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Tsetse fly control in Kenya's spatially and temporally dynamic control reservoirs: A cost analysis

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ABSTRACT

Human African trypanosomiasis (HAT) and animal African trypanosomiasis (AAT) are significant health concerns throughout much of sub-Saharan Africa. Funding for tsetse fly control operations has decreased since the 1970s, which has in turn limited the success of campaigns to control the disease vector. To maximize the effectiveness of the limited financial resources available for tsetse control, this study develops and analyzes spatially and temporally dynamic tsetse distribution maps of *Glossina* subgenus *Morsitans* populations in Kenya from January 2002 to December 2010, produced using the Tsetse Ecological Distribution Model. These species distribution maps reveal seasonal variations in fly distributions. Such variations allow for the identification of "control reservoirs" where fly distributions are spatially constrained by fluctuations in suitable habitat and tsetse population characteristics. Following identification of the control reservoirs, a tsetse management operation is simulated in the control reservoirs using capital and labor control inputs from previous studies. Finally, a cost analysis, following specific economic guidelines from existing tsetse control analyses, is conducted to calculate the total cost of a nationwide control campaign of the reservoirs compared to the cost of a nationwide campaign conducted at the maximum spatial extent of the fly distributions from January 2002 to December 2010. The total cost of tsetse management within the reservoirs sums to $14,212,647, while the nationwide campaign at the maximum spatial extent amounts to $33,721,516. This savings of $19,508,869 represents the importance of identifying seasonally dynamic control reservoirs when conducting a tsetse management campaign, and, in the process, offers an economical means of fly control and disease management for future program planning.

Introduction

Tsetse flies, the primary vector of African trypanosomiasis, infest the physical landscape in thirty-seven sub-Saharan African countries, an area of 8.5 million km^2 (Allsopp, 2001). They persist throughout the continent, posing a threat to physical and economic well-being despite existing knowledge and techniques capable of controlling and reducing fly populations (Molyneux, Ndung'u, & Maudlin, 2010). Significantly hindering efforts against the vector have been the costs of control and limited financial resources in tsetse-endemic areas (Kamuanga, 2003). In an effort to overcome this obstacle, this study presents a tsetse fly management simulation that accounts for the spatio-temporal dynamics of fly distributions. We then demonstrate the value of such a management campaign by conducting a costing analysis, which reveals a large savings when these dynamics are considered.

Active vector control has been waged against the tsetse fly since the beginning of the twentieth century when it most often took the form of removing the fly's preferred habitat (Jordan, 1986). Since then, fly control has ranged from aerial and ground spraying of DDT to more recent attempts to engage local communities by using point-source control techniques, such as traps and targets (Allsopp, 2001; Catley & Leyland, 2001). However, despite the active use of control techniques throughout the past century, sub-Saharan Africa continues to suffer under heavy disease and economic burdens from trypanosomiases (Fevre, von Wissmann, Welburn, & Lutumba, 2008; Grady, Messina, & McCord, 2011; Swallow, 2000; WHO, 2010).

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Torr, Hargrove, and Vale (2005) stated, "In the mid-1980s, the days of tsetse seemed numbered." This view was the result of successful management of large-scale control campaigns, development of more cost-effective technologies and baits, and proper attention, largely sparked by environmental concerns over insecticides, given to the field of vector control (Allsopp & Hursey, 2004; Torr et al., 2005). However, due to a shift in spending that began in the 1970s and gained momentum in the 1990s with the rise of community participation, funding for large operations dropped (Hargrove, 2000, 2003a), and the optimism that may have existed in the 1980s has largely vanished. It is against this backdrop of preference for localized control operations and limited financial resources that we conduct our study.

Past costing and control simulations have paid insufficient attention to the spatial and temporal dynamics of tsetse populations. Simulations have been conducted by placing tsetse in large and often isolated "control blocks" where control methods were applied indiscriminately within the block (e.g., Shaw, Torr, Waiswa, & Robinson, 2007; Vale & Torr, 2005). Such studies have represented fly distributions as spatially and temporally static, and in the process have missed an opportunity for reductions to control costs and improvements in control outcomes. It is therefore the goal of this study to conduct a control simulation that explicitly accounts for the spatial and temporal dynamics of fly distributions. We additionally carry out a costing exercise of fly management to demonstrate the value of accounting for these dynamics.

Management of fly distributions consists of field control operations as well as surveying, monitoring, and administration tasks. It encompasses all facets of a wide-scale campaign against the tsetse fly. We use the Tsetse Ecological Distribution (TED) Model (DeVisser, Messina, Moore, Lusch, & Maitima, 2010) to identify the timing and location of spatially constrained fly populations in Kenya from 1 January 2002 to 19 December 2010. By controlling in the identified constrained areas, fewer labor and capital resources are required for vector control, leading to a more efficient use of the limited financial and human resources.

Trypanosomiasis, tsetse fly in Kenya

African trypanosomiasis, a neglected tropical disease endemic in sub-Saharan Africa, affects both humans and animals. In humans the disease is referred to as human African trypanosomiasis (HAT) or sleeping sickness, while in cattle the disease is known as animal African trypanosomiasis (AAT) or nagana. Single-celled protozoa parasites of the *Trypanosoma* genus act as the causative agent in both humans and animals (WHO, 2010). In 2009, the number of reported cases of sleeping sickness dropped below 10,000 (WHO, 2010); however, as Cattand, Jannin, and Lucas (2001) discussed, the actual number of infected individuals is underreported, and misdiagnosis is common in low endemic areas (Katsidzira & Fana, 2010). If left untreated, the disease is fatal (Simarro, Jannin, & Cattand, 2008).

The threat of nagana has been listed as the foremost issue concerning livestock development (Spedding, 1981). It is estimated that at least 46 million cattle are at risk of AAT with countless sheep, goats, donkeys, and horses additionally threatened with infection (Budd, 1999; Kristjanson, Swallow, Rowlands, Kruska, & de Leeuw, 1999). Sickened livestock exact a heavy economic loss on agricultural production in tsetse-infested areas, with the rural poor bearing a disproportionately larger share of the economic burden due to their reliance on livestock as a form of savings and income (Feldmann, Dyck, Mattioli, & Jannin, 2005). Direct and indirect impacts of trypanosomiasis on livestock include increased calf mortality rates, decreased calving rates, decreased milk and meat yields, and the disease's effect on the use of animal traction (Shaw, 2004). All told, trypanosomiasis reduces livestock productivity by 20–40 percent (Hursey, 2001; Swallow, 2000), which results in $4.5 billion lost to the disease each year (Budd, 1999; Oluwafemi, 2009). The health and economic implications of trypanosomiasis thus make the tsetse fly a critical socioeconomic threat to sub-Saharan Africa.

Tsetse are biting flies from the genus *Glossina*. The fly feeds on wild ungulates and ruminants, which play important roles as reservoirs of trypanosomes (Jordan, 1986; Pollock, 1982a). Tsetse are classified as one of the few k-strategist insects meaning that they have low fecundity rates, are relatively long-lived compared to other insects, and their offspring have a higher degree of survival (Leak, 1999). It is due to their stable populations and low reproduction rates that even with low sustained mortality induced through fly control techniques, elimination of isolated tsetse populations is possible (Hargrove, 2003a; Hargrove & Vale, 1979; Weidhaas & Haile, 1978). Elimination has been defined as the complete removal of a tsetse species from a geographic area (Molyneux, Hopkins, & Zagaria, 2004). However, due to the difficulties in measuring complete removal, we define elimination as a fly density of 0.5 flies per km^2 or less, a density in which difficulties will arise in finding mates (Shaw et al., 2007). The target control method, which we employ in our analysis and describe in detail below, relies on these biological traits to eliminate fly populations through low daily mortalities (i.e., removal of 8 percent of a fly population each day).

In Kenya, eight species of tsetse are present in distributions described by Bourn, Reid, Rogers, Snow, and Wint (2001) as "relatively isolated" due to expanding agriculture and deforestation. It was estimated that 34 percent of Kenya was infested with the fly in 1996 (202,774 km^2) (KETRI, 2008), up from the estimated 22 percent infestation of 1973 (Ford & Katondo, 1977). The fly population in Kenya, as is the case with all tsetse distributions, relies on the presence of ecologically suitable habitat, including climate and land cover types (Pollock, 1982b). Populations concentrate in cooler, moister habitat in the dry season in order to mitigate the effects of high temperatures and/or dry conditions (Pollock, 1982b). The *Morsitans* group, which is the most widely dispersed subgenus in Kenya, seeks woody vegetation as temperatures rise above 32 °C (Pilson & Pilson, 1967). These micro-habitats provide moisture levels and temperatures that are roughly 4.5°C cooler, which support their survival (Muzari & Hargrove, 2005; Torr & Hargrove, 1999). Tsetse spatial distributions in Kenya display temporal patterns that correspond with changing seasons, and thus, the fluctuations in suitable habitat: in general terms, contraction during the hot dry season of January and February, expansion during the long rains of March through the end of May, prolonged contraction during the cool dry season from June to the end of October, and expansion once again during the short rains of November and December (Awange et al., 2008; Camberlin & Wairoto, 1997; DeVisser et al., 2010).

Costing tsetse control

Concern regarding the cost of tsetse control has existed since the very earliest campaigns. In 1909, an estate manager on the Island of Principe determined it to be cost-effective to control the fly population by ordering laborers to wear black cloths on their backs with a glutinous substance coating the cloth's surface (Maldonado, 1910). Glasgow and Duffy (1947) concluded that, at the time, hand catching was the most economical means of eradicating the fly population, while DDT ground spraying was found to be the most economical with its introduction in the late 1940s and early 1950s (Wilson, 1953). Davies (1964) examined the savings and effectiveness of spraying only *Glossina tachinoides* and *Glossina morsitans submorsitans* habitat

Table 1
Reported costs of tsetse control techniques.

Tsetse control technique	Costs in US$ per km^2 (Year)	Control or eradication	Included in study	Source, *country*
Insecticide treated cattle: 44 cattle per km^2	60 (1996)	Annual control cost	Pour-on, tsetse monitoring, farmers' time, transport	Woudyalew et al. (1999), *Ghibe, Ethiopia*
Insecticide treated cattle: 15 cattle per km^2	250[a] (1990)	Eradication	Pour-on, delivery cost, dipping service	Barrett (1997), *Zimbabwe*
Aerial spraying	270(2000–2001)	Elimination	Operational costs for insecticide and aerial spraying	Allsopp and Hursey (2004), *Okavango, Botswana*
Aerial spraying	700–900[a] (1990)	Eradication	Operational costs for spraying, monitoring	Barrett (1997), *Zimbabwe*
Targets	219 (1996)	Control	Field costs for tsetse control division	Mullins, Allsopp, Nkori, Kolyane, and Phillemon-Motsu (1999), *Botswana*
Targets	96 (1999)	Control	Cost for initial deployment	Allsopp and Hursey (2004)
Trapping (mono – pyramidal traps)	26 (1992)	Annual control cost	All field level costs, capital items, local administration and salaries, donor costs	Shaw, Zessin, and Munstermann (1994), *Northern Côte d'Ivoire*
Trapping (isolated population – 4 traps per km^2)	283 (end of 2005)	Eradication	Administration, surveying, monitoring, field costs	Shaw et al. (2007), *Uganda*
Sterile insect technique (SIT)	800 (2004)	Post suppression: elimination of fly population	Cost of breeding and releasing sterile flies for 18 months post suppression	Feldmann (2004)

[a] Costs are as they appear in Budd (1999) who updated Barrett (1997) costs. Sources are as listed. Source: Adapted from Shaw (2004).

in the dry season. More recently, in an effort to increase the efficiencies of fly control through better placement of tsetse traps, Sciarretta, Tikubet, Baumgärtner, Girma, and Trematerra (2010) performed a clustering analysis to identify patches of tsetse in Ethiopia. Other recent cost studies have placed a greater focus on detailing field and administrative costs and have tended to compare the cost-effectiveness of several control options in the same study (e.g., Barrett, 1991, 1997; Brandl, 1988; Shaw et al., 2007).

The concern of this study, however, is not one of comparing the costs of different control techniques; rather, it is to examine the cost-effectiveness of controlling geographically constrained fly distributions using a single technique. A wealth of research has amassed evaluating the particular qualities of each technique (e.g., Feldmann, 2004; Hargrove, 2003a; Leak, Ejigu, & Vreysen, 2008; Tsetse.org, 2010; Vale & Torr, 2004). Recent estimates of the costs of control using these methods have been summarized by Shaw et al. (2007) (Table 1). However, comparing the costs of techniques from separate studies can be misleading due to differences in the goals of control campaigns, inconsistencies regarding the costs that are included in the compared studies, and the simple fact that costs vary by study location (Shaw, 2004). Economic guidelines have been suggested that must be followed when carrying out costing simulations in order to avoid the above errors. These include discounting costs to their net present value to create a temporally dynamic costing simulation, inclusion of costs from all facets of the management campaign (i.e., administration, surveying, monitoring, and field costs), and use of control input prices that are consistent with the region where the control campaign is taking place (Shaw, 2003).

Tsetse control using targets

Targets, commonly used tsetse control devices, are two-dimensional screens of blue and black cloth impregnated with pyrethroid insecticides, typically deltamethrin. For savannah flies such as *G. morsitans submorsitans* and *Glossina pallidipes*, the targets are baited with acetone and octenol (Kuzoe & Schofield, 2004; Vale, Hargrove, Cockbill, & Phelps, 1986), which have been shown to affect a two to six-fold improvement in fly attraction to control devices (summarized in Gibson & Torr, 1999). Baits are recommended to be replaced every three months for best performance (D. O. Gamba, Project Entomologist of PATTEC, Nairobi, Kenya, conversation, 24 August 2010). Regarding the density of targets, a high likelihood of flies encountering a target exists if the targets across a control area are deployed at 4 per km^2 (Hargrove, 2003b). Consequently, this will be the density of targets used in the ensuing tsetse management simulation. Theft or damage caused by rains or animals also occurs to targets; therefore, targets need to be checked regularly to ensure that they are adequately maintained. In order to provide an accurate cost of managing spatially constrained fly populations, the simulation in this study provides for the occurrence of target theft, damaged targets, and retreatment of targets with baits and insecticide.

Targets were chosen over the closely related tsetse traps as they have been revealed to be just as effective as traps, often times more effective, and are more economical (Barrett, 1997; Tsetse.org, 2010). Targets also lend themselves to control carried out at the local level, and due to the recent concern for community participation in tsetse control, this small-scale approach is attractive to both donors and governments.

Methods

Identifying the location and timing of the constrained fly distributions was of primary importance. We named these

Table 2
Model parameters.

Input variables	Parameter values	Sources[a]
TED model parameterization to identify suitable Glossina Morsitans habitat		
Land cover	Woody vegetation	**1**, **2**
NDVI	>0.39	**3**, 4
Suitable day temperature	>17 °C & <40 °C	**2**, **5**, 6, 7
Suitable night temperature	>10 °C & <40 °C	**2**, **5**, 6, 7
Selected parameters used in the Tsetse Muse model		
Adult flies per km^2	Females: 5000; Males: 2500	**8**
Pupal duration (days)	Females: 26; Males: 28	**9**
Interlarval period (days)	Females: 9	**9**
Maximum lifespan (days)	Females: 178; Males: 89	**8**
Pupal death rate	Females: 0.25; Males: 0.25	**9**
Larvae death rate	Females: 0.05; Males: 0.05	**9**
Kill rate per day using targets	Females: 0.08; Males: 0.08	**4**, **10**

[a] Sources in bold are primary sources; otherwise the sources were used to provide supplemental information. Sources – 1-Pollock (1982a), 2-Pollock (1982b), 3-Williams et al. (1992b), 4-Vale, Lovemore, Flint, and Cockbill (1988), 5-Leak (1999), 6-Muzari and Hargrove (2005), 7-Mellanby (1936), 8-Glasgow (1963), 9-Hargrove (2004), 10-Vale et al. (1986).

constrained fly distributions “control reservoirs” (CRs) and defined them as spatially constrained tsetse fly distributions limited by seasonal fluctuations to suitable habitat. And while CRs accounted for fluctuations in habitat, we also introduced “tsetse zones” (TZs) to act as a comparative feature for the CR; this detailed comparison will take place below. TZs are simply the maximum spatial extent of fly distributions over the period of study.

The locations of tsetse during the study period of 1 January 2002 to 19 December 2010 were identified using spatially and temporally dynamic species distribution maps. These maps were produced at a 250 m spatial resolution every sixteen days; as a result, twenty-three distribution maps were produced for each year and a total of 207 distribution maps were produced and used in this study. Species distribution models are increasingly being used for vector and

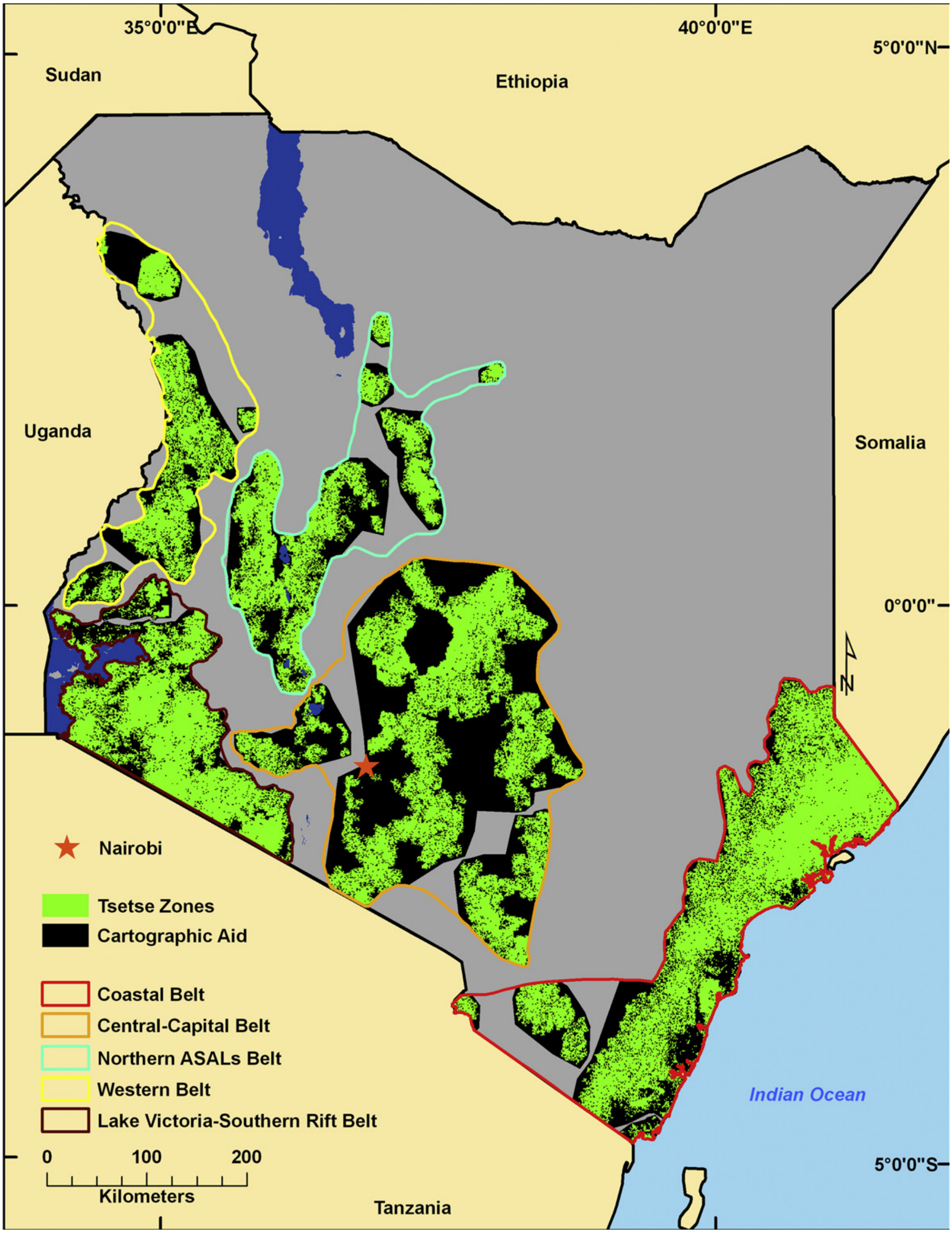


Fig. 1. Kenya’s tsetse fly belts and tsetse zones. The tsetse zones represent areas where the fly is present at least once from 1 January 2002 to 19 December 2010. The cartographic aid is simply used to help the reader visually distinguish between the separate tsetse zones within each belt.

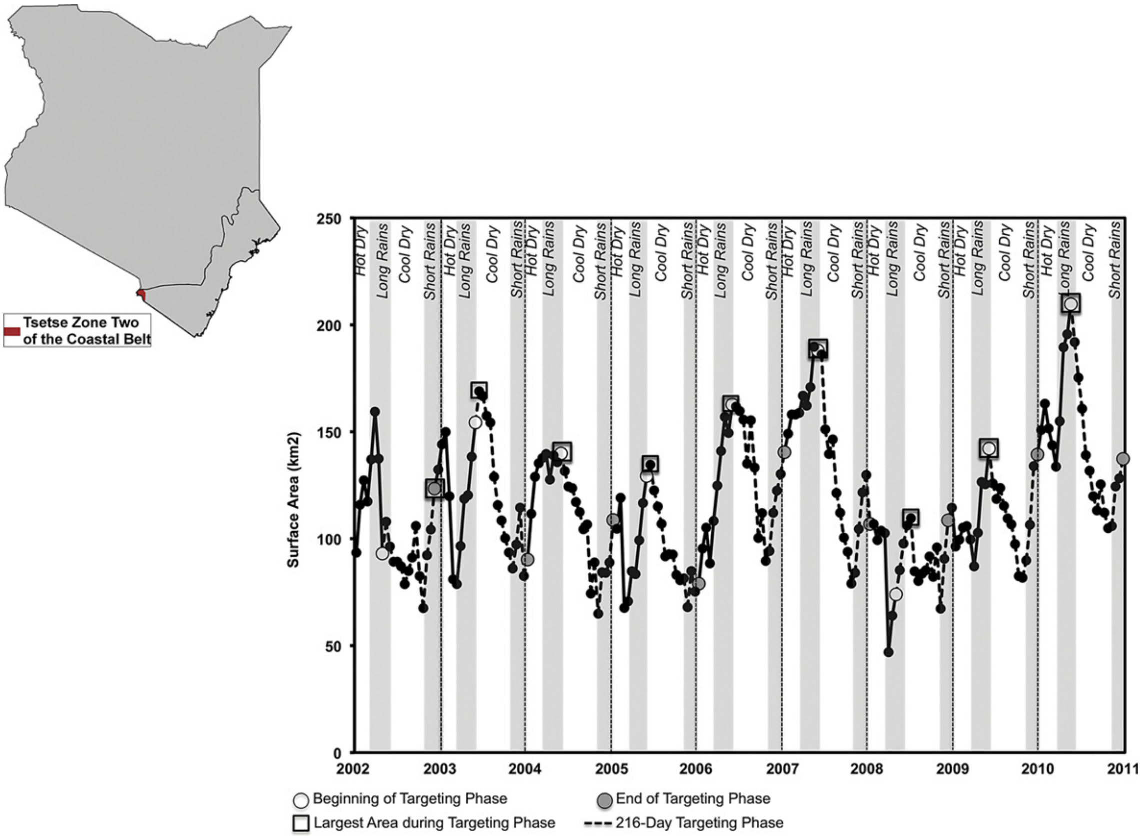


Fig. 2. Predicted tsetse distribution surface area for tsetse zone two of the Coastal Belt. Seasonal fluctuations in surface area occupied by the tsetse distribution in tsetse zone two of the Coastal Belt is displayed. The minimum area interval for each year is represented by the dashed lines, with the largest surface area date within each minimum area interval also shown, as well as the starting and ending dates of the targeting phase.

Table 3
Inputs and costs used in all activities of management campaign.

Inputs	Input life (yrs)	Total cost (annual cost)	Activity	Inputs	Input life (yrs)	Total cost (annual cost)	Activity
General equipment				*Specialized eq. (cont.)*			
4 × 4 vehicle	5	$30,000 ($6000)	ET, SS, SE, PS, EA, CF, EE, A, F	Sample Vial	1	$0.10 ($0.10)	ET, EE
Lorry	5	$30,000 ($6000)	F	Consum.Parasit.	8	$5000 ($625)	PS
Bicycle	8	$80 ($10)	SE, CF	Sampling Equipment	8	$1100 ($137.50)	EA, EE
Motorbike	8	$2500 ($312.50)	ET, SE, PS, EE	*Recurring specialized equipment*			
Laptop computer	3	$3000 ($1000)	ET, SS, CF, EE, A	Training – field staff	1	$125 ($125)	F
Radio set	5	$500 ($100)	ET, EA, EE	Delta-methrin	1	$350 ($350)	F
Camping equipment	5	$400 ($80)	ET, EE, F	Octenol	1	$1.50 ($1.50)	F
Specialized equipment				Acetone	1	$3.50 ($3.50)	F
Target	1	$8 ($8)	F	Fuel/maint. vehicles	1	$32/day	ET, SS, SE, PS, EA, CF, EE, F
Trap	1	$8 ($8)	ET, EE	*Staff salaries*			
Satellite imagery	8	$700 (87.50)	ET, EA, EE	Team leader	1	Varies[a]	ET, SS, SE, PS, EA, CF, EE, F
Land use/veg. map	8	$20,000 ($2500)	ET	Entomological ass't.	1	$25/day	ET, EE, F
GPS unit	3	$30 ($10)	ET, SS, EA, CF, EE, F	Laborer	1	$5/day	F
Dissection microscope	8	$1000 ($125)	ET, CF, EE	Driver	1	$17/day	ET, SS, PS, CF, EE, F, A

[a] "Team Leader" varies in cost depending on the control activity since responsibilities vary across activities. Team leaders include general team leaders ($30/day), biochemists ($30/day), medical officers ($30/day), veterinary officers ($30/day), consultants/ecologists ($130/day), and socio-economists ($130/day). Control campaign activities – ET – Entomological Survey and Tsetse Fly Population Genetics Survey. Includes trapping and sampling of flies and studying their genetics to assist in carrying out control operations. This survey also includes updating and identifying fly distributions. SE – Socioeconomic Survey. A survey to understand the socioeconomic status of households within tsetse areas before control operations. This information is to be used to assess the effect of fly removal in improving human livelihoods. SS – Sleeping Sickness Survey. A survey to identify areas at risk of sleeping sickness. PS – Parasitological and Serological Data Collection. Includes taking record of African animal trypanosomiasis cases to identify areas where livestock are most at risk and where intervention efforts should be targeted. EA – Environmental Impact Assessment. Study undertaken to identify key biotic and abiotic parameters to assist in monitoring the environmental impacts of fly control operations. CF – Sleeping Sickness Active Case Finding. Surveillance of areas where sleeping sickness is known to be endemic, and treatment of diagnosed cases. This operation is carried out during the entire duration of the field control efforts. EE – Environmental and Entomological Monitoring. Surveillance of key environmental and entomological parameters in order to assess the effects of fly control operations. Monitoring is conducted during the entire duration of the field control efforts. A – Administration and Office Support. Includes equipment, personnel, and attendance at meetings necessary to maintain a central tsetse management office. F – Field Control. Includes setting up targets, baiting with odors, spraying with insecticides as well as the retreating and replacement of targets during fly control.

Table 4
Fly management schedule including monitoring, surveying, and field control operations.

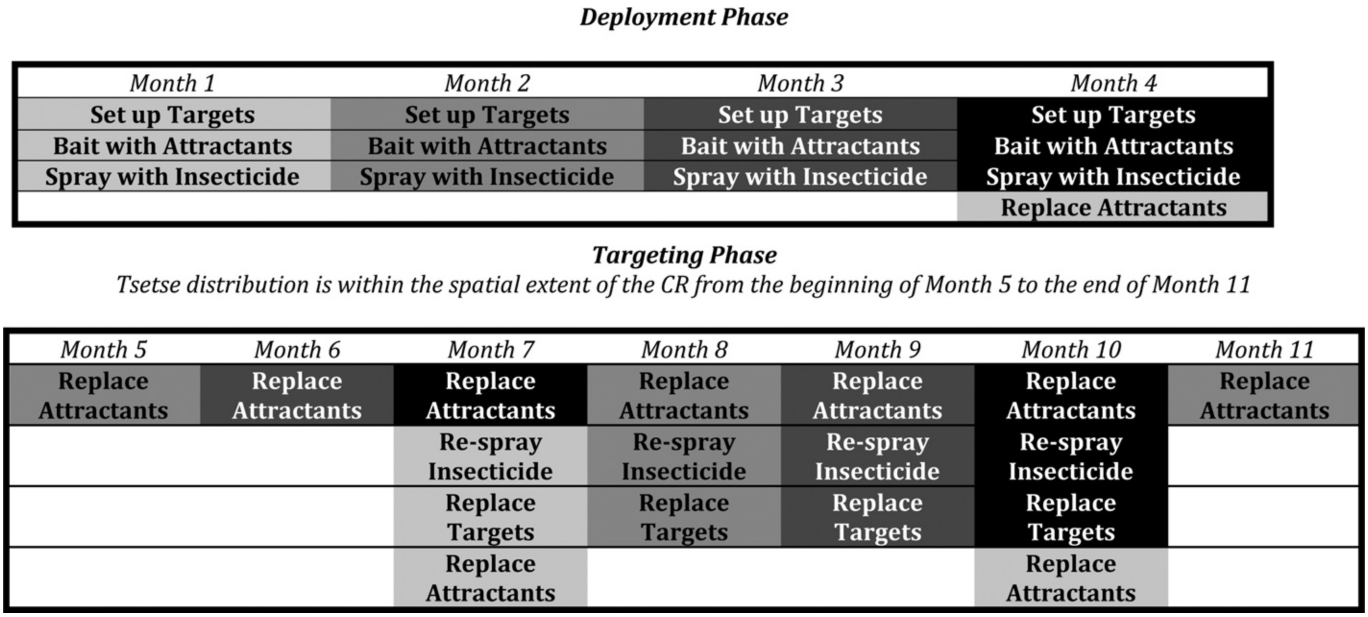
Year (discount factor)	Activity	Duration (days)
1 (1.210)	ET	180
	SE	60
2 (1.100)	SS	60
	PS	180
	EA	90
3 (1.000)	Coastal Belt Control	336
	CF	90
	EE	90
4 (0.909)	Cent.-Capital Belt Control	336
	CF	90
	EE	90
5 (0.826)	No. ASALs Belt Control	336
	CF	90
	EE	90
6 (0.751)	Western Belt Control	336
	CF	90
	EE	90
7 (0.683)	L. Vict.-So. Rift Belt Cont	336
	CF	90
	EE	90
8 (0.621)	PS	180

Notes: Fly management campaign activities – Belt Control includes the 120 days to set up, bait, and spray targets as well as the ensuing 216 days that targets are left in the field to eliminate the fly population. During these 216 days, targets are re-baited, re-sprayed, and replaced if damaged or stolen. Belts are only an administrative unit; the control operations are conducted in either the CRs or TZs, depending on the spatial extent used in the management campaign. ET – Entomological Survey and Tsetse Fly Population Genetics Survey. SE – Socioeconomic Survey. SS – Sleeping Sickness Survey. PS – Parasitological and Serological Data Collection. EA – Environmental Impact Assessment. CF – Sleeping Sickness Active Case Finding. EE – Environmental and Entomological Monitoring. Activities that take place in the same year (e.g., ET and SE in Year 1) are performed during different periods of that year to allow for sharing of capital. Belt Control efforts are allowed to take place at the same time as other activities (e.g., Coastal Belt Control taking place at the same time as CF in Year 3), since the capital items used for the belt control efforts are only shared amongst other belt control operations, which occur in separate years.

disease mapping (e.g., Machado-Machado, 2011). In this study, the species distribution maps were produced using the Tsetse Ecological Distribution (TED) Model (DeVisser et al., 2010), which uses habitat suitability and fly movement rates to predict the location of fly distributions every sixteen days. We chose the TED Model for our analysis because, unlike other models, the TED Model accounts for spatio-temporal dynamics of fly distributions, which is absolutely essential to identifying constrained fly distributions. Additionally, by coupling fly movement rates with habitat suitability, the TED Model predicts the realized niche of tsetse populations, unlike other models, such as that used to construct the FAO/IAEA distribution maps (Wint, 2001), which only account for suitable fly habitat (i.e., the fundamental niche). The TED Model was parameterized to identify suitable habitat for *Glossina* subgenus *Morsitans*, which, as stated earlier, is the most widely distributed subgenus in Kenya. As a result, hereinafter "tsetse" will refer to the *morsitans* group, and the concern of this study will accordingly be control of this subgenus. The suitability of habitat for the *morsitans* group was predicted using input variables for land cover; Normalized Difference Vegetation Index (NDVI), which was used as a surrogate for moisture; suitable day temperatures; and suitable night temperatures. Table 2 gives the parameterization of the TED Model to identify suitable tsetse habitat.

Fly belts and tsetse zones

To locate the CRs, as well as the TZs, it was first necessary to group fly distributions into fly belts. Currently and historically, fly belts have been produced by estimating the distributional limits of fly species based on vegetation type, meteorological records, and altitude (Ford & Katondo, 1975; Rogers & Robinson, 2004); therefore tsetse are not necessarily confirmed in all areas where fly belts represent them to be. The creation of fly belts was done in the current study to form administrative units for the fly management simulation and to allow for greater ease in distinguishing between separate control areas. To establish the fly belts, the TED Model was parameterized using daily mean maximum and minimum temperatures, and daily mean NDVI for each day across all years of



Deployment Phase

Month 1	Month 2	Month 3	Month 4
Set up Targets	Set up Targets	Set up Targets	Set up Targets
Bait with Attractants	Bait with Attractants	Bait with Attractants	Bait with Attractants
Spray with Insecticide	Spray with Insecticide	Spray with Insecticide	Spray with Insecticide
			Replace Attractants

Targeting Phase

Tsetse distribution is within the spatial extent of the CR from the beginning of Month 5 to the end of Month 11

Month 5	Month 6	Month 7	Month 8	Month 9	Month 10	Month 11
Replace Attractants	Replace Attractants	Replace Attractants	Replace Attractants	Replace Attractants	Replace Attractants	Replace Attractants
		Re-spray Insecticide	Re-spray Insecticide	Re-spray Insecticide	Re-spray Insecticide	
		Replace Targets	Replace Targets	Replace Targets	Replace Targets	
		Replace Attractants			Replace Attractants	

Fig. 3. Control period operations. All operations during the "Deployment Phase" and "Targeting Phase" are staggered. In other words, one fourth of all targets will be set up in the first month, then another fourth in the second month until all targets are set up by the fourth month. At the time of the fourth month, the targets that were set up in the first month need to have their attractants replaced. This rotation continues throughout the duration of the control period. The shading of the cells indicates what set of targets are receiving the treatment (e.g., in Month 7 the fourth set of targets that were set up are having their attractants replaced, while the first set of targets are being re-sprayed, re-baited, and replaced if they are damaged or missing).

the study period (i.e., from 1 January 2002 to 19 December 2010), as well as a land cover composite from 1 January 2002 to 19 December 2004. These parameterizations were established to reduce inter-annual variability from aberrant climatic events. This produced twenty-three daily averages scenes, with each scene representing the average value for that day over the nine-year study period. A percent probability map of tsetse presence using ArcGIS version 9.3 was then created by summing the daily averages scenes and then dividing by twenty-three (the total number of scenes). Areas where the fly was predicted to be present less than 50 percent of the time were then eliminated, a break point used in previous studies (e.g., ERGO, 1999). The break point of 50 percent was selected to ensure that belts represented locations where a high probability of encountering tsetse existed, not simply areas where the fly may be present only several days over a period of years. Next, tsetse distributions that occupied less than 150 km^2 were eliminated, as it was assumed that these small distributions would not be targeted as priority control areas by policy makers. Remaining tsetse distributions were then expanded by 1 km to join distributions that were expected to be continuous during the wet seasons following fly distribution expansion (see Hargrove, 2000). These final tsetse distributions were then classified as “major distributions” if their areas were greater than 8000 km^2, an area similar to the size of individual belts from Kenya’s 1996 fly belts (KETRI, 2008; Muriuki, Chemuliti, Changasi, Maichomo, & Ndung’u, 2005). Smaller distributions were identified as “pockets” and were grouped with the nearest major distribution. Grouping of pockets to the nearest major distributions was based on the Euclidean distance to each major distribution.

Following identification of the fly belts, the TZs (i.e., the maximum spatial extent of fly distributions during the study period) within each belt were identified. Using the maximum extent of fly distributions (i.e., Σ 207 distribution maps), distributions were expanded by 3 km. This distance is consistent with a fly front moving at a distance of 1 km each month for three months (Hargrove, 2000), the longest of Kenya’s wet seasons. If, after

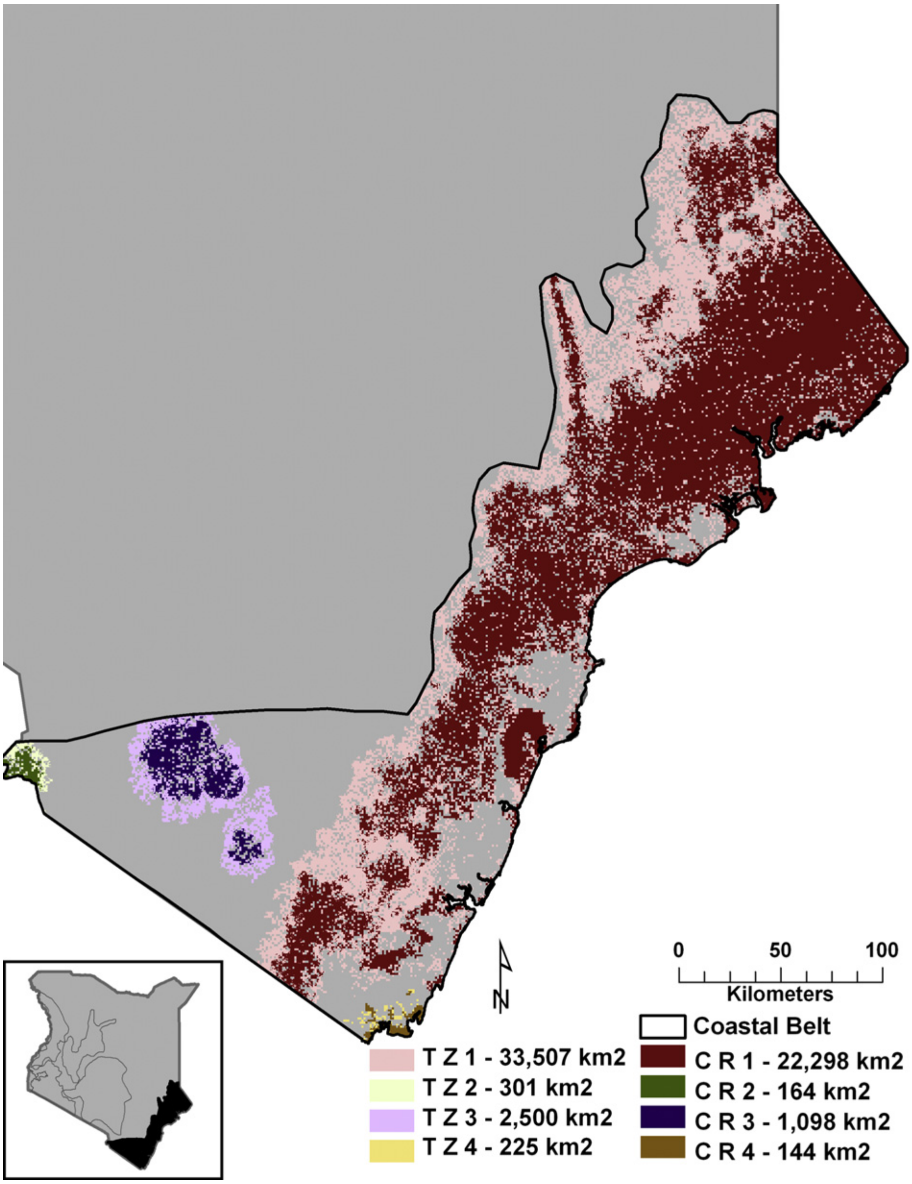


Fig. 4. Coastal belt: Control reservoirs and tsetse zones. Each control reservoir is laid on top of the corresponding tsetse zone. As a result, tsetse zones are present where control reservoirs exist, but notice that tsetse zones also expand beyond the control reservoirs. Areas for both tsetse zones and control reservoirs are given.

expanding, fly distributions remained separated from the major distributions and had an area of 150 km^2 or greater, they were considered isolated TZs. Isolated TZs with areas less than 150 km^2 were grouped with the nearest TZ meeting the 150 km^2 size requirement in an effort to take advantage of the economies of scale realized when tsetse management operations are spread over a large area (see Budd, 1999). The geographic extent of each of these TZs was then used to form a maximum area boundary for each of the CRs. In other words, each CR would be nested within a TZ. The fly belts created from the process above as well as the TZs are shown in Fig. 1.

Control reservoirs

CRs were identified by first plotting the predicted tsetse surface area for each TZ over the nine years of the study (see Fig. 2). DeVisser et al. (2010) similarly plotted predicted tsetse surface areas in their study. Tsetse control simulations using the population dynamic model Tsetse Muse (Vale & Torr, 2005), available at http://www.tsetse.org, revealed that sustained control using targets for 216 consecutive days led to elimination of a tsetse population, which again, for the purposes of this study is a density of 0.5 flies per km^2. Due to space constraints, Table 2 lists only a selection of the parameters used in the Tsetse Muse model.

The CRs were produced in two steps. First, the predicted surface area for each TZ was plotted, and the 216-day interval where the tsetse distribution occupied the least area for each year, measured in km^2, was identified (see Fig. 2). This continuous 216-day period will be referred to as the minimum area interval. A preference was given to minimum area intervals that occurred during the cool dry season, as it is easier to locate and reach targets for repair and replacement during the dry season, and targets tend to be better performing during the dry season as the rains have not limited the effectiveness of the insecticides (Williams, Dransfield, & Brightwell, 1992a). The distribution map representing the largest surface area, measured in km^2, was then identified for each minimum area interval (see Fig. 2). By choosing the largest surface area map, it was ensured that the CR would encompass the fly distribution during

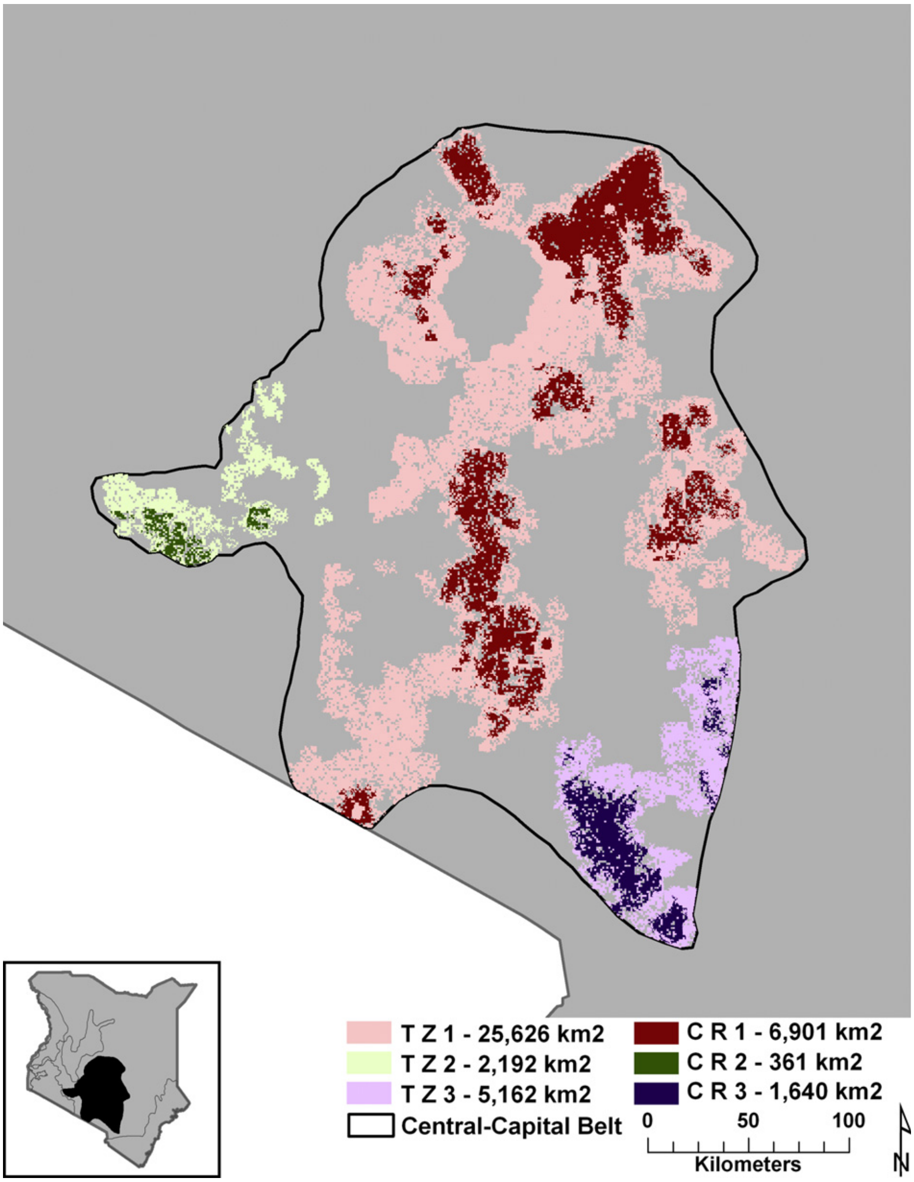


Fig. 5. Central-capital belt: Control reservoirs and tsetse zones. Each control reservoir is laid on top of the corresponding tsetse zone. As a result, tsetse zones are present where control reservoirs exist, but notice that tsetse zones also expand beyond the control reservoirs. Areas for both tsetse zones and control reservoirs are given.

the entire 216-day period needed to eliminate the fly distribution. Second, the nine "largest surface area distribution maps" (one for each year) selected in step one were summed in ArcGIS version 9.3 to create a probability map. The locations within these probability maps where the fly was predicted to be 50 percent of the time or more constituted a CR. The break point of 50 percent, which was also used in DeVisser et al. (2010), was chosen so that CRs represent locations where tsetse are reliably present, not sites where the fly is present only during abnormal climatic events. By definition, CRs occupied a smaller area than the TZs; thus, fly management within the CRs relates to a reduction in the capital and labor inputs needed to achieve fly elimination.

Costing exercise

Two studies (i.e., AU, IAEA, & ADB, 2004; Shaw et al., 2007) as well as personal correspondence were used to ensure accuracy and inclusion of all relevant costs. Shaw et al. (2007) provided a framework for structuring the schedule of target deployment and the various surveying and monitoring tasks. AU et al. (2004) provided an extensive list of the various inputs needed to control the fly in the field, and the inputs necessary to maintain a central control office, conduct surveys, and monitor. Taken together, these tasks constitute fly management. A list of several selected inputs to accomplish fly management used in this study, along with their costs, is given in Table 3. These costs were calculated at end 2010 prices, and are consistent with management projects in Kenya.

A discount rate of 10 percent was used to allow for the timing of different events. A 10 percent rate is often used for the valuing of livestock projects, and because nagana is much more common in Kenya compared to sleeping sickness (Bourn et al., 2001; Grady et al., 2011), we selected this as an appropriate figure. Discounting relies on the establishment of a baseline year. Compound interest is then removed from monies received or disbursed after the base year and added to monies received or disbursed before the baseline year. We chose year three, the year that fly control in the field began, to be the baseline year. The 10 percent discount rate was then used to calculate discount factors, and these discount

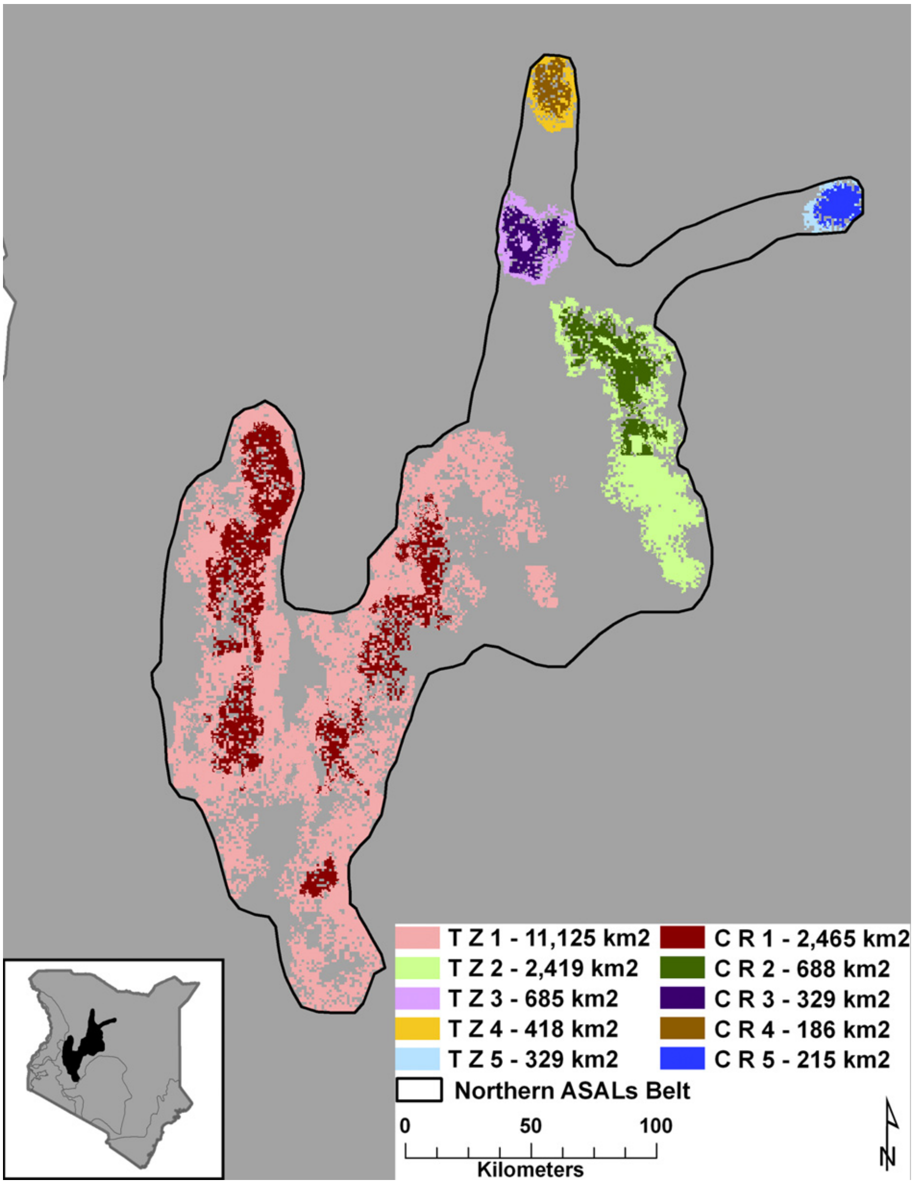


Fig. 6. Northern arid and semi-arid lands belt: Control reservoirs and tsetse zones. Each control reservoir is laid on top of the corresponding tsetse zone. As a result, tsetse zones are present where control reservoirs exist, but notice that tsetse zones also expand beyond the control reservoirs. Areas for both tsetse zones and control reservoirs are given.

factors were then multiplied by the cost incurred in each year to give the present value of each activity (see Table 4 for discount factors and the activities performed in each year). The discount factor for each year was calculated using the following equation:

$$\text{Discount Factor} = (1 + r)^t$$

where r is the discount rate of 10 percent, and t is the year for which the discount factor is being calculated. Therefore, t for Year 1 would equal 2, t for Year 3 would be 0, and t for Year 8 would be -5. Depreciation of capital was managed by using the straight-line depreciation method to spread the cost of each capital item evenly over the course of its useful life (Karris, 2003).

The period in which field control operations were taking place for each belt was split into two phases (Fig. 3). The first phase consisted of deployment of all targets, as well as baiting targets with odor attractants and spraying targets with insecticides. We assumed that one laborer was able to deploy four baited and sprayed targets each day (D. O. Gamba, Project Entomologist of PATTEC, Nairobi, Kenya, conversation, 24 August 2010). This phase took place during the four months before the fly was confined to the limits of the CR. Once the fly was confined to the CR, the second phase, known as the targeting phase, took place. During this phase, targets were re-baited every three months and re-sprayed after they had been in the field for six months. The targeting phase also allowed for the replacement of damaged or stolen targets after targets had been in the field for six months. More specifically, we assumed that 17 percent of all targets in each CR would need to be replaced after six months (D. O. Gamba, Project Entomologist of PATTEC, Nairobi, Kenya, conversation, 24 August 2010). The targeting phase began on the date that the fly was confined to the CR and extended for the 216 days needed to eliminate the fly population within the CR.

Results and discussion

All CRs as well as their corresponding TZs are shown in Fig. 4–8. In TZ two of the Central-Capital Belt and TZs two and three of the

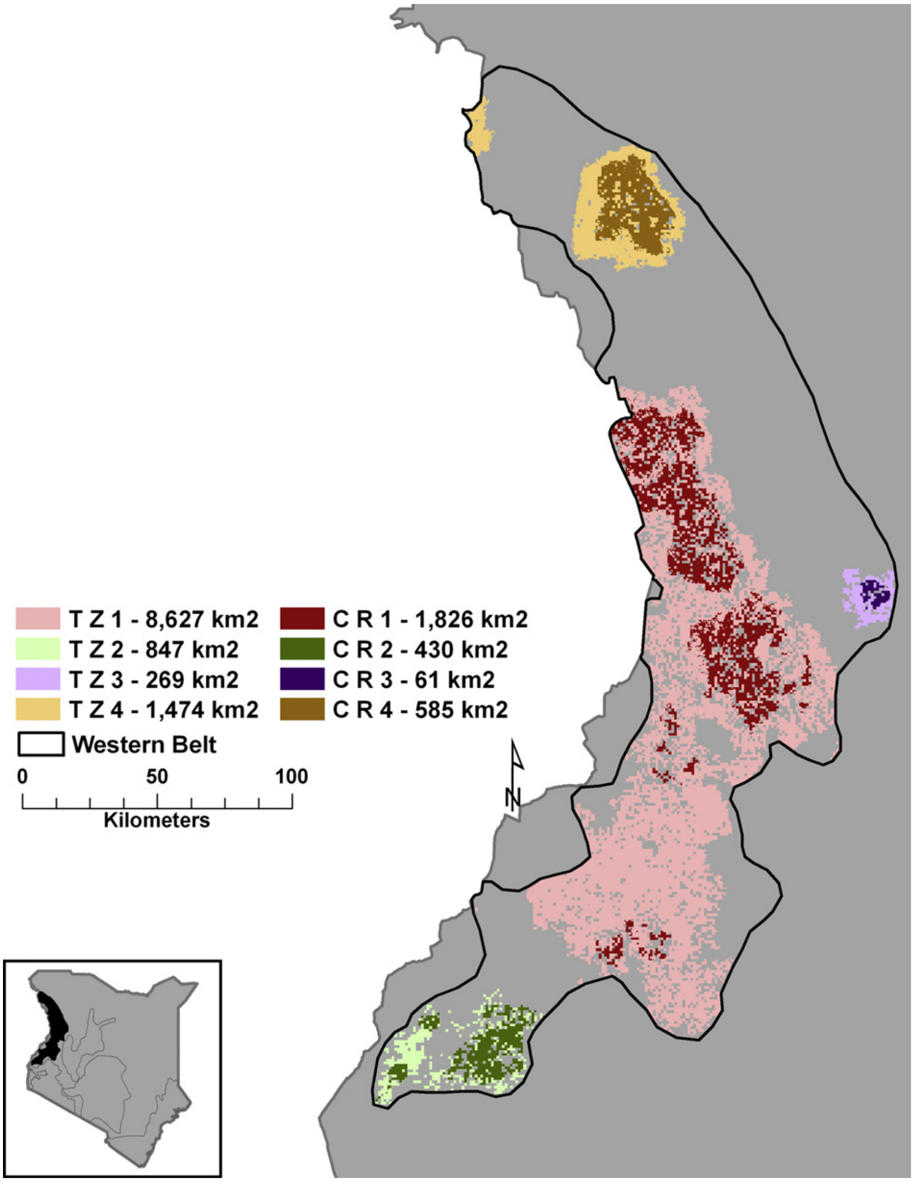


Fig. 7. Western belt: Control reservoirs and tsetse zones. Each control reservoir is laid on top of the corresponding tsetse zone. As a result, tsetse zones are present where control reservoirs exist, but notice that tsetse zones also expand beyond the control reservoirs. Areas for both tsetse zones and control reservoirs are given.

Lake Victoria-Southern Rift Belt, the predicted tsetse surface area fell to zero after 18 February 2004, 1 November 2006, and 7 April 2009, respectively. This occurred due to seasonal fluctuations in climate and lack of suitable tsetse habitat in these areas, which was likely brought about by below average monsoonal precipitation in 2004, a failed long rains season in 2005 leading to poor successive rains, and failed long rains in 2009 (KFSSG, 2009; Love, 2004, 2006). Because 207 distribution maps were not produced for these areas, the TZs, and their corresponding CRs, found in these areas have been excluded from the analysis. It is important to note here that the spatial resolution of the distribution maps (i.e., 250 m) may have prevented tsetse distributions from being modeled in these areas. The total area for all remaining TZs and CRs summed to 112,230 km^2 and 41,562 km^2, respectively. The former area would be representative of a management campaign that took place at all locations that evidence suggested tsetse presence. This would be the size of a campaign conducted at the maximum spatial extent of tsetse distributions. Conversely, the latter area would be representative of the size of a campaign that accounted for spatial and temporal dynamics of tsetse populations, while targeting areas of more frequent infestation (i.e., fly presence 50 percent of the time or more).

The costs of the tsetse management campaign have been broken into two categories, non-field control activities and field control activities. Non-field control activities consist of monitoring, surveying, and administration tasks; these tasks provide crucial fly management information including the environmental and economic impact of the campaign, as well as ongoing monitoring of the management campaign's success. Simply, non-field control activities are those that provide information necessary for the campaign to succeed, but do not involve the active control of the fly in the field. Field control activities, on the other hand, are those operations specifically conducted to eliminate the fly distribution from its habitat, such as deploying targets, spraying targets with insecticides, and adding or replacing odor attractants.

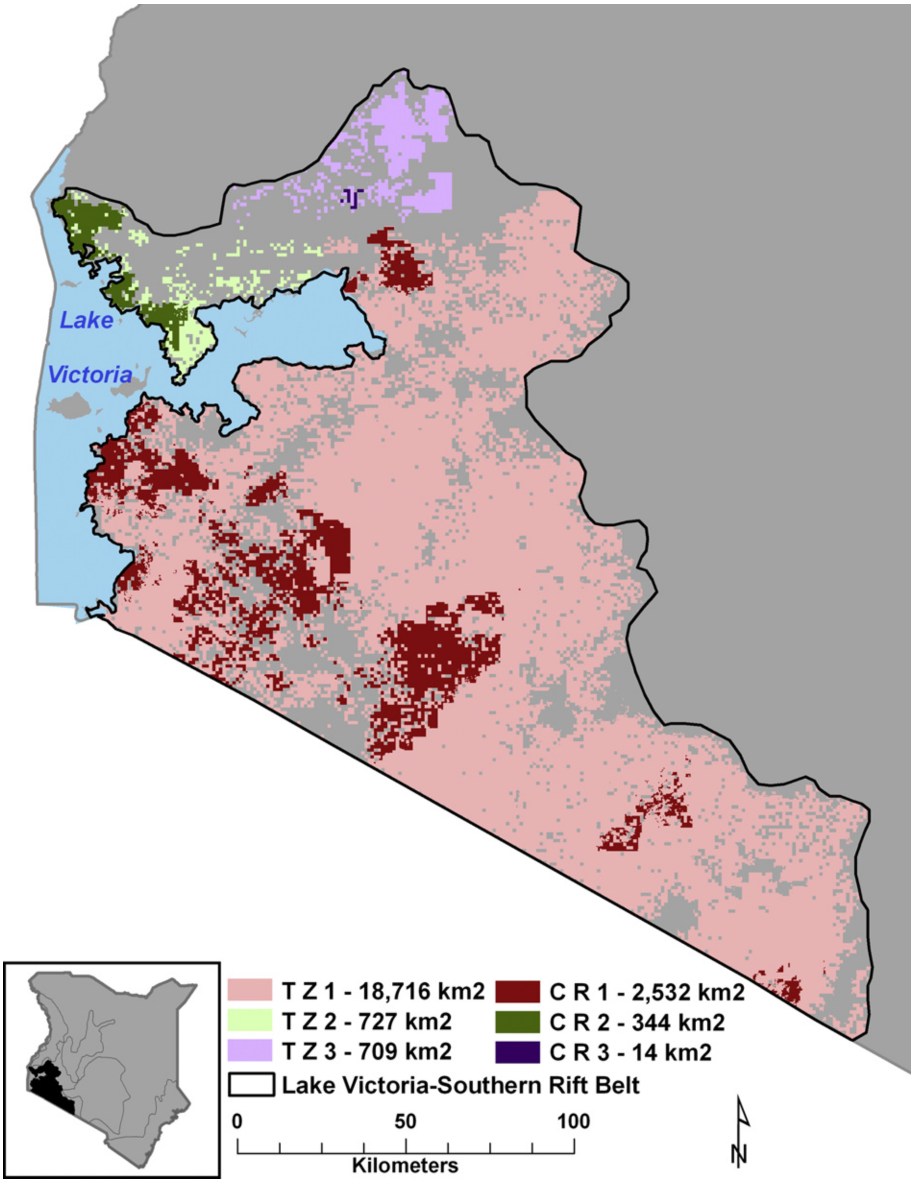


Fig. 8. Lake Victoria-southern rift belt: Control reservoirs and tsetse zones. Each control reservoir is laid on top of the corresponding tsetse zone. As a result, tsetse zones are present where control reservoirs exist, but notice that tsetse zones also expand beyond the control reservoirs. Areas for both tsetse zones and control reservoirs are given.

Table 5
Control reservoirs and tsetse zones: Non-field control costs (discounted at 10 percent).

Year	Admin. and office support	Ent. survey/tsetse pop. survey	Socioeconomic survey	Sleeping sickness survey	Parasitological and serological data	Environ. impact assessment	Sleeping sickness case finding	Environ. and Ent. case finding	Total costs
Control reservoirs									
1	$97,975	$1,101,893	$177,795	$0	$0	$0	$0	$0	$1,377,663
2	$89,068	$114,213	$13,546	$64,064	$800,560	$204,462	$0	$0	$1,285,913
3	$80,971	$37,740	$10,788	$8070	$65,483	$27,993	$84,400	$469,438	$784,883
4	$73,603	$29,588	$9807	$5454	$59,524	$25,406	$76,738	$433,082	$713,202
5	$66,882	$26,886	$8911	$4956	$54,089	$22,977	$69,731	$393,571	$648,003
6	$67,929	$6797	$3145	$0	$9525	$998	$72,336	$331,553	$492,283
7	$62,803	$6181	$2861	$0	$8662	$836	$66,825	$302,570	$450,738
8	$57,102	$5620	$2601	$0	$415,178	$760	$34,388	$37,371	$553,020
Total	$596,332	$1,328,918	$229,454	$82,544	$1,413,022	$283,432	$404,418	$1,967,583	*$6,305,705*
Cost km^{-2}	$14	$32	$6	$2	$34	$7	$10	$47	*$152*
Tsetse zones									
1	$97,975	$3,171,966	$488,737	$0	$0	$0	$0	$0	$3,758,678
2	$89,068	$309,273	$37,070	$176,176	$2,201,541	$562,125	$0	$0	$3,375,253
3	$80,971	$114,319	$30,369	$22,220	$180,367	$77,006	$84,400	$1,289,285	$1,878,937
4	$73,603	$86,099	$27,605	$14,999	$163,954	$69,888	$76,738	$1,194,276	$1,707,162
5	$66,882	$78,238	$25,085	$13,629	$148,983	$63,207	$69,731	$1,085,318	$1,551,073
6	$67,929	$15,898	$9176	$0	$26,410	$2764	$72,336	$918,960	$1,113,473
7	$62,803	$14,458	$8346	$0	$24,019	$2299	$66,825	$812,878	$991,628
8	$57,102	$13,146	$7588	$0	$1,141,903	$2090	$34,388	$86,370	$1,342,587
Total	$596,332	$3,803,397	$633,976	$227,024	$3,887,177	$779,378	$404,418	$5,387,088	*$15,718,791*
Cost km^{-2}	$5	$34	$6	$2	$35	$7	$4	$48	*$140*

Notes: All costs have been discounted to their present value in Year 3. The total area for all control reservoirs summed to 41,562 km^2, and the total area for all tsetse zones summed to 112,230 km^2. Inputs needed to carry out each of the tasks were adjusted from the inputs specified in the AU et al. (2004) document. The size of the control area in AU et al. (2004) varied from 10,000 km^2 to 40,000 km^2; as a result, the number of inputs for each task have been adjusted to agree with the total control reservoir area and the total tsetse zone area, respectively.

Non-field control costs

Using capital and labor inputs listed in AU et al. (2004) that were adjusted in number to agree with the area of the CRs and TZs listed above, the non-field control costs have been calculated following the previously described costing exercise. Over the course of an eight-year tsetse management campaign, these non-field control costs amounted to $6,305,705 for operations conducted in the CRs and $15,718,791 for operations conducted in the TZs (Table 5). Table 5 shows that Environmental and Entomological Monitoring was the most costly of the non-field control tasks for both the CRs and the TZs. This was not surprising since Environmental and Entomological Monitoring was performed over the course of five years (i.e., Years 3 through 7) alongside the field control operations in the CRs and TZs of each of the belts (see Table 4). Likewise, the Parasitological and Serological Data Collection task, which took place in Years 2 and 8, was a similarly expensive task. This operation was used to gather information regarding the location of AAT cases and to provide treatment to sickened livestock. On the other hand, aside from the Sleeping

Table 6
Control reservoirs and tsetse zones: Field control costs (discounted at 10 percent).

Year	Coastal Belt	Cent.-Capital Belt	Northern ASALs Belt	Western Belt	L. Victoria-So. Rift Belt	Total costs
Control reservoirs						
1	$0	$0	$0	$0	$0	$0
2	$0	$0	$0	$0	$0	$0
3	$4,170,381	$0	$0	$0	$0	$4,170,381
4	$247,421	$1,282,604	$0	$0	$0	$1,530,025
5	$188,229	$47,057	$742,194	$0	$0	$977,480
6	$147,136	$42,717	$33,224	$488,579	$0	$711,656
7	$120,864	$38,849	$30,216	$21,631	$305,778	$517,338
8	$0	$0	$0	$43	$19	$62
Total	$4,874,031	$1,411,227	$805,634	$510,253	$305,797	*$7,906,942*
Cost km^{-2}	$205.62	$165.23	$207.48	$175.83	$120.77	*$190.24*
Tsetse zones						
1	$0	$0	$0	$0	$0	$0
2	$0	$0	$0	$0	$0	$0
3	$6,420,681	$0	$0	$0	$0	$6,420,681
4	$276,191	$4,582,138	$0	$0	$0	$4,858,329
5	$183,000	$141,172	$2,205,555	$0	$0	$2,529,727
6	$122,443	$128,151	$85,434	$1,470,042	$0	$1,806,070
7	$53,629	$81,796	$67,453	$56,204	$2,128,544	$2,387,626
8	$0	$0	$0	$81	$211	$292
Total	$7,055,944	$4,933,257	$2,358,442	$1,526,327	$2,128,755	*$18,002,725*
Cost km^{-2}	$193.14	$160.23	$157.48	$136.07	$113.74	*$160.41*

Notes: All costs have been discounted to their present value in Year 3. For the control reservoirs, the cost per km^2 was found using the following areas for each belt: Coastal Belt, 23,704 km^2; Central-Capital Belt, 8541 km^2; Northern ASALs Belt, 3883 km^2; Western Belt, 2902 km^2; Lake Victoria-Southern Rift Belt, 2532 km^2. Cost per km^2 for the “Total Costs” field used the total area of all control reservoirs, 41,562 km^2. For the tsetse zones, the cost per km^2 was found using the following areas for each belt: Coastal Belt, 36,533 km^2; Central-Capital Belt, 30,788 km^2; Northern ASALs Belt, 14,976 km^2; Western Belt, 11,217 km^2; Lake Victoria-Southern Rift Belt, 18,716 km^2. Cost per km^2 for the “Total Costs” field used the total area of all tsetse zones, 112,230 km^2.

Sickness Case Finding task, the remaining non-field control surveying and monitoring activities were only performed over the course of one year each (see Table 4). These tasks, therefore, had a much smaller contribution to the total cost of the non-field control operations. In fact, combined, the Environmental and Entomological Monitoring task and the Parasitological and Serological Data Collection task accounted for more than 50 percent of non-field control costs for a management campaign conducted at the CR extent and nearly 60 percent of non-field control costs for a campaign conducted at the TZ extent.

Field control costs

Similar to the non-field control costs, the field control costs were calculated following the costing exercise described above. The total costs for field control activities conducted in the CRs amounted to $7,906,942 over the eight-year management campaign, while field control costs for the TZs summed to $18,002,725 over the same period (Table 6). Table 6 shows that field control operations did not begin until Year 3 of the management campaign to allow for initial surveying activities in Years 1 and 2. Field control then took place in one belt each year until control operations had been conducted in all belts (see Table 4). The Coastal Belt had the largest total area for both the CRs and the TZs; as a result, it was not surprising that field control in this belt was most costly. The Central-Capital Belt followed the Coastal Belt in total size of both the CRs and TZs, which is supported by the total cost figures of this belt from Table 6.

Table 7 provides a summary of selected inputs needed to carry out field control in the CRs and the TZs of each belt. Put differently, this table gives inputs that were needed to complete both phases of the 336-day control period, the deployment phase and the targeting phase. As the table demonstrates, all TZs required more inputs than their corresponding CRs, and some required a significantly greater amount (e.g., TZ one compared to CR one of the Lake Victoria-Southern Rift Belt), while others such as the TZs and CRs of the Coastal Belt, which had a much less dramatic fluctuation of fly distributions across seasons, had less disparity between control inputs. In areas such as the Lake Victoria-Southern Rift Belt where fluctuations of fly distributions across seasons were more dramatic, identification of the spatially constrained CRs allowed for large savings since total inputs were much fewer when controlling in the CRs compared to the TZs.

Additionally, in order to control spatially constrained populations, it was necessary to identify the date that the CR formed, which was also the date that the targeting phase began. This date is given for each CR in Table 7. Formation of the CR took place on the first day of the 216-day minimum area interval (see Fig. 2). To ensure that each year had a CR formation date, the minimum area interval was not allowed to extend into the following year. In other words, targeting, at the very latest, needed to begin by 25 May of each year, day 145 of each year, to ensure that 216 days of control operations took place. In cases where, over the nine-year period, multiple formation dates existed for a particular CR, the most frequent date was chosen as the date of formation for that CR. Table 7 demonstrates that 25 May was most frequently the date to start the targeting phase. This was not unexpected as 25 May corresponds with the end of the long rains season and is often followed by a prolonged decrease in tsetse surface area as the cool dry season sets in.

Table 7
Summary of control period capital and labor inputs for all belts.

CR (targeting date) TZ	Targets[a]	4 × 4 vehicles[b]	Deltamethrin (l)[c]	Team leaders[d]
Coastal Belt				
CR 1 (25 May)	104,355	23	798	23
TZ 1	156,813	35	1199	35
CR 2 (25 May)	768	1	6	1
TZ 2	1409	1	11	1
CR 3 (25 May)	5139	1	39	1
TZ 3	11,700	3	89	3
CR 4 (25 May)	674	1	5	1
TZ 4	1053	1	8	1
Central-Capital Belt				
CR 1 (25 May)	32,297	7	247	7
TZ 1	119,930	27	917	27
CR 3 (25 May)	7675	2	59	2
TZ 3	24,158	5	185	5
Northern Arid and Semi-Arid Lands Belt				
CR 1 (1 January)	11,536	3	88	3
TZ 1	52,065	12	398	12
CR 2 (25 May)	3220	1	25	1
TZ 2	11,321	3	87	3
CR 3 (25 May)	1540	1	12	1
TZ 3	3206	1	25	1
CR 4 (25 May)	870	1	7	1
TZ 4	1956	1	15	1
CR 5 (25 May)	1006	1	8	1
TZ 5	1540	1	12	1
Western Belt				
CR 1 (25 May)	8546	2	65	2
TZ 1	40,374	9	309	9
CR 2 (1 January)	2012	1	15	1
TZ 2	3964	1	30	1
CR 3 (1 January)	285	1	2	1
TZ 3	1259	1	10	1
CR 4 (1 January)	2738	1	21	1
TZ 4	6898	2	53	2
Lake Victoria-Southern Rift Belt				
CR 1 (25 May)	11,850	3	91	3
TZ 1	87,591	20	670	20

Notes: Targeting date is listed in parentheses for each CR.

[a] Targets are dispersed at 4 per km^2. Additionally, 17 percent of targets are replaced during the seven months of the targeting phase.

[b] One 4 × 4 vehicle will be used by each team. The number of teams for each CR is determined by the total number of initially dispersed targets divided by 3840; this is the number of targets that one team of eight laborers is able to set up in four months if one laborer sets up four targets each day.

[c] Sixty-seven liters of final solution is produced from 1 L of deltamethrin. 600 ml is applied to each target during the duration of the 336-day control period.

[d] One team leader is assigned to each team.

Comparison of costs

To arrive at the total cost of the tsetse management campaign, the non-field control and field control costs for the CRs were combined and the same was done for the TZs, which gave a total cost of $14,212,647 for an eight-year control campaign conducted in the CRs and a cost of $33,721,516 for an eight-year campaign conducted in the TZs. This sizable difference of $19,508,869 demonstrates the value of tsetse management of spatially constrained distributions. And with the amount allocated to agriculture and rural development decreasing by 3.5 percent in Kenya's 2011-2012 budget (Kenyatta, 2011), the importance of efficiently using the available tsetse control funds through methods such as identifying and controlling spatially constrained populations is evident. Additionally, in a draft document summarizing allocations to agriculture and rural development, the amount assigned to "Livestock Diseases Management and Control" was roughly $17 million during the financial year 2010–2011 (Republic of Kenya, 2011). This suggests that an appetite may exist for a $14 million fly management campaign (i.e., fly control of the CRs), but one costing nearly $34 million (i.e., control of the TZs) may be too financially consuming. Feldmann et al. (2005) point to other needs such as roads, schools, and medical services that are perceived to require more immediate attention over tsetse control. Such competing interests for limited

Table 8
Variations to tsetse management campaign costs.

Non-field control costs reduced by 25 percent					
CRs	Non-field control	$4,729,279	TZs	Non-field control	$11,789,093
	Total campaign	*$12,636,221*		Total campaign	*$29,791,818*
Non-field control costs reduced by 50 percent					
CRs	Non-field control	$3,152,853	TZs	Non-field control	$7,859,396
	Total campaign	*$11,059,795*		Total campaign	*$25,862,121*
Non-field control and field control costs discounted at 5 percent					
CRs	Administration and office support	$631,642	TZs	Administration and office support	$631,642
	Ent. survey/tsetse pop. survey	$1,233,637		Ent. survey/tsetse pop. survey	$3,528,101
	Socioeconomic survey	$216,121		Socioeconomic survey	$597,719
	Sleeping sickness survey	$80,378		Sleeping sickness survey	$221,068
	Parasitological and serological data	$1,496,623		Parasitological and serological data	$4,117,232
	Environmental impact assessment	$278,123		Environmental impact assessment	$764,793
	Sleeping sickness case finding	$448,451		Sleeping sickness case finding	$448,451
	Environmental and entomological mon.	$2,148,322		Environmental and entomological mon.	$5,877,433
	Belt field control	$8,288,570		Belt field control	$19,242,467
	Total campaign	*$14,821,867*		Total campaign	*$35,428,906*

government funds makes vital the identification of financially efficient means of fly control.

It should be recognized that of the total costs mentioned above, 44 percent was made up of non-field control costs for the CR total amount and 47 percent of the TZ total was made up of non-field control costs. Increased efficiencies or the elimination of needless surveys would lead to an overall reduction in total costs for the fly management campaign. Similarly, the costs of the fly management campaign were largely influenced by the chosen discount rate, which was 10 percent in this study. If a discount rate of 5 percent was used, which is more consistent with a human health campaign than a livestock campaign, the costs of each of the field control and non-field control tasks would be altered. Tenge, De graaff, and Hella (2005) performed similar sensitivity analyses when conducting a financial cost-benefit analysis of soil and water conservation efforts in Tanzania. Table 8 shows the variations in costs from our study with the elimination of some non-field control tasks and adjustment of discount rates. Reductions to non-field control costs would be beneficial to the cost-effectiveness of the management campaign as Table 8 suggests that total campaign costs would be reduced by over $3 million for management in the CRs and by nearly $8 million for management in the TZs with a cut of 50 percent to non-field control costs. Further analysis is needed to determine the source of these cuts and the practicality of such reductions. Regarding an adjustment of the discount rate to 5 percent, the total campaign costs would increase at both the CR and TZ level. This increase in fly management campaign costs, brought about by lowering the discount rate, reflects a greater importance placed on the success of the control campaign, which is consistent with human health, rather than livestock well-being, being the focus of the campaign.

Fly reinvasion

Reinvasion has been listed as one of the greatest, if not the greatest, obstacles to successful tsetse control (Hargrove, 2003a; Leak, 1999; Warnes et al., 1999). Barriers of targets and/or traps can provide a solution to keep tsetse from reinvading cleared areas, but they are typically expensive to maintain: one study showed a 30 to 60 percent increase in the cost per km^2 with the deployment of a trap barrier (Shaw et al., 2007). Fortunately, the identification of CRs may limit the need for barriers as they provide a more manageable area in which to conduct fly control, they largely identify the source from which tsetse are invading, and they account for the duration of continuous control needed to eliminate a tsetse distribution (i.e., 216 days). Additionally, by using properly maintained targets, control infrastructure can be left in place if tsetse return the following year. Despite the identification of CRs, fly reinvasion in Kenya may nonetheless remain troubling in several areas with external reinvasion sources (e.g., along the border with Tanzania in southern Kenya and along the border with Uganda in western Kenya).

Conclusions

This study showed the value of identifying spatially and temporally constrained fly distributions, termed CRs, when conducting a tsetse fly management campaign. These CRs resulted from intra and inter-seasonal fluctuations to suitable fly habitat and represented a dramatic decrease in tsetse-infested habitat when compared to the fly's maximum extent, which we termed TZs. The cost analysis performed in this study revealed a total cost of $14,212,647 if a tsetse management campaign was conducted at the extent of the CRs, while management at the TZ extent amounted to $33,721,516. This represented a savings of $19,508,869 if control was conducted in the seasonally dynamic CRs. von Wissmann et al. (2011) stated that, since the 1980s, cuts have been made to tsetse and trypanosomiasis control efforts in Kenya, which have placed the burden of disease control on local farmers rather than public officials. These cuts, as well as the shift toward localized control, are consistent with the continent-wide reduction in funding for tsetse and trypanosomiasis control projects that has taken place since the 1970s. We believe, therefore, that our analysis is both timely and vital given the trend in funding, and due to trypanosomisis' consistent classification as one of the most significant, if not the most significant, obstacle to agricultural development (e.g., Shaw, 2004; Spedding, 1981). Currently, a dearth of information exists that examines fly management during seasonal events. Given the need to efficiently use the limited financial resources available for tsetse fly control, we accordingly appeal for additional attention given to this cost-saving approach.

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