Mapping the benefit-cost ratios of interventions against bovine trypanosomosis in Eastern Africa

A. P. M. Shaw*[1], G. R. W. Wint[2], G. Cecchi[3], S. J. Torr[4], R. C. Mattioli[5] and T. P. Robinson[6]

[1] Division of Pathway Medicine and Centre for Infectious Diseases, School of Biomedical Sciences, College of Medicine and Veterinary Medicine, The University of Edinburgh, Chancellor's Building, 49, Little France Crescent, Edinburgh, EH16 4SB and AP Consultants, 22, Walworth Enterprise Centre, Duke Close, Andover, SP10 5AP, United Kingdom
[2] Environmental Research Group Oxford (ERGO), Department of Zoology, South Parks Road, Oxford, OX1 3PS, United Kingdom
[3] Food and Agriculture Organization of the United Nations (FAO), Sub-regional Office for Eastern Africa, CMC Road, P.O. Box 5536, Addis Ababa, Ethiopia
[4] Vector Biology Department, Liverpool School of Tropical Medicine, Pembroke Place, Liverpool, L3 5QA and Warwick Medical School, The University of Warwick, Coventry, CV4 7AL, United Kingdom
[5] Food and Agriculture Organization of the United Nations (FAO), Animal Production and Health Division, Viale delle Terme di Caracalla, 00153 Rome, Italy
[6] Livestock Systems and Environment, International Livestock Research Institute (ILRI), P.O. Box 30709, 00100 Nairobi, Kenya

Abstract

This study builds upon earlier work mapping the potential benefits from bovine trypanosomosis control and analysing the costs of different approaches. Updated costs were derived for five intervention techniques: trypanocides, targets, insecticide-treated cattle, aerial spraying and the release of sterile males. Two strategies were considered: continuous control and elimination. For mapping the costs, cattle densities, environmental constraints, and the presence of savannah or riverine tsetse species were taken into account. These were combined with maps of potential benefits to produce maps of benefit-cost ratios.
The results illustrate a diverse picture, and they clearly indicate that no single technique or strategy is universally profitable. For control using trypanocide prophylaxis, returns are modest, even without accounting for the risk of drug resistance but, in areas of low cattle densities, this is the only approach that yields a positive return. Where cattle densities are sufficient to support it, the use of insecticide-treated cattle stands out as the most consistently profitable technique, widely achieving benefit-cost ratios above 5. In parts of the high-potential areas such as the mixed farming, high-oxen-use zones of western Ethiopia, the fertile crescent north of Lake Victoria and the dairy production areas in western and central Kenya, all tsetse control strategies achieve benefit-cost ratios from 2 to over 15, and for elimination strategies, ratios from 5 to over 20. By contrast, in some areas, notably where cattle densities are below 20 per km^2, the costs of interventions against tsetse match or even outweigh the benefits, especially for control scenarios using aerial spraying or the deployment of targets where both savannah and riverine flies are present. If the burden of human African trypanosomosis were factored in, the benefit-cost ratios of some of the low-return areas would be considerably increased. Comparatively, elimination strategies give rise to higher benefit-cost ratios than do those for continuous control. However, the costs calculated for elimination assume problem-free, large scale operations, and they rest on the outputs of entomological models that are difficult to validate in the field. Experience indicates that the conditions underlying successful and sustained elimination campaigns are seldom met.
By choosing the most appropriate thresholds for benefit-cost ratios, decision-makers and planners can use the maps to define strategies, assist in prioritising areas for intervention, and help choose among intervention techniques and approaches. The methodology would have wider applicability in analysing other disease constraints with a strong spatial component.

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*Corresponding author at AP Consultants, 22 Walworth Enterprise Centre, Duke Close, Andover, SP10 5AP, United Kingdom. *E-mail address:* biz@apconsultants.co.uk (A.P.M. Shaw)

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1 Introduction

The importance of the spatial dimension in planning interventions against African trypanosomosis is linked, in both animals and humans, to its cyclical transmission by an insect vector – the tsetse fly (Genus: *Glossina*) – whose geographic distribution is closely related to the presence of suitable climate, hosts and vegetation. Over the last two decades, advances in remote sensing, geographical information systems (GIS) and spatial statistics have triggered the development of modelling approaches to tsetse distribution mapping (Rogers and Randolph, 1993; Robinson *et al*., 1997; Rogers and Robinson, 2004). Turning to the disease, the human form (sleeping sickness) is characterized by a pronounced focal nature, with the distribution of endemic foci remaining remarkably stable over the last century (Simarro *et al*., 2010) with a few notable exceptions (e.g. Fèvre *et al*., 2001). Recently, systematic data collation and mapping have made it possible to represent the current distribution of human African trypanosomosis with high accuracy (Cecchi *et al*., 2009; Simarro *et al*., 2010) and to assess the population at risk (Simarro *et al*., 2012). In domestic animals, although the prevalence of the disease varies between populations and localities, trypanosomosis generally presents as an endemic disease, with a widespread presence in livestock populations across the tsetse-infested area of sub-Saharan Africa. The use of GIS and satellite imagery to map animal trypanosomosis has been explored (Hendrickx *et al*., 2000; de la Rocque *et al*., 2005; Bouyer *et al*. 2006;) and recently work has begun on mapping the distribution of animal trypanosomosis as well as tsetse at a continental level (Cecchi *et al*., 2014, 2015).

Alongside spatially explicit data on the vector and the parasite, decision-making in the field of trypanosomosis control and elimination also requires other factors to be considered. In a number of studies in Zambia (Robinson, 1998; Robinson *et al*., 2002;) and Uganda (Gerber *et al*., 2008), a variety of GIS and decision-support approaches has been used to combine proxies for disease risk – usually the probability of tsetse presence – with other criteria, including human population and poverty, cattle density, land use and land tenure, agricultural potential and environmental fragility. Ultimately, these approaches have been addressing the same question: where are the benefits of intervention likely to outweigh the costs; be they financial, environmental or social? The present analysis addresses this question from an economics perspective.

This work builds on two recent studies. On the benefit side, a methodology was initially developed for West Africa (Shaw *et al*., 2006) and subsequently extended and adapted to eastern Africa (Shaw *et al*., 2014), including the mapping of livestock production systems (Cecchi *et al*., 2010). The methodology enabled the mapping of the potential economic

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[1]The views expressed in this publication are those of the author(s) and do not necessarily reflect the views or policies of FAO.

benefits to livestock keepers from removing bovine trypanosomosis from the eastern African region. Results showed considerable geographical variability in the potential benefits, ranging from less than US$ 10 to over US$ 12,500 per km^2.

However, the maps of benefits only tell part of the story. Should a benefit of US$ 500 per km^2 over 20 years be considered low or acceptable? Is US$ 5000 per km^2 high or just about justifiable? In order to address this type of question, the costs of intervening against tsetse and trypanosomosis need to be factored in. Costs for different interventions against tsetse and trypanosomosis, based on a hypothetical area of 10,000 km^2 in Uganda were provided by Shaw *et al*. (2013a). Since then, new information on costs has emerged from a number of recent field interventions (Adam *et al*., 2013; Bouyer *et al*., 2014).

The present analysis takes into account these recent cost data, and maps the costs in such a way that they can be compared to the mapped benefits for eastern Africa, thus enabling regional benefit-cost maps to be produced.

2 Materials and Methods

The study area includes all tsetse- and trypanosomosis-affected countries in the Intergovernmental Authority on Development (IGAD) region, namely Ethiopia, Kenya, Somalia, South Sudan, Sudan and Uganda. For these countries, cattle production systems and the impact of trypanosomosis were previously analysed in Shaw *et al*. (2014). For costs the present analysis follows the framework developed in Shaw *et al*. (2013a) for Uganda. Costs were refined and updated to 2013 levels by incorporating knowledge from recent publications and research and adjusting for inflation. The comprehensive set of prices and costs calculated for Uganda were taken as a basis, after validating them against those of the other study countries. The inflation rates were based on the Uganda Consumer Price Index for non-food items (UBOS, 2014) and Ugandan Shillings were converted to US dollars (US$) using the historical rates given by FX Oanda (http://www.oanda.com/currency/historical-rates-classic). On this basis, by 2013, prices had increased by 27.1% since 2006 and 11.2% since 2009, the reference years used in Shaw *et al* (2013a) and (2014) respectively. A discount rate of 10% was applied to all benefits and costs. This relatively high discount rate was selected as reflecting both the higher returns expected from investments in the livestock sector (when compared for example to human health interventions) and the economic growth rates and real interest rates in the study region which are higher than those currently experienced in Europe and North America. The African Development Bank currently applies 12% as the opportunity cost of capital for its projects in the region. The twenty-year time horizon used in Shaw *et al*. 2013a and 2014 was retained for both benefits and costs; a preparatory year was 0 added to the costs and benefits were assumed to start in year 1. This long period enables control and elimination scenarios to be compared.

2.1 Interventions

Two possible intervention strategies were considered: sustained control and the creation of permanently tsetse-free zones (here and after referred to as ‘control’ and ‘elimination’ respectively). Four control options (prophylactic use of trypanocides, targets, insecticide-treated cattle (ITC) and aerial spraying) and four options for elimination (targets, ITC, aerial spraying and the sterile insect technique (SIT)) were considered. For a comprehensive discussion of the strengths and weaknesses of the different techniques, which is beyond the scope of this paper, readers are referred to Maudlin *et al*. (2004). The elimination scenarios were costed as taking place on a large scale, as described in Shaw *et al*., 2013a, and being protected from tsetse reinvasion by barriers, whereas the continuous control operations were envisaged as being undertaken on smaller scales and subject to constant reinvasion pressure.

2.1.1 Trypanocide prophylaxis

For the continuous control scenarios, the cost of systematic use of chemoprophylaxis was estimated as an alternative to tsetse control. Trypanocides in Africa are widely used by cattle keepers, both curatively and prophylactically (Holmes *et al*., 2004). For comparison with other control interventions, the cost of blanket administration of four doses of trypanocide per bovine per year was estimated. This would emulate the use of isometamidium chloride, which is primarily prophylactic, and is effective for about 3 months depending on the breed of cattle and level of tsetse challenge. In rural areas, its current price is estimated at US$ 1.93 for a 300 kg adult dose or US$ 1.35 for the average bovine (210 kg) (personal communication, Dennis Muhanguzi, 2014). At current prices, delivery costs are US$ 0.65 (updated from Shaw *et al*., 2013a and personal communication, Dennis Muhanguzi, 2014) bringing the cost per dose to US$ 2.00 and thus US$ 8 per year per bovine if administered 3-monthly. This unit cost was applied to the cattle population over the study period, which was estimated to increase at 2.9% per annum, the average cattle population growth rate in the absence of trypanosomosis weighted over the twelve cattle production systems modelled in Shaw *et al*. (2014).

2.1.2 Stationary baits - targets and traps

The use of bait technologies such as traps, insecticidal targets and ITC is described in Vale and Torr (2004) and Van den Bossche and De Deken (2004).

The number and design of traps and targets required in different areas may vary greatly according to the behaviour and ecology of the tsetse species present, as well as their mobility and attraction to odours. For savannah (*morsitans*) flies present in the study area (i.e. *Glossina pallidipes, G. morsitans, G. swinnertoni*, and *G. austeni*) 4 traps or targets per km^2, baited with attractants, are considered sufficient to reduce tsetse populations by ≈ 95% in non-isolated populations or to eliminate an isolated population as demonstrated by field trials (Vale *et al*., 1986; Vale *et al*., 1988; Dransfield *et al*., 1990). Riverine (*palpalis*) flies (*G. fuscipes* and *G. tachinoides* in the study region) are relatively unresponsive to odours and higher densities of baits are therefore required (Green, 1994, Torr *et al*., 2011). The restriction of riverine vegetation to watercourses does, however, limit the actual area where baits need to be deployed. In West Africa, traps every 100 m in fringing riverine vegetation were shown to be sufficient to block reinvasion by tsetse (Politzar and Cuisance, 1983). Traps at an average density of 10 per km^2 were used in Uganda against *G. fuscipes* to control human African trypanosomosis (Lancien and Obayi, 1993). A recent small-scale trial covering 500 km^2 in north-western Uganda, with no barriers to reinvasion and an average density of 5.7 targets per km^2, based on 20 targets per linear km of riverine habitat, achieved a fall in tsetse populations by over 90% in the centre of the area and 85% on the periphery within three months (personal communication, Iñaki Tirados, 2014), with reductions of 98% and 90% expected over a longer period.

For the study area, targets were chosen as the stationary bait in this analysis, although traps had been costed in Shaw *et al*., 2013a. This enabled the tiny target technique, as tested in the study area, to be incorporated, but otherwise required few adjustments to the stationary bait deployment costs previously estimated. Accordingly, costs were estimated for two target-based control options. The first was based on the standard 1 m^2 targets with odour attractant, which are suitable against both savannah and riverine tsetse species. For savannah tsetse, 4 targets per km^2 were costed. Where riverine species were present this number was increased to 10 per km^2 (as in Shaw *et al*., 2013a). This average density actually resulted in much higher effective densities, as targets are deployed only in riparian vegetation where riverine tsetse species are found. Target costs were adapted from Shaw *et al*. (2013a) by applying inflation and replacing trap with target costs, yielding US$ 252 and 629 per km^2 for densities of 4 and 10 per km^2 respectively.

Where only riverine tsetse are present, odour baits are not required and much smaller 0.5 x 0.25 m 'tiny targets' can be highly effective (Esterhuizen *et al*., 2011). These can be transported by bicycle or motorcycle, leading to much lower logistics costs than those for installing and servicing conventional targets. The costs for these were based on detailed field data collected during the tiny target operation described above (Shaw *et al*., 2015) which included an intensive community sensitisation exercise (Kovacic *et al*., 2013). The costs were adapted by increasing logistics costs by 50% to allow for deployment in more isolated areas and allowing for 10 rather than 6 targets per km^2. This yielded a cost for control of US$ 142 per km^2. For elimination scenarios, targets were deployed at the same densities per km^2 as for control, as detailed in Shaw *et al*. (2013a) and protected from reinvasion. When used as barriers to prevent reinvasion of tsetse-free zones as part of an elimination strategy, the number of targets required was doubled.

2.1.3 Live baits - insecticide-treated cattle (ITC)

If insecticide is applied to cattle, either by pour-on or spraying, they act as mobile baits to which flies are attracted and thus pick up a lethal dose of insecticide (Vale and Torr, 2004; Van den Bossche and De Deken, 2004). This can be highly effective for controlling tsetse and reducing the prevalence and impact of bovine trypanosomosis (e.g. Rowlands *et al*., 1999; Muhanguzi *et al*., 2014). The approach costed here assumes the restricted application protocol (RAP) (Torr *et al*., 2007; Muhanguzi *et al*., 2014) whereby insecticide is only applied to the preferred feeding sites of tsetse and ticks: the legs, belly and ears. The cost of insecticide and delivery was estimated from field data at US$ 0.57 per bovine per treatment (personal communication, Dennis Muhanguzi, 2014) to which should be added an estimate of the cost of ropes used to restrain cattle, and of the farmers' time (personal communication Walter Okello, 2014), bringing the total to US$ 0.60.

Within cattle herds, tsetse prefer to feed on large animals such as cows and oxen. Because of their ability to attract flies, monthly treatment of 4 large bovines per km^2 is considered sufficient for control or elimination of all tsetse species (Vale and Torr, 2004). To add a safety margin the number was increased to 5. In the region's production systems, at least half of the cattle are cows, bulls or oxen. Therefore, in order to ensure that 5 large animals are available to treat in one km^2, a cattle density of at least 10 per km^2 is needed to enable ITC. For the elimination strategies, in areas with high sedentary cattle population densities, ITC can also be used as a barrier, placed on the periphery of cleared areas. For ITC barriers to be effective, a greater density of treated cattle would be needed, doubling it to 10 treated cattle per km^2. To support the creation of barriers to reinvasion of tsetse-free areas, the minimum cattle density required for elimination was doubled to 20 per km^2 throughout the area, although in most areas 10 per km^2 would be sufficient.

To be effective, it has been calculated that at least 10% of the tsetse flies' blood meals must be taken from insecticide-treated hosts (Hargrove and Packer, 1993; Hargrove and Williams, 1995). Where the cattle density rises above 50 per km^2, treating only 5 large adults per km^2 means that 10% or less of the cattle population is being treated. At such densities, cattle are likely to be the main host for tsetse. Accordingly, the numbers of treated animals will need to be increased so that at least 10% of meals are taken from cattle which have actually been treated with insecticide. Thus, for cattle populations above 50 per km^2 the costs are calculated for treating 10% of all cattle, and allow for growth in the cattle population over the period analysed at the rate of 2.9% per annum, as previously explained. For mapping, therefore, in areas with fewer than 50 cattle per km^2, the cost was a fixed amount per km^2. At cattle densities over 50 per km^2, the cost was proportional to the cattle density.

Though unproven in field conditions, modelling indicates that ITC applied on a sufficiently large scale would be effective in eliminating tsetse populations (Hargrove, 2000, 2003), if isolated from tsetse reinvasion. In this analysis, for the elimination scenario the costs were based on twice as many annual treatments per km^2, thus either doubling the number or the frequency of cattle treated. As with targets, where ITC could be used as a barrier to reinvasion, these numbers were doubled again, so that a minimum threshold of 20 cattle per km^2 was set for this technique to be applicable.

2.1.4 Aerial spraying using the sequential aerosol technique (SAT)

Whilst helicopters have been used to apply insecticides from the air, currently the most widely used method involves fixed-wing aircraft applying synthetic pyrethroids in the sequential aerosol technique (SAT) (Allsopp and Hursey, 2004). It is based on repeated spraying timed in relation to ambient temperature so that each spray cycle kills all tsetse alive at the time, and the subsequent cycle kills any that have since emerged from their puparia in the ground. Each subsequent cycle has to take place before females reach maturity and deposit new larvae in the ground. SAT operations usually require 5 cycles, applied at intervals of 15-20 days. SAT has been shown to be effective in eliminating tsetse in savannah environments (Kgori *et al*., 2006), although difficulties have been encountered with riverine tsetse species in areas of dense vegetation (Adam *et al*., 2013).

In order to be comparable with the other control options, 5 cycles of SAT were costed as being applied 7 times during the 21-year study period. The 3-yearly frequency was selected as a compromise between the likely rapidity of reinvasion (Hargrove, 2000) and cost. Because aircraft have to be flown at very low altitude, this technique is unsuitable for very rugged terrain. Such areas were therefore masked as 'unsuitable for the technique' when mapping.

2.1.5 Sterile insect technique (SIT)

SIT involves the release of sterile male tsetse flies from low flying aircraft (Feldmann, 2004). Sterile males must be released in sufficient numbers to outperform the wild males in finding and mating with females. As a result, this technique is ideally used where tsetse fly numbers have been greatly reduced by some other vector control method, a procedure usually described as 'suppression'. For this reason, and because of its relatively high cost, SIT is normally recommended only where elimination is the objective, and especially where other intervention techniques have failed or are considered unsuitable (Feldmann and Parker, 2010).

The costs of this technique were estimated by Shaw *et al*., (2013a) at US$ 758 per km^2, for an area of 10,000 km^2, based on information from African Development Bank (ADB) *et al*., (2004) and Feldmann (2004). Bouyer *et al*., (2014) indicate field costs of the SIT component to be US$ 4900 (EUR 3800) per km^2 for a project covering 1000 km^2 in Senegal. This higher cost is similar to the inflation-adjusted figure of US$ 5100 per km^2 reported by Msangi *et al*. (2000) for a similarly small (1600 km^2) operation on Unguja Island. Operations involving aircraft are very sensitive to scale. Aerial survey costs per unit area for 10,000 km^2 surveys in West Africa are 38% and 59% of that estimated for 1000 and 2000 km^2 operations respectively (Resource and Inventory Management, unpublished information). The elimination options costed here all follow Shaw *et al*. (2013a) in being based on an area of 10,000 km^2. For SIT the cost used here is therefore based on the figures reported in Bouyer *et al*. (2014) for a small scale operation, to which a scale deflator of 60% was applied to flying time and the other SIT-related field costs in order to adjust it to the hypothesized large scale operation. The cost of sterile males was also deflated to allow for economies of scale. In this case 20% was considered an appropriate figure (personal communication, U. Feldmann, 2011) which resulted in a figure very similar to that estimated in Shaw *et al*, (2013a). On these assumptions a figure of US$ 1748 per km^2 was obtained for adding an SIT component for one species.

Where more than one species of tsetse fly is present, SIT would involve rearing each species and incurring increased deployment costs. The feasibility of releasing more than one species in a single flight is currently being tested. Flight lines might need to be extended, so that flying costs might increase by some 15% (personal communication, U. Feldmann, 2011). The cost of rearing flies is approximately proportional to the numbers produced. However, some economies of scale can be realised and these could reduce production costs for additional species by 20% (personal communication, U. Feldmann, 2011). On this basis and after also assuming an increase of 20% in overheads, the field cost for each additional tsetse species present would reach US$ 664 per km^2.

These analyses assume that one of the three other techniques (targets, ITC and SAT) be used for suppression before deploying SIT. In each location, the cheapest feasible technique was selected depending on the characteristics of the area, namely the presence or absence of riverine flies, cattle population density and ruggedness. The combination of the above factors resulted in eight options. For SIT itself, no ruggedness threshold was considered, since flying is at higher altitudes than for SAT.

2.2 Additional costs

2.2.1 Overheads

Overheads are defined here as all non-field costs. In addition to non-field administrative and office costs for both control and elimination programmes, for elimination they also include any added research costs involved in preliminary entomological and parasitological studies as well as preparatory work and monitoring.

The figures detailed in Shaw (2013a), adjusted for inflation and rounded up to avoid giving an impression of spurious accuracy, were used as a basis and resulted in overheads for elimination of US$250 per km^2 for ITC, targets and SAT and US$ 350 for SIT. Ultimately, it is difficult to be categorical about the level of these costs as they are very closely linked to project and organisational structures and objectives. Projects often include significant research components. Thus Bouyer *et al*. (2014) report the cost of studies and preparation at over US$ 2000 per km^2.

The control scenarios would be smaller scale, more local efforts, sometimes undertaken by livestock-keepers, which would not be accompanied by a large project infrastructure. Monitoring, if any, would be intermittent rather than continuous. For the control strategies, aerial spraying would require significant preparation and oversight, so 20% was added to costs. For targets and ITC a 10% overheads figure was selected, based on the field data from Shaw *et al*. (2013a) and the project described in Kovacic *et al*. (2013). As trypanocide use is well established in the region, a 5% overhead was applied.

2.2.2 Barriers to reinvasion

To achieve and sustain elimination when the targeted tsetse populations are not isolated, a 'barrier' around the cleared area is needed to prevent reinvasion. These barriers consist of an area on the periphery of the cleared area where intense tsetse control measures are deployed. Barriers may be permanent or, if the cleared area is to be expanded, temporary. In this study, rather than try to locate barriers precisely, for simplicity of presentation the related costs were 'spread' over the whole region, by adding a barrier cost to 10% of every km^2 cleared. This was based on a theoretical square intervention area of 10,000 km^2, with 10 km wide barriers on one side, as costed in Shaw *et al*. (2013a).

Barriers were costed for 5 years, although it is not possible to be categorical about the length of time a barrier would be needed. Of the techniques considered in the present study, only ITC and targets would be suitable for barriers. Continuous application of SAT would be neither economic nor environmentally acceptable, and SIT is not considered appropriate as a barrier. For ITC and targets, barriers were costed under the assumption that they would be deployed at double the density used for elimination.

2.3 Mapping benefit-cost ratios

The first step in the process was to map costs. This involved using two possible denominators: costs were either incurred per bovine (trypanocides, ITC) or per km^2 (targets, SAT and SIT). The suitability criteria for each technique were then applied (i.e. minimum cattle densities for ITC, presence of riverine, savannah or mixed tsetse infestations for targets, exclusion of rugged terrain for SAT and number of fly species for SIT). Each map focuses on a single technique and masks the areas unsuitable for that technique. In the masked areas neither costs nor benefits were estimated and thus no benefit-cost ratios can be calculated. For the elimination scenarios, these criteria also applied to the barriers, with the cheaper option of ITC selected where cattle densities were sufficiently high.

To obtain benefit-cost ratios, the mapped benefits derived in Shaw *et al*. (2014) were divided by the mapped costs. First, the costs were converted to 2009 values to match the benefits, reflecting the 11.2% inflation rate. Second, assumptions had to be made regarding both the timing and the proportion of potential benefits (as mapped in Shaw *et al*., 2014) that are estimated to be 'harvested' by each technique. Regarding timing, the full benefits from the absence of trypanosomosis are assumed to be 'harvested' from year 1 onwards in the case of control activities and, for elimination, either from year 1 onwards or from half-way through year 2 onwards, in the case of SIT, to allow for extra time for deploying SIT following suppression by another method. Regarding the proportion of benefits harvested, subsequent to elimination, it was assumed that all losses due to the disease within the cleared area would be avoided, except in barrier areas where only half would be avoided. This implies that overall 95% of losses (90% plus half of 10%) would be avoided. For two of the three 'permanently deployed' control strategies (trypanocides and targets) the percentage was set at

75%. This is a relatively conservative figure: properly implemented control activities can remove almost all losses due to the disease (Rowlands *et al*., 1999; Muhanguzi *et al*., 2014). For the 3-yearly applications of SAT and for ITC a lower figure of 60% was applied. For ITC this very conservative figure reflects a degree of uncertainty about what proportion of cattle need to be sprayed over a large area in order to achieve tsetse control. For SAT it reflects evidence (Hargrove, 2000) that a tsetse population reinvasion front can move at 6 km per year where reinvasion occurs from one direction, but where reinvasion occurs from all directions, an area of 10,000 km^2 could be reinvaded within two years.

3 Results

3.1 Costs of interventions

The estimated costs for the continuous control of tsetse and trypanosomosis are presented in Table 1 and those for elimination in Table 2. These estimates were used for mapping.

For control, Table 1 shows both the annual field cost and the total cost over 21 years, discounted at 10%. The use of trypanocides is the cheapest control option at cattle densities below those that would sustain ITC, regardless of the tsetse species. Otherwise, ITC is the cheapest. The ‘tiny target’ technology allows for low cost control in areas where only riverine tsetse are present. Used only every three years, SAT is relatively cheap but should be balanced against the risk of tsetse reinvasion that could be expected between applications. If SAT were applied every second year, the discounted cost over the whole time period would increase to US$ 4142 and, if applied every year, to US$ 5515.

Building up the costs of elimination (Table 2) was far more complex, because of the need to factor in the applicability criteria for barriers and, for SIT, for the initial suppression preceding its deployment. This created 8 SIT options, with extra costs if several fly species were present. Elimination strategies fall roughly into three cost bands: under US$ 700 for ITC, over US$ 2000 for SIT and between US$ 700 and 2000 for SAT and targets, depending on fly species and cattle population densities.

Table 1
Estimated costs of tsetse and trypanosomosis control using different techniques

Technique and applicability	Annual Field Cost US$	Administrative overheads %	Total discounted cost over 21 years US$
Trypanocide prophylaxis			
4 doses per bovine per year	8.0 per bovine	5%	98 per bovine
ITC (insecticide-treated cattle)			
< 10 cattle km^{-2}	Not feasible		
10-50 cattle km^{-2}	36 km^{-2}	5%	441 km^{-2}
>50 cattle km^{-2}	0.07 per bovine	5%	8.8 per bovine
Targets			
Savannah (4 targets km^{-2})	252 km^{-2}	10%	2634 km^{-2}
Riverine (10 tiny targets km^{-2})	142 km^{-2}	10%	1484 km^{-2}
Riverine + savannah (10 km^{-2})	629 km^{-2}	10%	6585 km^{-2}
SAT (aerial spraying)			
Applied every 3 years (non rugged areas only); total of 7 applications	483 every 3 years	20% every 3 years	3104 km^{-2}

Notes: Costs per bovine increase in line with projected average annual cattle population growth (2.9%) over the period analysed and are discounted to their present value in the first year and expressed as a value per bovine present at the start of the analysis. Total cost refers to the present value over 21 years, including year zero, discounted at 10%.

Table 2
Estimated costs of 'large scale' tsetse elimination using different techniques

Technique and applicability	Overheads US$ km^{-2}	Initial tsetse suppression US$ km^{-2}	Field cost of main technique US$ km^{-2}	Cost of Barriers US$ km^{-2}	Total Discounted cost US$ km^{-2}
ITC (insecticide-treated cattle)					
< 20 cattle km^{-2}	Not feasible				
20-50 cattle km^{-2}	250	0	105	76	430
>50 cattle km^{-2}	250	0	2.10 / bovine	1.52 / bovine	250 plus 3.62 / bovine
SAT (aerial spraying)					
< 20 cattle km^{-2} savannah tsetse only	250	0	483	290	1023
< 20 cattle km^{-2} riverine tsetse only	250	0	483	163	896
< 20 cattle km^{-2} sav. + riv. tsetse	250	0	483	724	1457
20-50 cattle km^{-2}	250	0	483	88	821
>50 cattle km^{-2}	250	0	483	1.77 / bovine	733 plus 1.77 / bovine
Targets					
Savannah (4 targets km^{-2})	250	0	352	246	848
Riverine (10 tiny targets km^{-2})	250		288	138	676
Riverine + savannah (10 km^{-2})	250	0	881	614	1745
SIT for one tsetse species					
< 20 cattle savannah, not rugged	350	483	1748	339	2920
< 20 cattle riverine only, not rugged	350	483	1748	191	2772
< 20 cattle sav. and riv., not rugged	350	483	1748	848	3429
< 20 cattle savannah, rugged	350	352	1748	339	2789
< 20 cattle riverine only, rugged	350	288	1748	191	2577
< 20 cattle sav. and riv., rugged	350	881	1748	847	3826
20-50 cattle km^{-2}	350	105	1748	93	2296
>50 cattle km^{-2}	350	2.10 / bovine	1748	1.85 / bovine	2098 plus 3.95 / bovine
SIT more than one tsetse species	Add US$ 664 km^{-2} per additional species.				

Notes: Costs are US$ km^{-2} unless otherwise indicated and total costs are discounted at 10% over the period covered by elimination and the deployment of barriers. Costs per bovine increase in line with projected average annual cattle population growth (2.9%) over the period analysed and are discounted to their present value in the first year and expressed as a value per bovine present at the start of the analysis.

3.2 Maps of benefit-cost ratios

Eight maps summarize the output of the benefit-cost ratio (BCR) analysis. Figure 1 shows the four control scenarios and Figure 2 the four elimination scenarios. In order to interpret these correctly, it should be recalled that the mapped ratios already incorporate a 10% annual profit as a minimum cut-off rate by virtue of the discounting process. In investment economics, for a project to be acceptable, the BCR after discounting should be 1 or more, which implies that the investment receives a return of 10% (compounded per annum) or more. Thus the colour palette assigns progressively darker shades of green to these values. The areas in white are those where tsetse are absent. Areas deemed unsuitable for cattle production are shown in pale grey. The latter includes some of the larger protected areas. Some areas are unsuitable for the technique mapped, these are shown in dark grey, notably where the cattle density is deemed to be too low to sustain ITC. For SAT, the rugged areas which are unsuitable for the technique comprise narrow bands which are not visible in the printed maps.

There are also some areas where benefits are accrued outside the tsetse-infested zones due to emigration of cattle outside tsetse areas. The emigration is consequent on the expansion of cattle populations because of better productivity as a result of disease interventions (Shaw *et al*., 2014). In these areas, no geographically anchored benefit-cost ratio can be calculated, since the measures for dealing with the disease were applied inside the tsetse-infested zones. These occur on the fringes of the tsetse belt, and are coloured pale yellow.

The maps show that, for all control and elimination interventions, certain areas consistently offer high returns. These 'high return areas' include parts of western Ethiopia, with its high work oxen numbers, the intensive dairying areas of central and western Kenya and the crescent-shaped area north of Lake Victoria. Benefit-cost ratios are also high for parts of Somalia and extensive areas along the Kenya coasts, in north-western Uganda, neighbouring western South Sudan, and the south-westernmost part of Sudan.

3.2.1 The control scenarios

Of the control scenarios, trypanocides consistently achieve benefit-cost ratios > 1, and exceed 2 in the core 'high return' areas. In contrast, for SAT and targets, benefit-cost ratios are <1 over much of the area, although in other areas both do achieve benefit-cost ratios >10, occasionally >15. This is particularly the case in parts of western Ethiopia and the Lake Victoria crescent, especially for targets in the latter area where only riverine flies are present. Lastly, as ITC is restricted to areas with over 10 cattle per km^2, and its costs are linked to the density of cattle, it is both relatively cheap and yields benefit-cost ratios of >5 in well over half of the area, reaching levels of >20 in sizeable parts of the high return areas. The maps also show that where ITC cannot be used, the benefit-cost ratios of targets and SAT are also generally < 1. In these regions, trypanocides are the only option which yields a positive return.

3.2.2 The elimination scenarios

Turning to elimination, Figure 2 shows the benefit-cost ratios to be similarly distributed, but, as would be expected, generally higher than for the control scenarios. For ITC, the increase in the stipulated minimum cattle density from 10 to 20 cattle per km^2 reduces its area of applicability, but BCRs remain high with almost all over 10 and with a high proportion over 20. The maps for aerial spraying and targets are very similar. Some narrow bands of Ethiopia which would be accessible to targets are not suitable for SAT due to the ruggedness, but SAT performs better in some areas where savannah flies are present. There are a few areas where targets or SAT could yield benefit-cost ratios of 2 to 5 but elimination using ITC is not mapped as feasible – in small zones of western Ethiopia, on the fringes of the coastal tsetse fly belts of Kenya and Somalia and in western Sudan and South Sudan. Looking at SIT, despite its higher cost which reflects the complex combinations of techniques and increased costs for extra fly species, benefit-cost ratios of 5 or over can be achieved in the core regions of the ‘high return’ areas.

Figure 1. Estimated benefit-cost ratios for four options for long term bovine trypanosomosis control

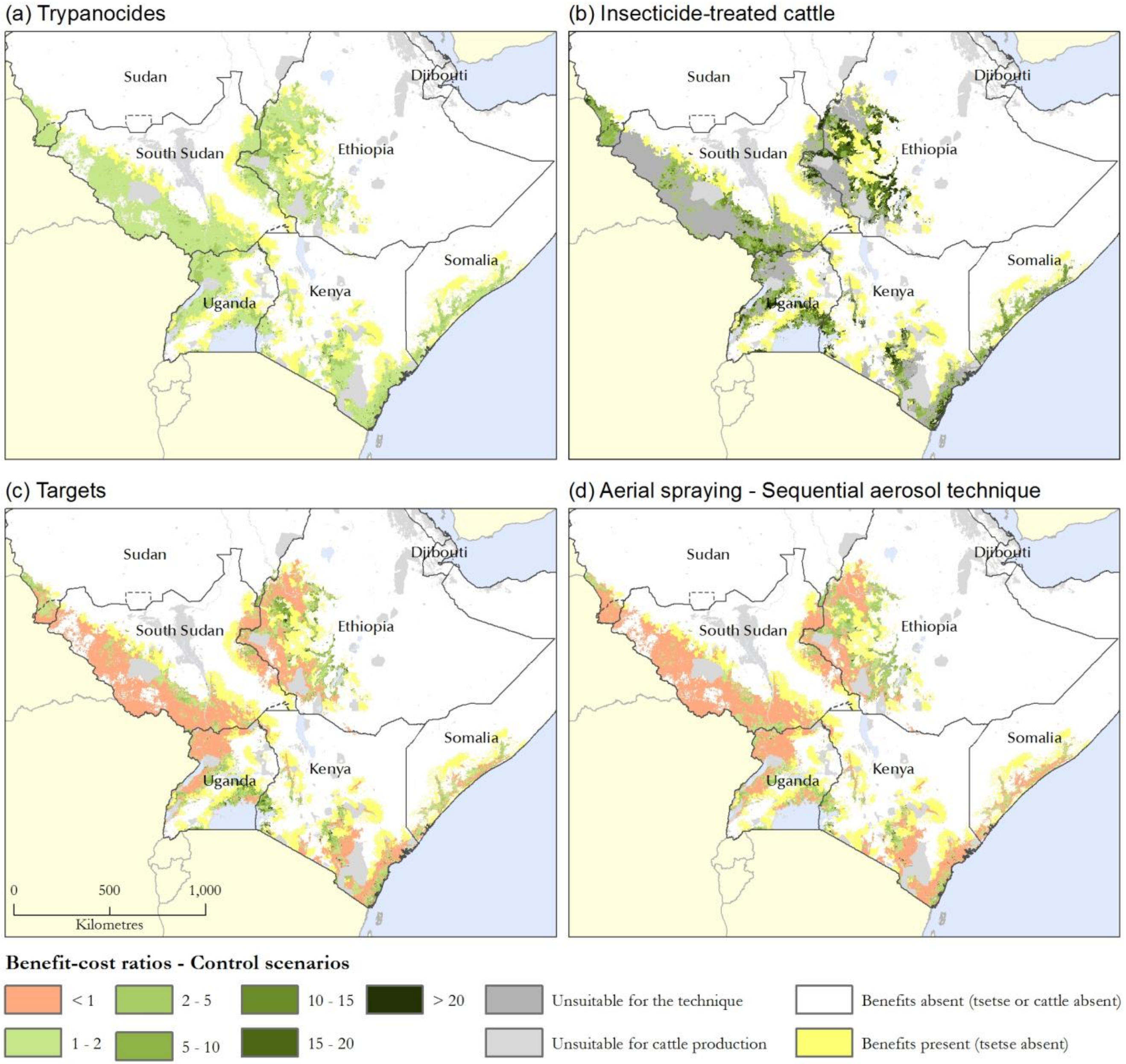
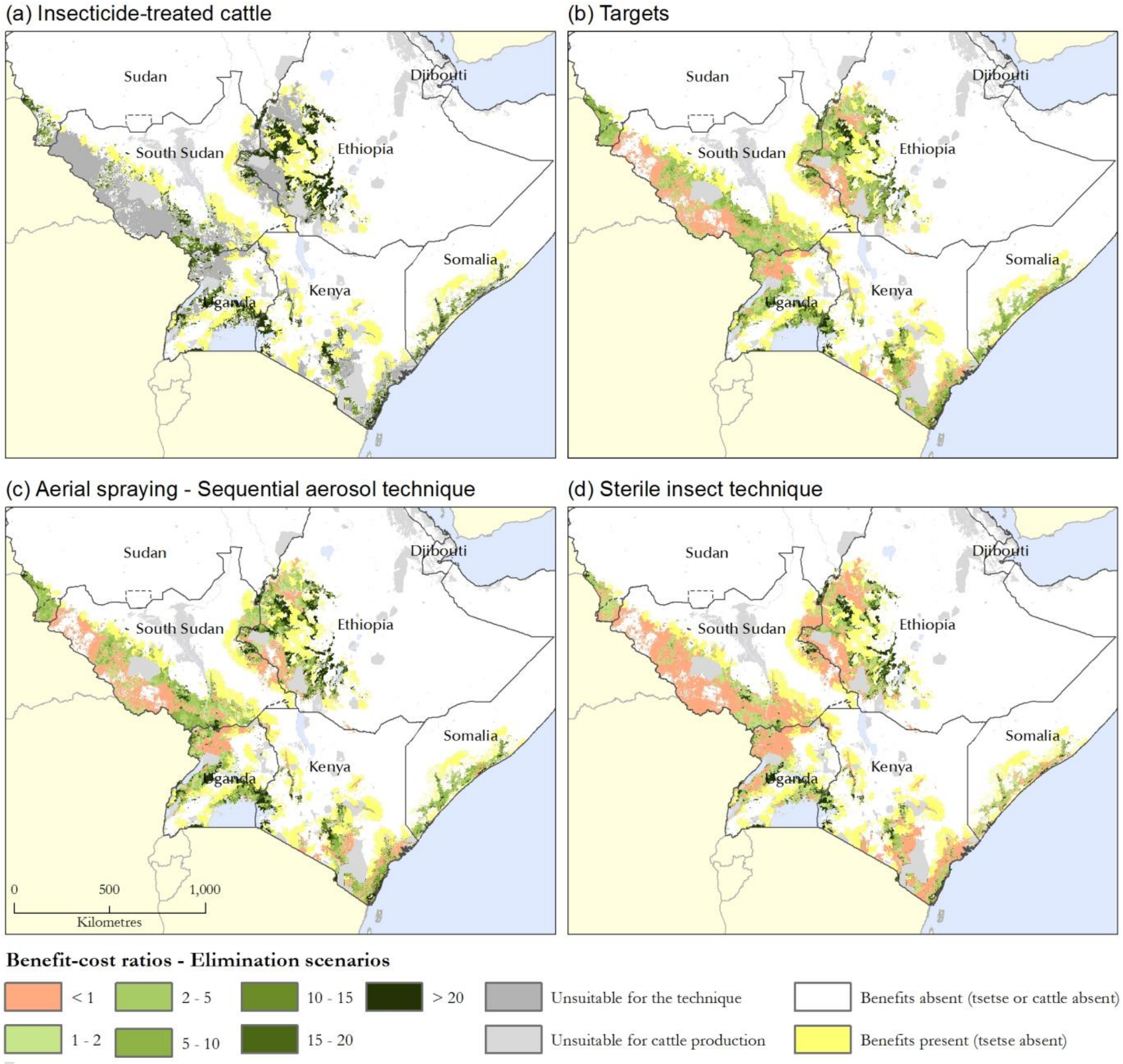


Figure 2. Estimated benefit-cost ratios for four options for large scale tsetse elimination



4 Discussion

The benefit-cost ratio maps presented in this paper represent the synthesis of several modelling activities. All models were based on the best available information, but their accuracy is inevitably constrained by the assumptions underpinning them. For example, even though 12 cattle production systems were modelled and mapped (Shaw *et al*., 2014), there is evidence to support a broader diversity of systems. Similarly, much diversity in tsetse species, vegetation, settlement, climatic patterns and socio-economic conditions fails to be captured in full. Ground-truthing and more detailed modelling of the key entomological, logistical and economic variables would be required when translating these results into operational scenarios.

Uncertainty and risk have not been explicitly included. The herd models are deterministic and tsetse challenge has been taken into account indirectly by modelling the impact of disease as observed in the different cattle production systems. More importantly, while the costs for both control and elimination have been generously estimated, they do not allow for such factors as interruptions in funding, other delays and, in the case of elimination, for barriers being breached or not maintained (Shaw *et al*., 2013a; 2013b; Bouyer *et al*., 2013).

Although mapped outputs may offer economic insights into trypanosomosis control and elimination at a range of scales, they should not be interpreted as recommending that a certain approach be applied throughout the region. Instead, the maps aim to show the expected economic yield of each approach in each area. In a regional scale study such as this, care must be taken not to be misled by the apparent detail in the maps. For example, selecting small high-return areas for intervention without undertaking further studies would not be advisable. Also, when interpreting the maps it should be borne in mind that, with the exception of SAT, the control scenarios can mostly be applied at smaller scales. By contrast, the elimination scenarios are predicated on large scale interventions (10,000 km^2 as in Shaw *et al*., 2013a).

Despite modelling limitations, the maps provide a consistent and coherent picture across a large geographical area. In particular, the maps are an aid to identify where interventions other than trypanocide use are profitable, and thence to inform the choices between interventions and strategies. Most field interventions integrate several approaches, for example using traps or targets alongside ITC where there are specific areas with low cattle densities or relatively high densities of wild hosts (e.g. Torr and Vale, 2011). Mapping BCRs for combinations of techniques was not addressed in this study as it would involve a huge range of options with outcomes that would be difficult to evaluate. The single method approach provides a baseline from which to assess combinations of the costs given in Tables 1 and 2.

Comparing the different techniques from the economic point of view, the following considerations are relevant. For trypanocides, the present costing exercise in no way implies that their continued use at the modelled level for twenty years would be a desirable strategy. Indeed, based on current understanding, it could contribute to the emergence of widespread drug resistance (Geerts *et al*., 2001; Holmes *et al*., 2004). However, it might also reduce the cattle reservoir of the disease and thus the infection rate in flies and ultimately lower disease transmission to cattle. As explained above, the trypanocide costing was designed to provide a baseline for comparison with other options targeted at tsetse. Thus, a widespread current practice of livestock keepers, that of treating clinically sick high-value animals (cows and work oxen, as described in Shaw *et al*., 2014), is possibly the most economic solution.

For fixed baits – targets or traps – effective deployment and servicing relies on good organisation, manpower and logistical support. In some remote areas, this strategy may also require road-building, adding considerably to costs, as would the presence of particularly dense vegetation. The 'tiny targets' without odours, which are effective where only riverine flies are present, yield high benefit-cost ratios, as do the standard size targets deployed at 4 per km^2 where only savannah flies are present. However, the presence of large areas of mixed infestation, which require standard size targets to be deployed at 10 per km^2 at a relatively high cost, is mainly responsible for the low returns for control using targets shown in much of map (c) in Figure 1. In many of these mixed infestation areas, riverine flies predominate and it may be that effective control could be achieved using the cheaper, tiny targets.

Insecticide-impregnated nets or fences offer another option not considered here, which has been applied to defined sub-populations within livestock keeping areas (e.g. improved dairy cattle or pigs – Bauer *et al*., 2006; 2011; Kagbadounou *et al*., 2011). As with traps or targets, provided a sufficient density of units exists, control or elimination of tsetse populations could be contemplated using these.

ITC is the one strategy that is necessarily and proportionally linked to the mapped benefit units, cattle. Those areas with low cattle densities that yield benefit-cost ratios < 1 for the other techniques are mostly the same as those shown as unsuitable for ITC because there are too few cattle for its effective application. Thus, the low return areas in the ITC map show up as unsuitable (coloured dark grey) rather than unprofitable (coloured pink) as for the other strategies. ITC also has important spill-over benefits on other livestock and human health problems. In certain areas its use may reduce populations of *Anopheles arabiensis* mosquitoes and the incidence of malaria (Mahande *et al*., 2007). ITC reduces the tick burden on treated cattle and can combat tick-borne diseases such as East Coast Fever, a major cause of cattle mortality and economic loss (Minjauw and McLeod, 2003). Since ITC focuses on treating adult animals and not all animals need to be treated, it can be used without undermining the endemic stability of tick-borne diseases present in the indigenous cattle population. ITC can also impact on nuisance flies and, conceivably, even on other related health problems such as trachoma in humans and mastitis in cattle (personal communication, Sue Welburn, 2014). Thus the maps may underestimate ITC's overall profitability, although it must be recalled that its effectiveness as an elimination strategy is as yet unproven in the field. Furthermore, the maps illustrate a situation where cattle are treated throughout a large area with the clear objective of controlling tsetse. Where individual villages, or even more so, only individuals within villages treat their own cattle, higher numbers will need to be treated to achieve the same level of tsetse control. More information on this is emerging from field work (Muhanguzi *et al*., 2014) and modelling (Hargrove *et al*., 2012, Kajunguri *et al*., 2014).

SAT has the advantage of being undertaken over only a few months, and not having to rely on a large pool of organised manpower in the field. However, as Figure 1 shows, repeated applications of SAT taken alone as a control strategy do not offer high returns. On the other hand, in an elimination context, SAT performs very well.

Lastly, SIT is used in conjunction with other techniques and usually recommended where other approaches are not able to deal with tsetse effectively (Feldmann and Parker, 2010). The cost mapped here is based on interventions on a larger scale than has so far been attempted. Despite the fact that the mapped cost was estimated to be less than half of that of recently recorded small-scale interventions (Msangi *et al*., 2000; Bouyer *et al*., 2014), SIT is still significantly more costly than other approaches and this is reflected in the benefit-cost ratios illustrated in Figure 2.

Turning to the choice of strategy, continuous control or elimination, the issues around the feasibility and sustainability of elimination have been frequently debated (Hargrove, 2003), most recently in the context of costing interventions (Bouyer *et al*., 2013, Shaw *et al*., 2013b). The question of which techniques, or which combinations of techniques are effective, in what contexts and whether or not and on what scale sustained elimination can be achieved, are ultimately entomological ones and beyond the scope of this paper. They are also dependent on the financial and other resources which can be deployed. This cannot be addressed by economic modelling, except to point out that where the extra expenses associated with elimination are incurred and then elimination fails or reinvasion occurs, the end result is usually less economically attractive than control would have been. In this analysis, quite generous assumptions have benefitted elimination scenarios. Techniques are assumed to be implemented in an ideal manner, to follow the predictions of available entomological models, and to be free from disruptions. Barriers are always costed, but in only 10% of the area and only for 5 years following elimination. For SIT a low cost which would be applicable to very large scale interventions is used. Conversely, the use of a relatively high discount rate is less advantageous to elimination than a lower rate would be. For the elimination scenarios, applying a lower rate of 7.5% would increase the benefits by 26%, while having little effect on costs as they are normally incurred at the start of the time period. Thus, benefit-cost ratios would increase by around 26%. For control, averaged over the different strategies, benefits would increase by 28%, while costs would increase by 19%, so that benefit-cost ratios would only increase by 8%. Conversely, if the discount rate were increased to 12.5%, the benefit-cost ratios would typically be 82% and 92% of their mapped values for elimination and control respectively. For the control strategies, very conservative assumptions about impact (preventing 60 – 75% of disease losses) have been made. Although presenting elimination in a relatively favourable light, the mapped benefit-cost ratios for elimination do not always show overwhelmingly higher returns than for control. The feasibility, success and economic return of control operations are well documented, whereas elimination is subject to far greater uncertainties as demonstrated by the few successful and sustained elimination campaigns. The maps reinforce the view that, in many contexts, tsetse and trypanosomosis control should be pursued as a highly viable strategy in economic terms regardless of possible future elimination prospects. Control could rely on current low cost options that can be applied by livestock keepers and/or appropriate local government departments, ideally reinforcing each other.

Lastly, the choice of benefit-cost ratio to quantify economic returns makes the results largely independent of a particular time period and set of prices, provided there are no major changes in relative prices. For some techniques, such as trypanocides, ITC and targets and traps, a substantial proportion of the costs may be borne by livestock keepers. Urgent and competing demands for cash and labour, a lower risk profile and – especially in mixed farming communities – a more limited commitment to investment in livestock, means that livestock keepers have to look for higher returns before investing their very scarce resources. Since it is obtained by a simple division, the benefit-cost ratio leaves the planner free to choose a threshold to meet expectations or even implicitly adjust the assumptions made in the analysis. If, for example, it proves possible to deliver odour-baited targets or traps for controlling savannah fly populations more cheaply, the benefit-cost ratios for these would increase, and could be readily visualised. Thus the maps are designed to lend themselves easily to calibration or interpretation by the user.

5 Conclusion

The results of the study clearly illustrate the diversity of areas affected by tsetse and animal trypanosomosis in eastern Africa. The benefit-cost ratios vary greatly between regions, with no single technique or strategy emerging as universally the most profitable. A few areas consistently emerge as important. These are the mixed farming, high oxen use areas of Ethiopia, the highly productive crescent on the northern shores of Lake Victoria in Kenya and Uganda, the dairy production areas of west and central Kenya, parts of Uganda's 'cattle corridor' and the coastal areas of Kenyan and Somalia, as well as some smaller areas of western South Sudan and south-western Sudan. In these zones all interventions against tsetse achieve high returns, with benefit-cost ratios of over 10 in the core areas. Here, the high losses due to trypanosomosis undermine the livelihoods of cattle keepers and it would appear that some form of intervention is essential. This should really be factored in to any rural development programmes implemented in such areas.

To develop this work further, it would be useful to explore ways of incorporating sleeping sickness in the analysis. This is important as some of the areas endemic for the human form of the disease, south-eastern Uganda for example, correspond to areas with high benefit-cost ratios for bovine trypanosomosis, and thus offer significant co-benefits. Other areas affected by sleeping sickness, such as South Sudan and north-western Uganda, which have a lower profile in relation to bovine trypanosomosis, would become important if sleeping sickness were accounted for. In the realm of animal health and production, future work could also attempt to incorporate spill-over benefits such as the impact of ITC on tick-borne diseases in cattle.

The concept of economic maps, and their potential application in a wide range of contexts, makes them a planning tool of great relevance. They can be used for looking at the impact of diseases and other production constraints to overall assessments of the relative contributions made by different livestock species or crops in terms of monetary output. Adding the costs of the intervention to the maps, and thus providing a mapped indicator of the relative returns to be expected from different interventions, completes the economic information needed to underpin macro-level decision making. It helps to inform the choices of both where to intervene and how. While maps have been extensively used in epidemiology and for some monetary human health indicators, only the fields of transport economics and environment seem to have adopted monetary maps (e.g. Naidoo and Rickets, 2006). The approach developed here to map the benefit-cost ratios of interventions against bovine trypanosomosis could be applied far beyond vector-borne livestock diseases to include other types of livestock disease, other interventions to improve livestock productivity, and indeed other agricultural contexts such as crop pests.

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