Preventive Veterinary Medicine 113 (2014) 197–210

Contents lists available at ScienceDirect

Preventive Veterinary Medicine

journal homepage: www.elsevier.com/locate/prevetmed

Mapping the economic benefits to livestock keepers from intervening against bovine trypanosomosis in Eastern Africa

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ARTICLE INFO

Article history:
Received 31 January 2013
Received in revised form 25 October 2013
Accepted 28 October 2013

Keywords:
Tsetse
Bovine trypanosomosis
Economic benefits
Maps

ABSTRACT

Endemic animal diseases such as tsetse-transmitted trypanosomosis are a constant drain on the financial resources of African livestock keepers and on the productivity of their livestock. Knowing where the potential benefits of removing animal trypanosomosis are distributed geographically would provide crucial evidence for prioritising and targeting cost-effective interventions as well as a powerful tool for advocacy. To this end, a study was conducted on six tsetse-infested countries in Eastern Africa: Ethiopia, Kenya, Somalia, South Sudan, Sudan and Uganda. First, a map of cattle production systems was generated, with particular attention to the presence of draught and dairy animals. Second, herd models for each production system were developed for two scenarios: with or without trypanosomosis. The herd models were based on publications and reports on cattle productivity (fertility, mortality, yields, sales), from which the income from, and growth of cattle populations were estimated over a twenty-year period. Third, a step-wise spatial expansion model was used to estimate how cattle populations might migrate to new areas when maximum stocking rates are exceeded. Last, differences in income between the two scenarios were mapped, thus providing a measure of the maximum benefits that could be obtained from intervening against tsetse and trypanosomosis. For this information to be readily mappable, benefits were calculated per bovine and converted to US$ per square kilometre. Results indicate that the potential benefits from dealing with trypanosomosis in Eastern Africa are both very high and geographically highly variable. The estimated total maximum benefit to livestock keepers for the whole of the study area amounts to nearly US$ 2.5 billion, discounted at 10% over twenty years – an average of approximately US$ 3300 per square kilometre of tsetse-infested area – but with great regional variation from less than US$ 500 per square kilometre to well over US$ 10,000. The greatest potential benefits accrue to Ethiopia, because of its very high livestock densities and the importance of animal traction, but also to parts of Kenya and Uganda. In general, the highest benefit levels occur on the fringes of the tsetse infestations. The implications of the models' assumptions and generalisations are discussed.

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http://dx.doi.org/10.1016/j.prevetmed.2013.10.024

1. Introduction

Interventions against tsetse and trypanosomosis in Africa should neither be planned nor implemented without considering the geospatial and biogeographic dimensions of the problem (Cecchi and Mattioli, 2009). Tsetse flies of different species occupy what is often described as the 'tsetse belt', which spans – Africa's humid and sub-humid zones. Spatial patterns are particularly important in the human form of the disease, which has long been recognised as occurring in distinct and relatively stable geographical foci (WHO, 1998). In recent years advances in spatial analysis have made it possible not just to predict a range of mapped variables, but also to combine them, by using geographic information systems (GIS). A number of key variables affecting trypanosomosis has been selected and brought together by FAO, most notably in the framework of the Programme Against African Trypanosomosis (PAAT) Information System. This has enabled the analysis not just of the correlates of tsetse distribution (climatic and land cover factors, for example) but also of the livestock and human populations affected. Recently the numbers of cattle and poor cattle-owners affected by animal trypanosomosis was estimated, by livestock production system, in Uganda (MAAIF et al., 2010) and a series of studies has mapped the distribution and risk of human trypanosomosis (Cecchi et al., 2009a, 2009b; Simarro et al., 2010, 2011, 2012a, 2012b).

After two decades, which saw a gradual reduction in the activities and capacities of both tsetse control departments and national veterinary services, and reduced surveillance for sleeping sickness leading to a widespread epidemic of the diseases, it was recognised that the problem of trypanosomosis was becoming seriously neglected on a continental scale. A declaration by the African Heads of State and Government in 2000 followed by the creation of a pan-African programme to deal with tsetse and trypanosomosis brought this issue back to the foreground. At the same time, measures were being implemented to control the massive resurgence of human African trypanosomosis (Simarro et al., 2008). Interest in larger scale interventions means that resource allocation and prioritisation are, more than ever, key issues. Thus, it is particularly important to add to our knowledge of the disease the economic component and, moreover, for that economic component to be spatially explicit.

Though data on costs and benefits of interventions are essential for decision-making, handling the economic aspects of the disease and its control has generally been regarded as especially complex. Knowledge about the impact of the disease on livestock productivity is patchy; based entirely on individual, site-specific studies yielding very variable results (Swallow, 2000; Shaw, 2004). In humans, although estimates of burden per affected individual now exist (Lutumba et al., 2007; Fèvre et al., 2008), variation in levels of under-diagnosis make it difficult to estimate a global burden. Historically, the economic analysis of African trypanosomosis began with estimates of the costs of control, progressing to studies on the impact on livestock productivity and to project-based benefit–cost studies for specific areas where disease control operations were undertaken (Shaw, 2004). Generalising from such work to look at the wider picture proved difficult, although work in Nigeria (Putt et al., 1980) suggested that field interventions on the fringes of the tsetse distribution yielded particularly high benefits, since livestock, especially cattle, were already in these areas and dealing with tsetse could be relatively cost-effective. However there was no spatially explicit information on these economic aspects. Assessments of the global magnitude of the problem have taken the approach of estimating uniform losses per bovine, and scaling these up based on estimated numbers of bovines in Africa's tsetse-infested areas. These have produced highly variable results, ranging from annual losses of US$ 0.7 billion (Kristjanson et al., 1999) to 4.5 billion (Budd, 1999). With a view to providing a more refined aid to decision making, maps of the economic benefits from removing trypanosomosis in cattle were developed, initially covering Togo, Ghana and Benin (Shaw et al., 2003), and subsequently extended to include Burkina Faso and Mali (Shaw et al., 2006).

The present study builds on that work, testing the approach used by extending it to a more diverse and complex set of cattle production systems in the Intergovernmental Authority on Development (IGAD) region, which includes six tsetse-affected east African countries: Ethiopia, Kenya, Somalia, South Sudan, Sudan and Uganda. A separate paper has explored the cost of controlling tsetse and trypanosomosis in the region (Shaw et al., 2013).

The focus of the study remains on cattle production systems for two reasons. Within the livestock economies of the region, it is estimated that cattle account for about 70% of ruminant livestock biomass in trypanosomosis-affected areas. Evidence-based information on disease impact is mostly available for cattle production systems, with only a handful of studies covering small ruminants (Swallow, 2000; Shaw, 2004). The emphasis of the study is on rural areas and the more extensive forms of traditional cattle rearing and smallholding practiced by the vast majority of livestock keepers in the region. This analysis thus aims to provide an insight into how trypanosomosis affects Africa's rural smallholders and traditional cattle keepers.

2. Materials and methods

The potential benefits from the removal of bovine trypanosomosis (equivalent to reducing the physical and financial losses due to the disease) were calculated by first using demographic herd parameters (birth, death and offtake rates) to project the cattle population numbers in a series of spatially defined production systems over a 20-year study period using 'with trypanosomosis' production parameters. Then, the output from the herd, in terms of milk, meat, animal traction and offtake was calculated and prices applied to estimate income year by year. The same procedure to calculate income was then repeated using the 'without trypanosomosis' production parameters. The difference between the two income streams gives the potential benefits from the disease's absence. These figures were estimated per bovine and applied to cattle population density maps, projected using herd growth and spread models to provide a monetary value for the benefits of disease removal per square kilometre.

2.1. Input data

The integration of economic information into a spatially explicit framework required a diverse range of input datasets to be assembled. Published and unpublished literature on animal diseases, livestock productivity and production systems were collected for each study country. Information on the impact of tsetse and trypanosomosis was also assembled. Economic data included: (i) cattle production parameters; (ii) costs of keeping cattle; (iii) prices for meat, livestock, milk and hiring of draft oxen. In all, well over 200 documents were consulted.

GIS data on the distributions of tsetse flies, cattle population densities and livestock production systems were also compiled. Six tsetse species of veterinary importance are present in Eastern Africa: *Glossina fuscipes*, *G. tachinoides*, *G. pallidipes*, *G. morsitans*, *G. swinnertoni* and *G. austeni*. The predicted presence of these species was derived from the PAAT Information System. Regional maps at 1 km resolution were used (Wint, 2001), complemented by 5 km resolution continental datasets (Wint and Rogers, 2000) where 1 km resolution maps were unavailable. Predicted areas of suitability for individual tsetse species were converted into masks of presence, defined as areas having a probability of presence of 50% or greater. The species-specific masks were subsequently combined into a single regional map of predicted absence or presence of the genus *Glossina*.

Cattle population densities were available from a series of 1 km resolution datasets created within the framework of the IGAD LPI using the most recent national statistics available for the period 2000–2005. The mapping methods were those developed to generate the Gridded Livestock of the World (Wint and Robinson, 2007).

For the geographic distribution of livestock production systems in Eastern Africa, a map based on livelihood analysis was used (Cecchi et al., 2010). This was generated from data collected between 2001 and 2007 and it included three categories defined in terms of the ratio L/C, L being the total income derived from livestock and C that derived from crops. The three production systems included in the map were pastoral ($L/C \geq 4$), agro-pastoral ($1 < L/C < 4$) and mixed farming ($L/C \leq 1$).

2.2. Defining and mapping cattle production systems

The map of livestock production systems in Eastern Africa depicting pastoral, agro-pastoral and mixed farming systems (Cecchi et al., 2010) was the starting point for mapping cattle production systems. Within these three broad categories, sub-systems for cattle were defined based on their use of two categories of economically important cattle: work oxen and grade dairy cattle. Work oxen are male cattle, including both bulls and castrates that play a critical role in mixed livestock-crop agriculture by providing animal traction. Dairy cattle are bovines containing varying degrees of exotic genetic material, usually of the main European dairy breeds, which have been widely adopted in high value smallholder dairy production in Eastern Africa. These dairy cattle are often referred to as "exotic" or "grade" cattle, distinguishing them from indigenous breeds that are also kept for milk and breeding in all three livestock production systems. The challenge was to define a sufficient number of systems to capture the diversity but not so many that either the available data would not support the models or that ultimate mapping and integration with the spatial and spread models would become over-complicated.

Data on the use of work oxen were obtained from in-country informants, reports, census data, livelihood studies (Cecchi et al., 2010) and other sources (Itty, 1992; Starkey and Kaumbutho, 1999; Rege et al., 2001; Otte and Chilonda, 2002; Ocaido et al., 2005). Only in Ethiopia are oxen numbers systematically collected during surveys or censuses. Combining these sources across the region by administrative area, and studying data on herd compositions, enabled three broad categories of oxen use to be distinguished and mapped depending on the proportion of cattle used for draught: low (≤10%), medium (>10% and <20%), and high (≥20%) where draught power was generally the main reason for keeping cattle.

Evidence on dairy cattle numbers from census data was restricted to Kenya and Uganda. District level estimates of the number of dairy cattle were available for Kenya from the FAO Global Livestock Impact Mapping System (GLIMS) (Franceschini et al., 2009). For Uganda, county level estimates of the number of exotic cattle were available, also from GLIMS, which were taken as a proxy for dairy animals, based on the assumption that the use of exotic livestock for beef production is very limited in rural Uganda. The assumption is corroborated by livelihood analyses. In order to increase the resolution of the comparatively coarser Kenyan dataset, the proportion of dairy or exotic cattle was subjected to multivariate logistic regression modelling (Wint and Robinson, 2007). The modelled data for Kenya were combined with the original, fine scale information for Uganda to produce a GIS layer of dairy production. For the production of the final regional map of cattle production systems, "high dairy" areas were defined as those where 20% or more cattle were grade dairy cattle. In these areas oxen use fell into the "low" category. Within the tsetse-infested zones the "low" dairy cattle areas are not extensive, and occur only as bands on the fringes of the high use areas, so these were not modelled separately.

The GIS layers of oxen use and dairy cattle were then combined with the map of pastoral, agro-pastoral, and mixed farming systems to derive a series of twelve cattle production systems. These systems and the domains of applicability of the dairy and different oxen categories are summarised in Table 1. In the region's pastoral systems work oxen are not much used and grade dairy cattle are rarely kept. Therefore, the medium and high work oxen categories, as well as high dairy, were only applied to the agro-pastoral and mixed farming systems. Furthermore, the mixed systems of Ethiopia were distinguished from those of the other countries because of considerably different production practices and productivity, most notably different patterns of oxen use.

Table 1
Modelled (×) cattle production system combinations.

Cattle production system	Pastoral	Agro-pastoral	Mixed farming	
			General	Ethiopia
Low oxen	×	×	×	×
Medium oxen		×	×	×
High oxen		×	×	×
High dairy with low work oxen		×	×	

Note: Cattle populations consisting of 20% or more work oxen or of 20% or more grade dairy cattle were defined as "high". 0% to 10% were defined as low, 10% to 20% as medium. The latter two categories were only mapped for work oxen. The high dairy areas had low work oxen numbers. In the areas modelled as low, medium and high oxen, grade dairy numbers were not included.

2.3. Parameterising the cattle production systems

Economic and herd growth models were produced for each cattle production system. The inputs to the cattle herd models are demographic production parameters, offtakes and prices, and these were defined separately for each of the 12 cattle production systems identified in Table 1. For each system, parameters for two alternative scenarios were sought: with or without trypanosomosis. The scenario with trypanosomosis was considered the baseline.

For calculating herd dynamics and output in these production systems a set of baseline parameters was compiled from various sources. A few sources provided information relating to all production systems (Peeler and Omore, 1997; Otte and Chilonda, 2002), others for the pastoralist systems (Roderick et al., 1998, 1999, 2000), for the agro-pastoral and mixed farming systems (Itty, 1992; Itty et al., 1995; Muraguri, 2000; Rege et al., 2001; Machila, 2005; Musa et al., 2006; Maichomo et al., 2010) and for the grade dairy cattle kept in a separate system alongside indigenous cattle in the agro-pastoral and mixed farming systems (Omore et al., 1999; Mudavadi et al., 2001; Ongadi et al., 2007). The studies of the impact of trypanosomosis on cattle, listed below, were also used to estimate baseline parameters.

Current production costs and output prices were assembled for each country from market data, other local sources and through personal communications from key informants. They included prices of milk and cattle, as well as costs for curative and prophylactic trypanocidal treatments and approximate costs of keeping cattle in each production system. In particular, cattle prices varied substantially among countries and a number of specific events caused prices to fluctuate greatly. A single set of prices was, however, used in the analysis. The set was selected to reflect typical prices for the countries studied, weighted by each country's cattle populations in tsetse-infested areas.

The value of a work oxen's labour and the amount worked per year were separately investigated and information was collected via local informants. Estimates of how much work oxen undertake during the course of a year and how this is divided between rainy season work – mainly ploughing, and dry season work – transporting crops, building materials and such-like, vary greatly (Itty, 1992; Itty et al., 1995; Otte and Chilonda, 2002; Ocaido et al., 2005; Shaw et al., 2006; Urga and Abayneh, 2007). One of the indirect effects of removing the constraint of trypanosomosis from an area is thought to be that people will increase their use of bovine traction (Swallow, 2000). This was incorporated in the herd models by selecting a greater proportion of young males for draught work.

Production systems with a high proportion of grade dairy cattle, which are owned mostly by smallholders, play a significant role in the economics of trypanosomosis in Eastern Africa. There is a considerable body of literature on the development of dairying, especially in Kenya. As well as obtaining general information from some of the references cited above, a number of additional sources was of particular relevance to dairying (Laker, 1998; Omore et al., 1999; Muraguri, 2000; Mudavadi et al., 2001; Muraguri et al., 2004, 2005; Fonteh et al., 2005; Machila, 2005; Swai et al., 2005; Nakiganda et al., 2006; Ongadi et al., 2006; Grimaud et al., 2007; Mburu et al., 2007; Thuranira-McKeever et al., 2010).

The longitudinal and cross-sectional studies comparing the productivity observed in infected and uninfected individual cattle or whole herds, under conditions of both high and low trypanosomosis challenge, and with and without interventions against the disease have been summarised elsewhere (Swallow, 2000; Shaw, 2004). A few of these focus on the east Africa region (Fox et al., 1993; Jemal and Hugh-Jones, 1995; Laker, 1998; Rowlands et al., 1999; Ocaido et al., 2005; Mugunieri and Matete, 2010; Tesfaye et al., 2012). These and other unpublished studies were used to estimate how much productivity might improve in the absence of the trypanosomosis, in order to derive the 'without trypanosomosis' parameters used in the herd models.

2.4. Herd models

The usefulness of bio-economic herd simulation models in analysing and comparing livestock production systems has long been recognised (Dahl and Hjort, 1976; Upton, 1989). Such models have been used to analyse the impacts of trypanosomosis on cattle production since the early 1980s (Camus, 1981; Brandl, 1985; Rushton, 2009). Within the east African region examples available (Itty et al., 1995; Kristjanson et al., 1999), both of which use a previously developed model (von Kaufmann et al., 1990). Livestock productivity in Africa has been comprehensively modelled (Lalonde and Sukigara, 1997; Otte and Chilonda, 2002).

The model used here (Fig. 1) is derived from that originally developed by Shaw (Shaw, 1990; Shaw et al., 2006). The model is described in more detail in Appendix A. Like the others models cited above, it is deterministic. The parameters, especially for the impact of trypanosomosis

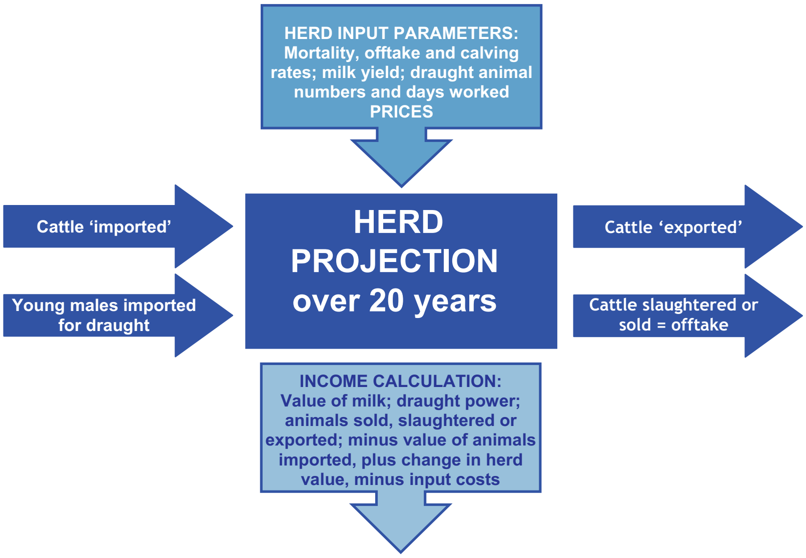

Fig. 1. Structure of the basic cattle herd model.

on productivity, vary greatly between studies and sites (Swallow, 2000; Shaw, 2004). To accommodate this, the parameters selected were such as to come up with a conservative estimate of benefits. In addition, sensitivity analyses allowing for substantial variation in the key parameters was conducted (Appendix B).

The present herd model differs from other existing models which have studied the impact of trypanosomosis, in valuing draught power as well as meat and milk, and incorporating explicit trypanosomosis-related features such as the use of trypanocides for the 'with' and 'without' disease scenarios. Two other innovations are the capacity to set a target for the number of work oxen required, so that these are 'imported' into the model if the number available from the local cattle herd is insufficient and the existence of a sub model for 'exporting' animals out of areas when the carrying capacity limit is reached (see Section 2.5). The model does not incorporate direct links to feed resources.

For the calculated benefits to be mappable they needed to be reduced to a single figure that could be assigned to the mapped cattle populations. This was done by converting the benefit stream into a single monetary value (US$). The standard practice in economic analyses for studies spanning several years (in this case 20 years) is to discount the monetary values so as to convert future sums of money to a single present value, using a pre-selected discount rate. In this study 10% was used, high in relation to currently applied rates of interest, but a conventional value to use in an analysis such as this, and in line with the previous work (Shaw et al., 2006) and accepted as appropriate for agricultural production, when compared to the value of 3% used by the World Health Organisation for discounting human health outcomes. For mapping the results, the single figure thus obtained was divided by the number of bovines present at the end of the twenty-year period, in the absence of trypanosomosis. This ensured that the benefits were distributed per square kilometre in line with the final cattle population, as mapped.

A further dimension was introduced by analysing the potential for livestock population spread. It has often been argued that in the absence of trypanosomosis, with healthier herds leading to greater cattle population growth, these populations would spread into areas whose grazing is currently not fully utilised. The spatial dimension of this is addressed in a separate model (see Section 2.5). The economic dimension of livestock population spread is also estimated in the herd model, which allows for a proportion of the cattle population to be moved to another area when populations increase above sustainable densities. In the absence of the disease, cattle population growth would be higher and thus there would be more spread. The core herds 'export' cattle to the export herd sub-model, where these animals then continue to produce and multiply in that new location, generating a separate income stream (Appendix A).

The monetary benefits per bovine were mapped by attaching them to the map of projected cattle numbers, some in the 'core' herd location, and some occupying new areas in their 'export' herd locations. Benefits per bovine were slightly lower in the latter since they would only have been generated for a shorter period, since the cattle migrated.

As regards the dairy component of the cattle production systems, it must be stressed that the populations of exotic crossbred cattle exist alongside zebu cattle, often within the same farming households (Ongadi et al., 2007). Thus, initially, the dairying system was modelled as a separate entity, and subsequently integrated with the other systems. The proportion of grade dairy cattle in the 'high' dairy areas within the agro-pastoral and mixed farming systems in Kenya and Uganda was modelled as 30%. The work oxen populations, however, are zebu cattle, sourced from within the zebu herds and were therefore modelled within the basic models for pastoral, agro-pastoral and mixed herds. In some situations, with high use of work oxen, it becomes necessary to bring in young male cattle for

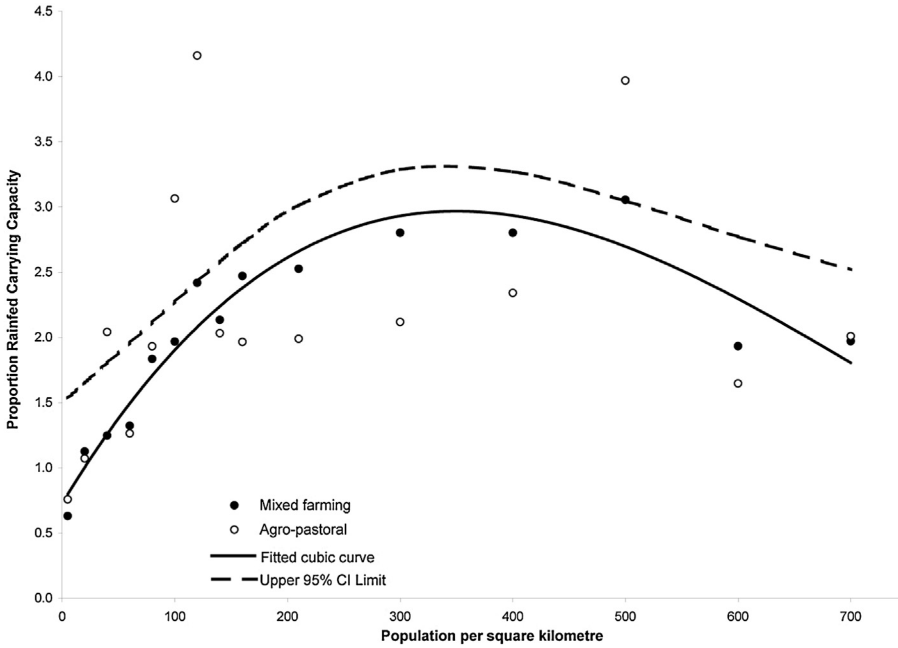

Fig. 2. Observed cattle densities within agropastoral and mixed systems, expressed as a proportion of carrying capacity calculated according to rainfall, in relation to human population density.

draught use from further afield, so the herd model allows for the 'import' of young male cattle for draught as required.

Improvements in the production parameters from the "with" trypanosomosis to the "without" trypanosomosis scenario were modelled to take place over a period of five years, reflecting the rate at which the disease might be controlled in a given area. The increases in the proportion of cattle being used for draught power were modelled to happen more gradually over a period of ten years. This was because the other parameters (deaths, births, milk yields) are directly and inevitably affected by a change in the disease situation, whereas an increased adoption of animal traction is an indirect effect, which depends on people deciding to take advantage of the lifting of a disease constraint by changing their production methods.

2.5. Mapping cattle population spread

The analysis of how cattle populations might be distributed at the end of the study period began with an estimate of carrying capacity in the region. In pastoral areas in particular, the concept of a 'carrying capacity', or maximum stocking rate, is highly problematic since rangeland productivity is so variable spatially and temporally. Pastoralists respond to this variability by gradually building up stocks during times of relative plenty, but stocking levels crash dramatically in times of drought. Whilst this variability renders average values somewhat meaningless, some sort of limit to herd growth in a given area must be imposed and some effort must be made to estimate density limits beyond which animals must be exported or slaughtered. In this study, with no changes assumed to occur in offtake rates, export was assumed to take place when maximum stocking rates were surpassed.

In pastoral areas, maximum stocking rates were derived from rainfall-based thresholds (Jahnke, 1982) and subsequently adjusted depending on human population densities (Putt et al., 1980; Shaw, 1986; Shaw et al., 2006).

For both the agro-pastoral and mixed farming systems, it was necessary to develop an empirical limit to cattle densities based on reported values. In order to derive an empirical limit, the actual cattle densities were calculated as a proportion of the maximum stocking rate, based on rainfall (Jahnke, 1982), and then summarised by human population density classes. A cubic polynomial curve was then fitted, thus representing the mean observed stocking rates in relation to human population density. The maximum stocking rate was then taken to be the upper limit of the 95% confidence interval. Data for mixed and agro-pastoral systems were combined, as shown in Fig. 2.

Based on this analysis it was then possible to map the estimated average maximum stocking rate derived from the maximum proportion of the rainfall-based carrying capacity.

In order to simulate the potential spread of the cattle populations over time, a model was used (Gilbert et al., 2004) that combines short and long-range dispersal to define sequential areas of spread ('timesteps'), and provides the opportunity to define the rate of spread by short-range diffusion per timestep as well as the number and maximum distance of new foci established over long distances. This is achieved by using a dispersal function that combines the conventional short-distance curvilinear decrease with a linear function to determine the probability of long distance movements, thereby increasing the numbers of long distance establishment events without influencing the short distance diffusion pattern. The model also incorporates the possibility of preventing spread into areas masked by a particular factor (e.g. water or desert), as well as modifying the rate of spread according to a multiplier variable (e.g. suitability or amount of grazing).

This model allowed the identification of sequential bands of expansion from known foci, i.e. areas of overstocking, in which modelled herd growth resulted in densities that exceed the estimated maximum stocking rate. Each timestep was separately coded and could therefore be assigned fixed proportions of the population to be exported. In the present analysis, four timesteps were defined. Forty percent of the cattle population to be exported from areas defined as overstocked were assigned to the first timestep (which included the export source area and a narrow initial spread band), 30% to the second, 20% to the third and 10% to the fourth, and final band. Spread was prevented into areas defined as unsuitable for livestock (Wint and Robinson, 2007) or already overstocked, and was scaled according to accessibility to markets (Pozzi et al., 2008) so that spread was greatest into areas most likely to support livestock marketing.

Two spread models were defined and implemented: the first for cattle in the presence of the disease and the second in the absence of the disease. In the second model, the additional cattle numbers resulting from improved productivity in the absence of the disease were added to those resulting from normal cattle population growth in the presence of the disease. Cattle were 'exported' only from the resulting overstocked areas within the current tsetse fly distribution; these being the only regions from which the disease constraint could be removed. These animals were, however, allowed to spread outside the currently tsetse infested areas as long as these new destination zones were not already overstocked. Ultimately, therefore, some benefits from controlling trypanosomosis would be located in non-tsetse infested areas. The spread model criteria for the second export stage were modified to allow a total movement of 60 km over twenty years, rather than the 15 km used in the 'with trypanosomosis' model, on the assumption trypanosomosis is major constraint on livestock expansion and, were it to be removed, the potential distance of spread by cattle populations would increase.

3. Results

3.1. Map of cattle production systems

By combining the livelihood-based map of livestock production system (Cecchi et al., 2010) with the layers of work oxen and dairy animals, a map depicting the distribution of 12 cattle production systems was generated (Fig. 3).

The map shows the predominance of high oxen systems in Ethiopia. In Kenya, both the agro-pastoral and mixed farming systems show a marked tendency to make use of oxen or dairy cattle – in contrast to Somalia, South Sudan and western Uganda where the mixed farming areas are less specialised. Uganda's 'cattle corridor' stands out as an agro-pastoral area running roughly from the southwest to the northeast of the country.

3.2. Production parameters selected

Following the analysis of the literature and the iterative modelling exercise, the key parameters ultimately selected as inputs to the herd models are given in Table 2, which refers to the main cattle production systems and includes the values for scenarios both with and without trypanosomosis. As can be seen, similar impacts for trypanosomosis were applied across the production systems, although slightly more severe in the Ethiopian mixed farming system.

Table 2 also shows that baseline cattle mortality rates observed in Eastern Africa tend to be high. This reflects not just the presence of trypanosomosis, but also of tick-borne diseases, especially East Coast fever (Minjauw and McLeod, 2003) and, locally, very high stocking rates leading to nutritional stress, especially in parts of the Ethiopian highlands (Wilson et al., 2002). Adult mortality rates are high, i.e. well over 5%, as compared to 1.5–3% in Western Africa (Shaw et al., 2006). Calf mortality rates are also high.

In this analysis, no changes were assumed to occur in offtake rates. Livestock keepers determine offtake and the evidence from different studies indicates that it can be expected to increase, to decrease or to remain largely unchanged in response to improvements in livestock health (Dahl and Hjort, 1976; Jemal and Hugh-Jones, 1995; Roderick et al., 1998). Thus, in this study, a 'neutral' assumption of no change was adhered to.

Table 3 summarises the prices of cattle and cattle products and the costs of keeping cattle. The same prices were used in the herd models for scenarios both with and without trypanosomosis.

Lastly, Table 4 summarises the estimated proportion of oxen in each of the cattle production systems based on the literature on oxen use, along with the assumptions for a gradual increase in oxen use leading to an increase in the proportion of cattle allocated to this purpose.

The importance of trypanosomosis for the dairy sector also emerges from the models. In the absence of trypanosomosis the share of grade dairy cattle is 9% greater in the mixed farming system and 12% greater in the agro-pastoral system than it would otherwise have been.

3.3. Herd model outputs

Using the parameters given in Tables 2–4, the herd models were run and the following results obtained.

The overall cattle population growth, death and offtake rates resulting from the herd models are summarised in Table 5. In the presence of trypanosomosis, cattle populations were growing slightly in all the production systems except the mixed farming system in Ethiopia. Overall mortality rates in the presence of trypanosomosis were highest in the grade dairy system and in the Ethiopian mixed farming system (12.0% and 11.4% respectively). Offtake rates (net sales plus slaughter) were highest in the grade dairy system, simply because most male calves are disposed of.

Table 6 gives the calculated monetary benefits for each of the cattle management systems. Cumulative benefits per bovine at the start of the period, after discounting, ranged from US$ 120.6 in the pastoral system to US$ 275.5 in the

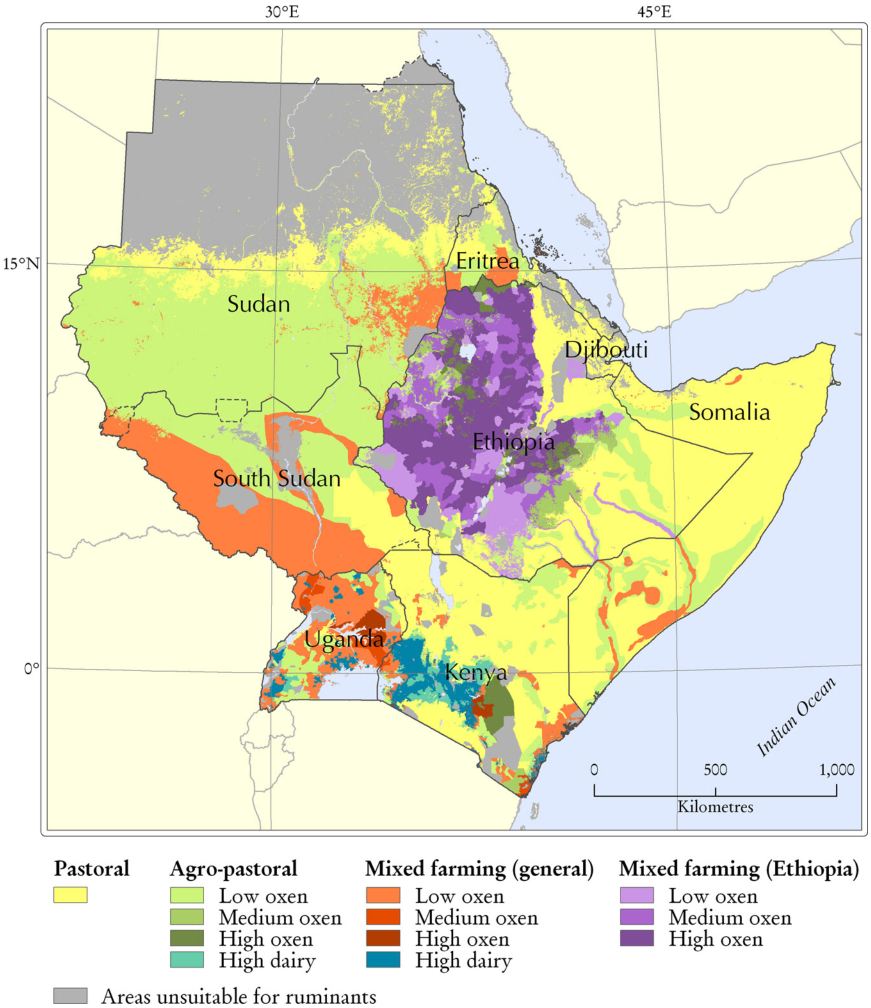

Fig. 3. Cattle production systems in Eastern Africa.

Table 2
Key production parameters, both with and without trypanosomosis, by cattle production system.

Parameter	Cattle production systems									
	Pastoral		Agro-pastoral		Mixed farming (general)		Mixed farming (Ethiopia)		Grade dairy	
	T+	*T*–	*T*+	*T*–	*T*+	*T*–	*T*+	*T*–	*T*+	*T*–
Mortality (% per year)										
Female calves	20	17	18	15	16	13	24	20	21	18
Male calves	25	22	20	17	18	15	26	22	26	23
Adult females	7.5	6.5	7.0	6.0	8.0	7.0	9.0	7.5	12	10
Work oxen	9.0	7.2	8.5	6.75	9.0	7.2	10.0	8.0	–	–
Fertility and milk										
Calving rate (% per year)	54	58	52	56	51	55	49	54	53	57
Lactation offtake (litres per year)	275	296	285	306	300	322	280	301	1900	2042
Days oxen work per year	80	87.6	100	108	130	138.7	80	86.1	–	–

Note: *T*+ with trypanosomosis present; *T*– if trypanosomosis were absent. The grade dairy system consists of grade cattle kept in a similar way alongside either agro-pastoral or mixed farming cattle, so a single set of parameters was modelled.
Source: Parameters selected from studies as explained above and in Appendix B.

Table 3
Prices of cattle and cattle outputs and costs of keeping cattle, by cattle production system.

US$	Cattle production systems				
	Pastoral	Agro-pastoral	Mixed farming (general)	Mixed farming (Ethiopia)	Grade dairy
Litre of milk	0.33	0.33	0.33	0.33	0.33
Average ox day's work[a]	2.1	2.1	2.1	2.6	–
Breeding female	225	240	255	250	570
Breeding male	275	295	320	300	450
Working ox	270	300	370	360	–
Basic production costs[b]	18	22	25	20	75
Dose of trypanocide[c]	1.45	2.35	3.85	2.85	6.35

Source: In-country data collection.
[a] The price difference reflects the proportion of ploughing days at $2.75 to other days at $1.50.
[b] These double for work oxen.
[c] The variation in price reflects the cost of administering the trypanocide, which increases in production systems where animal health workers rather than livestock keepers undertake this task.

Table 4
Modelled percentages of work oxen in the herd by cattle production system.

Cattle production system	Pastoral		Agro-pastoral		Mixed farming (general)		Mixed farming (Ethiopia)	
	T+	*T*−	*T*+	*T*−	*T*+	*T*−	*T*+	*T*−
Low oxen	4.0	5.0	6.0	7.5	4.0	5.0	5.0	6.25
Medium oxen	–	–	13.0	15.0	13.0	15.0	15.0	17.25
High oxen	–	–	20.0	22.5	22.5	25.0	25.0	27.5
High dairy	–	–	4.2	5.3	2.8	3.5	–	–

Note: *T*+ with trypanosomosis present; *T*− if trypanosomosis were absent.
Source: Modelled assumptions based on herd composition data, sample census data (Ethiopia) and in-country sources.

Table 5
Summary herd level parameters derived from the herd models by cattle production system.

% per annum	Cattle production systems									
	Pastoral		Agro-pastoral		Mixed farming (general)		Mixed farming (Ethiopia)		Grade dairy	
	T+	*T*−	*T*+	*T*−	*T*+	*T*−	*T*+	*T*−	*T*+	*T*−
Growth rate	1.4	3.4	1.3	3.3	0.9	3.0	-0.6	2.3	0.5	3.0
Death rate	10.1	8.9	9.0	7.8	9.2	7.9	11.4	9.6	14.0	12.0
Offtake rate	9.6	9.6	9.6	9.7	9.4	9.5	8.3	8.3	12.0	12.7

Note: *T*+ with trypanosomosis present; *T*− if trypanosomosis were absent.
Source: Herd model runs.

high oxen general mixed farming system. In general, benefits were highly influenced by the presence of draught oxen and grade dairy cattle. In the two high dairy systems, the benefits were US$ 257.8 and US$ 260.1 per bovine in the agro-pastoral and the general mixed farming systems respectively. Adding the dairy component thus made more of a difference than adding a similar proportion of work oxen in the agro-pastoral system. In the general mixed farming system, because of the high number of days on which draught oxen are reported to work, their impact was greater. However, in the agro-pastoral and pastoral systems, households may gain between 50 and 100% of their incomes from livestock, so that although lower in absolute monetary terms, these benefits are nevertheless very significant.

Where some cattle move out of their areas of origin, the benefits are redistributed geographically in line with the modelled cattle movements as explained in Section 2.5. Looking at the location of cattle at the end of the period, the exported cattle will have been in their new locations for less than the full 20 years, so the benefits are about 25% lower than the figures if no exports take place (range:

Table 6
Potential benefits over 20 years per bovine present at the start of the period across all cattle management systems (US$ discounted at 10%).

Cattle production system	Pastoral	Agro-pastoral	Mixed farming (general)	Mixed farming (Ethiopia)
Low oxen	120.6	154.2	157.5	158.0
Medium oxen	–	185.8	216.6	210.0
High oxen	–	228.4	275.5	254.7
High dairy	–	257.8	260.1	–

Source: Model runs for each cattle production system.

14–40%). Conversely, the cattle remaining in the core areas accrue slightly more benefits; some 13% (range: 10–18%) more than the figures for no exports.

Lastly, a modelling exercise of this type necessarily involves many assumptions. In this case, the most crucial are those relating to the impact of trypanosomosis. As noted above, different studies have yielded highly variable results (Swallow, 2000; Shaw, 2004). The assumptions about impact modelled (Table 2) have been conservative, around the middle to lower end of the range reported in studies, acknowledging the fact that such studies tend to be conducted in areas where the disease's impact is relatively severe. The results of the sensitivity analyses conducted are given in the Appendix B. These show that while changing the assumptions the impact of disease on milk yield and oxen days worked has limited impacts, changing either fertility or mortality has a much greater impact on benefit levels. The impact of small changes in the discount rate on the benefits obtained was also examined across all twelve livestock systems (Appendix B). As would be expected for a twenty-year programme, these impacts were relatively higher than those for changes in the herd production parameters. However, all the sensitivity analyses showed very similar impacts across all the cattle production systems occurring for each parameter analysed. Thus, relative values across systems and across regions, as illustrated in the maps, would remain almost unchanged.

3.4. Map of potential benefits

The monetary values summarised in Table 6 were applied to the cattle density map according to the distribution of the cattle production systems (Fig. 3). These were then masked by the tsetse distribution so that benefits would be shown only where flies were present at the beginning of the 20 year period. Results of the cattle export model were also incorporated, adding the benefits accruing to cattle which had moved outside their area of origin, in some cases to locations outside the tsetse-infested zones. The final map of benefits per square kilometre is shown in Fig. 4.

This map shows the total benefits per square kilometre that could be realised from the removal of trypanosomosis in cattle. The benefits are calculated as accumulating over a twenty year period, discounted to a present value in year 0, with the disease constraint being lifted gradually over the first five years. The mapped values should thus be interpreted as representing a ceiling, in the form of an estimate of the maximum benefits that could be realised. In practice, the proportion and timing of the benefits realised will depend on when and how the disease is dealt with, ranging from different levels of control of the vector or the disease, to localised or more widespread elimination. These, together with choice of location, different timing and control methods represent a large range of intervention options and associated shares of benefits harvested. About half the discounted benefits could be accessed in the first ten years. Once the models have stabilised with the new production parameters, annual income per bovine (including the value of herd growth) in the absence of trypanosomosis would be on average 43.5% higher (ranging from 32.3% in the pastoral system to 67.2% in the low oxen use mixed farming system of Ethiopia).

For the most part the distribution of benefits follows the tsetse distribution, although some areas – all falling into the US$ 10 to US$ 500 benefits band – are just beyond the fringes of the tsetse distribution. These represent areas into which cattle from within the tsetse-infested zones might migrate as their populations expanded if trypanosomosis were absent.

Greater benefits per square kilometre are estimated to accrue to areas of high animal density, as in the Ethiopian highlands. However, the weighting by production system adds further dimensions by highlighting areas of high draught oxen and grade dairy cattle use, for example in western Kenya and eastern Uganda along the shores of Lake Victoria. The benefits range from under US$ 500 to well over US$ 10,000 per square kilometre.

The greatest benefits are shown to accrue along the borders of the tsetse distribution in south-west Ethiopia, parts of western, central and coastal Kenya, and south-western and central Uganda, i.e. close to established cattle rearing regions. Comparatively little benefit is estimated for much of the Sudanese tsetse belts, with the notable exceptions of those areas bordering north-west Uganda, and parts of western Ethiopia.

Because monetary benefits are calculated for each pixel the methodology allows total benefits to livestock keepers to be estimated for any defined area. Whilst less reliable for small areas, in that the results of any modelling process for a small number of pixels is likely to be representative rather than precise, the summed results for each country are more reliable. Table 7 shows the aggregated national maximum benefits over 20 years, after discounting, which could be realised if trypanosomosis were removed. The total benefit to the IGAD region amounts to nearly US$ 2.5 billion – an average of approximately US$ 3300 per square kilometre infested at the start of the period.

4. Discussion

Given the complexity of the modelling approaches adopted, there is a number of provisos that must be attached to the results presented.

First, the modelling approaches used have been successfully combined, but nevertheless there are inherent limitations to the extent to which they can be integrated. The bio-economic herd models make a linear projection of cattle income and population growth under different assumptions about the cattle production system and its productivity. These were made for the absence and presence of trypanosomosis and for situations where the cattle population did or did not outstrip the grazing available in their area of origin. The links between the timing of movements in the cattle population in the spread model to that in the herd models were approximate rather than exact. Similarly, within the scope of this study, which focussed on cattle and tsetse, it was not possible to link into a detailed estimation of how rural populations and their agricultural practices may evolve over time.

Second, the above evolution would also incorporate changes in cattle production conditions in the absence of

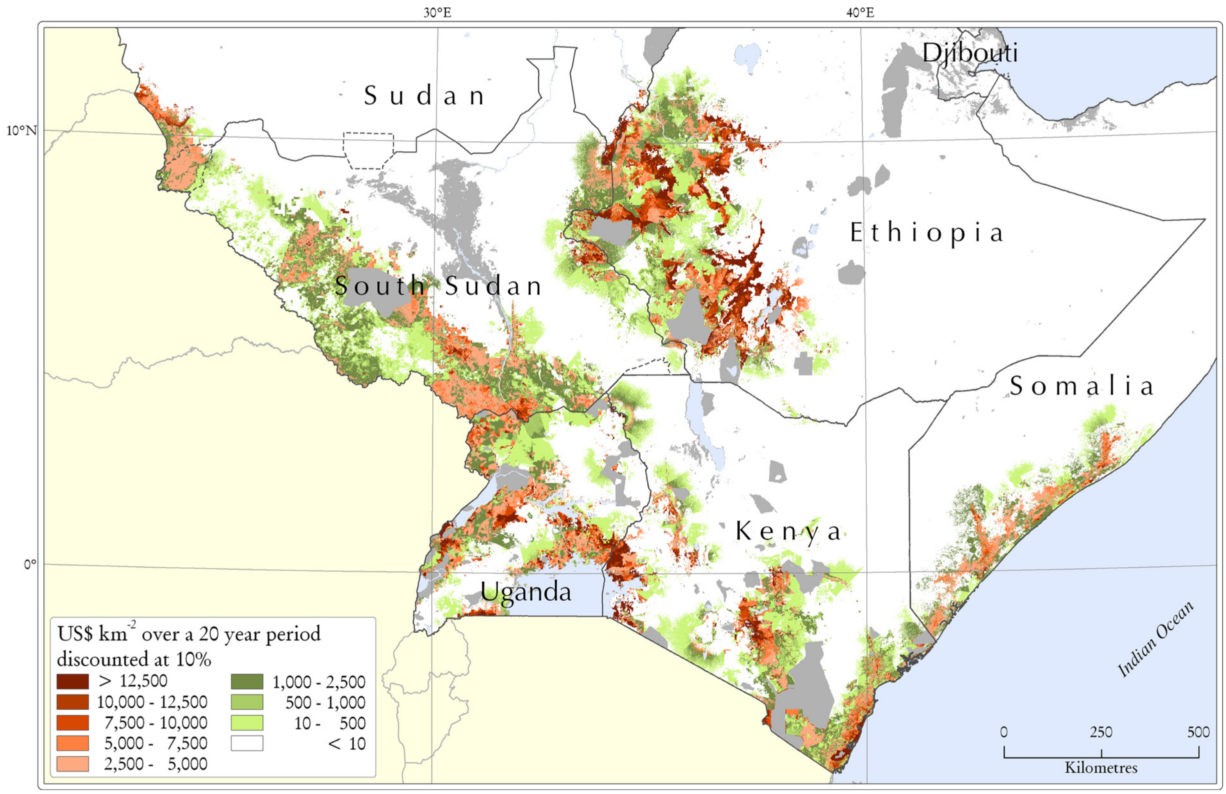

Fig. 4. The maximum potential benefits of intervening against bovine trypanosomosis.

trypanosomosis, which together with changes in consumer incomes, would impact on prices of cattle, meat, milk and animal traction. This study's objective was to produce a set of maps designed to assist prioritisation. Thus the maps should be interpreted by comparing different locations rather than by assuming the wholesale disappearance of the disease. This is in contrast with the analysis undertaken relating to vaccine development (Kristjanson et al., 1999) where the availability and application of an hypothetical trypanosomosis vaccine would have an Africa-wide effect and price change would need to be modelled, since keeping cattle would become universally more cost-effective. Through interactions in the market, producers would pass on some of this improvement to consumers in the form of lower prices whilst also benefitting from an overall increase in output, so that both groups would benefit. Kristjanson et al. (1999) quantified these producer and consumer surpluses for meat and milk outputs for a single cattle production system in their assessment. In the present study, it was deemed appropriate to use a single price for the scenarios with and without trypanosomosis in the herd models, given the complexity of modelling 12 different cattle production systems which evolve at different speeds. Thus, the quantification of benefits was limited to producer benefits, measured in terms of increased output adjusted for changes in production costs. Further analysis could go on to investigate how this might translate into consumer and producer surpluses, and ultimately into different monetary benefits. Integrating this aspect into an analysis over time for multiple production systems would enable net benefits to society overall to be estimated.

Third, the reduction of the cattle production systems to a manageable number (i.e. 12) means that much of their internal variability has not been fully accounted for.

Table 7
Maximum benefits over 20 years from interventions against tsetse and trypanosomosis in cattle (US$ discounted at 10%).

Country	Area of fly belt (sq km)	Total benefit from absence of trypanosomosis (US$ million)	Mean benefit per sq km (US$)
Ethiopia	156,793	834	5317
Kenya	128,905	590	4576
Somalia	37,733	158	4181
South Sudan and Sudan	310,084	485	1564
Uganda	103,051	390	3786
Total	736,566	2457	3335

Source: Aggregated from mapped benefits based on model runs.

Within the adopted systems there are differences in breeds of cattle, local cattle-keeping practices, varying degrees of susceptibility to local trypanosomes and varying levels of contact between bovines and tsetse. These situations will change over time. Beyond these, different areas will be presented with different market opportunities, which will be reflected in the benefits reaped. As well as physical access to markets there may be spatial variation in the institutional barriers to market access.

Fourth, whilst every effort was made to find studies illustrating a 'typical' situation within and outside the tsetse-infested areas of each cattle production system, applying a single set of parameters and disease impacts throughout each system necessarily involved simplification and a loss of internal variability. Variations in tsetse challenge and trypanosomosis risk were taken into account implicitly, by selecting typical parameters for cattle in tsetse-infested zones within each of the 12 cattle production systems, rather than explicitly by introducing yet another layer of modelling that would reflect some estimate of tsetse challenge or disease risk.

Last, as with any study covering such a large area and including so many layers of information, the data used are inevitably of varying quality, and there are significant gaps. Whilst modelling approaches have been used to fill gaps wherever possible, for example with the cattle distributions and production systems, the results produced are in some cases based on approximations and are thus bound to include some inaccuracies.

In the bio-economic component, data on livestock productivity (fertility, mortality, milk yields and output of draught power) were mostly obtained from a limited number of in-depth studies in specific localities. As the large number of references testifies, cattle systems in the study region have been much studied and there is enough information to paint a good general picture, and to cross-check and validate. However, although trypanosomosis has been relatively well researched, there remains a need for more specific studies on this disease's impact, explicitly linked to cattle production systems. In particular, there is hardly any quantitative evidence of its impact on the draught animals that play such a big role in the cattle economics of the region. The sensitivity analysis conducted shows how sensitive benefits are to assumptions about the parameters influencing herd growth – fertility, and especially mortality. While the sensitivity analyses affected the absolute value of benefits, their impact across production systems and therefore across the study area was very similar, so that the regional patterns illustrated by the maps would be maintained. By choosing modest assumptions about impact, this study provides a baseline for benefits which decision-makers can confidently assume should be realised or exceeded under normal circumstances. When climatic or political upheavals occur which radically alter cattle numbers, the distribution and geographical magnitude of these benefits will change, but the levels per bovine are likely to remain similar. Lastly, consideration should also be given to the effect of tick-borne diseases, which are usually endemic in the same areas, and whose impacts can be mitigated by some tsetse control methods.

Although the final map is necessarily reminiscent both of the cattle and tsetse distributions, the weighting by production system does add a crucial dimension by highlighting areas of high draught oxen and grade dairy cattle use. It thus provides proof of concept for this approach to illustrating the spatial distributions of the losses from an endemic disease. Such an approach is likely to have wider applicability to other pests and diseases. It has begun to be adopted in the field of ecology (Troy and Wilson, 2006).

5. Conclusions

The results of this study demonstrate that while there are substantial benefits to be reaped from investing in tsetse and trypanosomosis control and elimination, the geographic distribution of the benefits is markedly uneven. The opportunity to inject up to US$ 2.5 billion, in present value terms, into the economy must not be overlooked in one of the world's poorest regions, where economic development is hampered not only by diseases such as trypanosomosis but also by conflicts and frequent droughts.

The uneven distribution of benefits implies that decision-makers need carefully to consider matching their interventions and expenditures to these very different levels of potential benefits. To accomplish this, the figures need to be interpreted at different levels: per bovine, in relation to production system and per square kilometre. On a per bovine basis, livestock keepers across the production systems can ultimately increase their annual incomes by an average of 43.5% per bovine. Thus, even where benefits per square kilometre are low, often reflecting low cattle population densities, livestock keepers can benefit substantially, and immediately, from measures to control the disease. Furthermore, in the pastoral and agro-pastoral production systems lower absolute gains must be balanced against households' dependence on livestock, thus these apparently more modest gains in fact have a very significant impact on livelihoods. In terms of benefits per square kilometre, the sizeable differentials mean that any measures which are either expensive or which increase per square kilometre rather than per bovine, need to be costed out and compared to the likely benefits. Within the time horizon analysed some of these measures are not likely to be cost-effective in some regions, unless other factors, such as the presence of human African trypanosomosis, also play an important role. Elsewhere, where the potential benefits per square kilometre are very high, more ambitious and costly investments would be justifiable.

The benefits of disease interventions cannot be taken in isolation from their costs. The economic benefit maps described here complements an earlier investigation of the costs of intervening against tsetse and animal trypanosomosis in Eastern Africa, taking Uganda as a case study (Shaw et al., 2013). In combination, these two studies present the opportunity to combine the costs and the benefits of interventions against trypanosomosis at a regional scale, with a view to assisting with planning, priority setting and impact assessment.

Disclaimers

The boundaries and names shown and the designations used on the maps presented in this paper do not imply the expression of any opinion whatsoever on the part of FAO concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. Dotted lines on maps represent approximate border lines for which there may not yet be full agreement.

The views expressed in this paper are those of the authors and do not necessarily reflect the views of FAO.

Acknowledgments

This work was a collaborative initiative carried out under the aegis of FAO by the Pro-Poor Livestock Policy Initiative (PPLPI), the Intergovernmental Authority on Development Livestock Policy Initiative (IGAD LPI) and the Programme Against African Trypanosomosis (PAAT). Funding under these programmes was provided, respectively, by the European Commission (EC grant: GCP/INT/963/EC); the UK Department For International Development (DFID – grant: GCP/INT/804/UK), the International Fund for Agricultural Development (IFAD – grants GCP/RAF/403/IFA: "Strengthening the Information System of PAAT", and GCP/RAF/442/IFA: "Pro-poor Integrated Packages to Enhance Policy and Decision Making against the African Animal Disease Burden in sub-Saharan Africa"), and the Government of Italy through the FAO Trust Fund for Food Security and Food Safety ("Improving food security in sub-Saharan Africa by supporting the progressive reduction of tsetse-transmitted trypanosomosis in the framework of the NEPAD" – GTFS/RAF/474/ITA). In-country information collection was undertaken by Temesgen Alemu, Michael Eregae, Joel Kanunga, Abdullatif Abdi, Solomon Muchina, Samuel Mugasi and Charles Waiswa whose contributions are gratefully acknowledged.

Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.prevetmed.2013.10.024.

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