International Journal of Infectious Diseases 46 (2016) 49–55

Contents lists available at ScienceDirect

International Journal of Infectious Diseases

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

Association of ecological factors with Rift Valley fever occurrence and mapping of risk zones in Kenya

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ARTICLE INFO

Article history:
Received 7 December 2015
Received in revised form 1 February 2016
Accepted 14 March 2016

Corresponding Editor: Eskild Petersen, Aarhus, Denmark.

Keywords:
Rift Valley fever
Evapotranspiration
Normalized difference vegetation index
Animal density
Disease mapping

SUMMARY

Objective: Rift Valley fever (RVF) is a mosquito-borne infection with great impact on animal and human health. The objectives of this study were to identify ecological factors that explain the risk of RVF outbreaks in eastern and central Kenya and to produce a spatially explicit risk map.

Methods: The sensitivity of seven selected ecological variables to RVF occurrence was assessed by generalized linear modelling (GLM). Vegetation seasonality variables (from normalized difference vegetation index (NDVI) data) and 'evapotranspiration' (ET) (metrics) were obtained from 0.25–1 km MODIS satellite data observations; 'livestock density' (N/km^2), 'elevation' (m), and 'soil ratio' (fraction of all significant soil types within a certain county as a function of the total area of that county) were used as covariates.

Results: 'Livestock density', 'small vegetation integral', and the second principal component of ET were the most significant determinants of RVF occurrence in Kenya (all $p \leq 0.01$), with high RVF risk areas identified in the counties of Tana River, Garissa, Isiolo, and Lamu.

Conclusions: Wet soil fluxes measured with ET and vegetation seasonality variables could be used to map RVF risk zones on a sub-regional scale. Future outbreaks could be better managed if relevant RVF variables are integrated into early warning systems.

1. Introduction

Kenya has experienced several outbreaks of Rift Valley fever (RVF), resulting in human disease with a high case fatality[1] and considerable loss of livestock.[2] The disease is caused by the Rift Valley fever virus (RVFV), which is transmitted to vertebrates through the bites of the mosquito vector and through contact with the body fluids of infested animals.[3] In general, RVF outbreaks are triggered by periods of above normal rainfall events and higher temperatures. Outbreaks typically occur at 5–15-year intervals, and the occurrence is sporadic in inter-epidemic/epizootic periods.[4] However, little is known about the role of key ecological determinants of RVF on the landscape and regional scales and regarding the exploration of spatially explicit models for risk mapping.[1,5]

Large scale and data-driven RVF occurrence studies in Africa have relied primarily on modelling approaches that use ecological proxies such as climate data or vegetation activity averages over a certain period (i.e., normalized difference vegetation index (NDVI) data metrics).[2,6] These modelling studies have not, in the most part, explored the use of spatially explicit, localized, and temporally varying ecological factors to assess risk zones.[7,8] Spatially varying proxies for ecological processes on inter-annual vegetation seasonality and 'actual' (as opposed to modelled) land surface fluxes from water bodies would greatly improve RVF occurrence and risk zone modelling (regional scale) and mapping (local to landscape scales). Specifically, RVF occurrence on the landscape scale is driven largely by inter-annual changes in flooding and vegetation density dynamics.[9] Ecological variables are key determinants of mosquito habitat availability.[2,10] Satellite imagery offers the ability to derive 'actual' land surface dynamics information, which improves the mapability of specific ecological variables.[11] Fine spatially and temporally, as well as well-processed remote sensing-based datasets, essentially help

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http://dx.doi.org/10.1016/j.ijid.2016.03.013
1201-9712/

to reduce model over-fitting (over-predicting), which thus enhances the meaningfulness and accuracy of disease modelling outputs.[12]

In this study, RVF occurrence and risk zones were primarily defined by the ecological conditions that ascribe vector habitat suitability and vector propagation. It is acknowledged that there are specific 'non-mapable' socio-economic and cultural factors and risk dimensions, including meat handling procedures of infected animals, seroprevalence in livestock (number of infected animals), and small-scale herd density and migration patterns.[3,6] RVF-relevant ecological factors have the advantage that most of them can be mapped effectively over larger areas and be used as disease trigger mechanisms in early warning systems.[13]

For RVF occurrence, ecologically driven risks are related to primary and secondary vector habitat availability and dynamics.[14] Above average rainfall events (i.e., El Niño-Southern Oscillation (ENSO) events) usually trigger flooding and enhanced vegetation growth, which enable the breeding and propagation of secondary RVF vectors in particular.[2] Thus, if ecological trigger variables (as proxies) for RVF outbreaks can be recognized and the interactions between these variables (factors) can be identified, disease occurrence or risk zone maps can be produced.[15] Risk maps in disease mapping and modelling refer to the differentiation of endemic- from epidemic-prone and non-epidemic areas in time and space.[16]

Most previous studies on RVF in Kenya have used sea surface temperature (SST) abnormalities, climate variables, coarse resolution (>1 km pixel resolution) NDVI metrics (averages over 1 year), and the presence of hydrographic soils to model RVF occurrence and risk zones.[2,6,17] Most studies have made the assumption that there is a causal relationship between green vegetation development (i.e., NDVI) and vector breeding spaces on a regional scale. However, no attempt has yet been made to include other spatial invariant and more relevant remote sensing variables over larger areas and to investigate the seasonality of NDVI at moderate pixel resolutions (<300 m) in order to better mimic the temporal dynamics of vegetation dynamics. Moreover, there is a need to use intrinsic socio-ecological factors (other than climate), such as livestock densities, in data-driven RVF occurrence mapping approaches.[18]

2. Methods

2.1. Ecological setting and epidemiology of RVF in the study area

The study area stretches from the eastern to the central part of Kenya and covers the newly created counties of Baringo, Laikipia, Meru, Isiolo, Garissa, Tana River, and Lamu (Figure 1), spanning over 142 745 km^2 (Figure 1). Although semi-arid, this region is prone to large-scale flooding during the two rainy seasons of April to May and November to December.[19] The study area is slightly undulating with large tracts of black cotton and alluvial soils that are known to exhibit high water retention potential. Flooding and consequently mosquito hatching often occur in water-filled topographic depressions, or so called 'dambos'.[9] The most dominant natural woody species are acacias, which occur alongside open grasslands; the predominant land use is pastoralism.[20]

The region has been prone to multiple epizootics and epidemics since the 1960s and exhibits seasonal flooding conditions that provide ideal breeding conditions for the primary and secondary RVF vectors.[13] The study region was also selected because some districts had experienced two RVF outbreaks, one in 1997/1998 and one in 2006/2007, while other districts, such as Baringo, were newly affected in the 2006/2007 outbreak period.[21,22]

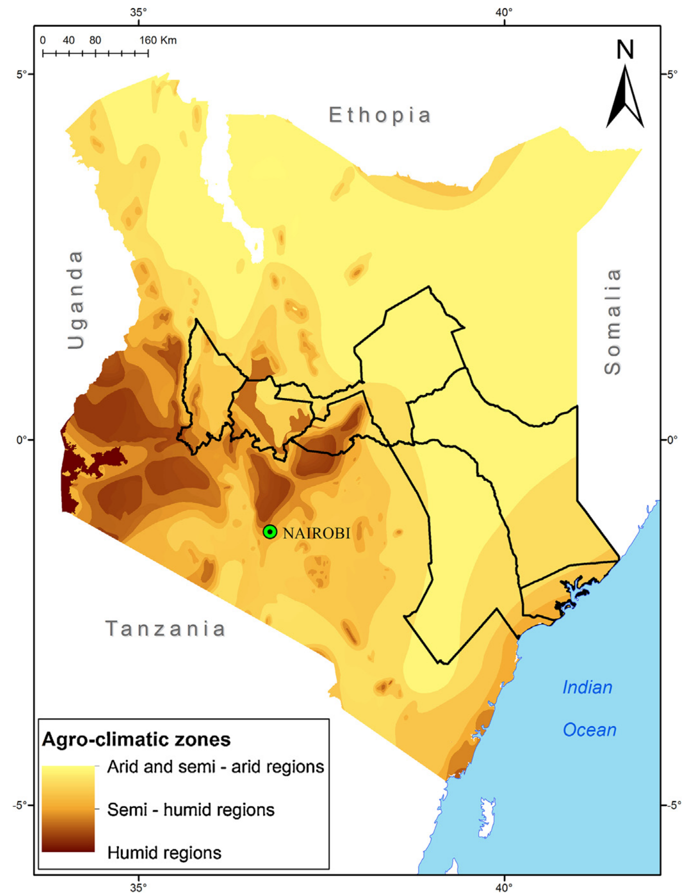

Figure 1. Agro-ecological zone map for Kenya showing the counties, outlined in black, constituting the study region (RVF occurrence area).

2.2. Methodological approach and risk mapping approach

2.2.1. Overview of variables and selection criteria

Table 1 shows the data characteristics of the ecological variables (covariates) used. Each of the covariates is explained in the sections below. The 'soil ratio' was derived from a geographical information system (GIS) vector data layer; otherwise all covariates used in the modelling were derived from pixel-based raster datasets. The two remote sensing variables (evapotranspiration (ET) and NDVI) varied temporally and spatially according to pixel sizes and the observation time frames and frequencies.

The best available datasets were chosen as covariates in terms of spatial resolution, consistency, and temporal alignment with the

Table 1
Ecological covariates (variables) that were used in the statistical analysis

Variable name	Units	Resolution and source
Animal density	Numbers/km^2	5 km (FAO)
Elevation	m (above mean sea level)	90 m SRTM
Season length	N/A	250 m MODIS NDVI
Small integral	N/A	250 m MODIS NDVI
Soil ratio	N/A	5 km (Kenya Soil Survey)[a]
PC1_ET	N/A	1 km MODIS ET
PC2_ET	N/A	1 km MODIS ET

FAO, Food and Agriculture Organization; SRTM, Shuttle Radar Topography Mission; MODIS, moderate resolution imaging spectroradiometer; NDVI, normalized difference vegetation index; ET, evapotranspiration; PC1, first principal component; PC2, second principal component; N/A, non-applicable (unit-less).
[a] Derived from a geographical information systems data layer.