ali, A. M. Abdulla, Z. R. Zhu, K. G. Juma, V. A. Dyck, A. R. Msangi, P. A. Mkonyi, and H. U. Feldmann.** 2000. *Glossina austeni* (Diptera: Glossinidae) eradicated on the island of Unguja, Zanzibar, using the sterile insect technique. *Journal of Economic Entomology* 93: 123–135. <https://doi.org/10.1603/0022-0493-93.1.123>
- Vreysen, M. J. B., J. Gerardo-Abaya, and J. P. Cayol.** 2007. Lessons from area-wide integrated pest management (AW-IPM) programmes with an SIT component: an FAO/IAEA perspective, pp. 723–744. *In* M. J. B. Vreysen, A. S. Robinson and J. Hendrichs (eds.), *Area-wide control of insect pests. From research to field implementation*. Springer, Dordrecht, The Netherlands. <https://www.iaea.org/sites/default/files/area-wide-control-insect-pests-book.pdf>
- Vreysen, M. J. B., M. T. Seck, B. Sall, and J. Bouyer.** 2013a. Tsetse flies: their biology and control using area-wide integrated pest management approaches. *Journal of Invertebrate Pathology* 112(Suppl.): S15–S25. <http://dx.doi.org/10.1016/j.jip.2012.07.026>
- Vreysen, M. J. B., T. Balenghien, K. M. Saleh, S. Maiga, Z. Koudougou, G. Cecchi, and J. Bouyer.** 2013b. Release-recapture studies confirm dispersal of *Glossina palpalis gambiensis* between river basins in Mali. *PLOS Neglected Tropical Diseases* 7(4): e2022. <https://doi.org/10.1371/journal.pntd.0002022>
- Vreysen, M. J. B., K. Saleh, F. Mramba, A. Parker, U. Feldmann, V. A. Dyck, A. Msangi, and J. Bouyer.** 2014. Sterile insects to enhance agricultural development: the case of sustainable tsetse eradication on Unguja Island, Zanzibar, using an area-wide integrated pest management approach. *PLOS Neglected Tropical Diseases* 8(5): e2857. <https://doi.org/10.1371/journal.pntd.0002857>
- Vreysen, M. J. B., M. T. Seck, B. Sall, A. G. Mbaye, M. Bassene, A. G. Fall, M. Lo, and J. Bouyer.** 2021. Area-wide integrated management of a *Glossina palpalis gambiensis* population from the Niayes area of Senegal: a review of operational research in support of a phased conditional approach, pp. 275–303. *In* J. Hendrichs, R. Pereira and M. J. B. Vreysen (eds.), *Area-wide integrated pest management. Development and field application*. CRC Press, Boca Raton, FL, USA.
- (WB) World Bank.** 2001. Heavily Indebted Poor Countries (HIPC) in the world. <http://www.worldbank.org/hipc/about/map/map.html>
- (WB) World Bank.** 2016. GDP growth (annual %). World Bank national accounts data, and OECD National Accounts data files. https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG?end=2016&name_desc=false&start=2000
- (WB) World Bank.** 2018. Poverty. Overview. <http://www.worldbank.org/en/topic/poverty/overview>
- (WHO) World Health Organization.** 2016. Latest updates on the Ebola outbreak. <http://www.who.int/csr/disease/ebola/top-stories-2016/en/index2.html>
- (WHO) World Health Organization.** 2017. Eliminating sleeping sickness as a public health problem is on track. http://www.who.int/trypanosomiasis_african/news/HAT_elimination_on_track/en/
- (WHO) World Health Organization.** 2018. Third WHO stakeholders meeting on gambiense human African trypanosomiasis. 18–20 April 2018. Recommendations. http://www.who.int/neglected_diseases/events/Third_WHO_stakeholders_meeting_on_ghat/en/
- Zerihun, W.** 2017. Achievements and challenges of T and T control operations in the Southern Rift Valley of Ethiopia. Paper presented at the Third FAO/IAEA International Conference on Area-Wide Management of Insect Pests: Integrating the Sterile Insect and Related Nuclear and Other Techniques, 22–26 May 2017, IAEA, Vienna, Austria. <http://www-naweb.iaea.org/nafa/ipc/Zerihun-Woldesenbet-Geleta.pdf>