Risk factors for foot-and-mouth disease in Tanzania, 2001-2006

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Abstract

We developed a model to quantify the effect of factors influencing the spatio-temporal distribution of Foot-and-mouth disease (FMD) in Tanzania. The land area of Tanzania was divided into a regular grid of 20 km × 20 km cells and separate grids constructed for each of the 12-month periods between 2001 and 2006. For each year, a cell was classified as either FMD positive or negative dependent on an outbreak being recorded in any settlement within the cell boundaries. A Bayesian mixed-effects spatial model was developed to assess the association between the risk of FMD occurrence and distance to main roads, railway lines, wildlife parks, international borders and cattle density. Increases in the distance to main roads decreased the risk of FMD every year from 2001 to 2006 (ORs ranged from 0.43 to 0.97). Increases in the distance to railway lines and international borders were, in general, associated with a decreased risk of FMD (ORs ranged from 0.85 to 0.99). Increases in the distance from a national park decreased the risk of FMD in 2001 (OR 0.80; 95% CI 0.68-0.93) but had the opposite effect in 2004 (OR 1.06; 95% CI 1.01-1.12). Cattle population density was, in general, positively associated with the risk of FMD (ORs ranged from 1.01 to 1.30). The spatial distribution of high risk areas was variable and corresponded to endemic (2001, 2002 and 2005) and epidemic (2003, 2004 and 2006) phases. Roads played a dominant role in both epidemiological situations; we hypothesise that roads are the main driver of FMD expansion in Tanzania. Our results suggest that FMD occurrence in Tanzania is more related to animal movement and human activity via communication networks than trans-boundary movements or contact with wildlife.

Key words: Foot-and-mouth disease, FMD, Tanzania, risk factors, spatial model

Introduction

Tanzania is one of the poorest countries in the world in terms of income per capita. The Tanzanian economy depends heavily on agriculture, which accounts for more than 40% of gross domestic product. Trans-boundary animal diseases (TBD) such as foot-and-mouth disease (FMD) have a serious impact on animal well being and productivity, precluding the establishment of stable domestic and international markets for livestock and products. In Tanzania controlling FMD and other TBD is one of the current priorities to alleviate poverty in rural areas and strengthen the livestock sector.

FMD, caused by an *Aphthovirus* (*Picornaviridae*), is difficult to control as it spreads rapidly among domestic and wild even-toed ungulates. In Tanzania, the control of FMD is particularly complex for several reasons. Firstly, at least four different virus serotypes circulate in the country causing an irregular but continuous number of FMD outbreaks (Kasanga et al., 2012). Secondly, there are little or no controls on the movement of livestock in the national territory and from neighbouring countries and there are a large number of susceptible wild animals such as the African buffalo, in the wildlife reserves distributed along the country (Kivaria, 2003). Finally, control efforts are limited by a lack of detailed knowledge of the epidemiology of FMD and its behaviour in Tanzania.

A recent study described the spatiotemporal distribution of reported FMD outbreaks in Tanzania from 2001 to 2006 (Picado *et al.*, 2011) . This study highlighted the complexity of FMD virus transmission in the country as the number and location of FMD outbreaks varied over the study period. Clustering of outbreaks along border areas and roads suggested that human activity was the main driver of FMD virus transmission in Tanzania (Picado et al., 2011). While this work raised a number of useful hypotheses concerning FMD spread no formal analyses were conducted to quantify the role of these and other factors in the spatiotemporal distribution of FMD in Tanzania.

A number of epidemiological studies have assessed geographical, ecological, farm-level and animal-level factors associated with FMD occurrence (see, for example Bessell et al., 2010;

Taylor et al., 2004 and Hayama et al., 2011). Most of them are related to particular epidemic episodes, mainly the 2001 FMD epidemic in Europe and, as a result, their findings cannot be extrapolated to the situation in Tanzania and its neighbouring countries where FMD is endemic. Most of the sub-Saharan countries share some characteristics that have been associated with FMD virus incursion and maintenance. The presence and proximity to susceptible wildlife populations such as the African buffalo has been identified as a risk factor for FMD in South Africa (Dion *et al.*, 2011), Uganda (Ayebazibwe *et al.*, 2010a, Ayebazibwe *et al.*, 2010b), Cameroon (Bronsvoort *et al.*, 2004), Zimbabwe (Hargreaves *et al.*, 2004) and Ethiopia (Molla *et al.*, 2010). Uncontrolled animal movement has been identified as a factor associated with the within-country spread of FMD spread in Uganda, Ethiopia (Molla et al., 2010), South Africa (Jori *et al.*, 2009) and Cameroon (Bronsvoort *et al.*, 2004). Similarly, trans-boundary animal movements associated with seasonal grazing (Megersa *et al.*, 2009, Picado et al., 2011) has been recognized as one of the main factors explaining the difficulties to control FMD in East Africa (Ayebazibwe et al., 2010b, Balinda *et al.*, 2010).

FMD control in Tanzania would benefit from a knowledge of factors that render areas either susceptible to incursion or disease spread once an incursion has occurred. This information would allow high risk areas to be delimited which would, in turn, allow resources to control the disease to be better targeted. To address this goal, the objective of this paper was to identify factors associated with the spatial and temporal distribution of FMD in Tanzania for the period 2001 to 2006.

Material and methods

Data

A database comprised of the details of FMD outbreaks in cattle was provided by the Epidemiology Section of the Tanzanian Ministry of Livestock and Fisheries Development. A total of 878 FMD outbreaks were reported in mainland Tanzania from 1 January 2001 to 31 December 2006 (inclusive). Households with FMD affected stock were diagnosed by district veterinary officials on the basis of clinical signs and outbreak details were then reported to the Ministry. The geographical location and the date on which the clinical signs of FMD were first observed were extracted from the FMD database. Information on the FMD virus serotypes associated to the outbreaks was not available.

The spatiotemporal distribution of FMD outbreaks in Tanzania has been described in detail elsewhere (Picado et al., 2011). Briefly, the spatial distribution of FMD outbreaks was inhomogeneous and variable. The highest densities of outbreaks were located in the Tanzania-Kenya border area in 2001, 2002 and 2005. In 2003, 2004 and 2006 the outbreaks had a broader distribution and were reported along the international borders and the communication networks in the centre of Tanzania.

Geographical data on the country boundaries and the main communication networks (roads and railway lines) were obtained from the Food and Agriculture Organization (FAO) (http://www.fao.org/geonetwork/srv/en/main.home). Cattle density was obtained from the livestock density maps generated by FAO's Animal Production and Health Division (http://www.fao.org/ag/againfo/resources/en/glw/GLW_dens.html). The location of national parks was retrieved from the World Database on Protected Areas (http://www.wdpa.org/). All geographical data were projected in the World Geodetic Datum 1984 UTM zone 36S.

For modelling purposes mainland Tanzania was divided into a regular grid comprised of 20 km × 20 km cells. The cattle density map of Tanzanian was superimposed on this grid and those cells with zero cattle density were removed from the analysis. For each year (January to December) the FMD status of a grid cell was considered as positive if it had at least one positive household, that is a location where an FMD outbreak was reported during the study period, and negative otherwise.

Statistical analyses

One model was developed for each year of the study (i.e. 2001 to 2006). The probability of a grid cell being FMD positive each year (p_i) was modelled by assuming a Bernoulli distribution for the status of each of the i = 1754 grid cells, O_i:

$$O_i \sim Bernoulli(p_i) \qquad \text{Equation 1}$$

In order to link the probability of infection of each grid cell with specific explanatory variables we used the logit transformation.

To assess the risk associated to the communication networks and to human activity we included the distance to main roads and railways lines as covariates in the model. For each grid cell, cattle population was calculated as the mean of the values of those raster cells that fell within each grid cell. The distances from the centroid of each cell to the border of the nearest national park and to an international border were used as proxy measures for domestic animal-wildlife interaction and uncontrolled transboundary animal movements, respectively. To facilitate the model fit the covariates were centred prior to adding them to the model by subtracting each of them by the mean value of their distribution:

$$\text{logit}(p_i) = \alpha + \beta_1 DP_i + \beta_2 DR_i + \beta_3 DT_i + \beta_4 DB_i + \beta_5 CP_i \qquad \textit{Equation 2}$$

In Equation 2, α represents the intercept and DP_i, DR_i, DT_i and DB_i were the Euclidean distances of the ith grid cell centroid to the nearest national park, road, railway line and border, respectively. CP_i was the mean cattle population within each grid cell. Model residuals for each grid cell (R_i) were computed as:

$$R_i = \frac{(O_i - p_i)}{\sqrt{p_i \times (1 - p_i)}} \qquad \textit{Equation 3}$$

Where p_i was the predicted probability of a cell being FMD positive and O_i was the observed cell FMD status. Models were run using a Bayesian framework. Non-informative uniform prior distributions with values ranging from 0 to 100 were assigned to all the regression coefficients (i.e., β_1 to β_5) (Gelman et al., 2006). For the intercept, a prior flat distribution (i.e. uniform distribution on an infinite interval) was assigned, as recommended by Lawson et al. (2003)).

The models were run in WinBUGS 1.4 (Bayesian inference Using Gibbs Sampling (Spiegelhalter et al., 2003) from the statistical software R 2.13.1 (R Development Core Team 2011) using the R2WinBUGS package (Sturtz et al., 2005). Two chains were simulated and the Gibbs sampler was run for 10,000 iterations with a burn-in of 1,000 iterations. Convergence was assessed using the R-Hat statistic. In order to achieve convergence the value of this statistic should lie between 0.95 and 1.05 (Brooks and Gelman 1998).

To test for spatial autocorrelation in model residuals we plotted as a correlogram of the Moran's I statistic from the 1st to the 8th spatial lag. The Moran's I statistic quantifies the similarity of a value between areas defined as neighbours (Moran 1950). Its value ranges from -1 to +1, and when no correlation exists between neighbouring areas the value approximates to zero (Pfeiffer et al., 2008).

Due to evidence of spatial autocorrelation in the model residuals, we extended the model as suggested by Besag et al., (1991) adding spatially structured (S_i) and unstructured components (U_i):

$$\mathrm{logit}(p_i) = \alpha + \beta_1 DP_i + \beta_2 DR_i + \beta_3 DT_i + \beta_4 DB_i + \beta_5 CP_i + U_i + S_i \qquad \textit{Equation 4}$$

Following Besag et al., (1991) the prior distribution of the spatial correlated random effect was assumed to follow a conditional normal autoregressive (CAR) distribution where its mean was based in the set of grids adjacent to each grid and the precision was proportional to the number of neighbours (Richardson et al., 2006). The unstructured random effect was assumed to follow a normal distribution with mean 0. The precision of both random effects (hyperpriors) were assumed to follow a uniform distribution with values ranging from 0 to

100 (Gelman et al., 2006). The model residuals were retested for spatial autocorrelation and plotted using the same procedure described for the fixed effects model.

To facilitate convergence, distance covariates were divided by 10,000 prior to including them in the model. The interpretation of their effect on the risk of being a FMD positive grid cell was based on the posterior distribution of the regression coefficients obtained from the 10,000 MCMC simulations (after a burn-in of 1,000 simulations). A covariate was considered to be significantly associated to the risk of being FMD positive if the 95% Bayesian credible interval (CI) of the posterior distribution of its regression coefficient was completely over (positive effect) or below (negative effect) zero. In order to measure the effect of each variable on the risk of being an FMD positive cell, we calculated the odds ratio (OR) and its 95% CI per unit of increase (i.e. 10 km or 10 cattle) as the exponential value of the mean of the posterior distribution of each regression coefficient.

A Receiver Operating Characteristic (ROC) curve was constructed for each year to test the ability of the model to discriminate between positive and negative grid cells by using the pROC package (Robin et al., 2011) in R. The area under the curve (AUC) is related to the performance of the model. An AUC value greater than 0.8 and between 0.7 and 0.8 was indicative of good and moderate discriminate capacities, respectively. As suggested in Liu et al., (2005), a predicted probability greater than the yearly prevalence was set us as the cutoff to determine the predicted state of a grid cell. Yearly prevalence was used as the cutoff in each of the map legends.

Results

A map of Tanzania showing the location of national parks, roads, rail road's and cattle density is shown in figure 1. Mainland Tanzania was divided in 1,785 (20 km × 20 km) grid cells from which 1,754 (i.e., cells where cattle density was greater than zero) where included in the analysis. The number of positive grid cells (i.e., cells with at least one FMD-positive case) varied by year. For the period 2001 to 2006 (respectively) the number of FMD-positive grid cells was 38, 47, 95, 215, 42 and 87, respectively.

Risk factors for FMD

Adjusted odds ratio and their 95% CI for each of the risk factors included in the model, by year are presented in Figure 2. Ten kilometre increases in the distance of a grid centroid to the nearest main road decreased the odds of FMD (ORs ranged from 0.43 in 2003 to 0.97 in 2001). Increases in the distance of a grid centroid to the nearest railroad were also associated with a reduction in FMD risk. However the magnitude of the effect of railroad distance was less than that identified for major roads and was only significant in 2002, 2004 and 2006 (OR 0.91, 95% CI 0.85-0.97), 2004 (OR 0.93, 95% CI 0.88-0.96) and 2006 (OR 0.93, 95% CI 0.86-0.97). Similarly, increases in the distance of a grid centroid to the nearest international border reduced the risk of FMD in 2001 (OR 0.90, 95% CI 0.86-0.94), 2002 (OR 0.96, 95% CI 0.93-0.99), 2005 (OR 0.93, 95% CI 0.90-0.97) and 2006 (OR 0.95, 95% CI 0.93-0.97).

The association between distance to the nearest national park and FMD risk varied throughout the study period. Ten kilometre increases in the distance to the nearest national park reduced the risk of FMD occurrence in 2001 (OR 0.80, 95% CI 0.68-0.93) but had the opposite effect in 2004 (OR 1.06, 95% CI 1.01-1.12). Finally, increases in the average number of cattle per grid cell by increments of 10 was associated with an increased risk of FMD in 2001 (OR 1.21, 95% CI 1.12-1.30), 2003 (OR 1.12, 95% CI 1.01-1.27) and 2006 (OR 1.11, 95% CI 1.05-1.19). Further details on the estimated regression coefficients, the odds ratios and their 95% CIs are provided in the Annex.

Spatial distribution

A map of Tanzania showing, for each year, the predicted probability of FMD is shown in Figure 3. Two distinct spatial patterns of FMD risk can be identified. First, in 2001, 2002, and 2005, the high-risk cells were predominantly located in the areas bordering Kenya in the east and Uganda, Ruanda, Burundi, The Democratic Republic of the Congo and Zambia in the west. In those years the high risk areas closely followed the geographical extent of Tanzania's international borders. For example, on the border with Zambia the high risk areas were located around the bordering city of Tunduma. On the Kenyan border the high risk areas for FMD were around region of Arusha and towards the south. Second, in 2003, 2004 and 2006 in addition to the international borders, the high risk zones expanded towards the north and the centre of the country. The concentration of high risk areas was particularly evident along the main communication networks, for example the major road connecting Mbeya (in the west) to Dar es Salam (in the east). The area around Dar es Salam had a consistently high risk for FMD. Throughout the study period the risk of FMD was generally lower in the south of the country, compared with the north. However in 2005 limited high risk areas for FMD where identified around the city of Songea in the west and on the east coast closer to the border with Mozambique (Figure 3).

The area under the ROC curve generated using predictions from the model ranged from 0.76 (95% CI: 0.71-0.80) to 0.83 (95% CI: 0.77-0.89) , indicative of a model with moderate to good ability to discriminate between FMD positive and FMD negative grid cells (see Annex 1 for details).

The residuals of the random effect models correlograms, showing the Moran's I statistic (and its 95% confidence interval) for the model residuals at 1 to 8 spatial lags are shown in Figure 4. The spatial distribution of the model residuals varied throughout the study period. In 2003 most of the positive residuals were located in the north and central part of the country. In 2004 most of the positive residuals were located in the border with Kenya and in the central part of the country. As shown in Figure 4 spatial correlation was not completely eliminated by inclusion of the CAR spatial random effect term and there was some residual spatial correlation present in years 2001, 2003, 2004 and 2006. However, this spatial correlation was small with a maximum value of 0.15 in 2003 and 2004.

Discussion

Throughout the study period (2001 to 2006) the number and location of FMD outbreaks varied but proximity to main roads was a consistent risk factor for FMD occurrence, both during endemic (2001, 2002 and 2005) and epidemic (2003, 2004 and 2006) phases. Other spatial factors played a variable role on the risk of FMD. Increases in the distance from railways and international borders were, in general, associated with a decreased risk of FMD. Increases in distance from national parks decreased the risk of FMD in 2001 but had the opposite effect in 2004. Cattle density was, positively associated with FMD risk in 2001, 2003 and 2006. The distribution of FMD high risk areas was also variable over the study period but showed some interesting patterns. Bordering areas in the west, north and east were the main risk areas during endemic phases (2001, 2002 and 2005). FMD risk increased in these bordering areas and expanded to the centre of the country, particularly areas along the main communication networks, during epidemic phases (2003, 2004 and 2006).

Foot-and-mouth disease is endemic in eastern and central African regions and endemic phases are associated with regular, but relatively low number of FMD outbreaks every year (Kivaria 2003). Throughout the period of study presented in this paper three years seemed to correspond to an endemic phase (2001, 2002 and 2005) and during those years, the risk of FMD was consistently associated with proximity to main roads and international borders. This would indicate that movement of livestock across international borders and within-country movement of livestock (along major road networks) contributed to the persistence of FMD during endemic phases. In Tanzania, control of livestock movements are difficult to achieve and most of these movements are issued without health certificates. Besides, smuggling and illegal slaughter of animals across borders have been reported to occur quite often (Kivaria, 2003). This could be linked to the high risk areas (Figure 3) associated with bordering urban areas such as Tunduma on the Zambian-Tanzanian border in the west and Arusha in the east which could contribute to the introduction of infected animals. Moreover, uncontrolled trans-boundary animal movements have also been associated with pastoralist communities in bordering areas (Megersa et al., 2009, Picado et al., 2011). This observation is supported by our findings that show the presence of high FMD risk areas in the pastoral production areas in the North of Tanzania.

The strength of the association between railways and FMD risk was less than that observed for roads, with proximity to railways associated with an increased risk of disease in 2002, 2004 and 2006 and a lower magnitude effect. Rail is rarely used for cattle transportation in Tanzania because trips by train tend to take longer than by road. On the other hand, proximity to roads could be interpreted not only as a proxy for cattle movement but also for human activity or type of cattle production. Cases included in this study are based on passive surveillance data and in areas closed to roads the report of cases could be more effective, as veterinary officials would have an easier access. Also, in the last years, the country has experienced a trend towards increased intensification and commercialization of livestock production in urban and peri-urban areas (Kivaria, 2003) so it is reasonable to speculate that in those production systems FMD reporting would be more likely.

Cattle density had a lower effect than expected, with only a significant effect on 2001, 2003 and 2006 (both endemic and epidemic years). This could also be explained by the role of animal movements in FMD transmission within the country. Two types of movements have been reported in the country, i) the official system through livestock markets and ii) the informal system where the livestock keepers deal directly with vendors. The second one plays a greater role in FMDV spread from one place to another (Kivaria, 2003). This type of movements could be done among areas with high or low cattle density and therefore, despite cattle density has a role in FMD transmission it might not be the main determinant.

Proximity to national parks, and potential wildlife reservoirs, has been identified as a risk for FMD in other endemic countries in Africa (Ayebazibwe et al., 2010a, Ayebazibwe et al., 2010b; Bronsvoort et al., 2004; Hargreaves et al., 2004; Molla et al., 2010). In Tanzania, being closer to a national park was a significant risk factor for FMD in 2001 but not during the other two endemic years (2002 and 2005). The likelihood of FMD virus transmission from wildlife to domestic livestock may vary among each of the wildlife parks in Tanzania. Also, other domestic animals, such as goats and sheep, might have a role in FMD virus transmission and they were not evaluated in this study. Sheep and goats rarely show clinical signs and therefore, we did not have reported data about outbreaks in those species. More detailed risk analyses in space (i.e. smaller geographic areas) and time (e.g. by season or month instead of years) might better define the role of wildlife and other domestic species different than cattle in the epidemiology of FMD in domestic animal populations in Tanzania. Similarly, different FMD virus serotypes may be associated to different risk factors. The lack of data on serotypes in the database precluded including this factor in the analyses.

FMD epidemic phases were associated with a sudden increase in the number and distribution of reported cases. In Tanzania the number of FMD cases increased significantly in 2003, 2004 and 2006 (Picado et al., 2011). During those years communication networks (roads but also to some extent railways) were risk factors for FMD occurrence. The impact of communication networks, particularly the road that crosses the country from the Zambian border to Dar Es Salam and Arusha, is clearly seen in the risk distribution maps (Figure 3). The same maps also show that proximity to border areas was risk for FMD both in endemic and epidemic phases. In the epidemic phases (2003 and 2004), proximity to international borders was not identified as a risk factor by the model; however the magnitude of its effect was probably reduced because of the relatively large numbers of cases that occurred along the communication networks in the central part of the country.

The data used for this study are based on passive reports by staff of the Tanzanian Ministry of Livestock and Fisheries Development and clinical diagnoses made by field veterinarians (Picado et al., 2011, Kivaria 2003). The use of passive surveillance data has some limitations that should be considered when interpreting the results. There the reporting of FMD cases throughout the country may be variable. For example, reporting may be more likely in areas more often visited by veterinary officers (e.g. areas closer to transport links or with higher cattle density). In spite of the inevitable limitations in data of this type we were able to identify biologically plausible risk factors for FMD as well as delimit high FMD risk areas in different epidemiological scenarios. Indeed, the use of distance-based measures (i.e. distance to the nearest major road, railway, international border, and national park) were proxy variables used to represent proximity to within- or between-country trade or wildlife-domestic livestock interaction. We believe that aggregating the data to 20 km × 20 km grids and expressing the outcome of interest as a dichotomous variable (i.e. FMD-positive, FMD-negative) as opposed to a count of the number of outbreaks per grid minimised the impact of the bias created by the varying intensity of reporting that would be typically present in the study data set. Delimiting areas with different risk and epidemiological characteristics has implications for FMD control (Kivaria 2003). For example, the south of Tanzania, which had low numbers of FMD outbreaks throughout the study period, may be a potential FMD-free zone if appropriate control measures are put in place (Picado et al., 2011). That said, our analyses identified two high risk areas for FMD within that zone (around the city of Songea and on the southern coast) which may need to be monitored closely if a FMD-free zone was declared. It would also be of interest to identify livestock populations important in the transmission of FMD in the south.

Despite the addition of a term in the model to account for spatially correlated heterogeneity (Equation 4) residual spatial autocorrelation remained in the 2003 and 2004 models. We believe this could be due to ‘sustained’ disease transmission during the course of the year resulting in relatively large geographic areas that were disease positive and, similarly, large areas that were disease negative. We propose that the CAR approach, in which spatially correlated heterogeneity is accounted-for by the use of a pre-defined spatial adjacency criteria (in this study grid cells were defined as adjacent if they shared a common border), might not be the most appropriate for accounting for unexplained variation in the spatial distribution of highly dynamic infectious diseases such as FMD. In order to partially mitigate this issue, we developed a spatial model for each year, allowing the unexplained variation in the spatial distribution of FMD risk to vary, rather than using a single spatio-temporal model which would have assumed constant spatial autocorrelation over time.

Of the risk factors that were assessed, roads played a role in endemic and epidemic phases suggesting that animal movement and human activity via communication networks are the main drivers of FMD transmission in this country. Our findings support the hypothesis that trans-boundary movements or contact with wildlife contribute to the maintenance of FMD during the endemic phases. When combined with other information on FMD occurrence in Tanzania, the results of this study should help FMD control programme managers to define effective measures to reduce the risk of FMD in different areas of the country and in different epidemiological situations.

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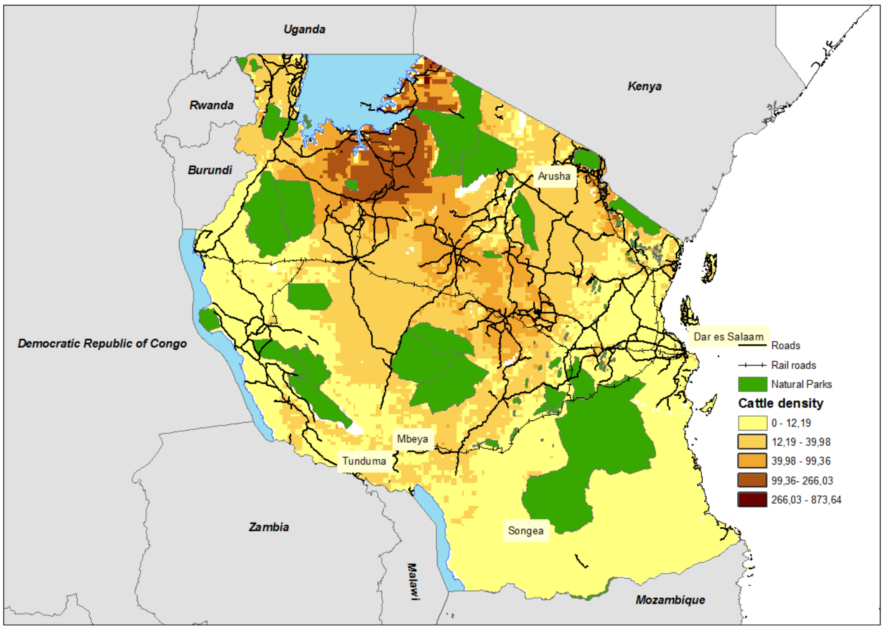

Fig. 1. Map of Tanzania showing the location of national parks, roads, rail road's and cattle density.

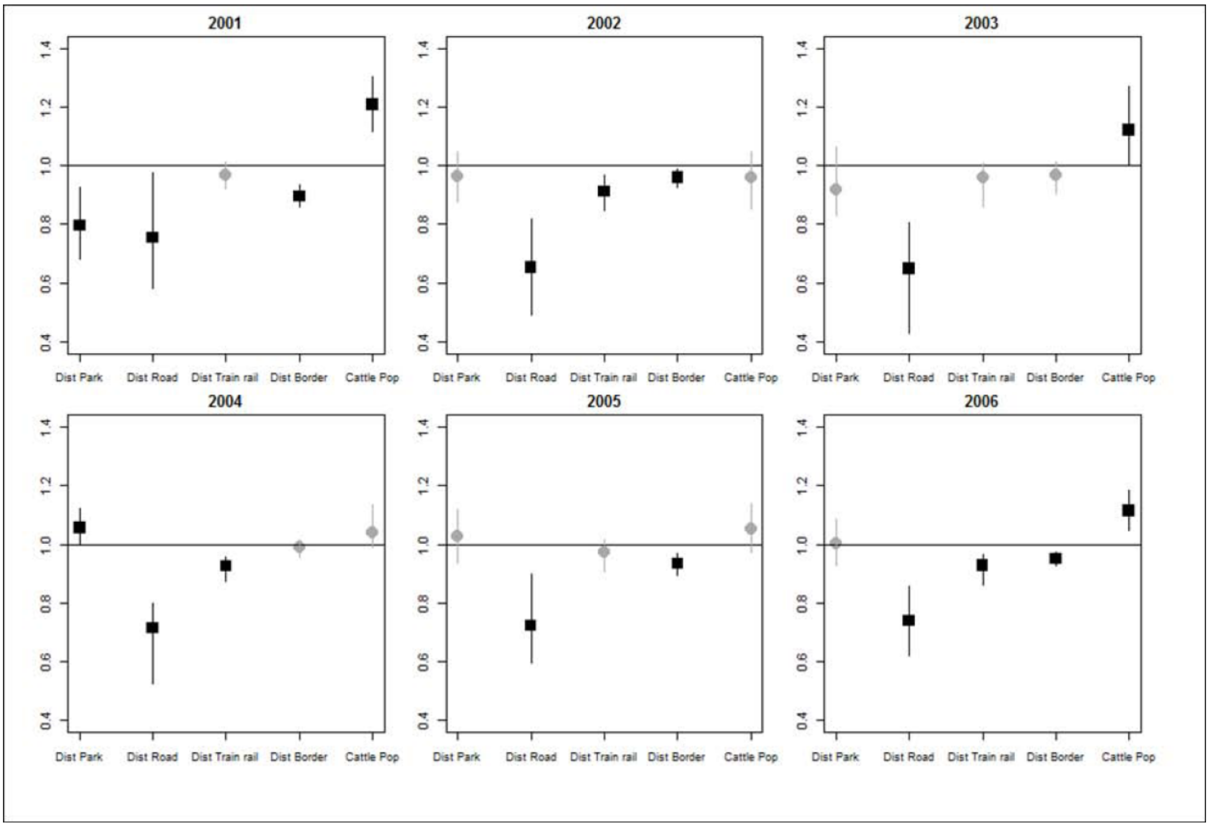

Fig. 2. Risk factors for foot-and-mouth disease (FMD) in Tanzania, 2001-2006. Error bar plots showing odds ratios (OR) and their 95% credible intervals (CI) for five characteristics of grid cells thought to be associated with FMD. The distance-based measures represent the increase (or decrease) in the odds of a grid cell being FMD-positive in response to 10 km increases in the respective distance measure. For human population the ORs represent the increase (or decrease) in the odds of a grid cell being FMD-positive in response to 10,000 increases in grid cell population size. Those characteristics significantly associated with FMD occurrence (95% CI does not include 1) are represented by a black square.

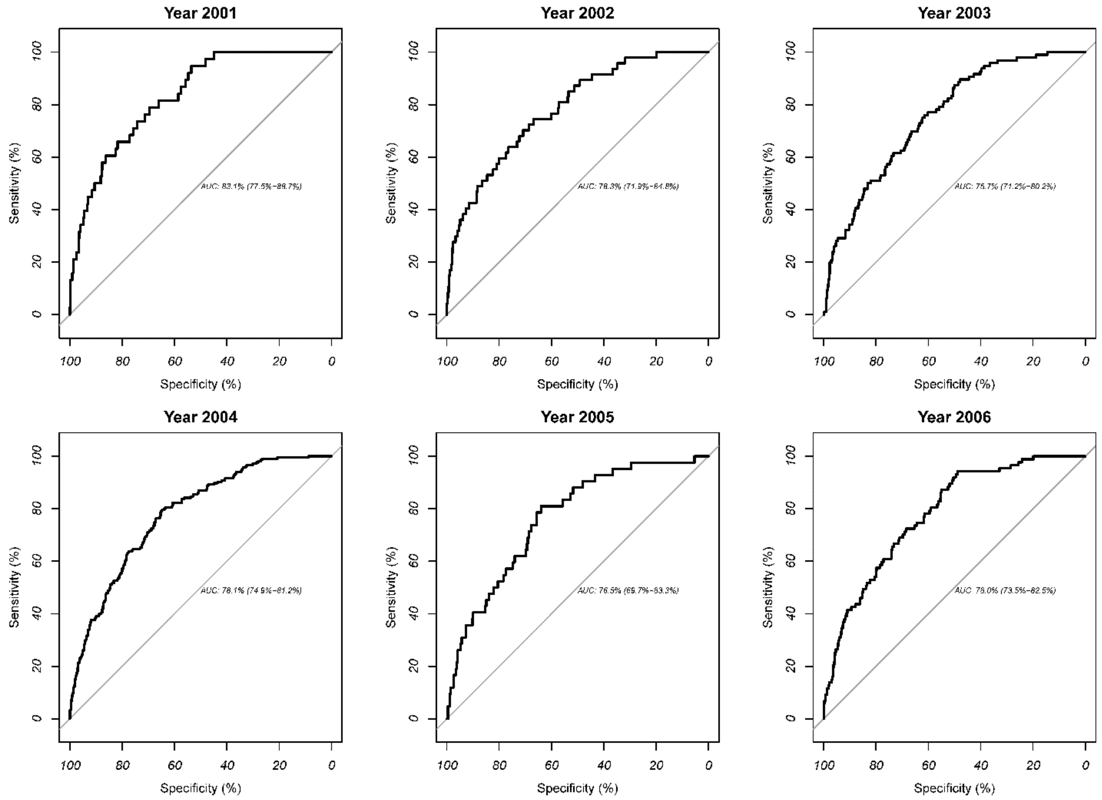

Fig. 1 (Annex 1): Receiver Operating Characteristic (ROC) curve to test the ability of the model to discriminate between positive and negative FMD grid cells

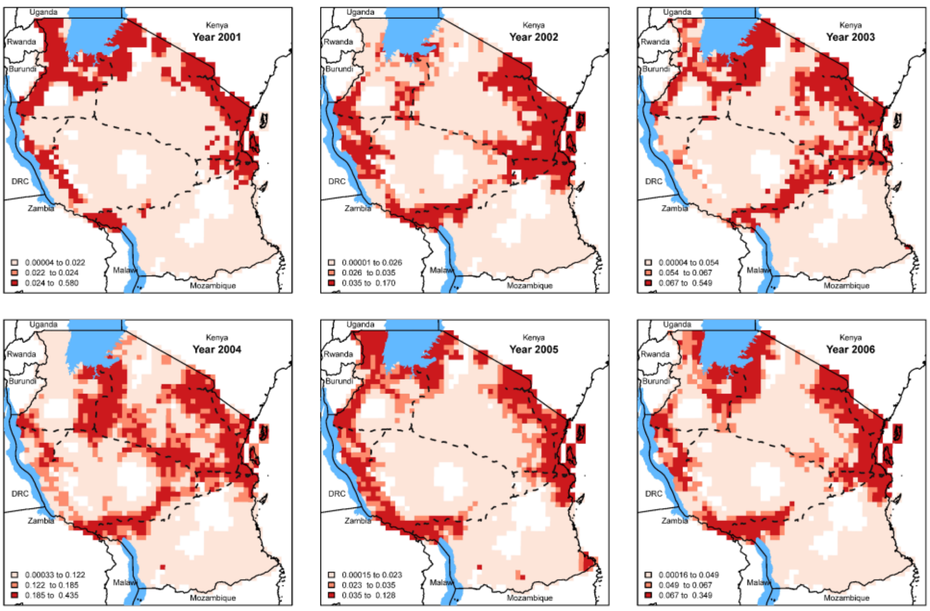

Fig. 3. Choropleth maps showing the spatial distribution of the predicted probability of a grid cell being FMD-positive, 2001-2006. Also shown on each plot are the locations of the major road networks throughout Tanzania.

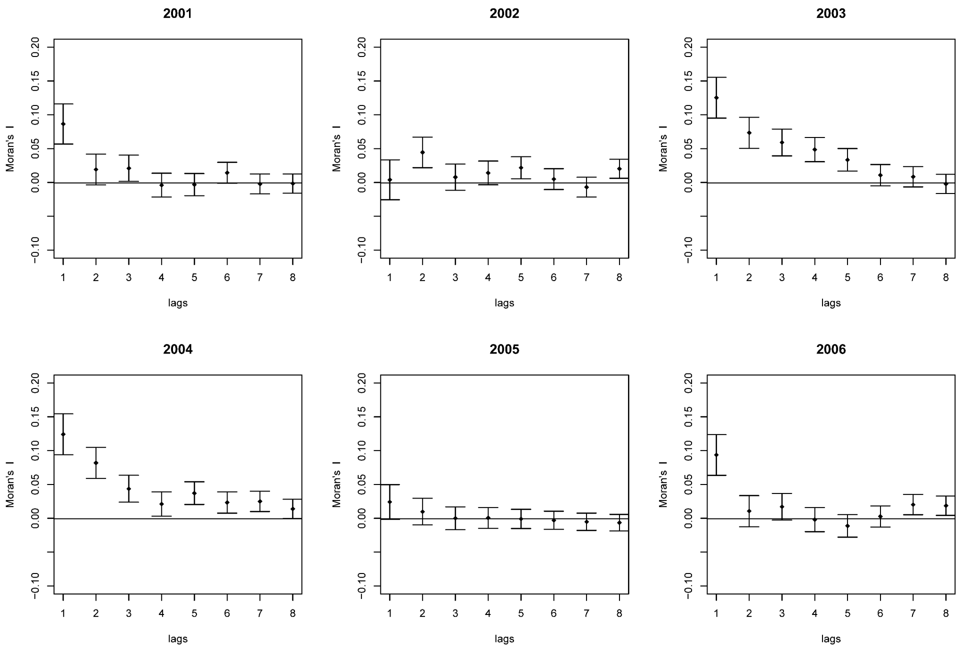

Fig. 4. Moran's I statistic correlogram of the residuals of the random effect model assessing the risk of FMD associated to distances to communication networks, international borders and parks as well as human population. Statistic presented from the 1st to the 8th spatial lag for each year of study (2001 to 2006). Each spatial lag represents grid size i.e., 20km.