INSIGHTS INTO LAND USE/COVER AND HUMAN ACTIVITIES PATTERN FOR EXPLANATION OF PLAGUE INFECTION RISKS IN WESTERN USAMBARA MOUNTAINS, TANZANIA

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EXTENDED ABSTRACT

Land cover, land use, and human activities pattern have been reported to be important determinants of vector borne diseases transmission including plague. Plague, still occurring in different parts of the world, has been a threat in the Eastern Africa region including the Western Usambara Mountains, Tanzania. Plague is a severe, rodent associated, bacterial zoonosis caused by *Yersinia pestis.* Literature suggests that factors influencing the critical contact between rodent hosts, flea vectors, and humans as well as human behaviours that may enhance or diminish this contact are not well understood in many areas particularly in the Eastern Africa region. Hence, studies that link a complete geographic perspective including land use and land cover, host, vector and human activities pattern dimensions are important. Understanding the influence of the landscape factors on small mammals like rodents and flea abundance and their spatial distribution as well as the human exposure risks is vital and can assist in formulating prevention and surveillance mechanisms.

Studies carried out in East Africa and elsewhere report a wide variety of potential health impacts arising from land use and land cover and terrain factors most of which are not well studied in the Western Usambara Mountains. Hence, the current research aimed to contribute to efforts of giving an insight into the roles of land cover, land use and human activities pattern in plague infection risks in the Western Usambara Mountains, Lushoto District, Tanzania. Specifically the study aimed: (i) to map land cover and terrain attributes and determine their association with plague hosts and vectors at landscape level (ii) to identify land use and land management practices associated with abundance and distribution of plague hosts and vectors at farm level

(iii) to model people’s movements and activities pattern in order to determine chances of their exposure to plague in space and time.

The study was carried out in three selected landscapes in the Western Usambara Mountains in Lushoto District, Tanzania. Study sites were selected to reflect a geographic gradient in plague incidence for the period 1980-2004, based on results from previous research on rodents, fleas and plague casualties in the area. The findings from those studies concur in distinguishing high, medium, and low incidence zones. Within this gradient three representative landscapes were selected differing in terms of (i) the incidence of plague, (ii) diversity in land use and associated human activities, (iii) landform characteristics, and (iv) climatic conditions. The selected landscapes are named Shume (high plague incidence), Lukozi (medium plague incidence) and Mwangoi (low plague incidence). In the context of the current study, Landscape is defined as “an area of land covering two to three villages with a repetition of similar relief types or an association of dissimilar relief types (valleys, plateaus, mountaineous hilly relief types), more or less homogeneous land use/cover types (natural forest, cultivated land, plantation forest and built up areas) and having specific historical plague incidence rate”.

Twenty four observation sites (quadrats) of 100 x 100 m were established per sample landscape area. A Stratified random sampling procedure based on broad land cover types and topography was used to locate the observation sites in each sample landscape area. Decision on the number of observation sites considered representative sample size, time and human resources availability. Data collection was done in the wet season (April-June 2012) and the dry season (August-October 2012). The study used a geospatial approach to examine the influence of land cover/use and terrain factors on the abundance and spatial distribution of plague hosts (small mammals) and plague vectors (fleas). The approach included use of remote sensing and Geographic Information System (GIS), field observational survey and household questionnaire survey for mapping land cover/use, human movements and activities pattern, and, trapping of small mammals. Isolation and counting of fleas was done from the trapped rodents. During field survey, various visible indicators of land use were mapped and quantified within the quadrats. Two major categories of land use were defined: (a). Land management practices e.g. terrace, (b). Crop types and their associated elements e.g. maize farming. These land uses are named as 'individual land use types' in the current study. Each quadrat was also classified based on its aggregated land uses. For example whenever the quadrat was dominated by both annual and perennial crops, the aggregated land use type for that particular quadrat was classified as 'Mixed annual perennial crops'.

Data analysis on land cover/use and terrain factors was done using remote sensing image processing tools and GIS. The approach used to determine the human activity spaces was kernel density estimation. Interpolation and zonal statistics GIS analyses were used to determine human-flea co-occurrence. Analysis of Variance (ANOVA) was used to evaluate differences in the data (Aggregated land use types, small mammal and flea abundance, human-flea co-occurrence) whenever the data passed normality and homogeneity tests and in case of non-success the non-parametric ANOVA on Medians (Mood's Median test) was used. The Boosted Regression Tree

(BRT) modeling technique was used to clarify the relationships between the individual land use types, land cover types, and terrain attributes, with small mammal and flea abundance.

Results indicate that elevation positively influenced the presence of small mammals (plague hosts). This could be attributed to the increased resource availability (water and food) as one moves from low to high altitude on the landscape. The presence of fleas (plague vectors) was clearly influenced by land management features such as *miraba* which tended to increase in intensity with increase in slope gradient. *Miraba* is an indigenous land management practice with grass strips surrounding crop fields in a rectangular shape in the Western Usambara Mountains, Tanzania (a unique indigenous soil erosion control practice in the Usambara Mountains). Medium to high resolution remotely sensed data and field collected data integrated in GIS have been found to be quite useful in studying plague infection risks. These findings contribute to efforts on plague surveillance and awareness creation among communities on the probable risks associated with various landscape factors during epidemics. The identified land cover/use and terrain characteristics integrated in the expert GIS engine provide future potential analysis and understanding of the association of plague risk indicators including human behaviour variables at farm scale. The results also show that there was a significant variation ($p \leq 0.05$) of small mammal abundance among land use types. Plantation forest with crop farming, natural forest and fallow had higher populations of small mammals than the other aggregated land use types. Plantation forest with crop farming, and fallow which is mainly surrounded by agricultural fields, offer conducive environment for small mammals in terms of

food and shelter. Natural forest also provides food, water and shelter for small mammals. Shelter and food are important factors in breeding, recruitment and survival of rodents. Both *miraba* and fallow tended to favour small mammals' habitation whereas land tillage practices had the opposite effect in dry season. Tillage of land could have resulted in the destruction of rodents burrows and mounds, destruction of nest sites, alteration of microclimate, and removal of vegetation some of which comprise food sources and shelter for the rodents. In addition, during the wet season crop types such as potato and maize appeared to positively influence the distribution and abundance of small mammals which was attributed to both shelter and food availability.

A significant variation ($p \leq 0.05$) of flea indices in different land use types was also identified. Fallow and natural forest had higher flea indices whereas plantation forest mono-crop and mixed annual crops had the lowest flea indices among the aggregated land use types. The observed variations of flea index among aggregated land use types could be attributed to the impact of land use practices on flea habitat structure. Fallow structure, which in most cases is also surrounded by agricultural fields, provides conducive microclimate for fleas on one hand and a supply of both food and shelter for rodents on the other. The influence of individual land use types on flea indices was variable with fallow having a positive effect and land tillage showing a negative effect. Fallow fields have also been associated with plague cases in many countries including Uganda and hence findings from this study further lend credence to the hypothesis that plague infection risk could be associated with fallow in the study area. This is because previous studies showed that flea index could be used as

an indicator of plague infection risk. Tillage of land which destroys surface and subsurface microclimate could be detrimental to flea survival. This observation is of practical significance with regard to the need of clearing surroundings of homesteads and avoiding long fallow cycles.

The results also demonstrated a seasonal effect, part of which could be attributed to different land use practices such as application of pesticides. These findings suggest that land use factors have a major influence on rodent flea abundance which could be taken as a proxy for plague infection risk. The results further point to the need for a comprehensive package that includes land tillage and crop type considerations on one hand and the associated human activities on the other, in planning and implementation of plague control interventions.

The results indicate further that, the degree of spatial co-occurrence of potential plague vectors (fleas) and humans in Lushoto focus differs significantly ($p \leq 0.05$) among the selected landscapes for both dry and wet seasons. For the dry season, the Mood's Median test indicated that Shume had the highest median average flea index (Median = 0.983) followed by Lukozi (Median = 0.575) and Mwangoi (Median = 0.380). For the wet season, the ANOVA means also followed the gradient of plague incidence rates i.e. 0.54 for Shume, 0.50 for Lukozi and 0.24 for Mwangoi. The study suggests that plague surveillance and control programmes at landscape scale should consider the existence of plague vector contagion risk gradient from high to low incidence landscapes due to human presence and intensity of activities. The current study has demonstrated the importance of land use/cover and human activity spaces

in the study of plague infection risks. Based on the findings from the current study the following conclusions can be drawn:

i. The relationship between land cover and terrain attributes on one hand and small mammals and fleas as potential hosts and vectors of plague, has been well elaborated by remote sensing and GIS integration of geodatabase at different spatial scales and resolutions. Hence a geomatic approach using remote sensing data and GIS technologies is valuable in studying plague infection risks.

ii. Small mammals and fleas abundance and distribution is influenced by the specific land use and land management types namely Fallow, *Miraba*, Tillage, Plantation forest with farming, Natural forest and Woodlot. Tillage has a negative influence whereas the other five land use and management types have positive influence.

iii. Small mammal presence in different land use types can influence abundance of fleas. These findings therefore, make a significant contribution towards efforts in the control of plague risk factors in space and time.

iv. Spatial co-occurrence of a potential disease vector and humans differs significantly among the plague incidence landscape areas and follows the established plague incidence gradient of high, medium and low for both dry and wet seasons. This trend gives a coarse indication of the possible association of the plague outbreaks and the human frequencies of contacting environments with fleas.

v. The findings from this study are of public health relevance because they may guide plague surveillance, prevention and control programmes at fine scales by providing information to health workers to focus control measures on land use/cover and landscape units with high concentration of rodent fleas, especially during epizootic periods.

vi. Systematic trapping of small mammals and collection of rodent fleas for surveillance should target *miraba*, fallow land, plantation forest with farming, natural forest and woodlot.

The following recommendations are made in the light of gaps revealed from the findings of this study so as to provide further insights into the plague disease.

i. Land management practices including tillage of land and crop types and the associated human activities should be included in the general scheme of plague control and management.

ii. Future efforts to predict and map spatial and temporal human plague infection risk at farm scale should consider the role played by land use on small mammals and rodent fleas abundance and distribution.

iii. The study suggests that plague surveillance and control programmes at landscape scale should consider the existence of plague vector contagion risk gradient from high to low incidence landscapes due to human presence and intensity of activities.

iv. Further studies should be conducted to investigate how land use practices influence surface and subsurface microclimate conditions of various small mammals and flea species

v. Outdoor application of insecticides to control flea abundance has been found to be an effective measure against plague. However, further studies on timing of applications during epizootics vis-à-vis crop type should be considered.

DECLARATION

I, PROCHES HIERONIMO, do hereby declare to the Senate of Sokoine University of Agriculture that this thesis is my own original work done within the period of registration and that it has neither been submitted nor concurrently being submitted in any other institution.

__________________________ ____________________

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The above declaration is confirmed by:

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Prof. L.S. Mulungu Date

(Co-Supervisor)

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DEDICATION

This work is dedicated to my father, Mr. Hieronimo Elemegio, who laid the foundation of my education.

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LIST OF ABBREVIATIONS AND SYMBOLS

ANOVA	Analysis of Variance
ASTER DEM	Advanced Spaceborne Thermal Emission and Reflection Radiometer Digital Elevation Model
a.s.l.	above sea level
BRT	Boosted Regression Trees
CDC	Centers for Disease Control and Prevention of the United States
CV	Cross Validation
ERDAS	Earth Resources Data Analysis System
ESRI	Environmental Systems Research Institute
ETM	Enhanced Thematic Mapper
FAO	Food and Agriculture Organisation of the United Nations
GIDEON	Global Infectious Disease Epidemiology Network
GIS	Geographic Information System
GPS	Global Positioning System
IDW	Inverse Distance Weighting interpolation technique
ISODATA	Iterative Self-Organizing Data Analysis Technique algorithm
ITCZ	Intertropical Convergence Zone
LEPUS	Landscape-Ecological Clarification of Bubonic Plague Distribution and Outbreaks in the Western Usambara Mountains, Tanzania
^{o}C	degree Celsius
MODIS	Moderate Resolution Spectroradiometer
NDVI	Normalized Difference Vegetation Index
RF	Random Forest algorithm

SAS	Statistical Analysis System
Sp.	Species
SPOT 5	Satellite Pour I’observation de la Terre 5 ; a high resolution satellite launched in 2002
SUA	Sokoine University of Agriculture
TRMM	Tropical Rainfall Measuring Mission
URT	United Republic of Tanzania
UTM	Universal Transverse Mercator
VIF	Variance Inflation Factor
VLIR-OUS	Flemish Inter-University Council-University Development Cooperation
WHO	World Health Organisation
WRF	Weather Research and Forecasting Model

CHAPTER ONE

1.0 GENERAL INTRODUCTION

1.1 Land use, land cover and disease transmission

Land use is defined as “the total arrangements, activities, and inputs that people undertake in a certain land cover type; the man’s activities on land which are directly related to the land” (Anderson *et al.*, 1976; FAO, 2006). Land use is also defined as the purpose for which humans exploit the land cover (Lambin *et al.,* 2003). On the other hand, land cover is the observed physical and biological cover of the earth’s surface such as vegetation or man made features (FAO, 1997). The increasing world population, the desire to achieve higher levels of food production and the changing nutritional patterns of growing urban populations, have led to an extensification and intensification of agricultural production in most developing countries (WHO, 1996).

Agricultural development policies usually aim to improve food security, socio-economic conditions and the quality of life. Unfortunately, agricultural development may also have adverse health effects, notably through the spread and intensification of vector-borne diseases which may invade new areas, increase transmission rate and/or season with resulting higher numbers of cases, or cause more severe disease symptoms (WHO, 1996). For example, many of the plague affected areas in African countries including Tanzania are potential agricultural areas and have high population densities (Laudisoit, 2009; Ndakidemi and Semoka, 2006). It has also been reported that humans get infected with the causative agent of diseases when they enter zones with infected wild animals through activities such as cultivation, hunting and recreational activities in forest (Lambin *et al*., 2010; Zimba *et al*., 2011). Movements into high-risk areas not only lead to individual infection, but can also contribute to local transmission when infected hosts return home and infect competent vectors (Stoddard *et al*., 2009).

Anthropogenic land use changes are the primary drivers of a range of infectious disease outbreaks and emergence events and also modifiers of the transmission of endemic infections (Patz *et al*., 2000). For example, expansion and changes in agricultural practices are intimately associated with the emergence of Nipab virus in Malaysia, cryptosporidiosis in Europe and North America and a range of food-borne illness globally (Chua *et al*., 1999; Rose *et al*., 2001; Lam and Chua, 2002). Deforestation is reported to increase interaction among pathogens, vectors, and hosts and humans due to decrease in the overall habitat available for wildlife species and modifiers of the environmental structure (Patz *et al*., 2004).

It is clear from the reported literature that detailed and clear studies on land cover and terrain characteristics would improve the understanding of the presence of vectors and hosts (Ostfeld *et al*., 2005; Lambin *et al*., 2010; Vanwambeke *et al*., 2011). On the other hand studies on land use would attempt to identify which places people visit for specific activities, at what time of the day and of the year, and at what frequency and the chances to interact with infection risks (Lambin *et al*., 2010).

Therefore, in order to attain insight into plague infection risks in the Western Usambara Mountains, Tanzania, the current study attempted to bring on board land cover and terrain attributes as well as land use and human activities pattern as landscape determinants of plague risks.

1.2 Human Plague

1.2.1 Global transmission and geographical distribution of plague

Plague is a severe, rodent associated, bacterial zoonosis caused by *Yersinia pestis* (Gage and Kosoy, 2005). According to notifications received by the World Health Organization (WHO), from 1989 through 2003, there have been 38 310 cases of plague with 2 845 deaths worldwide. The majority of plague cases have been clustered in 25 countries in Africa and Asia. Due to lack of systematic surveillance, poor diagnostic facility and reluctance to report outbreaks, these statistics are likely underestimates of the true magnitude of plague in the world (Pham *et al.,* 2009).

Yersinia pestis, the etiologic agent of bubonic and pneumonic plague, is a gram-negative bacterium with an extraordinary pathogenicity. Transmitted by infected fleas, the bacteria cause a hyperplasia of the draining lymph node (bubo), followed by septicemia and the patient's death within one week if an effective antibiotherapy is not administered on time. Furthermore no safe and efficient vaccine against plague is currently available (Blisnick *et al.*, 2008). Humans are extremely susceptible to *Y. pestis* infection, and the disease is generally fatal when not appropriately treated (WHO, 2008). A complete plague cycle as proposed by Stenseth *et al.* (2008) is shown in Figure 1.

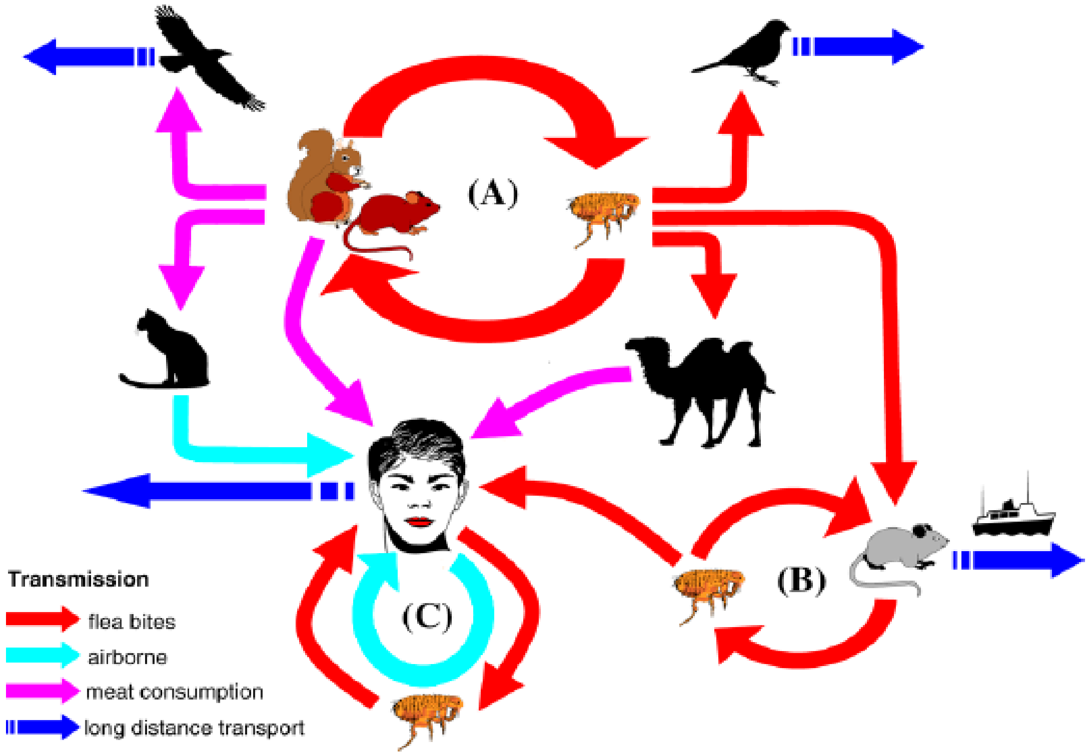

Figure 1: Possible transmission pathways for *Y. pestis*. These pathways include wildlife rodent-flea cycles (A), the commensal rodent-flea cycles (B), and the pneumonic transmission in humans (C). The colour of the arrows indicates the mechanism (flea bites, air particles, meat consumption) through which the bacteria are transferred from one host to another. Dark blue arrows indicate ways in which plague can move to other areas

Source: Stenseth *et al.* (2008)

The disease is endemic in natural foci on all continents except Australia, Antarctica and Europe (Neerinckx, 2010). It is widely distributed in the tropics, the subtropics and in warmer areas of temperate regions between the parallels 55°N and 40°S (Laudisoit, 2009). Plague foci can be found in a variety of habitats such as grasslands, native forests, altitude rainforests, and desert- and steppe-like areas (Dennis *et al*., 1999). Although several natural foci are known (Fig. 2), a recent World Health Organization report concluded that additional foci likely remain to be discovered, and hence it is unknown how many people live in plague-risk areas (WHO, 2008). Furthermore, plague foci are not fixed and their distribution can shift in response to changes in environmental conditions with respect to climate, land use, rodent and flea distributions, etc (Duplantier *et al*., 2005).

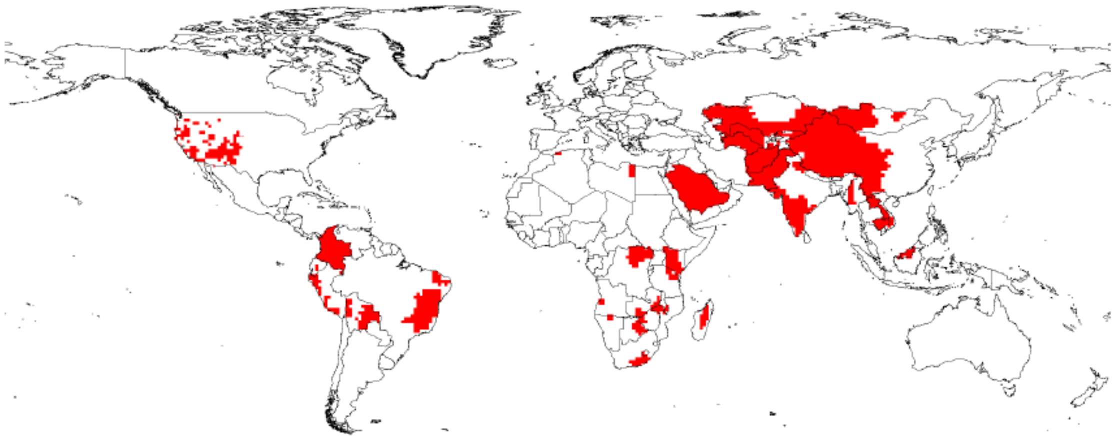

Figure 2: Distribution of plague regions in countries which reported human plague after 1970 (compiled from GIDEON, WHO, CDC, and country sources). The red areas are regions wherein plague areas exist; they are demarcated by the borders of the regions at administrative levels 1, 2, or 3, depending on the detail of spatial occurrence information available, and then converted to an overall resolution of 100 x 100 km in order to make all plague areas visible

Source: Neerinckx (2010)

1.2.2 Human plague distributions in Tanzania

Plague has been endemic in Tanzania for more than a century (Kilonzo *et al.*, 2005). The first recorded outbreak of human plague in the country occurred in Iringa in 1886 (Davis *et al.*, 1968). Between 1886 and 1969 many foci were established in the country. These include the Iringa, Lake Victoria, Singida/Kondoa, Mbulu, Meru, Kilimanjaro and Pare foci (Kilonzo *et al.*, 1992). Many outbreaks of human plague occurred in these foci during the period 1886 to 1979 and involved large numbers of human cases and deaths (Kilonzo, 1981). Between 1985 and 1999, Tanzania accounted for 25.4% of African plague cases, and 22.0% of African plague deaths (Laudsoit, 2009). According to Kilonzo *et al.* (2005), over the years, outbreaks of the disease have occurred in various parts of the country and involved large numbers of human cases and substantial case-fatality rates. Since 1980, however, only four districts (Lushoto, Singida, Karatu and Mbulu) have experienced outbreaks of the disease (Ziwa *et al.*, 2013). Of these districts, Lushoto District has the highest incidences of the disease (Table 1) (Kilonzo *et al.*, 1997; Ziwa *et al.*, 2013).

In Lushoto, plague outbreaks have occurred yearly from 1980 to 2003 and involved the largest number of recorded cases and deaths in the country (Ziwa *et al.*, 2013) (Table 1). According to Kamugisha *et al.* (2007), during the 17-year period (1986 to 2002), a total of 6 249 human plague cases were reported from all four affected divisions in Lushoto District. Bubonic plague was the most frequently diagnosed clinical form with a prevalence of 86.4% (Table 2).

Table 1: Plague cases and deaths in four foci in Tanzania for the period 1980-2011

District	Number of cases	Number of deaths	Percent of deaths
Lushoto	7 907	640	8.1
Karatu	197	14	7.1
Mbulu	190	19	10.1
Singida	196	2	1.0

Source: Ziwa *et al*. (2013)

Table 2: Distribution of plague cases (%) by clinical form in Lushoto focus for the period 1986-2002

Affected areas		Cases	Clinical form		
Division	**No. villages**	**No. of cases**	**Bubonic**	**Septicaemic**	**Pneumonic**
Lushoto	6	343	249(74.1%)	51(15.2%)	36(10.7%)
Mlalo	19	3 476	3 022(89.1%)	211(6.2%)	160(4.7%)
Mlola	14	1 135	906(88.6%)	59(5.8%)	57(5.6%)
Mtae	11	1 177	913(78.3%)	70(6.0%)	183(15.7%)
Mombo	1	212	212(99.1%)	0(0%)	2(0.9%)
Total	51	6 249	5 302(86.5%)	391(6.4%)	438(7.15)

Note: 118 cases were not categorized into plague forms
Source: Kamugisha *et al.* (2007)

1.3 Land use and human activities pattern as determinants of plague infection risks

Land use and human activities pattern have been reported to be important determinants of vector borne diseases transmission worldwide (WHO, 1996; Patz *et al*., 2004; Linard *et al*., 2007; Arinaminpathy *et al*., 2009). A study conducted by Perry and Fetherston (1997), showed that land use changes in many parts of the world increase the probability of interaction between sylvatic and peridomestic rodents, and between sylvatic rodents and humans. Sylvatic rodents are wild rodents and peridomestic rodents live in and around human settlements. It has to be noted that many outbreaks of plague in Tanzania have been associated with or preceded by large increases and/or mortalities of rodents in the infected area (Kilonzo *et al*., 2005).

Another study conducted in Madagascar (Duplantier *et al*., 2005) showed that the population of fleas on *Rattus rattus* was very different under different land use types, such as forest and agricultural land. Changes in land use induced by deforestation, urbanisation and associated factors, induce changes in flea and rodent populations, and thus, in the potential plague reservoirs. Furthermore, Land use and changes in landscape structure caused by human activities may affect plague dynamics by significantly altering the composition of ecological communities of both vector and potential *Y. pestis* hosts, thereby altering key ecological interactions involved in pathogen transmission pathways (Ziwa *et al*., 2013). Such phenomenon has been witnessed in the two plague active foci of Mbulu and Lushoto in Tanzania where there is greater encroachment into natural wild rodent habitats which leads to more frequent contacts between wild and domestic rodents, thus facilitating transfer of both fleas and the plague bacteria and hence human infection (Collinge *et al.,* 2005; Makundi *et al*., 2008; Ben Ari *et al*., 2011). According to Mbilinyi (2000), Tanzania is generally categorised by land use/cover types into small scale agriculture, large scale agriculture, grazing land, forest and woodland, and other land (Table 3). Other land includes settlements, road insftrasture, etc (Mbilinyi, 2000). The total area of Tanzania is 939 701 km^2 of which 58 100 km^2 is water and average cultivated land per year is about 51 000 km^2 (URT, 2011).

Table 3: Proportion of different land use/cover types in Tanzania

Land use	Area (thousands km^2)	% of the total Land
Small-Scale Agriculture	41	5
Large-Scale Agriculture	11	1
Grazing Land	350	39
Forest and Woodland	440	50
Other Land	44	5
TOTAL	**886**	**100**

Note:

Other land includes settlements, road infrastructure, etc.

Wildlife protected areas which cover about 25% of the total land are included in grazing land and woodland.

Source: Mbilinyi (2000) as modified from National environmental action plan of 1994.

In the plague endemic area of Western Usambara Mountains, Lushoto District; rainfed agriculture is the most important land use followed by irrigated agriculture, livestock keeping, natural forestry, plantation forestry and utility woodlots (Kaoneka and Solberg, 1994; Msita *et al*., 2010). The area is potential for production of vegetables mainly grown on valley bottoms under irrigation (Pfeiffer, 1990; Tenge *et al*., 2004). The land management in the study area includes some of the introduced technologies such as bench terraces, strips of Napier grass (*Pennisetum purpureum*) or Guatemala grass (*Tripsacum laxum*), *fanya juu* (which are hillside contour ditches made by throwing excavated soil on the upper part of the ditch), infiltration ditches and cut-off drains, and different forms of agroforestry (Kaoneka and Solberg, 1994; Tenge *et al*., 2004; Msita, 2013).

Miraba (Msita, 2013) is a prominent indigenous land management practice in the study area. It is a land management practice involving grass strips surrounding crop fields arranged in a rectangular shape and is unique to the West Usambara Mountains, Tanzania (Msita *et al*., 2010). Apart from filtering sediments from the runoff, the grasses grown in *miraba* construction may be used as animal fodder which is an added advantage. *Miraba* and associated Guetemala grass have been reported to provide good shelter, breeding site and source of food for rodent population (Kamugisha *et al*., 2007). Other indigenous technologies include use of *Vernonia myriantha* and other shrubs (*tughutu*) along the border of field partitions and trash line (Msita, 2013). In the valley bottoms where intensive vegetable and potato cultivation is carried out, the land management includes irrigation and addition of manure and forest soils (Kimaro *et al*., 2014). Land use and human activities in the valley bottoms have led to pronounced development of fertile anthropogenic soils which support land use patterns that are potential habitats for rodents and fleas (Kimaro *et al*., 2014). Anthropogenic soils are surface soil layers (horizons) found where people have practiced agriculture for a long period of time.

Plague epizootics, the periods when humans are at great risk of being exposed to infected fleas, are dependent on critical thresholds of rodent hosts and vector fleas (MacMillan *et al*., 2011). That is, as host abundance and flea infestation rates increase, so does the probability of epizootic activity (Gage and Kosoy, 2005; Kilonzo *et al*., 2005; Laudisoit, 2009; MacMillan *et al*., 2011). According to Randolph *et al*. (2010), the risk of human infection of vector borne zoonosis varies not only with the abundance of infected vectors, but also with the amount of human exposure to that hazard, either one of which may change independently. Human risk for exposure to plague has been associated with behaviours that increase the probability of contact with infectious fleas or practices that increase the availability of food or harbourage for rodents for example agricultural crops and fallows (MacMillan *et al*., 2011).

Human movement is critical in exposure risks but understudied behavioral component underlying the transmission dynamics of many vector-borne pathogens (Stoddard *et al.*, 2009). For example, according to Eidson *et al.* (1988), specific (seasonal) outdoor human activities like hunting, farming and mining can increase the risk of the plague infection. According to Zimba *et al.* (2011), humans get infected with the causative agent of plague when they enter zones with infected wild rodents through activities such as cultivation and hunting. Also, socio-cultural and economic factors have been reported to influence the incidence of plague in families and within the community in the study area (Ziwa *et al*., 2013). Females and children (reported to have high prevalence than adult men) are actively involved in production activities such as collecting firewood from the nearby forests, forest soils, farming and grazing livestock (Davis *et al*., 2006; Kamugisha *et al*., 2007; Kimaro *et al.,* 2014).

1.4 Use of remote sensing and Geographic Information System technologies in health studies (geoepidemiology)

Remote sensing and GIS techniques have been widely applied in various health studies in order to understand landscape system complexities in relation to vector borne diseases including malaria (Ceccato *et al*., 2005), dengue (Palaniyandi, 2012) and plague (Eisen *et al*., 2010; McMillan *et al*., 2011; Eisen *et al.,* 2012). There are numerous satellite-based remote-sensing systems that have been used to monitor environmental conditions with respect to health and these systems vary in spatial resolution (Ratmanov *et al*., 2013). The spatial resolution is commonly measured by the picture element (pixel) resolution which provides information about the level of spatial detail that can be interpreted.

Presently, high-resolution systems are of increasing interest in disease studies (Ostfeld *et al*., 2005). However, satellite images with high spatial resolutions are very expensive hence slowing progress in advancing the technology in unravelling geographic health related problems to humans. This has prohibited their wide usage (Zhang *et al*., 2013) particularly in Africa (Tanser and Sueur, 2002). Consequently, despite their importance, there are very few research undertakings involving remote sensing and GIS, which have studied plague in East Africa, the disease that has affected many lives in the region. For example, in Tanzania, only few studies have applied remote sensing and GIS techniques to explain the recurrence of plague disease in Western Usambara Mountains (Debien *et al.,* 2010; Neerinckx *et al.,* 2010). Even these few reported studies used coarse resolution remotely sensed data and were exploratory in nature (Debien *et al.,* 2010; Neerinckx *et al.,* 2010; Eisen *et al.,* 2010; MacMillan *et al*., 2011). The current study has contributed towards elucidation of plague infection risk using remote sensing and GIS coupled with field survey techniques. The study intended to demonstrate the use of geospatial approach in the integrated analysis of landscape factors to explain plague risks in Western Usambara Mountains, Tanzania.

1.5 Justification of the study

Plague, still occurring in different parts of the world, has been a threat in Western Usambara Mountains, Tanzania since 1980. Although a number of studies conducted to explain the presence and the recurrence of plague in the Western Usambara Mountains, Tanzania have generated some useful information on plague risk related to natural and land use factors (Kilonzo *et al*., 1997; Kamugisha *et al*., 2007;

Makundi *et al*., 2005; Laudisoit *et al*., 2007, 2009a, b; Laudisoit, 2009; Debien *et al*., 2010; Neerinckx *et al*., 2010), they fall short of elucidating the spatial variability of plague incidence with respect to land cover/use in the landscape and at farm scale. The reported studies did not document the specific land use types and land management practices associated with small mammal and flea distribution and abundance at a fine scale and within a wider geographic coverage which is important for delineation of potential risk areas (Eisen *et al*., 2012).

Small mammals and fleas abundances as well as a number of small mammal and flea species have been reported to play a dynamic role in the plague transmission cycle in Western Usambara Mountains and elsewhere (Kilonzo *et al*., 2005; Makundi *et al*., 2008; Laudisoit, 2009; Hubbart *et al*., 2011; Eisen *et al*., 2012). For example, according to Kilonzo *et al*. (1992), in Lushoto plague focus, Flea indices < 1.0 were reported during non-outbreak periods whereas indices > 1.0 were observed during plague outbreaks. Despite that, knowledge on the link between land use, land cover and terrain attributes with the distribution and abundance of small mammals and fleas and the human risks of exposure to plague is still lacking. Hence plague research to investigate how land use, land cover and terrain attributes influence presence and pattern of small mammals (host) and fleas (vectors) in Western Usambara Mountains is of paramount importance given the role of small mammals and fleas in the dynamics of plague as reported in many studies in East Africa and elsewhere (Kilonzo *et al*., 1997; Kamugisha *et al*., 2007; Laudisoit *et al*., 2007, 2009a, b; Hubbart *et al*., 2011; Eisen *et al*., 2012). It should be noted that the abundance and spatial distribution of small mammals and fleas vary along the different land use and land cover types and landscape units (Vanwambeke *et al.*, 2011). According to Arinaminpathy *et al.* (2009), the risk of exposure to vector-borne diseases including plague is influenced by the numbers and distribution of the animal species that make up the environmental reservoir of the disease; the numbers and distribution of the vectors and the behaviour and activities of humans that influence the probability of being bitten by the vector. Available literature suggest that factors influencing the critical contact between rodent hosts, flea vectors, and humans as well as human behaviours that may enhance or diminish this contact with infectious vectors or hosts are not well understood (Kilonzo *et al.*, 1997; Kamugisha *et al.*, 2007; MacMillan *et al.*, 2011; Neerinckx *et al.*, 2010).

Hence, a study in a geographic perspective that includes land use and human activity pattern dimensions is vital in understanding the human exposure risk, the phenomenon which is still not well understood (Kilonzo *et al.*, 1997; Kamugisha *et al.*, 2007; Stoddard *et al.*, 2009; Neerinckx *et al.*, 2010). Such kinds of studies are important in formulating surveillance, and control mechanisms during epizootic periods (Ostfeld *et al.*, 2005; Kamugisha *et al.*, 2007; Makundi *et al.*, 2008). Despite the relevance of human activity space for assessing environmental exposure, this technique is barely employed in geoepidemiologic studies including plague research (Laudisoit, 2009; Neerinckx *et al.*, 2010; Perchoux *et al.*, 2013). Since mobility is seen as a key determinant of environmental exposure, incorporation of human activity space in the current study allowed taking into account the full range of environments people get exposed to during their daily activities (Perchoux *et al.*, 2013). The study tried to link human life resources (water, firewood, farming, etc.) to people's movement in different land cover and landscape settings with the abundance of plague hosts and vectors. The human movements leading to the physical contacts with landscape factors at farm scale is a likely condition for contagion with the plague vectors. Also, the social contacts between villages, sometimes over considerable distances and across different landscape units engender other possible pathways of contagion. Thus, this study attempted to demonstrate the importance of land use/cover and human activity spaces on the plague infection risks. The knowledge and information generated from this study is of immediate use by the Ministry of Health and Social Welfare, District council, and institutions and agencies responsible for disease surveillance, control and rural land management. The results obtained from the study could contribute significantly to the Tanzania Health Sector Reform Strategy (URT, 2000) which calls for provision of equal access and cost-effective quality healthcare close to the family. The study is also in line with the National Health Policy (URT, 2003) and Tanzania Health Sector Strategic Plan III 2009-2015 (URT, 2009).

1.6 Objectives

1.6.1 Overall objective

The overall objective of this study was to establish a relationship between land use/cover and human activity spaces on one hand and plague infection risk on the other so as to provide guidance for plague surveillance, prevention and control programmes at fine scale during epizootic periods.

1.6.2 Specific objectives

1. To map land cover and terrain attributes and determine their association with plague hosts and vectors abundance and distribution at landscape level
2. To identify land use and land management practices associated with abundance and distribution of plague hosts and vectors at farm level
3. To model people's movements and activities pattern in order to determine chances of their exposure to plague in space and time

It was hypothesized that:

- Land use, land cover and topographic factors impact the distribution and abundance of potential hosts (rodents) and vectors (fleas) of plague and explain plague infection risks at landscape and farm scales.
- Different plague incidence levels in Western Usambara Mountains correspond to differences in spatial co-occurrence of the potential plague vectors on one hand, and people on the other hand.

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CHAPTER TWO

2.0 PAPER I: Integrating Land Cover and Terrain Characteristics to Explain Plague Risks in Western Usambara Mountains, Tanzania: a Geospatial Approach

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Integrating land cover and terrain characteristics to explain plague risks in Western Usambara Mountains, Tanzania: a geospatial approach

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Abstract: Literature suggests that higher resolution remote sensing data integrated in Geographic Information System (GIS) can provide greater possibility to refine the analysis of land cover and terrain characteristics for explanation of abundance and distribution of plague hosts and vectors and hence of health risk hazards to humans. These technologies are not widely used in East Africa for studies on diseases including plague. The objective of this study was to refine the analysis of single and combined land cover and terrain characteristics in order to gain an insight into localized plague infection risks in the West Usambara Mountains in north-eastern Tanzania. The study used a geospatial approach to assess the influence of land cover and terrain factors on the abundance and spatial distribution of plague hosts (small mammals) and plague vectors (fleas). It considered different levels of scale and resolution. Boosted Regression Tree (BRT) statistical method was used to clarify the relationships between land cover and terrain variables with small mammals and fleas. Results indicate that elevation positively influenced the presence of small mammals. The presence of fleas was clearly influenced by land management features such as *miraba*. Medium to high resolution remotely sensed data integrated in a GIS have been found to be quite useful in this type of analysis. These findings contribute to efforts on plague surveillance and awareness creation among communities on the probable risks associated with various landscape factors during epidemics.

Keywords: land cover, remote sensing, GIS, small mammals, fleas, plague, Tanzania

Introduction

Transmission of zoonotic vector-borne diseases forms complex systems in the landscape (Vanwambeke et *al.*, 2011). These systems are influenced by a broad spectrum of environmental factors operating at diverse scales, including climate (Debien *et al.*, 2009; Ben Ari *et al.*, 2011), land cover (Lambin et *al.*, 2010), soil, landscape and land use (Patz *et al.*, 2004; Neerinckx et *al.*, 2010; Vanwambeke *et al.*, 2011; Ben Ari *et al.*, 2011; Baumgardner *et al.*, 2012; Chammartin *et al.*, 2013). In Tanzania, plague (caused by *Yersinia pestis*) has occurred in West Usambara Mountains and in the Mbulu district since 1980 (Kilonzo & Mhina, 1982; Kilonzo *et al.*, 1997, 2005; Makundi *et al.*, 2003, 2007, 2008; Laudisoit *et al.*, 2009a,b; Neerinckx *et al.*, 2010). Most of the data and analytical techniques in these studies concentrated on biological and microbiological factors for which, unlike in the current study, little or no appeal was made to detailed terrain and land cover data involving remote sensing and geographical information systems (GIS).

Coarse resolution remote sensing and GIS techniques have been widely applied to understand the relation of regionally distributed environmental factors in relation to vector borne diseases including malaria (Ceccato *et al.*, 2005), dengue (Palaniyandi, 2012) and plague (Eisen *et al.*, 2011, 2012; MacMillan *et al.*, 2011). Debien *et al.* (2009) used Tropical Rainfall Measuring Mission (TRMM) at 0.25x0.25km resolution and MODIS monthly NDVI (1x1km) data to reconstruct rainfall patterns at 1x1km resolution for predicting occurrence of plague in north-eastern Tanzania. Neerinckx *et al.* (2010) used environmental dataset assembled from MODIS

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data at 250m resolution to predict potential risk areas of human plague in the Lushoto area of Tanzania and in larger parts of East and Southern Africa. Eisen *et al.* (2010) and MacMillan *et al.* (2011), attempted to identify elevated risk of human exposure to plague bacteria at sub-village level, using SRTM DEM (90m), and Landsat ETM^+ (30x30m). Eisen *et al.* (2012) used 2-km resolution climate dataset derived from a suite of atmospheric simulations with the Weather Research and Forecasting Model (WRF) (Monoghan *et al.*, 2012) to compare host and flea abundance and diversity along an elevation gradient performed specifically for the West Nile region plague focus in Uganda.

Land cover is an important determinant of habitat suitability for disease vectors and hosts (Linard *et al.*, 2007) and hence of health risk hazards to humans. The abundance and spatial distribution of small mammals and fleas vary along the different land cover types and between landscape units (Vanwambeke *et al.*, 2011). Higher resolution remote sensing data are of increasing interest in disease studies (Ostfeld *et al.*, 2005); especially when land cover and landscape factors enter the picture. These factors also ask for spatial analytical tools and GIS. However, some factors including cost, access to equipment or insufficient skills in remote sensing and GIS have prohibited such approach (Le Sueur & Martin, 1996; Tanser & le Sueur, 2002; Ostfeld *et al.*, 2005; Zhang *et al.*, 2013). The objective of this study was therefore to refine the analysis of single and combined land cover and terrain characteristics in order to gain a better understanding of localised plague infection risks in the West Usambara Mountains in north-east Tanzania. It is expected to provide useful information for plague and other rodent borne disease control programmes as well as information for further in-depth research on the complex ecology of the plague system.

Materials and Methods

Study area

This study was carried out in the Western Usambara Mountains in Lushoto district of north-eastern Tanzania. The study area is located between Universal Transverse Mercator (UTM) coordinates 4000000 m E and 430000 m E and between 9480000 m N and 9500000 m N, Zone 37M, covering an area of about 34,000ha (Figure 1). The altitude ranges from 480 to 2,271m. In the Western Usambara Mountains, two rainy seasons exist: short rains *(vuli)* from October to December and long rains *(masika)* from March to May (Debien *et al.*, 2009). The rainy seasons are associated with the seasonal movement of the Intertropical Convergence Zone (ITCZ). Rainfall in the study area is influenced by topography (Debien *et al.*, 2009). The rainy seasons are associated with the seasonal movement of the Intertropical Convergence Zone (ITCZ). Rainfall in the study area is influenced by topography (Debien *et al.*, 2009). The area has mean annual precipitation ranging from 600 to 1200 mm. The study area shows large differences in relief dissection and intensity, vegetation and land use patterns, and human activities. Land use is dominated by mixed rainfed farming, followed by irrigated agriculture, livestock keeping and off farm activities including petty cash and carpentry (Msita *et al.*, 2010). These land uses are bordered or surrounded by natural forests, and plantation forest and utility woodlots.

Previous research on rodents, fleas and plague (Njunwa *et al.*, 1989; Kilonzo *et al.*, 1997; Davis *et al.*, 2006; Kamugisha *et al.*, 2007; Laudisoit *et al.*, 2007, 2009a, b; Neerinckx *et al.*, 2010) allowed defining the study area in such a way that it reflects a geographical gradient in the frequency of plague incidence. These authors concur in distinguishing high, medium, and low incidence zones. Within this gradient three representative landscapes were selected differing in terms of (i) the incidence of plague, (ii) diversity in land use and associated human activities, (iii) landform characteristics (relief intensity and level of dissection), and (iv) climatic conditions. The selected landscapes are named Shume (high plague incidence), Lukozi (medium plague incidence) and Mwangoi (low plague incidence) landscapes, after the name of their most important settlement.

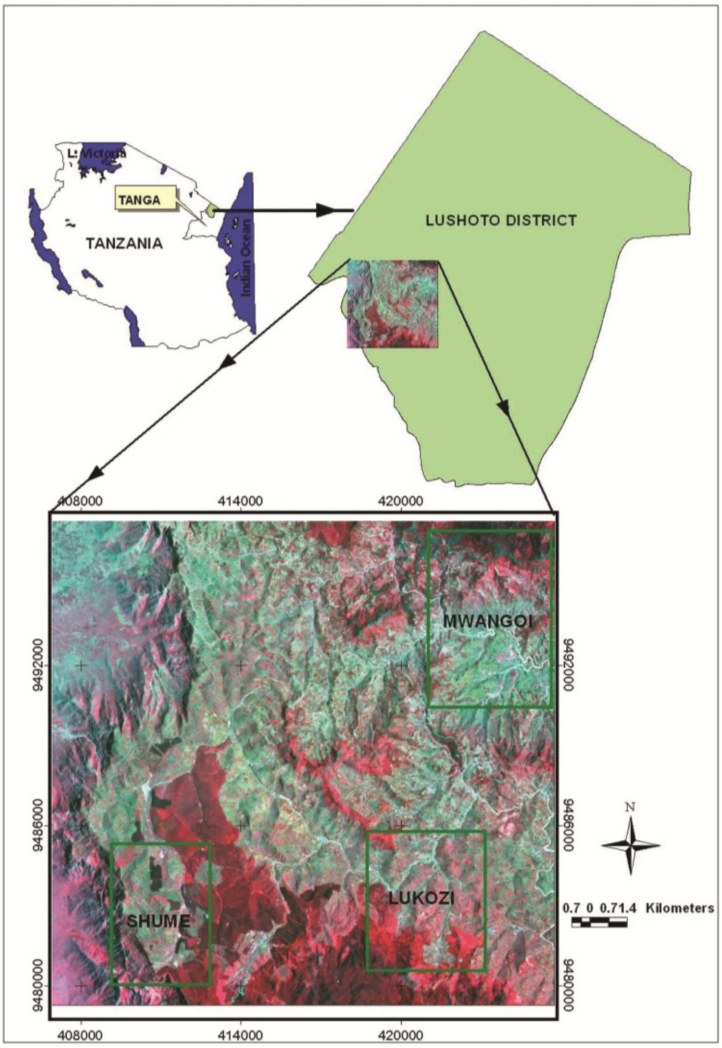

Figure 1: Selected study landscapes in West Usambara Mountains, Tanzania

Data collection and analysis

This study included the generation of terrain attributes from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Digital Elevation Model (DEM) with 30m resolution, a land cover map from three-band SPOT 5 image (nominal spatial resolution 2.5m) and the collection of small mammals and fleas. Boosted Regression Trees (BRT) was used to identify terrain and land cover predictors of abundance of small mammals and fleas. Both categories of organisms are seen as indicators of potential plague occurrence at landscape scale. The final layers were saved in raster (geotiff) format. Land cover was also defined in vector (shapefile) format. Data extraction and zonal statistics were carried out in ARCGIS 9.3 and QGIS respectively to generate spatial and attribute data for each 100x100m quadrat in which small mammals and fleas were collected. The developed spatial geodatabase associated with their attributes were used as independent variables in BRT analysis. Small mammal and flea data were used as dependent variables.

The developed geospatial database can be used in desktop GIS with ARCGIS, ARCVIEW, QGIS and other related GIS software. The methodological flow chart (Figure 2) summarises the steps followed in spatial geodata capturing, processing, integration, storage, and BRT modelling.

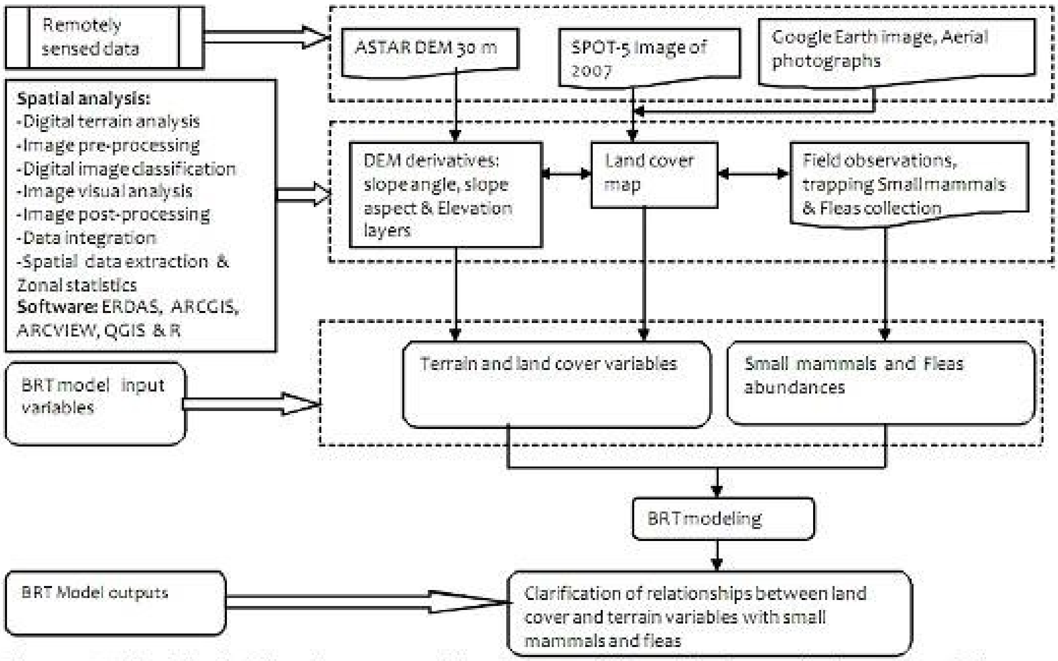

Figure 2: Methodological flow chart summarising the steps followed for data collection and analysis

Mapping of terrain variables

Three topographical variables (elevation, slope gradient and slope aspect) were derived from the ASTER DEM (30m) using ARCGIS 9.3 software. Elevation strongly determines climate in this area. Slope gradient strongly influences the choice of land management types, and is correlated with soil characteristics (Msita *et al.*, 2010). Slope aspect, measured clockwise in degrees from 0 (north) to 360, has been reported to influence rainfall in the West Usambara Mountains (Kajembe, 1994). Flat areas are given a slope aspect value of -1.

Generation of a land cover map

A cloud free three-band SPOT 5 image captured on 27 February 2007, nominal spatial resolution 2.5m, was used in this study. The image was orthorectified in ERDAS 2011 software. The initial classification of land cover was based on 20 spectral classes generated using the unsupervised ISODATA clustering technique in ERDAS2011. GPS supported field observation was conducted in August to September 2011, April to June 2012 and in August to October 2012, and allowed to define characteristic tone, texture and pattern of the land cover classes on the display of the SPOT 5 colour composite image. Also aerial photographs and Google Earth provided essential independent reference data to help in identifying land cover types within the SPOT 5 image.

The description of the different land cover categories was in the first instance based on Anderson *et al.* (1976) and then refined to match the terminology of the FAO Guidelines for Soil Description (FAO, 2006). Because of the occurrence of mixed pixels, similarity in spectral signatures of some land cover types, and heterogeneous illumination conditions in this undulating area, a hybrid image classification method was used (Wang *et al.*, 2005; Horning, 2010a). This approach combines the advantages of the automated and manual methods to produce land cover maps (Horning, 2010a). Expert information and visual interpretation allowed refining and correcting the automated classification (Horning, 2010a). Also existing information, for example on the location and extent of plantation forest, was directly inserted in the land cover map, to avoid confusing recently harvested patches with bare land.

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Supervised classification was done using Random Forest (RF) algorithm (Breiman, 2001) in R software (R Development Core Team, 2006). Random Forest is known to be one of the most efficient classification methods (Akar & Gungor, 2012). A script written by Horning (2010b) was used. The script requires that training areas are digitized as polygons and saved as an ESRI shapefile. The training dataset is defined as multiple polygons for each class.

Post-processing of classified image included majority neighbourhood filter, clump and eliminate. The classified map was later compared with the original image and reference data used in this study. Classes which were not labelled correctly were spotted and edited. Five classes out of twelve were successfully generated: Cropland (Rainfed maize and beans), Agroforestry, Settlement, Woodlot and Shrub. Seven out of twelve classes were not sufficiently well classified by this algorithm due to similarity in spectral signatures: Cropland (perennials and furrow irrigated vegetables), Cropland (supplemental irrigated vegetables and potatoes), plantation forest, natural forest, grassland with emergent trees, bushland and woodland. Their initial classification was corrected through onscreen digitisation after visual interpretation of the SPOT 5 image. Software used during pre and post processing of the classified SPOT 5 image includes Arc View 3.3, ARCGIS 9.3 and ERDAS 2011.

Collection of data on small mammals and fleas

Based on the land cover and terrain attributes generated above, a total of 72 quadrats of 100x100 m were established. Twenty four quadrats were established at random for each landscape. At each observation site (quadrat) data on land cover, rodents and fleas from rodents were collected. Data collection was conducted in the dry season (August to October) of 2012.

Small mammals were trapped using Sherman LFA live traps (7.5x9.0x23 cm; HB Sherman Traps, Tallahassee, USA) baited with peanut butter and maize flour. A total of 49 Sherman live traps spaced 10 m apart were set in a grid per observation site (quadrat) and per trapping session. For the sites in natural forests, additionally two wire cages were used to capture somewhat larger mammals like squirrels. Each trapping session lasted 3 nights. Each trap was inspected every morning and traps with captured animals were replaced by empty traps (Zimba *et al.*, 2011). The captured animals were identified to genus level or species level where possible (Eisen *et al.*, 2012) and carefully combed for fleas. Trap success (in percent) was calculated as the number of small mammals captured multiplied by 100 divided by the trap nights (i.e. number of traps x number of days) per quadrat (Mulungu *et al.*, 2008; Laudisoit *et al.*, 2009a). Fleas collected from each small mammal were counted. The flea index was calculated as the total number of fleas per total number of captured mammals in each quadrat (Laudisoit *et al.*, 2009a). Trap success and flea index were used as dependent variables in the Boosted Regression Tree (BRT) modelling (to be explained later).

Boosted Regression Tree modelling

Exploring plague disease infection risk patterns requires a statistical technique that effectively addresses the complexity of the landscape systems and the disease ecology (Skolow *et al.*, 2009; Williams *et al.*, 2010; Aertsen *et al.*, 2012). The Boosted Regression Tree (BRT) model in R software (R Development Core Team, 2006) was used in this case. Models were fitted using the gbm.step function and a Gaussian response type, with most effective settings for learning rate (0.01–0.00001) and bag fraction (0.5–0.75) as found by repeated trial-and-error (Elith *et al.*, 2008). Tree complexity was set to 3, according to recommendations by Elith *et al.* (2008) for small datasets. The 10-fold cross-validation (CV) was used for model development and validation, with the benefit of still using the full data set to fit the final model (Elith et al., 2008). The measure of model performance was cv deviance and standard error (Elith *et al.*, 2008; Williams *et al.*, 2010). The combination of learning rate and bag fraction settings with the lowest cv deviance and standard error was the one selected to produce the final BRT model (Williams *et al.*, 2010). Also during data exploration all predictor variables were tested for ecologically acceptable level of

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collinearity (i.e. individual variance inflation factor (VIF) of <5) between predictor variables (Zuur *et al.*, 2010; Artsen *et al.*, 2012).

Ethical considerations

This study received approval from Directorate of Research and Post-Graduate Studies of Sokoine University of Agriculture, Tanzania and Flemish Inter-University Council (VLIR-UOS) of Belgium.

Results

Land cover, terrain variables and small mammals

Figure 3A presents the land cover types of 2012 while in Table 1 their respective dominant coverage for the three studied landscapes are given. Figures 3B, 4A and 4B present elevation ranges, slope aspect and slope angle respectively, which are terrain attributes used as predictor variables along with land cover types for prediction of small mammal and flea abundance and spatial distribution. Table 2 provides the summary of the values for the terrain attributes extracted from the ASTER DEM and small mammal and flea abundances.

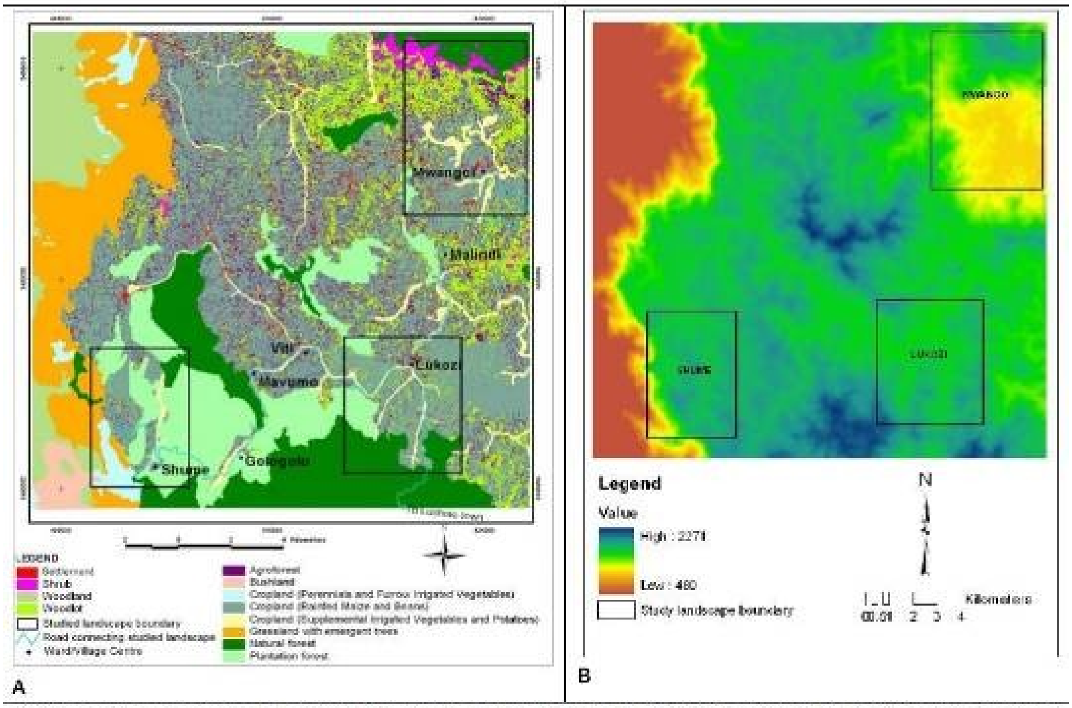

Figure 3 A: Land cover map covering the three studied landscapes (inside boxes); B: Elevation ranges used as terrain predictor variable for small mammal and flea abundance

Table 1: Land cover categories of the studied landscapes

Land cover (ha)	Landscape		
	Mwangoi	Lukozi	Shume
Agroforest	277.1 (9.1%)	83.6 (3.6%)	35.9 (1.8%)
Cropland (Rainfed Maize and Beans)	1229.5 (40.3%)	1169.8 (50.9%)	445.5 (22.9%)
Cropland (Irrigated Vegetables and Potatoes)	207.9(6.8%)	122.6(5.3%)	59.9 (3.1%)
Natural forest	330.3 (10.8%)	509.4 (22.1%)	107.9 (5.6%)
Plantation forest	48.3 (1.6%)	233.3 (10.1%)	857.4 (44.2%)
Shrub	194.9 (6.4%)	3.2 (0.1%)	2.1 (0.1%)
Woodlot	684.2 (22.5%)	161.9 (7.0%)	32.7 (1.7%)
Settlement	74.8 (2.5%)	16.1 (0.7%)	4.4 (0.2%)
Woodland			30.6 (1.6%)
Cropland (Perennials and Furrow Irrigated Vegetables)			185.8 (9.6%)
Grassland with emergent trees			171.5 (8.8%)
Bushland			7.4 (0.4%)
Total	3,047.1	2,300.0	1,941.1

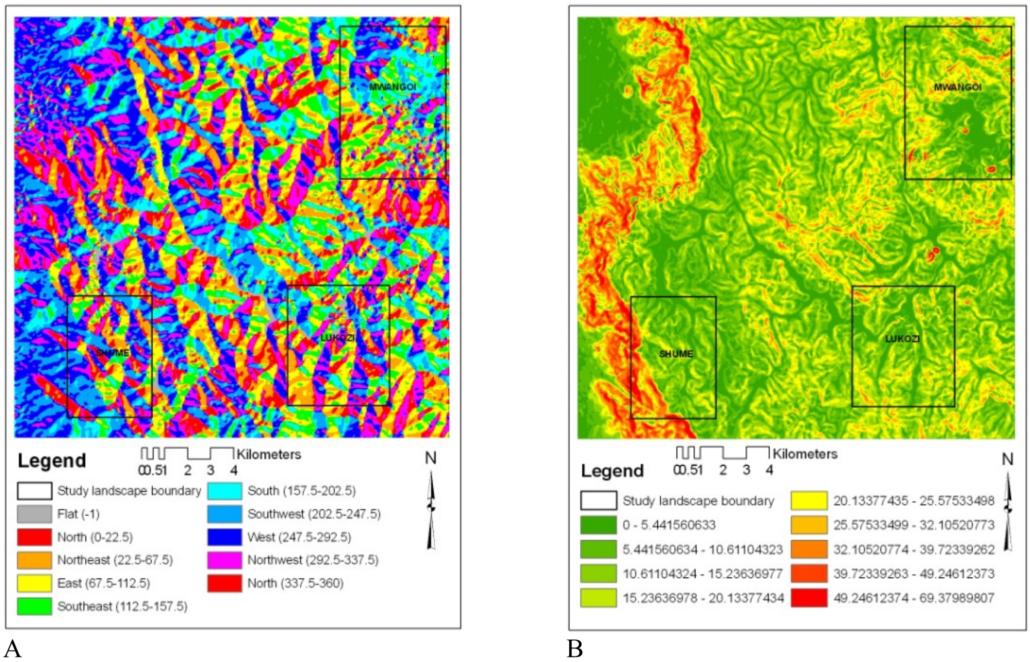

Figure 4 A: Slope aspects used as terrain predictor variable; and B: Slope angle in degrees used as predictor variable for small mammals and fleas abundance

Table 2: Summary of the terrain attributes values and small mammals and fleas

Landscape	Attribute	Attribute Mean	Small mammals	Fleas
Mwangoi	Elevation (m)	1589	79 (14%)	137 (20%)
	Slope angle (deg)	13.8		
	Slope aspect (deg)	163.3		
Lukozi	Elevation (m)	1855	232 (40%)	180 (27%)
	Slope angle (deg)	12.7		
	Slope aspect (deg)	169		
Shume	Elevation (m)	1819	265 (46%)	358 (53%)
	Slope angle (deg)	16.2		
	Slope aspect (deg)	192		

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Boosted Regression Trees (BRT) model for explaining the relationship between land cover, terrain attributes and small mammals

Four predictor variables were retained by the BRT model as being influential on the observed spatial pattern of trap success (Figure 5). All four predictor variables had the ecologically acceptable level of individual variance inflation factor i.e. VIF<5. Elevation was the most important predictor with contribution of more than two thirds of the total (80.1%) and a strong positive effect. The elevation of 1,700 m appeared to be the threshold for a sharp increase in trap success. The second important predictor was slope aspect with contribution of 11.4% and a moderate positive effect. The location on 150 degree aspect (south east facing slope) appeared to be an important condition for increased trap success. The slope angle and land cover had weak positive effect although with small contributions. The abundance of small mammals (trap success) seemed to increase slightly on slopes of 10 degrees and above. The abundance also gradually increased as the land cover types varied from natural forest (coded 1) to other land cover types (coded from 2 to 7).

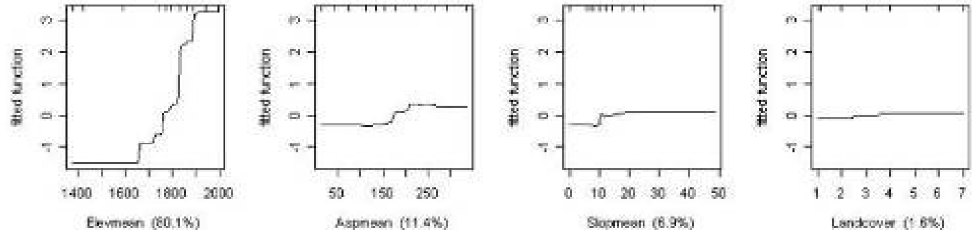

Figure 5: Partial dependence plots showing the effect of land cover & terrain variables on spatial pattern of small mammals. The relative contribution of each predictor is given in brackets. CV deviance=22.343, standard error=3.612, number of trees=1250. **Key:** Elevmean = Elevation, aspmean = Slope aspect, slopmean = Slope angle, Landcover = Land cover)

BRT model for explaining the relationship between land cover, terrain attributes and fleas

Four predictor variables were identified by the BRT model as having influence on the observed spatial pattern of flea index (Figure 6). All four predictor variables had the ecologically acceptable level of individual variance inflation factor i.e. VIF<5. Slope angle was the most important predictor with contribution of more than two thirds of the total (75.3%) and a strong positive effect. The presence of a slope angle of at least 10 degrees appeared to be an important condition for increased rodent flea abundance (flea index). The second important predictor was elevation with contribution of 17.3% and a moderate positive effect. The elevation of 1800 m appeared to be an important condition for increased flea index. Land cover and slope aspect had smaller contributions and showed weak effect. Land cover showed a slight negative effect as land cover types varied from that dominated by natural forest (coded 1) and plantation forest (coded 2) to the rest of the land cover types (coded from 3 to 7) (Figure 6).

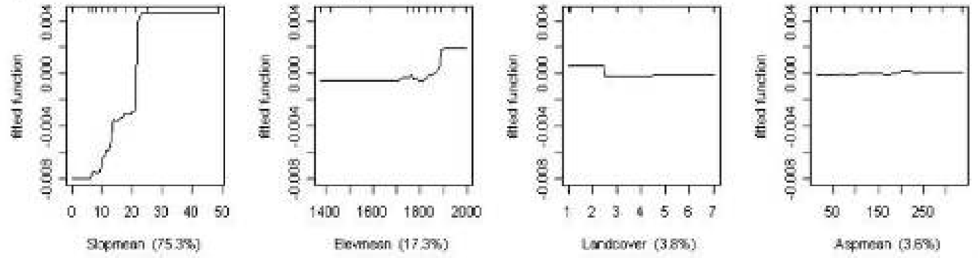

Figure 6: Partial dependence plots showing the effect of land cover and terrain variables on spatial pattern of flea index. The relative contribution of each predictor is given in brackets. **Key=**CV deviance=1.764, standard error=0.561, number of trees=1000. **Key:** Elevmean = Elevation, aspmean = Slope aspect, slopmean = Slope angle, Landcover = Land cover)

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Discussion

Small mammals trap success seems to be greatly influenced by altitude. This finding is contrary to the observations by Mulungu *et al.* (2008) who found a decrease in small mammals trap success with altitude along Mount Kilimanjaro in Tanzania. This could be attributed to the increased resource availability (water and food) as one moves from low to high altitude in the studied landscapes compared to Mount Kilimanjaro, where resources availability decreases with increase in altitude. Furthermore, the results of our study clearly demonstrate that there is a positive influence of slope aspect on the small mammals trap success in the range 112-157 degrees i.e. south east facing slopes. This could be due to availability of water for small mammals as a result of orographic effect. High rainfall in West Usambara Mountains occurs in areas located to the east and south east which are the first to receive moisture-laden south-easterly trade winds from the Indian Ocean (Kajembe, 1994). The findings of this study are consistent with earlier studies which reported that food, water, rainfall and shelter are important factors for small mammals' abundance (Mwanjabe, 1993; Makundi *et al.*, 2007; Mulungu *et al.*, 2011).

The current study shows that slope gradient has strong positive influence on flea index. This relationship could be attributed to the different land management types and crops found on different geographic locations across the studied landscapes. The valley bottom areas and foot slopes characterized by flat or gentle slopes are mostly under irrigated vegetables. The application of insecticides and pesticides may explain the very low flea indices. As slope increases from lower parts to middle and upper slopes rainfed agriculture (i.e. the land cover type described in the current study as cropland (rainfed maize and beans) becomes the dominant land use. Also intensive land management practices including contour farming and indigenous land management system with grassy hedges called *miraba* increase. According to another study in the same area (Msita *et al.*, 2011), the density of *miraba* (total length of *miraba* segments per unit area) increases with slope gradient. Therefore, this strong positive influence of slope angle on flea index could be attributed to land management practices and mainly *miraba* cultivation which are associated with many rodent burrows (Kamugisha *et al.*, 2007; Brabers, 2012).

It should be noted that rodent burrows are also likely to harbour adult 'free flea population' which sometimes stay off host in the burrows (Eisen *et al.*, 2012). According to Eisen *et al.* (2012), it is possible that off host adult flea populations of some infected species are able to survive for relatively long periods in burrows or nests, thus contributing to chances of plague persistence. Since the *miraba* in the study area provide suitable habitats for rodents, the possibility of rodents contacting high numbers of fleas inside burrows is most likely to be high (Hubbart *et al.*, 2011). The grasses grown along *miraba* can be a hiding place for pests like rats (Kamugisha *et al.*, 2007; Msita *et al.*, 2011). *Miraba* planted with Guatemala and elephant grass are frequently visited by humans during the dry season for fodder collection, a common practice for farmers practising zero grazing, hence high chances of flea bites (Vanwambeke *et al.*, 2011). Also natural forests and shrubs on rocky slopes in the area mostly found on upper slopes and ridges also favour rodents' and fleas' abundance. These observations support earlier suggestions of potential plague infection risks being associated with land management and farming practices during epizootic periods in the plague risk area (MacMillan *et al.*, 2011; Zimba *et al.*, 2011).

In this study, flea index also tended to decrease as land cover types varied from natural forest and plantation forest to other classes. Results suggest that land cover dominated by natural forest and plantation forest tended to favour more fleas than other land cover types, though with weak effect. The effect of land cover type on flea abundance was reported in earlier studies in the study area (Laudisoit *et al.*, 2009a, b). In these studies shrubs which are also present in forested zones, were reported to have the highest flea abundance levels when compared to the other land cover types. Furthermore, elevation showed strong positive influence on flea index especially above 1800m. These findings are in line with previous studies in

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the study area and elsewhere (Kilonzo *et al.*, 1992, 2005; Pham *et al.*, 2009; Winters *et al.*, 2009; Neerinckx *et al.*, 2010).

The middle and upper slopes of the study area dominated by *miraba* land management practices and contour farming favour the abundance of fleas. In addition, elevations above 1800 m have a strong positive influence on flea index. Furthermore, elevation has a strong positive relation with small mammals trap success, which can be explained by an increase of food and water availability with altitude. Land cover and terrain variables influence and predict the spatial distribution of small mammals and fleas abundance across the West Usambara Mountain landscapes.

The relationship between land cover and terrain attributes on one hand and small mammals and fleas as potential hosts and vectors of plague, hence as indicators of plague risks, on the other hand has been well elaborated by remote sensing and GIS integration of geodatabase at different spatial scales and resolutions. This has revealed that a geomatic approach using remote sensing data and GIS technologies is valuable in studying plague infection risks.

The developed spatial geodatabase is structured for easy access and use on desktop computer GIS. The framework developed by this study forms a useful tool for plague surveillance and to inform communities on the probable risks associated with various landscape factors during epidemics. The framework is also a powerful tool for land and pest management including management of rodents which are dominantly crop pests. The geodataset derived from the satellite data including land cover, and DEM derivatives integrated in the expert GIS engine provide future potential analysis and understanding of the association of plague risk indicators including climate and human behaviour variables. In addition the developed geodatabase is vital information for district land use planning and rural development programmes in the study area.

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CHAPTER THREE

3.0 PAPER II: Land use determinants of small mammal abundance and distribution in a plague endemic area of Lushoto District, Tanzania

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Land use determinants of small mammal abundance and distribution in a plague endemic area of Lushoto District, Tanzania

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Abstract: Small mammals are considered to be involved in the transmission cycle of bubonic plague, still occurring in different parts of the world, including the Lushoto District in Tanzania. The objective of this study was to determine the relationship between land use types and practices and small mammal abundance and distribution. A field survey was used to collect data in three landscapes differing in plague incidences. Data collection was done both in the wet season (April-June 2012) and dry season (August-October 2012). Analysis of variance and Boosted Regression Trees (BRT) modelling technique were used to establish the relationship between land use and small mammal abundance and distribution. Significant variations ($p \leq 0.05$) of small mammal abundance among land use types were identified. Plantation forest with farming, natural forest and fallow had higher populations of small mammals than the other aggregated land use types. The influence of individual land use types on small mammal abundance level showed that, in both dry and wet seasons, *miraba* and fallow tended to favour small mammals' habitation whereas land tillage practices had the opposite effect. In addition, during the wet season crop types such as potato and maize appeared to positively influence the distribution and abundance of small mammals which was attributed to both shelter and food availability. Based on the findings from this study it is recommended that future efforts to predict and map spatial and temporal human plague infection risk at fine scale should consider the role played by land use and associated human activities on small mammal abundance and distribution.

Keywords: land use, small mammals, abundance, distribution, plague, infection risk, Tanzania

Introduction

Land use determines the spatial distribution of vectors and hosts according to their food and habitat preference (Linard *et al.*, 2007). Like other animals, small mammals must obtain sufficient energy, nutrients and vitamins and escape predators to survive and reproduce. Their patterns of distribution may thus be influenced by the distribution and abundance of habitat resources. The most critical factors that have been found to influence small mammal distribution are thought to be food and shelter (Cooney et *al.*, 1982). Total rodent abundance has been found to increase with increasing shrub cover in Kalahari in Namibia (Blaum *et al.*, 2007) and the Kibale Mountains of Uganda (Isabirye-Basuta & Kasenene, 1987). In the West Usambara Mountains of north-eastern Tanzania, the abundance of some rodent species has been shown to increase with food availability (Makundi *et al.*, 2007; Mulungu *et al.*, 2011).

Small mammals have been associated with plague in West Usambara Mountains, Tanzania (Kilonzo & Mhina, 1982; Mulungu *et al.*, 2010). It is known that irregular epizootics are a common feature of sylvatic plague (Gage & Kosoy, 2005) and such dynamics in the wildlife host populations in the Usambara Mountains provide the most likely explanation for the high degree of temporal variation in human plague cases. That is, years in which there are outbreaks of human plague are those that plague epizootics occur in the wildlife and peridomestic rodent communities (Davis et *al.*, 2006). Therefore, increasing densities of rodents in the West Usambara

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Mountains is likely to increase the risk of plague outbreaks in humans (Kilonzo *et al.*, 2005; Makundi et *al.*, 2007, 2008).

Various studies on the role of rodents in rodent-borne zoonoses transmission cycles have been conducted in the West Usambara Mountains and elsewhere in Tanzania (Kilonzo & Mhina, 1982; Kilozo et *al.*, 2005; Makundi et *al.*, 2003, 2008; Laudisoit *et al.*, 2009a; Mulungu et *al.*, 2010, 2011). These studies have demonstrated the role of shelter and food preferences of small mammals. However, the studies could not document the specific land use types and land management practices associated with small mammal distribution and abundance at a fine scale and within a wider geographic coverage which is important for delineation of potential risk areas (Eisen et *al.*, 2012).

Since, some rodent species have been reported to play a dynamic role in the plague transmission cycle and the fact that these rodents are hosts of fleas (plague vectors) it is important to study their association with various land use types. This will contribute to an understanding of how to device ways and means to implement ecologically-based rodent management strategies focussing on specific land use types and land management practices which is currently lacking. The objective of this study was therefore to determine the relationship between land use types and practices and small mammal abundance and distribution in the West Usambara Mountains in Tanzania. Although, the role of individual species of small mammals and fleas in persistence and transmission of bubonic plague is not well known, gaining more insight in the relationship between land use and small mammals in general is certainly an important step towards an understanding of the plague system in a specific area.

Materials and Methods

Study area

The study was conducted in West Usambara Mountains, Lushoto District, Tanzania, in an area selected between Universal Transverse Mercator (UTM) coordinates 400000 m E and 430000 m E and between 9480000 m N and 9500000 m N, Zone 37M, covering about 34,000ha. The altitude ranges from 480 to 2 271 m above sea level (Figure1). The area has a bimodal rainfall pattern with an annual total ranging from 600 to 1,200mm. The study area is characterized by a mixed farming system. Rainfed agriculture is the most important land use followed by irrigated agriculture, livestock keeping and off farm activities including petty cash and carpentry (Msita et *al.*, 2010). Other land uses include natural forestry, plantation forests and utility woodlots (Kaoneka & Solberg, 1994). Study sites were selected to reflect a geographic gradient in the frequency of plague incidence, based on results from previous research on rodents, fleas and plague casualties conducted in the area (Njunwa et *al.*, 1989; Kilonzo et *al.*, 1997; Davis et *al.*, 2006; Kamugisha et *al.*, 2007; Laudisoit et *al.*, 2007, 2009a,b; Neerinckx et *al.*, 2010).

In selecting the study sites four criteria were used for detailed studies which include: (a) The incidence of plague as recorded for the period from 1986 to 2004, which in former studies allowed to subdivide the study area into three major landscapes of high (villages where plague incidence rates on average were 4.17–10.46 cases/1000 inhabitants), medium (1.91–4.17 cases/1000 inhabitants) and low (0.02–1.91 cases/1000 inhabitants) incidence; (b) Land use and human activity diversity; (c) Landform characteristics (plain, escarpment, plateau dissected at different levels and valleys); and (d) Climatic conditions. On the basis of these criteria, three landscapes were selected: (i) The Shume landscape (high plague incidence) - dissected upper part of the escarpment-edge of the plateau. The area is located in the cold dry zone (average temperature ranges between 15-19° C, elevation 953-2040m and annual rainfall of 500-800 mm); the irregularly shaped 500 m deep escarpment has slopes up to 68 degrees and rock outcrops (Pfeiffer, 1990); (ii) The Lukozi landscape (medium plague incidence) - characterised by strongly dissected plateau, with broad ridge crest/summits and deep soils. The area is also situated in the cold dry zone. The average annual temperature ranges between 18-23°C with an average annual

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rainfall of 1,000mm and elevation of 1,750-2,205m (Pfeiffer, 1990; Kaoneka & Solberg, 1997); (iii) The Mwangoi landscape (low plague incidence) is characterised by strongly dissected sunken part of the plateau. The climate in this area is hot and dry (average temperature 22°C), annual rainfall of 500–800 mm with an elevation of 1346-2002m (Pfeiffer, 1990)).

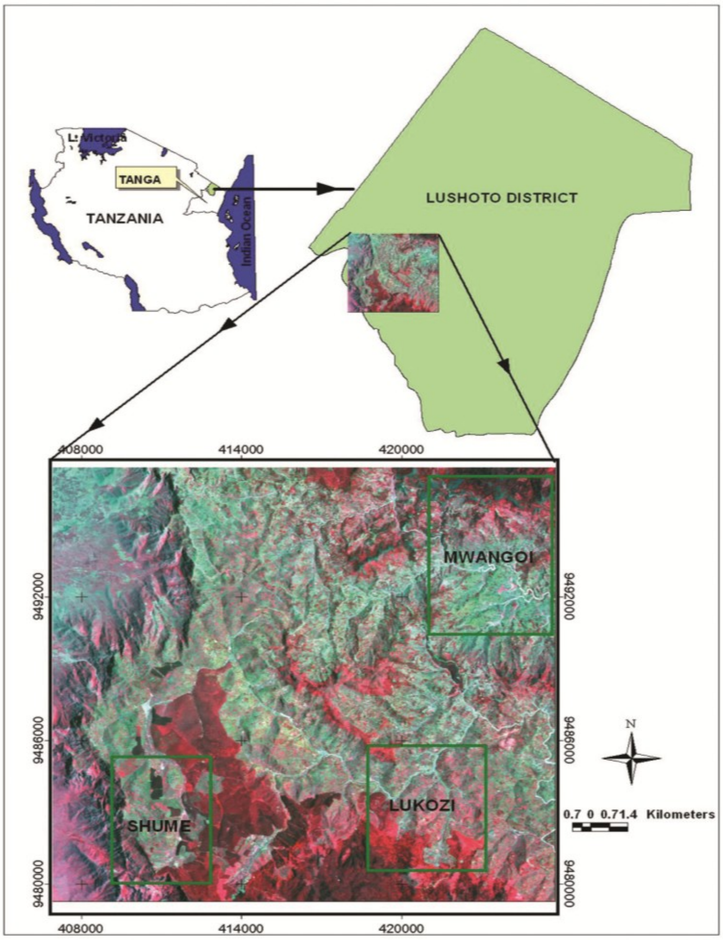

Figure 1: Location of study area: The Shume, Lukozi and Mwangoi landscapes

Sampling procedure

A total of 72 observation sites (quadrats) 100x100m were established. Twenty four quadrats were established per sample area (landscape). Stratified random sampling procedure based on broad land cover types and topography was used to locate the quadrats in each sample area. Decision on the number of observation sites considered representative sample size, time and human resources availability. At each observation site, data on land use including farm practices and management, small mammals and fleas combed out from small mammals were collected. Data collection was done in both wet (April-June 2012) and dry (August-October 2012) seasons.

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Land use data

At each of the observation sites various visible indicators of land use were georeferenced and mapped. Two major categories namely, land management practices and crop types were classified. The land management practices were identified by characteristic land cover patterns as seen in the field. For example a rectangular *Guatemala*/elephant grass strips cover was identified as *miraba* (an indigenous land management practice with grass strips surrounding crop fields). Thus in this category five land use management types were mapped which include *miraba*, terraces, other hedge-like structures, tree stumps (dead and live) and fallow. "Other hedge-like structures" included crop fields demarcating grass/shrub strips, and hedges along footpath/roads and around houses. Fallow was composed of such land cover type as bushed grassland, bushes, shrubs, unattended banana bushes, and inter-seasonal weedy/shrub fallow, or a mixture of these.

Crop types and other elements were also identified by characteristic land cover patterns as seen in the field. For a field with a mixture of crops, each crop type was differentiated from other crop or physical features. In this group a total of 15 categories were mapped: maize, cassava, beans, potato, sugarcane, vegetables, settlement, *Guatemala* grass fields, tilled land, woodlot, rock outcrop, natural forest, plantation forest (monocrop), plantation forest (with annual crop farming going on or recently stopped) and other land uses. The "vegetables" category had a mixture of vegetables commonly grown in Lushoto (Kaoneka & Solberg, 1997). "Other land uses" category had a mixture of crops which were scant within quadrats (not one of the above listed crops). "Woodlots" had one or mixture of such land cover types as eucalyptus, grevillea, black wattle and pine woodlots. Each of the categories natural forest, plantation forest monocrop and plantation forest with farming activities were treated as single use in their respective observation sites.

Data on small mammals

Small mammals were captured mainly using Sherman LFA live traps (7.5 x 9.0 x 23 cm; HB Sherman Traps, Tallahassee, USA) baited with peanut butter and maize flour. A total of 49 Sherman live traps spaced 10 m apart were set in grids per trapping (observation) site for each trapping session. For the sites in natural forests, additionally two wire cages were used to capture somewhat bigger mammals like squirrels. Each trapping session lasted 3 nights. Each trap was inspected every morning and traps with captured animals were replaced by empty traps. Each captured animal was weighed; its sex identified and morphological measurements (length of body, tail, ear and hind foot) recorded and identified. For small mammals species that could not be identified to species level due to lack of morphological differences that were detectable in the field, individuals were identified to genus level (Eisen *et al.*, 2012).

Data analysis

Data collected in the dry and wet seasons were compiled and descriptive statistical analysis and one-way analysis of variance (ANOVA) were carried out. Data included: Land use variables for Shume, Lukozi and Mwangoi landscapes; small mammals (genus/species name), trap success and overall fleas index per landscape. The trap success was calculated as number of animals trapped times 100 divided by the product of number of traps used and duration in terms of nights during which the trap was set (Laudisoit *et al.*, 2009a). Overall flea index was calculated as the total number of fleas collected in a landscape per total number of captured small mammals in that landscape (Laudisoit *et al.*, 2009a).

Prior to ANOVA, data was checked for normality and homogeneity (Zuur *et al.*, 2010). Whenever normality was not fulfilled, data were $\log_{10}(x+3/8)$ transformed to achieve normal distributions (Axelsson *et al.*, 2011; SAS Resource on the web, 2012). All statistical analyses were done using MS Excel and Minitab 14 software at the 95% confidence level. A one-way ANOVA of trap success among land use types was carried out on aggregated land uses data. For example wherever the observation site was dominated by both annual and perennial crops, the aggregated land use type for that particular observation site was classified as 'Mixed annual perennial crops' and wherever the observation site was composed of natural forest only the aggregated land use type became 'Natural forest'. A total of seven groups of aggregated land use (Plantation forest with farming, Natural forest, Fallow, Mixed annual crops, Mixed annual perennial crops, Plantation forest monocrop, Woodlot) were classified. Trap success was treated as dependent variable and aggregated land use was treated as independent variable.

Boosted Regression Trees (BRT) modelling technique was used to establish the relationships between small mammals' abundance (trap success) and individual land use variables. The individual land use variables used in BRT model are the originally sampled variables before aggregation. Boosted Regression Trees were constructed in R statistical program version 2.6.2 (R Development Core Team, 2006) using custom code (Elith *et al.*, 2008). Analyses were based on a Gaussian distribution. The 10-fold cross-validation (CV) was used for model development and validation, with the benefit of still using the full data set to fit the final model. Models were fitted using the gbm.step function (aimed at minimising squared error), with most effective settings for learning rate (0.01–0.000001) and bag fraction (0.5–0.75) as found by repeated trial-and-error.

Tree complexity, i.e. the number of nodes in a tree, was set to 3, according to recommendations by Elith *et al.* (2008) for small datasets. The measure of model performance was cv deviance and standard error (Elith *et al.*, 2008; Williams *et al.*, 2010). The combination of learning rate and bag fraction settings with the lowest cv deviance and standard error was the one selected to produce the final BRT model (Williams *et al.*, 2010). Also during data exploration all predictor variables were tested for ecologically acceptable level of collinearity (i.e. individual variance inflation factor (VIF) of <5) between predictor variables (Zuur *et al.*, 2010; Aertsen *et al.*, 2012). Partial dependency plots were used for interpretation and to quantify the relationship between each predictor variable and the trap success (Elith *et al.*, 2008). The unit of measurement for *Miraba*, Other hedge-like structures and Terraces predictor variables was length (m) whereas Tree stumps were counted (number). The rest of land uses variables were measured as proportions of coverage (%) of each land use within sampled 100 x 100 m quadrat area.

Ethical considerations

This study received approval from Directorate of Research and Post-Graduate Studies of Sokoine University of Agriculture, Tanzania and Flemish Inter-University Council (VLIR-UOS) of Belgium.

Results

Influence of aggregated land use types on small mammal abundance

The trap success among aggregated land use types indicated significant variation at $p \leq 0.05$. The highest trap success was found in Plantation forest with farming followed by Natural forest and Fallow whereas the lowest was recorded in Woodlot (Table 1).

Table 1: Influence of aggregated land use types on small mammal abundance

Season	Land use	Mean Trap success (%)
Dry season	Plantation forest with farming	10.33
	Natural forest	8.16
	Fallow	6.43
	Mixed annual crop	4.46
	Mixed annual perennial crop	3.63
	Plantation forest monocrop	1.27
	Woodlot	1.99
Wet season	Natural forest	8.33
	Plantation forest with farming	8.18

Fallow	4.45
Mixed annual crops	4.11
Mixed annual perennial crops	2.69
Plantation forest monocrop	1.57
Woodlot	0.58

Influence of individual land use variables on small mammal abundance as demonstrated by BRT model

Seven land use variables (predictor variables) were selected by the BRT model to have influence (to be important) on the observed spatial pattern of trap success (small mammal abundance) during the dry season (Figure 2). All seven predictor variables had the ecologically acceptable level of individual variance inflation factor (VIF<5). *Miraba* was the most important predictor with contribution of more than a third of the total (40.5%) and a strong positive effect. The presence of at least 25m of *miraba* was enough for trap success increase. Fallow was the second important predictor with contribution of 22.9% and a strong positive effect. A threshold value of 20% fallow appeared to be an important condition for an increase of trap success. The third important predictor was other hedge-like structures (13.1% contribution) with immediate strong negative effect followed by weak positive effect with the higher and lower values respectively lying around zero. Tillage had contribution of only 8% and a weak then strong negative effect. The presence of at least 5% of tilled land appeared to be an important condition for a decrease of trap success. Other predictors had relatively weak influence and small contributions.

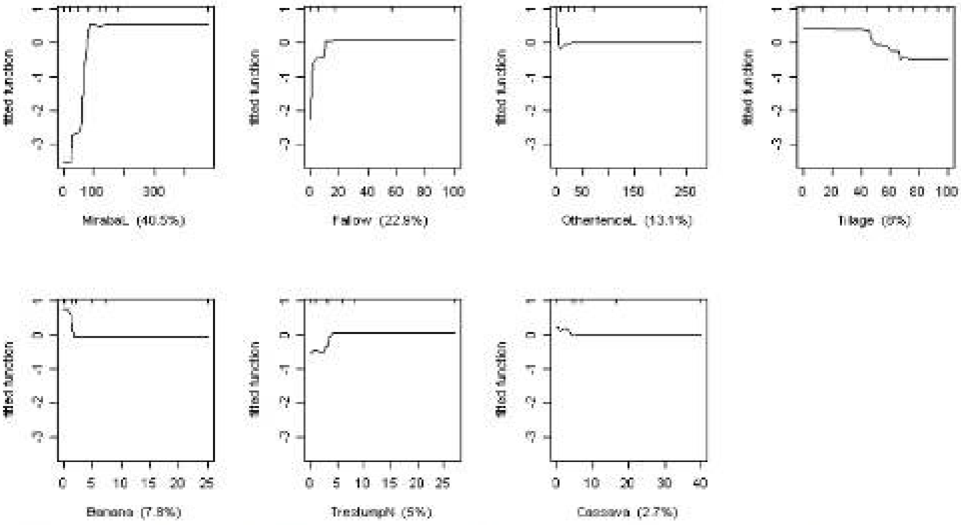

Figure 2: Partial dependence plots showing the effect of land use on spatial pattern of trap success during dry season. The relative contribution of each predictor is reported between brackets. CV deviance=21.6, standard error=5.943, number of trees=3250.

Key: TrestumpN= Tree stump, MirabaL=Miraba, OtherfenceL= Other hedge-like structures, CV = cross validation

Five land use variables (predictor variables) were selected by the BRT model to have influence (to be important) on the observed spatial pattern of small mammals in the wet season (Figure 3). All five predictor variables had the ecologically acceptable level of individual variance inflation factor (VIF<5). Potato was the most important predictor with contribution of half of the total (51.8%) and immediately showed a strong positive effect; the lower limit of the proportion of potatoes being only slightly greater than 0%. This implies that having just few potatoes in a field was enough to trigger off increased abundance of small mammals. *Miraba* and maize with contributions of 14% and 7.8%, respectively had weak positive influence. Other hedge-like structures (10.8% contribution) had immediate strong negative influence between 0 and 20m length. Tree stumps had a contribution of 15.5% but with a weak effect.

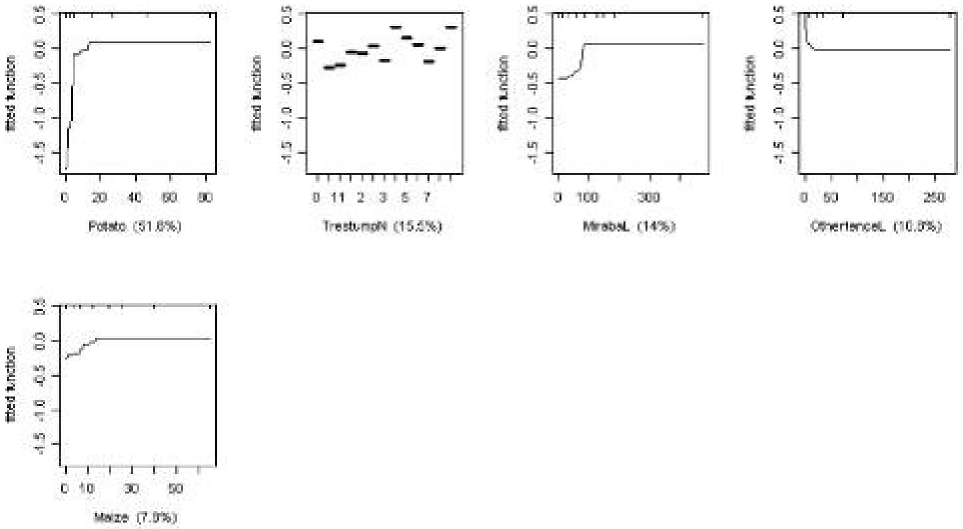

Figure 3: Partial dependence plots showing the effect of land use on spatial pattern of trap success during wet season. The relative contribution of each predictor is reported between brackets. CV deviance=12.911, standard error=2.633, number of trees=1200.

Key: TrestumpN= Tree stump, MirabaL=Miraba, OtherfenceL= Other hedge-like structures, CV = cross validation

Table 2: Distribution of small mammals and fleas by season collected in the three landscapes

Season	**Dry season**			**Wet season**		
Landscape	**Shume**	**Lukozi**	**Mwangoi**	**Shume**	**Lukozi**	**Mwangoi**
Small mammal (Genus/Species)						
Mastomys natalensis	166 (62.6%)	140 (60.3%)	26 (32.9%)	111 (47.4%)	73 (37.8%)	34 (36.6%)
Lophuromys sp.	30 (11.3%)	19 (8.2%)	5 (6.3%)	51 (21.8%)	24 (12.4%)	6 (6.5%)
Praomys sp.	9 (3.4%)	36 (15.5%)	14 (17.7%)	11 (4.7%)	54 (28.0%)	33 (35.5%)
Arvicanthis sp.	14 (5.3%)	4 (1.7%)	3 (3.8%)	9 (3.8%)	5 (2.6%)	0 (0.0%)
Crocidura sp.	9 (3.4%)	0 (0.0%)	1 (1.3%)	12 (5.1%)	14 (7.3%)	5 (5.4%)
Mus sp.	13 (4.9%)	19 (8.2%)	10 (12.7%)	10 (4.3%)	10 (5.2%)	1 (1.1%)
Grammomys sp.	13 (4.9%)	11 (4.7%)	8 (10.1%)	16 (6.8%)	9 (4.7%)	12 (12.9%)
Aethomys sp.	6 (2.3%)	0 (0.0%)	9 (11.4%)	10 (4.3%)	0 (0.0%)	0 (0.0%)
Lemniscomys sp.	3 (1.1%)	1 (0.4%)	1 (1.3%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Otomys sp.	2 (0.8%)	1 (0.4%)	0 (0.0%)	1 (0.4%)	2 1.0%)	1 (1.1%)
C.gambianus	0 (0.0%)	1 (0.4%)	0 (0.0%)	0 (0.0%)	2 (1.0%)	0 (0.0%)
Beamys sp.	0 (0.0%)	0 (0.0%)	1 (1.3%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Rattus rattus	0 (0.0%)	0 (0.0%)	0 (0.0%)	3 (1.3%)	0 (0.0%)	0 (0.0%)
Paraxerus sp.	0 (0.0%)	0 (0.0%)	1 (1.3%)	0 (0.0%)	0 (0.0%)	1 (1.1%)
Total small mammals	265	232	79	234	193	93
Total fleas	358	180	137	179	124	67
Flea index	1.4	0.8	1.7	0.8	0.6	0.7

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Abundance and diversity of small mammals in different landscapes with historical plague incidence

Mastomys natalensis, *Lophuromys sp.* and *Praomys sp.* were the dominant species in both wet and dry seasons and make up a total of 842 animals which is 76.8 % of the total catch (Table 2). Shume landscape had many *M. natalensis* and *Lophuromys* sp. than the rest of the landscapes in both seasons. *Aethomys sp.* were captured only in Shume and Mwangoi landscapes. Other captured small mammals were *Rattus rattus* in Shume landscape only and *Paraxerus sp.* and *Beamys sp.* in Mwangoi landscape only. Figure 4 shows the mean trap success per trapping (observation) site. The results show that in both seasons, Shume landscape had more small mammals per observation site than Lukozi and Mwangoi. Seasonal difference is also clear whereby dry season had higher values compared to wet season for Shume and Lukozi whereas in Mwangoi it was the opposite. The overall flea indices for all three landscapes ranged from 0.6 to 1.7.

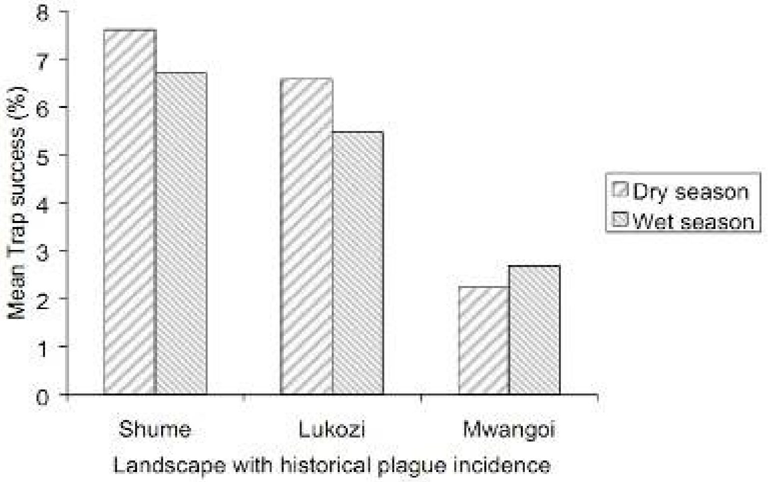

Figure 4: Mean trap success per sampling site in different landscapes in dry and wet seasons

Discussion

Variation in distribution of small mammals as influenced by land use types as observed in the current study is consistent with previous observations in the area (Laudisoit *et al.*, 2009a). These variations may be attributed to the fact that, Plantation forest with crop farming provides both shelter and food resources (Tews *et al.*, 2004). Fallow land is mainly surrounded by agricultural fields - a combination that provides shelter, breeding sites and supplementary food for rodents (Mwanjabe, 1993). Natural forest also provides food, water and shelter for small mammals. Generally, the results confirm findings from previous studies that small mammal abundance and distribution is critically associated with availability of food and shelter (Cooney *et al.*, 1982). Results with the BRT model suggest *miraba* to be the most important predictor of small mammal abundance. *Miraba* is a unique indigenous soil erosion control practice in the Usambara Mountains (Msita et *al.*, 2011). *Miraba* filter sediments from the runoff but the grasses grown in *miraba* construction may be used as animal fodder which is an added advantage. *Miraba* have many attributes as habitat for small mammals. They provide better locations for rodent burrows which do not easily get flooded with water during rainy season as well as shelter against predators (Kamugisha *et al.*, 2007; Msita *et al.*, 2011).

Fallows which were identified and discriminated as being composed of such vegetation types as bushed grassland, bushes, shrubs, unattended banana bushes, and inter-seasonal weeds and shrub fallow had positive influence on small mammal abundance during the dry season.

These vegetation types were previously found to be associated with rodents in the study area (Makundi *et al*., 2007; Laudisoit et *al*., 2009a). Indeed, these vegetation types not only provide nesting sites and diverse food sources, but also offer an effective shelter for ground dwelling small mammals from carnivores and avian predators (Tews *et al.*, 2004), and, hence, there is lower predation risk in these closed habitats (Laudisoit *et al*., 2009a). Fallow land matrices thus serve as refuges for rodents that infest crop fields (Makundi *et al*., 2007; Mulungu *et al*., 2011). These findings shed light on the possible link between these two land management practices, i.e. *miraba* and fallow and plague infection risk during epizootic periods. This is because, previous studies in the Lushoto and Mbulu foci in Tanzania show that plague outbreak has been occurring after rodent increase (outbreak) followed by rodent mortality (Kilonzo et *al*., 2005; Makundi et *al*., 2008).

Land tillage, which takes place during the dry season, had a strong negative effect on trap success. Tillage of land could have resulted in the destruction of mounds, removal of vegetation and destruction of nest sites some of which comprise food sources and shelter for the rodents. It may also be associated with alteration of soil micro-environment including exposure of small mammals to predators. Similar findings have been reported by Massawe *et al*. (2006). These observations are of practical significance to the local communities with regard to keeping their surroundings clean and reducing the duration of fallow periods although the latter may be at variance with acceptable conservation practices. This could curtail rodent build-up and hence minimize risk of contracting plague.

During the wet season, both potato and maize crops appeared to have a direct and positive influence on small mammal abundance. This could be attributed to the fact that the most critical factors that have been found to influence rodent distribution are thought to be related to the availability of food and shelter (Cooney et *al*., 1982). Interviews with key informants revealed that maize and potato were among the crops reported to be highly preferred by rodents in the study area. Similar findings have been reported by Mulungu et *al*. (2011).

The three dominant species of small mammals (*Mastomys natalensis*, *Lophuromys sp.* and *Praomys sp.*) observed in this study have been previously reported to be involved in the plague transmission in the study area (Kilonzo & Mhina, 1982; Makundi et *al*., 2007, 2008). The overall flea index (0.6 - 1.7) which was associated with the captured small mammals in this study, further indicates the potential risk of transmitting the disease from small mammals to humans during epizootics (Kilonzo et *al*., 1992; Eisen et *al*., 2006; Laudisoit, 2009). The general trend of values of absolute number and mean trap success of small mammals was Shume>Lukozi>Mwangoi. This could be explained by land use pattern differences where Shume has more plantation forest with farming, fallow lands and rock outcrops which seem to attract more rodents (Laudisoit et *al*., 2009a; Mulungu et *al*., 2011). The other reasons might be related to topography which also varies in terms of providing food, water and shelter. In other words, Shume appears to be a natural habitat for small mammals.

The current study has demonstrated that small mammal abundance and distribution is strongly influenced by the specific land use types. These results suggest that land management practices including tillage of land and crop types and the associated human activities should be included in the general scheme of plague maintenance and transmission mechanisms. Future efforts to predict and map spatial and temporal human plague infection risk at farm scale should consider the role played by land use on small mammal abundance and distribution. These findings therefore, make a significant contribution towards efforts in the control of plague risk factors in space and time. Small mammal presence in different land use types can influence abundance of certain flea species. However, since rodent fleas are ectoparasites which tend to inhabit both rodents (hosts) and off-host environment, additional investigation on how land use practices affect microclimate conditions for fleas living on and momentarily off-host is vital.

Acknowledgements

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CHAPTER FOUR

4.0 PAPER III: Contribution of land use to rodent flea load distribution in the plague endemic area of Lushoto District, Tanzania

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Contribution of land use to rodent flea load distribution in the plague endemic area of Lushoto District, Tanzania

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Abstract: Fleas associated with different rodent species are considered as the major vectors of bubonic plague, which is still rampant in different parts of the world. The objective of this study was to investigate the contribution of land use to rodent flea load distribution at fine scale in the plague endemic area of north-eastern Tanzania. Data was collected in three case areas namely, Shume, Lukozi and Mwangoi, differing in plague incidence levels. Data collection was carried out during both wet and dry seasons of 2012. Analysis of Variance and Boosted Regression Tree (BRT) statistical methods were used to clarify the relationships between fleas and specific land use characteristics. There was a significant variation ($P \leq 0.05$) of flea indices in different land use types. Fallow and natural forest had higher flea indices whereas plantation forest mono-crop and mixed annual crops had the lowest flea indices among the aggregated land use types. The influence of individual land use types on flea indices was variable with fallow having a positive effect and land tillage showing a negative effect. The results also demonstrated a seasonal effect, part of which can be attributed to different land use practices such as application of pesticides, or the presence of grass strips around fields. These findings suggest that land use factors have a major influence on rodent flea abundance which can be taken as a proxy for plague infection risk. The results further point to the need for a comprehensive package that includes land tillage and crop type considerations on one hand and the associated human activities on the other, in planning and implementation of plague control interventions.

Keywords: plague, land use, rodent, fleas, Tanzania

Introduction

Land use and human activities have been reported to be important determinants of vector borne disease transmission worldwide (Patz *et al.*, 2004; Linard *et al.*, 2007; Arinaminpathy *et al.*, 2009). The transmission of vector-borne diseases including plague, have been related to peoples' exposure to vectors associated with land use patterns (Arinaminpathy *et al.*, 2009; Vanwambeke *et al.*, 2011).

Different studies have been conducted to explain the presence and the recurrence of plague in Lushoto District in north-eastern Tanzania. Some of these studies include those on persistence and continued outbreaks of plague (Kilonzo *et al.*, 1997), patterns and spatial distribution of plague (Kamugisha *et al.*, 2007), ecology and status of potential hosts and vectors (Laudisoit *et al.*, 2007, 2009b; Laudisoit, 2009). Other studies focused on the influence of rainfall patterns on plague occurrence (Debien *et al.*, 2010) and variation of flea abundance within and among habitat types (Laudisoit *et al.*, 2009a). Hubeau (2010) found plague occurrence to be closely related to activity spaces for a number of land uses such as fetching water and collecting firewood.

Although a number of studies have generated some useful information on plague risk related to natural and land use factors, they fall short of elucidating the spatial variability of plague incidence in Lushoto District. Generally, human exposure to diseases has not been taken

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into account in studies of vector or host ecology (Linard *et al*., 2007). To complicate matters fleas have been reported to be an important vector of plague among wild rodents in scattered foci of the disease in equatorial Africa (Haeselbarth *et al*., 1966). Despite the important role played by rodent fleas in plague transmission (Makundi *et al*., 2008), knowledge on how land use practices affect the ecology of fleas living on and momentarily off-host is still lacking (Hubbart *et al*., 2011). This means, the association of fleas and specific land use types is poorly understood.

Detailed studies of landscape, land cover, and land use characteristics are important in the light of the coarse resolution of the available data of plague distribution and aggregated data of casualties at village or at most ward level (units of several square kilometres). A more detailed level of investigation is therefore necessary in order to link human related landscape characteristics to the presence of the potential hosts (rodents) and vectors (fleas) of plague, at comparable scale level. The main objective of this study was therefore, to investigate the contribution of land use to rodent flea load distribution at a fine scale in the plague endemic areas of Lushoto District in north-eastern, Tanzania. Specifically the study explored the land use attributes that can explain the abundance and distribution of rodent fleas at landscape scale.

Materials and Methods

Study area

The study was conducted in West Usambara Mountains, Lushoto District, Tanzania, in an area selected between Universal Transverse Mercator (UTM) coordinates 400000 m E and 430000 m E and 9480000 m N and 9500000 m N Zone, 37M (Figure 1). The size of the area is 34,000 hectares and lies at an altitude ranging from 480 to 2,271 m above mean sea level. The area has a bimodal rainfall pattern with an annual total of 600-1,200mm. The study area is characterized by a mixed farming system with rainfed agriculture being the most important land use followed by irrigated agriculture, livestock keeping and off-farm activities such as petty cash and carpentry (Msita *et al*., 2010). Other land uses include natural forestry, plantation forests and utility woodlots (Kaoneka & Solberg, 1994).

Study sites were selected to reflect a geographic gradient in the frequency of plague incidence, based on results from previous research in the area (Njunwa *et al*. 1989; Kilonzo *et al*., 1997; Davis *et al*., 2006; Kamugisha *et al*., 2007; Laudisoit *et al*., 2007, 2009a, b; Neerinckx *et al*., 2010). Four criteria were used for selection of sample areas: (a) The incidence of plague as recorded for the period from 1986-2004, which in former studies allowed to delineate the study area into zones of high incidence (plague incidence rate= 4.17–10.46 cases/1,000 inhabitants), medium (1.91–4.17 cases/1,000 inhabitants) and low (0.02–1.91 cases/1,000 inhabitants); (b) Land use and human activity diversity; (c) Landform characteristics (plain, escarpment, plateau dissected at different levels and valleys); and (d) Climatic conditions. On the basis of these criteria, three sample areas (landscapes) were selected: (i) The Shume landscape (High plague incidence) - dissected upper part of the escarpment-edge of the plateau. The area is located in the cold dry zone (average temperature ranges from 15-19°C), at an elevation ranging from 953-2040m with an annual rainfall of 500-800 mm. The irregularly shaped 500 m deep escarpment has slopes up to 68 degrees and rock outcrops (Pfeiffer, 1990); (ii) The Lukozi landscape (Medium plague incidence) is characterised by strongly dissected plateau, with broad ridge crest/summits, characterised by deep soils. It is also situated in the cold dry zone with an average annual temperature ranging from 18-23°C and average annual rainfall of 1,000mm at an elevation of 1750-2205 m (Pfeiffer, 1990; Kaoneka & Solberg, 1997); and (iii) The Mwangoi landscape (Low plague incidence) is characterised by a strongly dissected sunken part of the plateau. The climate of this area is hot and dry (average temperature 22°C), with an annual rainfall of 500–800 mm (Pfeiffer, 1990). The altitude of the area ranges from 1,346-2,002 m.

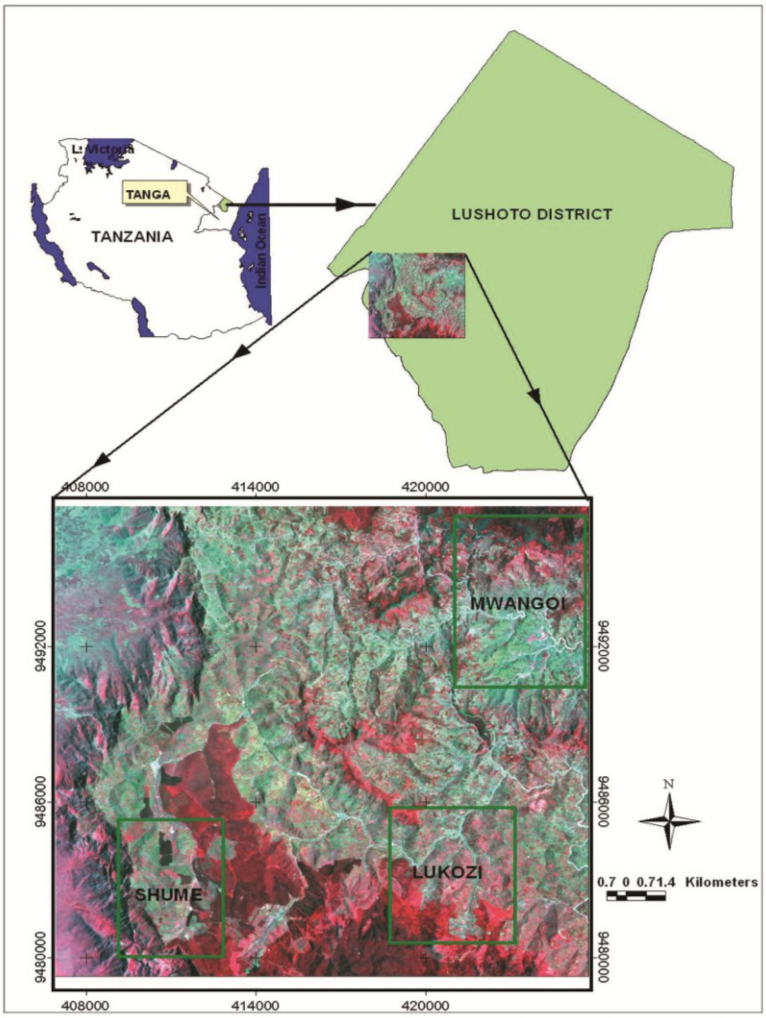


Figure 1: Location of study area: The Shume, Lukozi and Mwangoi landscapes in West Usambara Mountains, Tanzania

Data collection procedure

A total of 72 quadrats 100x100 m were established. Twenty four quadrats were established per sample area (landscape). A stratified random sampling procedure based on broad land cover types and topography was used to locate the quadrats in each sample area. Decision on the number of observation sites considered representative sample size, time and human resources availability. At each observation site, data on land use, rodents and fleas from rodents were collected. Data collection was done in the wet season (April-June 2012) and the dry season (August-October 2012).

Land use data

At each of the observation sites various visible indicators of land use were georeferenced and mapped. Two major categories were defined: (a) Land management practices which were identified by their characteristic land cover patterns as seen in the field. Thus in this category five land use management types were mapped which include *miraba*, terraces, other hedge-like structures, tree stumps (dead and live) and fallow. *Miraba* is an indigenous land management practice with grass strips surrounding crop fields. "Other hedge-like structures" included crop fields demarcating grass/shrub strips, and hedges along footpaths/roads and around houses. Fallow was composed of such land cover type as bushed grassland, bushes, shrubs, unattended banana bushes, and inter-seasonal weedy/shrub fallow, or a mixture of these. (b) Crop types and other elements which were also identified by characteristic land cover patterns as seen in the field for example a field with a mixture of crops; each crop type was differentiated from other crops or physical features. In this group a total of 15 categories were mapped: maize, cassava, beans, potato, sugarcane, vegetables, settlement, *Guatemala* grass fields, tilled land, woodlot, rock outcrop, natural forest, plantation forest monocrop, plantation forest with farming going on or recently stopped and other land uses. The "vegetables" category had a mixture of such crops as: paprika, broccoli, carrot, tomato, cabbage, Chinese cabbage, zucchini, onion, beetroot, cauliflower and African eggplant. "Other land uses" category had a mixture of crops which were scant within quadrats. "Woodlots" had one or mixture of such land cover types as eucalyptus, grevillea, black wattle and pine woodlots. Each of the categories, natural forest, plantation forest monocrop and plantation forest with farming activities, was treated as single use in their respective observation sites. In the subsequent sections all mapped and quantified visible indicators of land use are referred to as "land use".

Sampling and identification of rodent fleas

Fleas were collected from small mammals captured mainly using Sherman LFA live traps (HB Sherman Traps, Tallahassee, USA) baited with peanut butter and maize flour. A total of 49 Sherman live traps spaced 10m apart were set in a grid per trapping site (quadrat) and per trapping session. For the sites in natural forests, additionally two wire cages were used to capture somewhat bigger mammals like squirrels. Each trapping session lasted three nights. Each trap was inspected every morning and traps with captured animals were replaced by empty traps. Individual small mammals were identified to genus level or species level where possible (Eisen *et al.*, 2012) and carefully combed for fleas. Fleas were stored in 70% ethanol in individual vials for each host specimen for subsequent identification. From collected small mammals and fleas, flea indices were later calculated per observation site. Flea index was calculated as the total number of fleas per total number of captured mammals (Laudisoit *et al.*, 2009a). Flea index is a measure of flea abundance and was used as a response variable in the statistical analysis.

Data analysis

Two sets of data for Shume, Lukozi and Mwangoi were compiled and descriptive statistical analysis carried out.: The data set included: (a) Dry and wet season land use variables (b) Dry and wet season flea data (absolute number of fleas and flea index) and small mammal data (absolute number of animals). Prior to analysis of variance (ANOVA), data exploration to check for existence of outliers, normality and homogeneity was carried out (Zuur *et al.*, 2010). Existence of outliers in the data was tested using box plots whereas normality was tested using the Kolmogorov–Smirnov test and homogeneity was tested using the Leven's test (Nienhuis & Stout, 2009). Whenever normality was not fulfilled, data were $\log_{10}(x+3/8)$ transformed to achieve normal distributions (Axelsson *et al.*, 2011; SAS Resource on the web, 2012). All the aforementioned statistical analyses were done in MS Excel and Minitab 14 software at the 95% confidence level. A one way ANOVA of flea index among land use types was carried out on aggregated land uses data. For example wherever the observation site was dominated by both annual and perennial crops, the aggregated land use for that particular observation site was classified as 'Mixed annual perennial crops' and wherever the observation site was composed of natural forest only the aggregated land use type became 'Natural forest'. A total of seven groups of aggregated land uses (Plantation forest with farming, Natural forest, Fallow, Mixed annual crops, Mixed annual perennial crops, Plantation forest monocrop, Woodlot) were classified. Flea index was treated as a dependent variable and aggregated land use was treated as an independent variable.

Boosted Regression Trees (BRT) modelling technique in R software (R Development Core Team, 2006) was used to establish the relationships between flea index and individual land use types. Models were fitted using the gbm.step function and a Gaussian response type, with most effective settings for learning rate (0.01–0.000001) and bag fraction (0.5–0.75) (Elith *et al.*, 2008). Tree complexity was set to 3, according to recommendations by Elith *et al.* (2008) for small datasets. BRT-models were developed and validated using 10-fold cross validation (cv), with the benefit of still using the full dataset to fit the final model (Elith *et al.*, 2008). The measure of model performance was cross validation deviance and standard error (Elith *et al.*, 2008; Williams *et al.*, 2010). The combination of learning rate and bag fraction settings with the lowest cv deviance and standard error was the one selected to produce the final BRT model (Williams *et al.*, 2010). Partial dependency plots were used for interpretation and to quantify the relationship between each predictor variable and the flea index. Also during data exploration all predictor variables were tested for ecologically acceptable level of collinearity (i.e. individual variance inflation factor (VIF) of less than five) between predictor variables (Zuur *et al.*, 2010; Aertsen *et al.*, 2012). In construction of BRT models, flea indices were used as response variable and individual land uses were used as predictor variables. The unit of measurement for *miraba*, other hedge-like structures and terraces was length (m) whereas tree stumps were counted (number). The rest of individual land use variables were measured as proportions of coverage (%) of each land use within the sampled 100x100m quadrat.

Results

Abundance and diversity of fleas in the landscapes

The total absolute number of fleas and corresponding small mammals collected in both seasons are presented in Table 1. Most fleas were collected during the dry season (64.6%). Similarly, more small mammals from which fleas were combed were collected during the dry season (52.6%).

Table 1: Total number and percentage (%) of fleas and small mammals collected

Landscape	Fleas		Small mammals	
	Dry season	Wet season	Dry season	Wet season
Shume	358 (53%)	179 (48%)	265(46%)	234 (45%)
Lukozi	180 (27%)	124 (34%)	232 (40%)	193 (37%)
Mwangoi	137 (20%)	67 (18%)	79 (14%)	93 (18%)
Total	675 (64.6%)	370 (35.4%)	576 (52.6%)	520 (47.4%)

There was significant variation of flea index means ($p \leq 0.05$) among aggregated land use types during the dry season but not in the wet season. During the dry season, the highest flea indices were observed in the fallow, natural forest, and woodlot land use types (Table 2). On the other hand, during the wet season, the highest flea index was observed in the fallow land use type but with a slightly lower value.

Table 2: Effect of aggregated land use on flea index

Season	Land use	Mean flea index
Dry season	Fallow	1.50
	Natural forest	1.24
	Woodlot	1.23
	Plantation forest with farming	0.9
	Plantation forest monocrop	0.24
	Mixed annual crop	0.25
	Mixed annual perennial crop	0.34

Wet season	Fallow	1.27
	Natural forest	0.81
	Plantation forest with farming	0.68
	Mixed annual crops	0.35
	Mixed annual perennial crops	0.35
	Plantation forest monocrop	0.21
	Woodlot	0.14

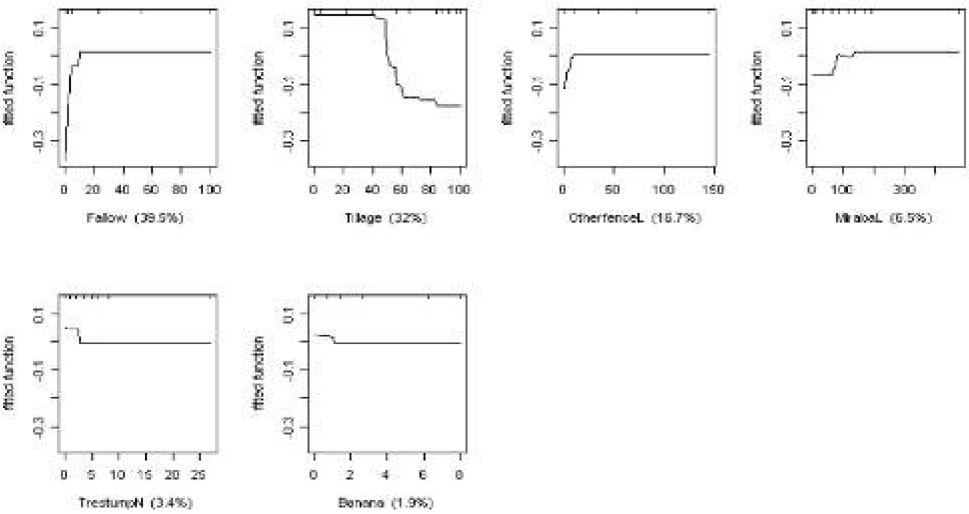
Table 3 shows the diversity of collected fleas for the dry season. A total of 675 rodent fleas belonging to 14 identified species were collected during this season. Shume and Lukozi had more species diversity as well as absolute numbers of fleas than Mwangoi. The two species namely *Xenopsylla brasiliensis* and *Dinopsyllus lypusus*, which account for 35% of the total collection, were dominant in all three landscapes and are reported to be good plague vectors in the study area.

Table 3: Diversity of collected dry season rodent fleas species and their proportions for each of the three studied landscapes

Landscape	**Shume**	**Lukozi**	**Mwangoi**
Rodent flea species	**Count/Proportion**	**Counts/Proportion**	**Counts/Proporti**
Xenopsylla brasiliensis	64 (17.9%)	15(8.3%)	66(48.2%)
Xenopsylla cheopis	1(0.3%)	0(0.0%)	1(0.7%)
Ctenophthalmus calceatus cabirus	26(7.3%)	15(8.3%)	6(4.4%)
Nosopsyllus incisus	63(17.6%)	23(12.8%)	4(2.9%)
Dinopsyllus lypusus	58(16.2%)	16(8.9%)	18(13.1%)
Dinopsyllus grypurus	8(2.2%)	28(15.6%)	27(19.7%)
Leptopsylla aethiopica aethiopica	53(14.8%)	16(8.9%)	14(10.2%)
Ctenophthalmus leptodactylus	0(0.0%)	17(9.4%)	0(0.0%)
Ctenophthalmus eximius	73(20.4%)	12(6.7%)	0(0.0%)
Ctenophthalmus sp.	8(2.2%)	9(5.0%)	0(0.0%)
Xenopsylla crinita	0(0.0%)	28(15.6%)	0(0.0%)
Dinopsyllus sp.	4(1.1%)	0(0.0%)	0(0.0%)
Lybiastus duratus	0(0.0%)	1(0.6%)	0(0.0%)
Ctenophthalmus sp.	0(0.0%)	0(0.0%)	1(0.7%)
Total	**358**	**180**	**137**

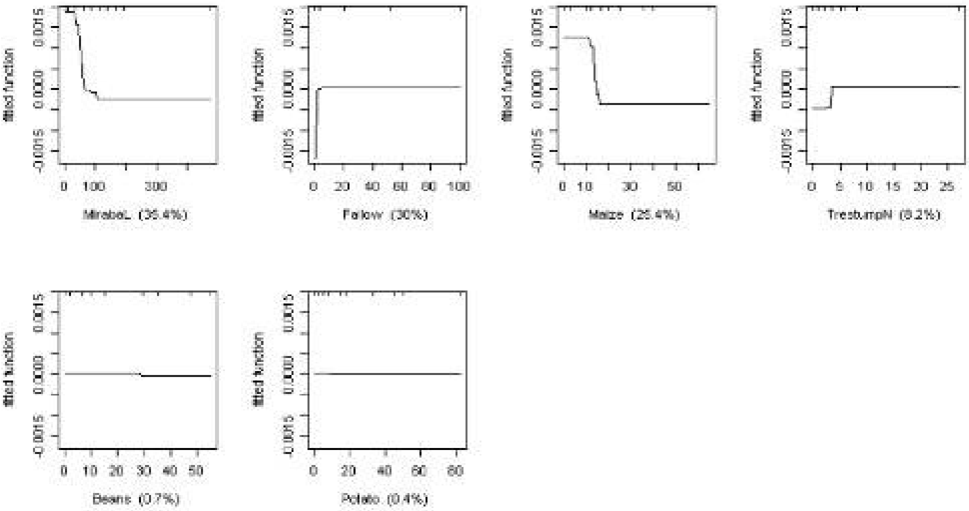
Influence of individual land use on flea index as demonstrated by BRT model

Six land use variables (predictor variables) were identified by the BRT model to have influence (to be important) on the observed spatial pattern of flea index in the dry season (Figure 2). All six predictor variables had the ecologically acceptable level of individual variance inflation factor (VIF<5). Fallow was the most important predictor with contribution of more than a third of the total influence (39.5%) and a strong positive effect. The presence of fallow between 0 and 20% appeared to be a precursor of increased rodent flea population (flea index). The second most important predictor was tillage with contribution of almost a third of the total influence (32%) and a strong negative effect. The presence of at least 40% of tilled land appeared to trigger off reduction in rodent flea population. Other individual land use variables had lesser influence on flea index with "other hedge-like structures" (16.7% contribution) and *miraba* (6.5% contribution) having a positive effect.



Key: TrestumpN= Tree stump, MirabaL=Miraba, OtherfenceL= Other hedge-like structures

Figure 2: Partial dependence plots showing the effect of individual land use on spatial pattern of flea index during dry season. The relative contribution of each predictor is reported between brackets; Cross Validation deviance = 0.637, Standard Error=0.354, number of trees=2,500



Key: TrestumpN= Tree stump, MirabaL=Miraba ,

Figure 3: Partial dependence plots showing the effect of land use on spatial pattern of flea index during wet season. The relative contribution of each predictor is reported between brackets; Cross Validation Deviance=0.471, Standard Error=0.096, Number of trees=1000

Six land use variables (predictor variables) were identified by the BRT model to have influence on the observed spatial pattern of flea index in the wet season (Figure 3). All six predictor variables had the ecologically acceptable level of individual variance inflation factor (VIF<5). *Miraba* was the most important predictor with contribution of almost a third of the total influence (35.5%)

and a strong negative effect. The presence of at least 50 m length of *miraba* was enough to trigger off a decrease in flea index. Fallow was the second most important predictor with contribution of close to a third of the total influence (30%) and had immediate strong positive effect similar to the dry season. Like *miraba*, maize also had a strong negative effect contributing a quarter of the total influence. Other individual land use variables had lesser influence on rodent flea abundance.

Discussion

The observed variations of flea index among land use types could be attributed to the impact of land use practices on flea habitat structure (Laudisoit *et al.*, 2009a; Hubbart *et al.*, 2011). According to Hubbart *et al.* (2011), the microclimate affecting rodent flea abundance varies among land use types. For example in the current study, fallow land use type generated the highest mean flea index during both dry and wet seasons. This might be attributed to fallow structure providing conducive microclimate for fleas (Laudisoit *et al.*, 2009a) on one hand and supply of both food and shelter for rodents on the other (Laudisoit *et al.*, 2009b; Mulungu *et al.*, 2011). Fallow fields have also been associated with plague cases in Uganda (Eisen *et al.*, 2010; MacMillan *et al.*, 2011). Since previous studies showed that flea index could be used as a proxy for plague infection risk in many areas including East Africa (Laudisoit *et al.*, 2007; Pham *et al.*, 2009; Zimba *et al.*, 2011), findings from the current study further lend credence to the hypothesis that plague infection risk could be associated with fallow in the study area. On the other hand, the negative effect of land tillage (which takes place in the dry season) on flea index would seem to counteract the dry season build-up of rodent fleas in the area. This is because tillage of land which destroys surface and subsurface microclimate (Hubbart *et al.*, 2011) could be detrimental to flea survival. In a study by Massawe *et al.* (2006) it was found that land preparation negatively affects the spatial distribution of rodents probably due to reduced cover (habitat) and food. The destruction of burrows may also lead to burying momentarily off host fleas hence reducing the load of fleas on rodents visiting or temporarily living in those burrows. This observation is of practical significance with regard to the need of clearing surroundings of homesteads and avoiding long fallow cycles.

The positive, albeit moderate influence of *miraba* and other hedge-like structures on flea index could be attributed to the fact that such land use types are associated with many rodent burrows (Kamugisha *et al.*, 2007; Msita *et al.*, 2011), and live rodent burrows are also likely to harbour adult 'free fleas' populations which momentarily stay in the burrows (Eisen *et al.*, 2012). Since these land use types provide suitable habitats for rodents, there is a high possibility of rodents contacting higher number of fleas inside burrows (Hubbart *et al.*, 2011). The study by Eisen *et al.* (2012) reported that off host adult populations of some flea species are able to survive while infected for relatively long periods in burrows or nests, thus contributing to the persistence of plague. The study conducted in the area by Kamugisha *et al.* (2007)~~,~~ showed that *miraba* with *Guatemala* grass which is usually grown on the steep slopes to prevent soil erosion and provision of pasture for zero grazed cattle, is likely to provide good shelter, breeding site and source of food for rodent populations. Such *miraba* planted with *Guatemala* and elephant grasses are frequently visited by humans during the dry season especially during fodder collection. Therefore, *miraba* are likely to be another potential plague infection risk land management practice that may need attention during epidemic periods.

The tree stumps appear to have variable influence on the spatial pattern of flea index, giving a positive effect during the wet season but a negative one during the dry season. Observations from the present study seem to suggest that tree stumps are an alternative choice for rodent nests especially in field areas where there are no *miraba* or terraces. On the other hand, the negative correlation depicted by *miraba* and maize land use types on flea index during the wet season could be a result of the effect of intensive use of fertilizers and pesticides leading to decreased populations of fleas (Hubbart *et al.*, 2011). This situation may have a cleansing effect on the rodents which despite their numbers due to favourable conditions in terms of shelter (Msita *et al.*, 2011) and food (Mulungu *et al.*, 2011) are devoid of fleas, hence lowering the flea index. These findings highlight on the need for further research on the role of fertilizer and pesticides in plague control during the wet season. In a previous study in the area, Makundi *et al.* (2005) recommended an approach for plague control which is to intensify the control of fleas with insecticides outdoors during peak plague outbreak season. Another reason for the negative influence of *miraba* and maize may be due to weather and microclimate change because temperature and relative humidity impact flea survival (Gage *et al.*, 2008; Ben Ari *et al.*, 2011; Eisen *et al.*, 2012). High rainfall may also cause flooding of burrows located in maize fields and hence resulting in death of fleas. Furthermore, the fact that all rodent fleas collected in the dry season are capable of transmitting *Yersinia pestis* with various vectors potential, this could have potentially important implications for the plague activity in relation to land use types in space and time (Eisen *et al.*, 2006; Laudisoit, 2009).

Findings from this study seem to suggest that land use types have major influence on rodent fleas' abundance. The fact that a significant number of rodent fleas collected in the dry season from the study area are capable of transmitting *Y. pestis*, lends credence to the generally held view that flea index could be used as a proxy for plague infection risk in the area. The negative effect of some land use types on flea index especially during the wet season suspected to result from intensive use of farm inputs including pesticides supports the proposed plague control measures by Makundi *et al.* (2005). This also highlights the need for further research on the role of farm inputs such as fertilizers and pesticides in plague control. Furthermore, other land use types which impact negatively on flea index such as land tillage done in the dry season, point to the need of clearing the surroundings of homesteads to create unfavourable conditions for both host and vector. While reduction of fallow cycles to minimize both host and vector populations would seem appropriate under such circumstances, there is need for a compromise between plague risk avoidance and environmental conservation in terms of erosion control.

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CHAPTER FIVE

5.0 PAPER IV: Human activity spaces and plague risks in three contrasting landscapes in Lushoto District, Tanzania

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Human activity spaces and plague risks in three contrasting landscapes in Lushoto District, Tanzania

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Abstract: Since 1980 plague has been a human threat in the Western Usambara Mountains in Tanzania. However, the spatial-temporal pattern of plague occurrence remains poorly understood. The main objective of this study was to gain understanding of human activity patterns in relation to spatial distribution of fleas in Lushoto District. Data were collected in three landscapes differing in plague incidence. Field survey coupled with Geographic Information System (GIS) and physical sample collections were used to collect data in wet (April to June 2012) and dry (August to October 2012) seasons. Data analysis was done using GIS, one-way ANOVA and nonparametric statistical tools. The degree of spatial co-occurrence of potential disease vectors (fleas) and humans in Lushoto focus differs significantly ($p \leq 0.05$) among the selected landscapes, and in both seasons. This trend gives a coarse indication of the possible association of the plague outbreaks and the human frequencies of contacting environments with fleas. The study suggests that plague surveillance and control programmes at landscape scale should consider the existence of plague vector contagion risk gradient from high to low incidence landscapes due to human presence and intensity of activities.

Keywords: plague, human activity spaces, risk gradient, flea index, Tanzania

Introduction

Human plague caused by *Yersinia pestis* has been a recurring public health threat in West Usambara Mountains in Lushoto District, Tanzania since the first outbreak in 1980. Despite intensive past biological and medical research, the question as to why plague kept emerging in the same set of villages remains unanswered. Different studies have been conducted in West Usambara Mountains and elsewhere in eastern Africa to explain the presence and the recurrence of plague. Some of these studies include those on persistence and continued outbreaks of plague (Kilonzo *et al.*, 1997), and on diversity, ecology and status of its potential hosts and vectors (Laudisoit *et al.*, 2009a,b) and contribution of flea diversity in plague persistence (Eisen *et al.*, 2012). Other studies dealt with the influence of rainfall patterns on plague occurrence (Debien *et al.*, 2010) and the modelling of plague at various scales in relation to factors such as altitude, soils and climate (Neerinckx *et al.*, 2010). Still other studies included land use and human activity patterns at coarse scale (Hubeau, 2010). Some studies considered the importance of human presence in disease transmission (Kilonzo *et al.*, 1997; Kamugisha *et al.*, 2007; Makundi *et al.*, 2008; Ben Ari et *al.*, 2011). A number of studies have already found a link between flea index and plague outbreak and persistence (Kilonzo et *al.*, 1992; Makundi et *al.*, 2008).

Knowing the social and spatial conditions that promote disease transmission is vital for better prediction and prevention of the emergence of vector borne diseases (Stoddard *et al.*, 2009; Randolph *et al.*, 2010; Vanwambeke *et al.*, 2011). Human movement is a critical (Zimba *et al.*, 2011) but understudied behavioural component underlying the transmission dynamics of many vector-borne pathogens (Stoddard *et al.*, 2009; Randolph *et al.*, 2010). Land use patterns and changes are drivers of human movements. Detailed knowledge of human flows in the landscape, and the human activities performed during such movements may be a valuable contribution to

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the understanding and the control of many vector-borne diseases (Linard *et al.*, 2007; Vanwambeke *et al.*, 2011; Stoddard *et al.*, 2009; Arinaminpathy *et al.*, 2009) including the spatial-temporal pattern of plague occurrence that remains poorly understood.

The main objective of this study was to gain understanding of people's activity patterns in their landscape in relation to spatial areas where fleas are present. The specific objectives were: (i) to determine the frequency of people's movements from home(s) to sampled activity destination(s); (ii) to model people's movements in order to assess chances of their exposure to plague in space and time; and (iii) to examine spatial variation of human-rodent fleas co-occurrence levels among the three landscapes varying in plague incidence rates. It is hypothesized in this study that different plague incidence levels correspond to differences in spatial co-occurrence of the potential plague vectors (fleas) on one hand, and people on the other hand. Where this spatial co-occurrence is higher, the exposure risk to plague will also be higher.

Materials and Methods

Study area

The study was conducted in West Usambara Mountains, Lushoto District in north-eastern Tanzania. The selected study area was between Universal Transverse Mercator (UTM) coordinates 400000 m E and 430000 m E and between 9480000 m N and 9500000 m N, Zone 37M, covering about 34,000ha (Figure 1). The altitude varies from 480 to 2,271m. The area has a bimodal rainfall pattern with an annual total ranging from 600-1,200mm. The study area is characterized by a mix of different farming systems. Rainfed agriculture is the most important, followed by irrigated agriculture, livestock keeping and some off farm activities (Msita *et al.*, 2010). Other land uses include natural forests, plantation forests and utility woodlots (Kaoneka & Solberg, 1994).

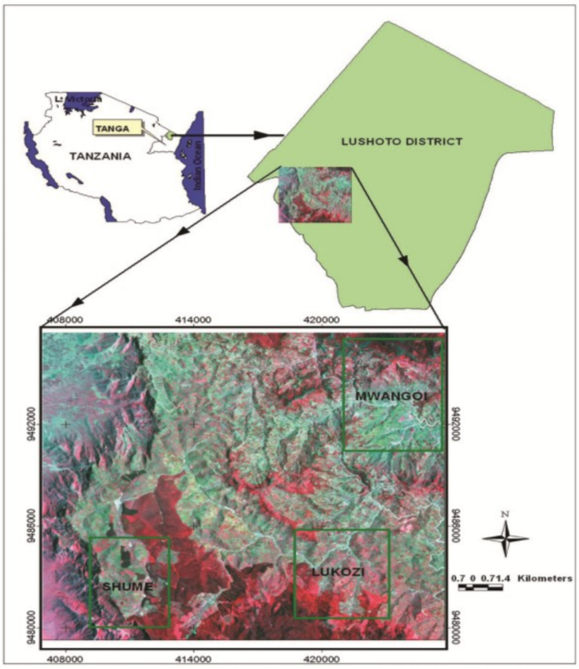

Figure 1: Study area showing the Shume, Lukozi and Mwangoi landscapes

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Study sites were selected to reflect a geographic gradient in plague incidence in the period 1980-2004, based on results from previous research on rodents, fleas and plague casualties in the area (Njunwa *et al.*, 1989; Kilonzo *et al.*, 1997; Davis *et al.*, 2006; Kamugisha *et al.*, 2007; Laudisoit *et al.*, 2007, 2009a, b; Neerinckx *et al.*, 2010). These studies defined zones of high incidence (villages with 4.17–10.46 plague cases/1000 inhabitants), medium incidence (1.91–4.17 plague cases/1000 inhabitants) and low incidence (0.02–1.91 plague cases/1000 inhabitants). Other criteria to differentiate the study landscapes were land use and human activity diversity, landform characteristics (plain, escarpment, plateau dissected at different levels and valleys) and climatic conditions.

On the basis of these criteria, 3 sample landscape areas were selected. These included the *Shume* landscape (high plague incidence) on the plateau edge bordering the escarpment (irregularly shaped 500m deep with slopes up to 68 degrees and rock outcrops (Pfeiffer, 1990), located in the cold dry zone (average temperature 15-19°C, elevation 953-2,040m and average annual rainfall 500-800mm); and 10.46 plague cases/1,000 inhabitants (Davis *et al.*, 2006); the *Lukozi* landscape (medium plague incidence) which lies on a strongly dissected plateau, characterised by deep soils also situated in the cold dry zone (average annual temperature 18-23°C, elevation of 1,750-2,205m, and average annual rainfall of 1,000mm (Pfeiffer, 1990; Kaoneka & Solberg, 1997); and the *Mwangoi* landscape (low plague incidence) located in a sunken part of the plateau with a hot and dry climate (average temperature 22°C, elevation of 1,346-2,002m, annual rainfall of 500–800mm) (Pfeiffer, 1990) and 0.57 plague cases/1,00 inhabitants (Davis *et al.*, 2006).

Human activities data collection procedure

Twenty four observation sites of 100m x100m were established per sample landscape area. Data collected from each observation site covered land use at farm level, associated human activities, and fleas from rodents. Stratified random sampling procedure based on broad land cover types and topography was used to locate the observation sites in each sample landscape area. Decision of the number of observation sites considered representative sample size, time and human resources availability. Data collection was done in the wet season (April-June 2012) and in the dry season (August-October 2012).

In each observation site, land use types were identified and mapped and the name of the main owner/user was recorded. In observation sites located within the public or government land e.g. natural forest, the hamlets surrounding it were recorded as owner/user. The ownership status was provided by key informants. The main user of an observation site was visited at his/her home and interviewed on the key outdoor activities linked to each land use type mapped, and about the whereabouts of other fellow users/owners of that same observation site, if any. Also recorded were the number of people involved, the number of days per week per activity, the time spent, and the routes from the residence to the activity site. For the observation sites located within public or government land, the hamlet leaders and village chairpersons were interviewed. Data for wet (*masika*) and dry (*kiangazi*) season activities were recorded separately.

The home of the main user of the observation site and the hamlet centres of other user(s) were georeferenced using Global Positioning System (GPS) receivers. The hamlet centres for the users of sites located within public or government lands were also georeferenced. The routes from home(s) to destination were also GPS-tracked.

Rodent flea data collection and calculation of flea index

Small mammals were captured from the established observation sites using Sherman LFA live traps (7.5x9.0x23cm; HB Sherman Traps, Tallahassee, USA) baited with peanut butter and maize flour. A total of 49 traps spaced at 10m apart were set in a grid, per trapping site (observation site) and for each trapping session.. For the sites in natural forests, additionally two wire cages were used to capture somewhat bigger mammals like squirrels. Each trapping session lasted 3 nights. Each trap was inspected every morning and traps with captured animals were replaced by empty traps. The rodents were identified to genus level or to species level where possible (Eisen *et al.*, 2012) and carefully combed for fleas. The flea index, which is the average number of fleas per animals recorded, was calculated per observation site. In this study it was interpreted as an indicator of plague transmission risk. This index was used as a response variable in the Analysis of Variance (ANOVA).

Analysis of route use

The human activities frequencies for each observation site per season were aggregated and an overall frequency (person-days) associated with each observation site established. This is the frequency of route (road/footpath) usage per observation site. These usage frequencies were obtained from the main users of observation sites, or from hamlet leaders for the sites within public/government lands. Each GPS-tracked route (road/footpath) segment was assigned its overall usage frequency in the attribute tables. Google earth images, SPOT image and existing maps were also used in the establishment of the network of routes. This was generated for both wet and dry seasons.

Activity space generation

An activity space can be defined as the area within which people move or travel to complete their daily activities (Newsome *et al.*, 1998). Spatial approximations of human activity spaces were generated by ARCGIS 9.3 software using the kernel density tool of the spatial analyst extension. The output map is a raster of density surface in kilometres per square kilometres. Two important variables were considered when generating a kernel density surface in ARCGIS 9.3 software: 'population field' and 'search radius'. A population field is the count or quantity to be spread across the landscape to create a continuous raster density surface. The search radius determines the size of the search neighbourhood.

During construction of activity space, a distance of 200 m off the pathway was used as search radius. This determines a strip at either road side for various purposes including collecting livestock fodder and firewood, and possibility for bypass opportunities on either side of the route, as observed during field work and as witnessed by key informants (Perchoux *et al.*, 2013). This should not be considered an extra burden in terms of travel time for an average agent (Schönfelder & Axhausen, 2002). The total route usage frequency (person-days/season) which was assigned to each route segment was used as population field inside a kernel density tool dialog box. When the route usage frequency is used as a population field, the length of route segment concerned becomes its actual length multiplied by the value of the population field for that route segment (ESRI, 2006).

A smoothly curved value surface is fitted over each line (road axis). The value is greatest on the line and diminishes as one moves away from the line, reaching zero at the end of the search radius from the line. A total of 144 kernel density surfaces maps (72 per season) were generated and maximum density surfaces in kilometres per square kilometre for each were recorded. The 144 kernel density surfaces maps were vectorised in order to obtain activity space vector maps. The activity space vector maps are polygons encompassing all none zero cells of the original kernel density surfaces raster map.

Generation of interpolated flea index surfaces

Inverse Distance Weighting (IDW) technique was used to generate interpolated flea index surfaces. The IDW produces surfaces by interpolation of scatter points and has been employed in studies on vector borne diseases and pest management (Beckler *et al.*, 2005; Naish *et al.*, 2011; Bhunia *et al.*, 2013). Prior to IDW, Spatial autocorrelation analysis was performed to check whether the flea index was distributed randomly over space and, if not, to evaluate any identified flea index cluster for statistical significance (Meng *et al.*, 2010; Naish *et al.*, 2011). The Moran's I statistics (ESRI, 2006; Bhunia *et al.*, 2013) was used to evaluate autocorrelation. A value close to '0' indicates spatial randomness. A value near 1.0 indicates perfect clustering while an index value near -1.0 indicates perfect dispersion (ESRI, 2006; Meng *et al.*, 2010). The Z-score and the p-value associated with Moran's I which indicates the likelihood that a point pattern is a result of random chance were also computed. The spatial autocorrelation analysis was carried out in ARCGIS 9.3 software and a confidence level of 95% (ESRI, 2006) was selected. The IDW analysis was also carried out using ARCGIS 9.3 software. The most commonly used, and default, power value of 2 and the default variable search radius, with 12 input points were chosen to allow for variable search neighbourhoods (Beckler *et al.*, 2005).

Calculation of flea indices within human activity spaces vector maps

Zonal statistics plug-in of QGIS 1.8.0 was used to calculate the average flea index which is the average value of the pixels that are within each activity space vector map after overlaying it with interpolated flea index surface. The technique enables calculation of several values of the pixels of the interpolated flea index surface including the sum, the average value and the total count of the pixels that are within a polygon of an activity spaces vector map. This was done for all 144 activity spaces vector maps. The "average flea index" resulting from zonal statistics overlay with polygons on raster is different from the originally calculated flea index per observation before interpolation and zonal statistics operations.

Analysis of variance of flea index, average flea index and maximum density surfaces among three landscapes

The data was first checked for normality and homogeneity prior to ANOVA (Zuur *et al.*, 2010). Whenever normality was not fulfilled, data were $\log_{10}(x+1)$ transformed to achieve normal distributions where possible (Axelsson *et al.*, 2011). In case of non success, the non-parametric ANOVA on Medians (Mood's Median test) was used. Otherwise, one-way ANOVA was used to evaluate differences in the data. The one-way ANOVA and Mood's Median test are widely used in different studies including ecological studies (Brook *et al.*, 2002; Forster *et al.*, 2005; Nienhuis and Stout, 2009; Laudisoit *et al.*, 2009a; Coors and Fische, 2011; Axelsson *et al.*, 2011). These analyses were carried out using MS Excel and Minitab 14 software for which a confidence level of 95% was selected.

Ethical considerations

This study received approval from Directorate of Research and Post-Graduate Studies of Sokoine University of Agriculture, Tanzania and Flemish Inter-University Council (VLIR-UOS) of Belgium.

Results

Human activity frequencies per activity destination

In the dry season the overall frequency of visiting the observation sites was highest in Lukozi, followed by Shume and Mwangoi, with Mwangoi having only about half the frequency of Shume. In the wet season the visiting frequency per season was also higher in Lukozi than Mwangoi and Shume, in that order (Table 1).

Table 1: Summary of average frequency of human movements for each landscape

Season	Landscape	Overall visit frequency (person-days)
Dry season	Mwangoi	6,806
	Lukozi	16,904
	Shume	12,615
Wet season	Mwangoi	14,614
	Lukozi	17,705
	Shume	13,203

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Abundance of fleas and small mammals

The results show that there were more rodent fleas in the dry season than in the wet season for all three landscapes. The absolute number of rodent fleas collected followed the plague incidence gradient (Table 2).

Table 2: Total number and percent of fleas and small mammals collected

	Fleas		Small mammals	
Landscape	Dry season	Wet season	Dry season	Wet season
Shume	358 (53%)	179 (48%)	265(46%)	234 (45%)
Lukozi	180 (27%)	124 (34%)	232 (40%)	193 (37%)
Mwangoi	137 (20%)	67 (18%)	79 (14%)	93 (18%)

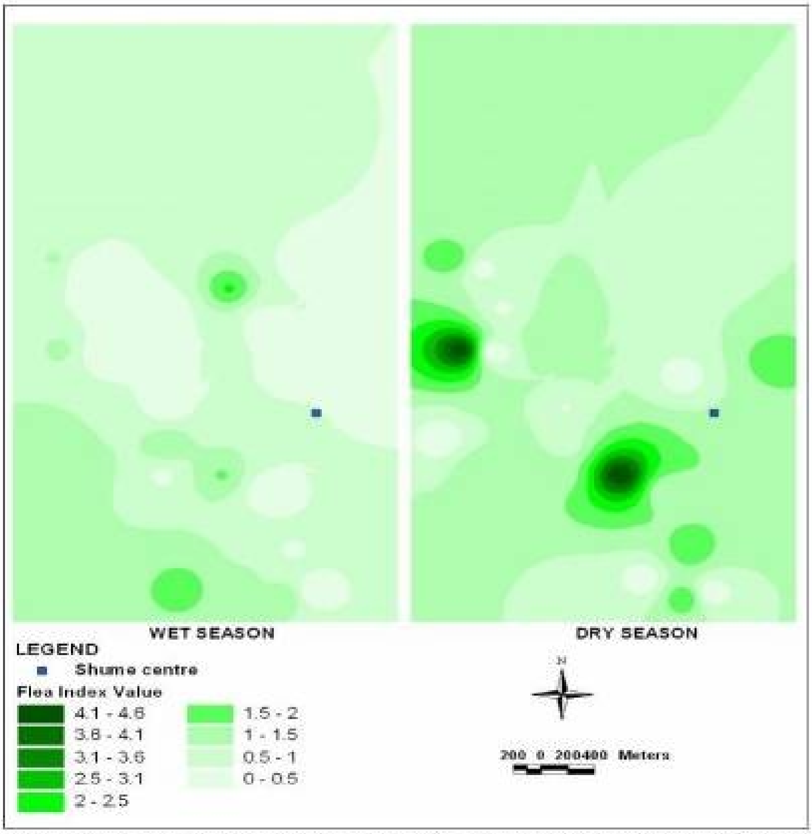

Figure 2: Shume flea index surface as an indicator of spatial variation of plague risks in wet and dry seasons

Interpolated raster surface of flea index

Six maps based on interpolation of flea index point data for Shume, Lukozi and Mwangoi landscapes are presented in Figures 2, 3 and 4, respectively. The general pattern of the maps indicates the dry season had higher flea index values compared to the wet season ones especially in Shume and Mwangoi landscapes. This implies that there was more potential plague infection risk in the dry season than in the wet season.

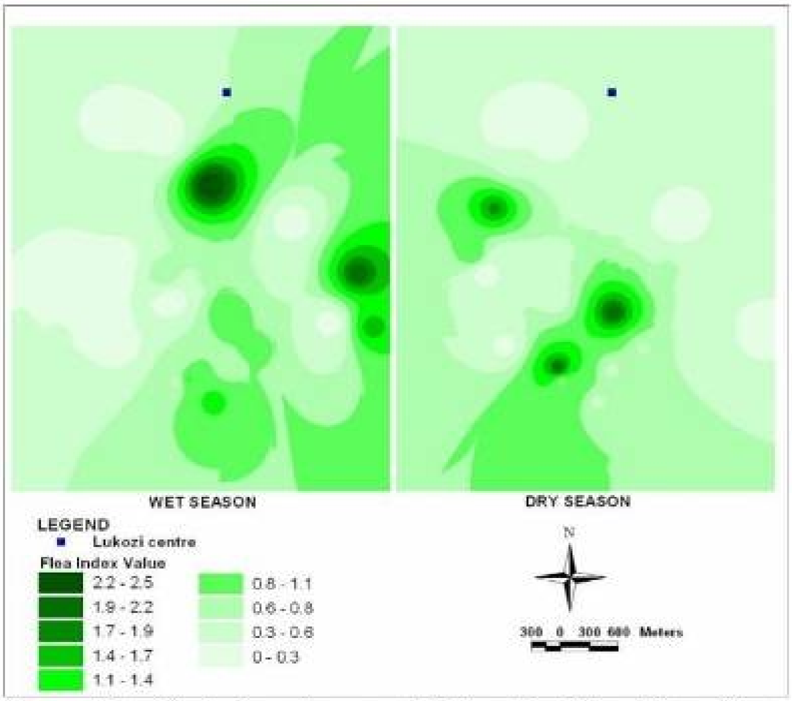

Figure 3: Lukozi flea index surface as an indicator of spatial variation of plague risks in wet and dry seasons

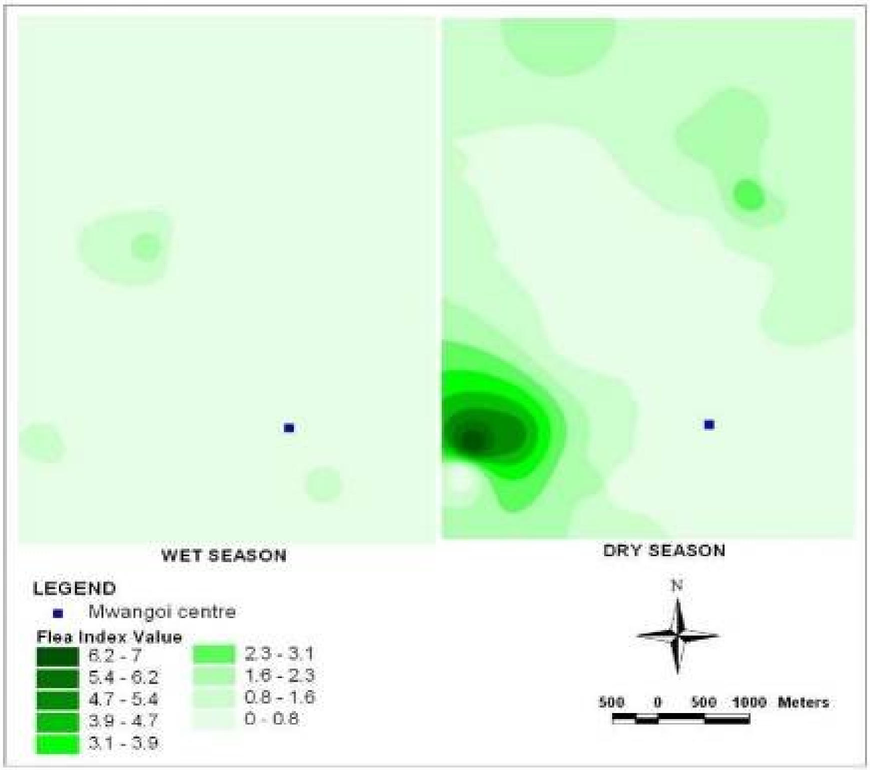

Figure 4: Mwangoi flea index surface as an indicator of spatial variation of plague risks in wet and dry seasons

Areas of Human activity spaces vector maps and corresponding average flea indices

Table 3 provides the total landscape area contacted by all users/owners (sum of the areas of all activity spaces vector maps) per landscape per season. The average of contacted area per observation site and the corresponding average flea index per observation site are also provided. In the dry season the human activity space was larger in Lukozi than in Shume and Mwangoi. In the wet season the trend is almost the same. During the dry season, the average flea index was higher in Shume followed by Mwangoi, while Lukozi had a lower index value. With respect to the average of contacted area per observation site, Lukozi has the highest value followed by Mwangoi in both wet and dry seasons.

Table 3: Human activity vector maps area (ha) and average flea index

Season	Landscape	Total area of human activity space vector maps (ha)	Average are of human activity space vector map per observation site (ha)	Average flea index
Wet season	Mwangoi	1,584.7	66.0	0.25
	Lukozi	1,712.6	71.4	0.58
	Shume	1,393.7	58.1	0.55
Dry season	Mwangoi	1,542.3	64.3	0.93
	Lukozi	1,704.2	71.0	0.58
	Shume	1,353.2	56.4	1.06

Variations of flea index, average flea index and maximum density surfaces among the three landscapes

For the original flea index (originally calculated flea index per observation before interpolation and zonal statistics operations), one-way ANOVA results show that there was no significant variation of flea index among the three plague incidence areas (landscapes) in both dry season ($p = 0.337$) and wet season ($p=0.097$). For the average flea index (resulting from activity spaces and interpolated flea index surfaces zonal statistics overlays) a significant variation was observed. In the dry season, the average flea index data couldn't pass the condition of homogeneity and therefore a non-parametric alternative of one-way ANOVA (Mood's Median test) was used. The Mood's Median test indicated that the medians of the average flea indices among the three plague incidence landscapes were significantly different ($p = 0.001$ and Chi-square=14.78). Shume had the highest median average flea index (Median = 0.983) followed by Lukozi (Median = 0.575) and Mwangoi (Median = 0.380).

Wet season average flea index data were normally distributed and passed the homogeneity test and therefore one-way ANOVA was used. The results show that there was a significant variation of average flea index among the three plague incidence landscapes ($p < 0.001$, Adjusted $R^2 = 24.8\%$). For this season, the means followed the gradient of plague incidence rates i.e. 0.54 for Shume, 0.50 for Lukozi and 0.24 for Mwangoi.

Furthermore, the one-way ANOVA results showed that the variation of area of activity space vector maps among the three plague incidence landscapes for both seasons was not significant (dry season $p = 0.331$ and wet seasons $p = 0.303$). The one-way ANOVA was also used to test the variation of maximum density surface (km/km^2), and the results showed that in the dry season there was a significant variation of maximum density surface (km/km^2) among the three plague incidence areas ($p = 0.002$, Adjusted $R^2 = 16.5\%$). In this season, Lukozi had the highest mean (761.61 km/km^2) followed by Mwangoi (440.76 km/km^2) while Shume had the lowest (200.84 km/km^2). For the wet season, there was no significant variation of maximum density surface ($p = 0.062$). The maximum density surface (km/km^2) represents the highest contacting density (km/km^2) of a particular road segment which indicates that it is used most frequently by persons to their destination.

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Discussion

Generally, the results show seasonal differences in the overall frequencies of human movements from home(s) to observation site(s). There was more movement in the wet season than in the dry season in all three landscapes, which may be attributed to more agricultural activities that are taking place in the area. Furthermore, the results showed differences in movement among the three plague incidence landscapes. In the dry season Lukozi had a higher overall activity frequency than Shume and Mwangoi with Mwangoi having only about half that of Shume. In the wet season Lukozi ranked highest but this time followed by Mwangoi. This may be attributed to the fact that Lukozi has a relatively good climate, more rainfall, and a good deal of fertile valley bottoms used for irrigated vegetables resulting in a higher frequency of movements than in Mwangoi and Shume.

Interpolation methods are useful for transforming point-based data into smooth risk surfaces. The outcome can be used to infer risk in areas that were not sampled, and they are most useful and reliable at fine spatial scale within the geographic area of point data sampling (Eisen & Eisen, 2011). The interpolated flea index surfaces in the current study are not spatial risk maps per se but serve as indicators of spatial variation of plague infection risks that might occur during epizootics. The results also show a general pattern of seasonality in flea index. The maps in the dry season reveal larger areas dominated by higher values of flea index than those in wet season, especially in Shume and Mwangoi landscapes. These findings are consistent with those of Laudisoit *et al*. (2009a) who found that each individual small mammal harboured more flea species during the dry season than during the rainy season. It is known that temperature, rainfall and relative humidity have direct effects on development and survival, as well as the behaviour and reproduction of fleas (Eisen *et al*., 2012; Gage *et al*., 2008; Ben Ari *et al*., 2011). The maps can also be used as base information for selecting areas for detailed plague infection risk studies.

Results from this study indicate that there was no significant difference in the means of area of human activity space vector maps among the three landscapes during both dry and wet seasons. There was also no significant difference in the mean of maximum density surface (km/km^2) among the three plague incidence areas (landscapes) for the wet season. The only significant difference was found in the dry season for the maximum density surface (km/km^2) with Lukozi (plague medium incidence landscape) having the highest mean followed by Mwangoi (plague low incidence landscape), and Shume (plague high incidence landscape) having the lowest. However, this gradient does not seem to match the plague incidence gradient. This could be attributed to the fact that the variation of the risk of vector zoonoses including plague depends on both abundance of infected vectors and the amount of human exposure to that hazard (Randolph *et al*., 2010; Vanwambeke *et al*., 2011), and not to the human movement pattern per se. The spatial variation of plague incidences among the three studied landscapes may be explained by considering not only human movement pattern or fleas in isolation but all three important plague transmission components i.e. hosts, vectors, and humans together.

Activities at fine scale have been reported to affect the degree of contact between people and vectors (Randolph *et al*., 2010; Vanwambeke *et al*., 2011). For vector-borne zoonoses, human induced environmental change may affect the transmission potential of wildlife cycles, whilst human activities rather determine the potential of contact with components of those cycles and so co-determine the risk of infection (Randolph *et al*., 2010; Zimba *et al*., 2011).

The flea index (flea abundance) is reported to give useful information for the surveillance of plague and serve as indicator of potential plague transmission (WHO, 1976; Kilonzo & Mhina, 1982; Makundi *et al*., 2008). The results of the current study showed that there was a significant variation of average flea index (resulting from activity spaces and interpolated flea index surfaces zonal statistics overlays) among the three landscapes for both dry and wet seasons. These findings are in line with an earlier study on vector-borne diseases by Randolph *et al*. (2010). The observed significant difference of the medians of the average flea index indicates that Shume has

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potentially high plague infection risk during epizootics compared to Lukozi and Mwangoi. The trend is the same in both wet and dry season. An earlier study in the area by Laudisoit *et al.* (2007), reported that abundance of human domestic flea (*Pulex irritans*) was correlated with plague incidence. The findings from the current study corroborate their assertion as rodent fleas were found in abundance in environments where humans and rodent fleas are likely to get in contact. Association of plague infection risk and flea index is also supported by other studies in Tanzania (Kilonzo *et al.*, 1992; Makundi *et al.*, 2008) and elsewhere (Pham *et al.*, 2009). Furthermore, Zimba *et al.* (2011) reported that humans get infected with the causative agent of plague when they enter zones with infected wild rodents, through activities such as cultivation and hunting.

Since all rodent fleas collected in both seasons are capable of transmitting *Yersinia pestis*, be it with different vector potential because of ecological and morphological factors (Eisen *et al.*, 2006; Laudisoit, 2009; A. Laudisoit, *personal communication*), the three studied landscapes together show a gradient of plague infection risk. The findings from the current study suggest that the risk of *Yersinia pestis* transmission from rodents to humans during epizootics may be explained by human movement at fine-scale i.e., people going about their regular daily activities on the studied landscapes found to have spatially varying rodent fleas abundances.

The current study has demonstrated the importance of human activity spaces in the study of plague infection risks. It has shown that the spatial co-occurrence of a potential disease vector and humans (giving "average flea index") differs significantly among the plague incidence landscape areas and follows the established plague incidence gradient of high, medium and low for both dry and wet seasons. This trend gives a coarse sign of the possible association of the plague outbreaks and the human frequencies of contacting environments with fleas. These results therefore, call for plague studies adopting a complete geographic perspective that includes human activity dimension. Moreover, the findings are of public health relevance because they may guide plague surveillance, prevention and control programmes at fine scales by advising people to avoid contact with soil, vegetation etc. in landscape units with high concentration of rodent fleas, especially during epizootic periods.

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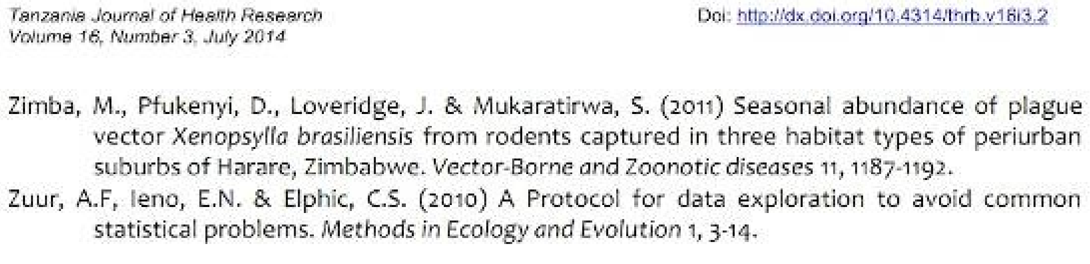

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CHAPTER SIX

6.0 GENERAL CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Few studies have focussed on association of land use, human activities pattern, land cover and terrain attributes with plague infection, especially in the plague endemic area of Western Usambara Mountains, Tanzania. Land use and land cover and associated human activities provide the required environment for host and vector harbourage and food as well as contagion of vectors and humans. Unlike previous studies in the area, the current study integrated many landscape factors that could play a role in plague transmission and maintenance (land use, land cover, terrain attributes, human movement and activities pattern, hosts, vectors, and historical plague incidence rate zoning) so as to gain an insight into the plague infection risks in the area. Based on the findings from the current study the following conclusions are pertinent:

The study has demonstrated the importance of land use/cover and human activity spaces in the study of plague infection risks. The relationship between land cover and terrain attributes on one hand and small mammals and fleas as potential hosts and vectors of plague on the other, has been well elaborated by remote sensing and GIS integration of geodatabase at different spatial scales and resolutions. Increasing slope gradient which is associated with increased *miraba* land management density has strong positive influence on flea abundance. Furthermore altitude appeared to have a positive influence on small mammal abundance due to increased availability of food and water. Areas with high altitudes have been identified in earlier studies to be at highest risks of plague infection in Eastern Africa. It has clearly been revealed by the study that a geomatic approach using remote sensing data and GIS technologies is valuable in studying plague infection risks.

The geodataset derived from the satellite data including land cover/use and Digital Elevation Model (DEM) derivatives integrated in the expert GIS engine are important and provide a springboard for future analyses in association with plague risk indicators such as climate and human behaviour variables. This augurs well for plague surveillance and awareness creation among communities on the probable risks associated with various land cover and topographical factors if contacted by humans especially during epizootic periods.

The study has demonstrated further that small mammal abundance and distribution is strongly influenced by the specific land use types. It has been shown that some land use types have strong positive effect on small mammal abundance whereas others have strong negative effect. *Miraba* and fallow were the most important land use types influencing small mammal abundance and distribution and had a strong positive effect during the dry season. Land tillage which takes place during the dry season had a negative effect. In the wet season, maize and potato crops appeared to have a direct and positive influence on small mammal abundance because these crops provide both food and shelter for small mammals. On the other hand plantation forest with crop farming, natural forest and fallow seemed to favour higher populations of small mammals than the other aggregated land use types. Presence of small mammals in different land use types can influence abundance of fleas. The findings suggest that land use factors have a major influence on rodent flea abundance which can be taken as a proxy for plague infection risk. Fallow was a very important land use type influencing flea abundance and distribution and had a positive effect. On the other hand land tillage which takes place during the dry season had a negative effect on flea abundance.

Findings from this study seem to suggest that in order to reduce the risk of outdoor flea bite there is a need of clearing the surroundings of homesteads and avoiding long fallow cycles. While reduction of length of fallow cycles to minimize both host and vector populations would seem appropriate under such circumstances, a compromise has to be struck between plague risk avoidance and environmental conservation in terms of erosion control. This suggests that conserving and managing a multi-functional landscape will require knowledge of the tradeoffs and synergies among ecosystem services and adaptive management to respond to unforeseen consequences resulting from land use decisions.

The study has demonstrated further that the spatial co-occurrence of a potential disease vector and humans differs significantly among the plague incidence landscape areas and follows the established plague incidence gradient of high, medium and low for both dry and wet seasons. This shows that the distribution and concentration of rodent fleas and human activities pattern overlap differently in each plague incidence landscape in space and time. These findings reveal the risks of environmental exposure which reflects the plague infection risks during epidemics. The fact that rodent fleas were found in abundance in environments where humans and rodent fleas are likely to get in contact, and since all rodent fleas collected in both seasons are capable of transmitting *Yersinia pestis*, it is obvious that such environments are potential risks for plague infection that can occur during epizootics. The observed spatial co-occurrence trend of a potential disease vector and humans among the studied landscapes gives a coarse indication of the possible association between plague outbreaks and the human frequencies of contacting environments with fleas.

The findings from this study are of public health relevance because they provide possibilities to guide plague surveillance, prevention and control programmes at fine scales by providing information to health workers to focus control measures on land use/cover and landscape units with high concentration of rodent fleas, especially during epizootic periods. This is important in targeting the country's limited resources for plague surveillance, prevention and control programmes.

Systematic trapping of small mammals and collection of rodent fleas for surveillance should spatially target *miraba*, fallow land, plantation forest with farming, natural forest and woodlot. These land use/cover and land management types provide a conducive environment for increased concentration of potential plague hosts (small mammals) and vectors (fleas) as identified in the current study.

6.2 Recommendations

The following recommendations are made in the light of gaps revealed from the findings of this study so as to provide further insights into the plague disease.

Land management practices including tillage of land and crop types and the associated human activities should be included in the general scheme of plague control and management.

Future efforts to predict and map spatial and temporal human plague infection risk at farm scale should consider the role played by land use on small mammals and rodent fleas abundance and distribution.

The study suggests that plague surveillance and control programmes at landscape scale should consider the existence of plague vector contagion risk gradient from high to low incidence landscapes due to human presence and intensity of activities.

Further studies should be conducted to investigate how land use practices influence surface and subsurface microclimate conditions of various small mammals and flea species. This is because rodent fleas are ectoparasites which tend to inhabit both small mammals (hosts) and off-host environment and hence the need for additional investigation on how land use practices affects microclimate conditions for fleas living on and momentarily off host.

Outdoor application of insecticides to control flea abundance has been found to be an effective measure against plague. However, further studies on timing of applications during epizootics vis-à-vis crop type should be considered.