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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).

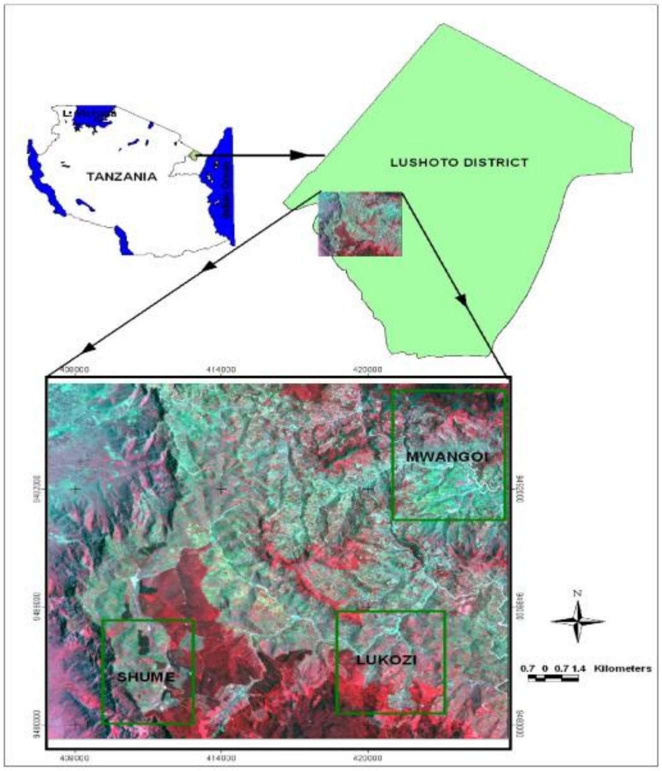

Figure 1: Study area showing the Shume, Lukozi and Mwangoi landscapes

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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

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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

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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

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%)

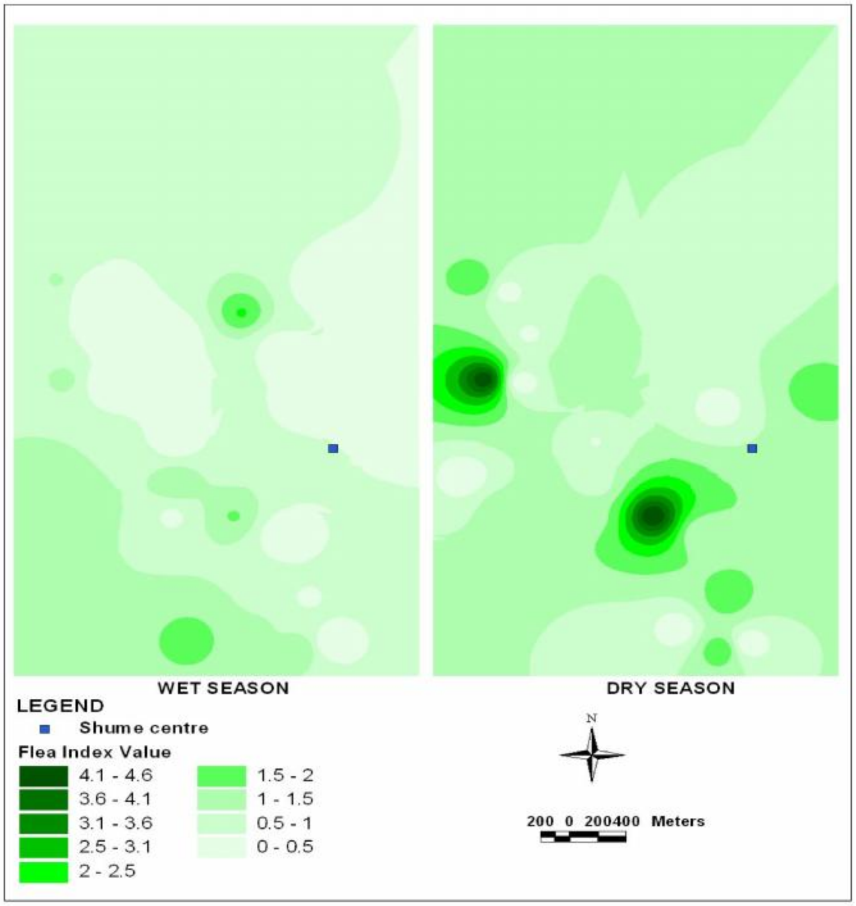

Figure 2: Shume flea index surface as an indicator of spatial variation of plague risks in wet and dry seasons

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.

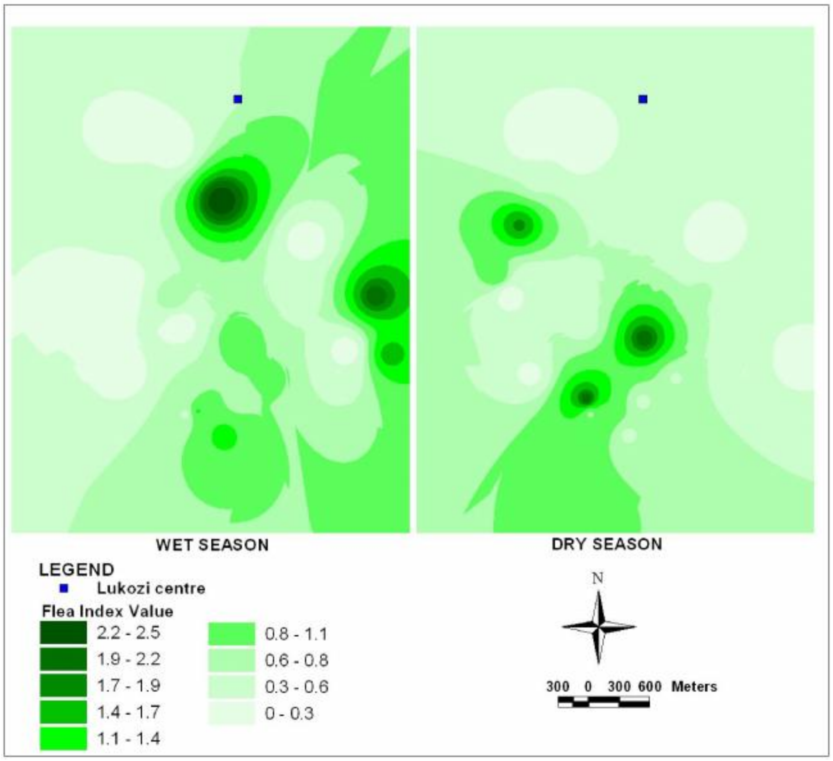

Figure 3: Lukozi flea index surface as an indicator of spatial variation of plague risks in wet and dry seasons

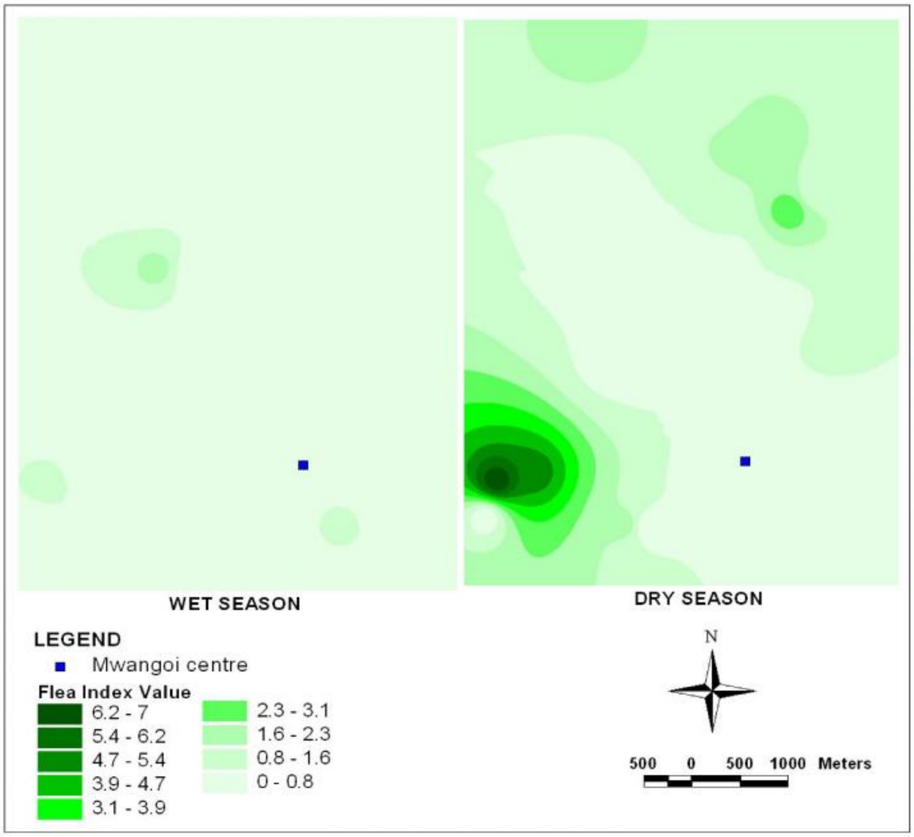

Figure 4: Mwangoi flea index surface as an indicator of spatial variation of plague risks in wet and dry seasons

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 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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