A geographical location model for targeted implementation of lure-and-kill strategies against disease-transmitting mosquitoes in rural areas

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Abstract

Background. Outdoor devices for luring and killing disease-transmitting mosquitoes have been proposed as potential complementary interventions alongside existing intra-domiciliary methods namely insecticide treated nets and house spraying with residual insecticides. To enhance effectiveness of such outdoor interventions, it is essential to optimally locate them in such a way that they target most of the outdoor mosquitoes.

Methods. Using odour-baited lure and kill stations (OBS) as an example, we describe a map model derived from: 1) community participatory mapping conducted to identify mosquito breeding habitats, 2) entomological field studies conducted to estimate outdoor mosquito densities and to determine safe distances of the OBS from human dwellings, and 3) field surveys conducted to map households, roads, outdoor human aggregations and landmarks. The resulting data were combined in a Geographical Information Systems (GIS) environment and analysed to determine optimal locations for the OBS. Separately, a GIS-interpolated map produced by asking community members to rank different zones of the study area and show where they expected to find most mosquitoes, was visually compared to another map interpolated from the entomological survey of outdoor mosquito densities.

Results. An easy-to-interpret suitability map showing optimal sites for placing OBS was produced, which clearly depicted areas least suitable and areas most suitable for locating the devices. Comparative visual interpretation of maps derived from interpolating the community knowledge and entomological data revealed major similarities between the two maps.

Conclusion. Using distribution patterns of human and mosquito populations as well as characteristics of candidate outdoor interventions, it is possible to readily determine suitable areas for targeted positioning of the interventions, thus improve effectiveness. This study also highlights possibilities of relying on community knowledge to approximate areas where mosquitoes are most abundant and where to locate outdoor complementary interventions such as odour-baited lure and kill stations for controlling disease-transmitting mosquitoes.

1 Introduction

Even though disease-transmitting mosquitoes spend a greater proportion of their adult life outside human dwellings than inside the dwellings, the primary interventions used to control them, namely house spraying with residual insecticides (IRS), insecticide treated nets (ITNs) and house screening [1-3], target only indoor host-seeking and indoor resting mosquitoes. There is evidence that, while most malaria transmission in Africa occurs inside houses, significant proportions of the transmission continue to occur outdoors as well [4, 5]. Moreover, there are numerous scenarios where mosquito vectors may prefer to feed and rest outdoors, either innately or as a temporary behavioural response to vector control interventions used indoors [6-9].

Studies of mosquito olfactory cues [10, 11] and particularly recent development of synthetic mosquito lures that attract significantly more mosquitoes than humans do [12]; have highlighted opportunities for developing new tools to control malaria by targeting adult mosquitoes while they are outside human dwellings, and in areas where mosquitoes are most abundant. For example, the recently developed Ifakara Odour-Baited Stations (Ifakara OBS) [13, 14], which lure and kill disease-transmitting mosquitoes may have significant potential of complementing current intra-domiciliary vector control methods.

Placing odour-baited stations (OBS) outside human dwellings, in areas where mosquitoes are most abundant or between residential areas and mosquito breeding habitats can potentially reduce the number of mosquitoes that eventually reach human houses [15, 16]. Furthermore, these techniques would also target vectors that feed outside houses at dusk or before people go under protection of their

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bed nets [6, 17]. With the renewed interests to eliminate and possibly eradicate diseases like malaria [18, 19], we envisage that outdoor mosquito control using tools such as the OBS will become vital components of the control agenda. We recognise however that the overall success of such complementary strategies in real life operations will depend not only on efficacies of the outdoor tools, but also on the way in which they are integrated with existing measures; for example, how many are used and where exactly they are located.

This paper describes development of geographical information system (GIS)-based location models to assist in optimal placement of odour-baited stations in order to maximize their potential benefits of luring, trapping, and killing disease transmitting mosquitoes away from human dwellings. The models are implemented with reference to a selected study area in rural Tanzania and consider: 1) location of mosquito larval habitats, 2) distribution of adult mosquitoes within the village, 3) road network, 4) distribution of human dwellings within the village, 5) characteristics of mosquito attractants used inside the prototype odour-baited stations and 6) the local knowledge and experience of people living within the study area.

2 Materials and Methods

2.1 Study area

The study was conducted in Lupiro village (8.3854°S and 36.6702°E), Ulanga district, approximately 30 km south of Ifakara town, south-eastern Tanzania. The village lies in the Kilombero river valley at 300 meters above sea level with the rainy season starting from December - May. The annual rainfall ranges from 1200 mm - 1800 mm and temperatures of between 20°C and 32.6°C. The Kilombero valley is a seasonally inundated flood plain experiencing intense malaria transmission [20]. The main malaria vectors in the study village belong to the *Anopheles gambiae* complex of which one sibling species, *An. arabiensis* constitutes more than 90% [12, 13, 20]. Other disease-transmitting mosquito species in the village include; *An. funestus* (a secondary malaria vector in the area) as well as *Culex* and *Mansonia* species which transmit filarial worms and arboviruses [21-23].

2.2 Participatory mapping of mosquito larval habitats

Mapping of mosquito larval breeding sites was done using handheld geographical position system (GPS) receivers (Garmin Inc. USA). The investigator with assistance from community resource persons systematically searched in and around the study village to identify and demarcate the main breeding sites present and active at the time of the study. To determine whether the breeding habitats were active or not, presence of mosquito larvae in the water bodies was checked using a standard 350 ml larval dipper (Clarke Inc. USA) and the larvae identified as either *Anopheles* larvae or non-*Anopheles* larvae. Since this exercise was conducted during the dry season when active breeding sites were mainly irrigated rice fields around the study village, it was considered essential to map also potential (rainy-season) breeding habitats, which included rain-fed rice fields on the northern part of the village. The GPS data were downloaded, then exported and displayed as point data in ArcMap(ESRI Inc. USA) and used to create polygon features representing the larval breeding sites.

2.3 Mapping human houses and other infrastructure

Data on locations of human dwellings in the study area were collected using handheld GPS receivers (Garmin Inc. USA). The positions of other land mark features such as the gas station, police post, grain mill and schools were also recorded using the GPS receivers. Since this model was based upon outdoor mosquito dispersal and was meant to guide outdoor interventions, we did not consider any indoor house characteristics such as the number of people sleeping in the houses or the physical condition of the houses. Instead we used only the house location data.

2.4 Determination of mosquito distribution gradients

To determine how mosquitoes including malaria vectors were dispersed relative to the main breeding sites and aggregations of humans in the study area, mosquito sampling was conducted during the dry season in September 2009, at different locations in the study village. Since the main breeding sites in the area were irrigated rice fields, we envisaged that the trend observed during the dry season would more accurately represent the overall annual pattern of mosquito distribution gradients than trends observed in the rainy season, when even very temporary pools might contribute to increased mosquito densities. We therefore argued that interventions targeting mosquitoes at all times including when mosquito populations are lowest (as in dry seasons), would be better based on dry season mosquito density patterns than by wet season patterns. Moreover, it would also be logistically more practical to establish the interventions based on locations of the more permanent breeding sites than on the temporary small pools which would otherwise just be readily destroyed. Outdoor interventions such as odour-baited lure and kill stations would work best if mosquitoes were targeted at the time when their densities are lowest, and not when their densities are highest, such as in wet seasons (when the outdoor interventions would likely have only minimal impact on malaria transmission). Also, wet season breeding sites, which could include several temporary pools and which could be too numerous to target with lure and kill interventions, could more feasibly be dealt with using other measures such as environmental management and good drainage systems. Thus, this strategy was tested with an overall focus on the more permanent, long lasting larval breeding fields, which are the ones more likely to be found during the dry seasons.

A map of the village was first prepared in which five transects each having four trap locations, were specified. Transects were oriented north-east to south-west such that the first traps (Trap 1) for each transect was at the edge of the residential area and closest to the rice fields (the permanent dry season larval habitat), whereas the last (Trap 4) was near the centre of the village. Transects were approximately 200m from each other whereas the distance between individual traps within each transect was approximately 80m (Fig. 1). These distances were chosen to enable description of mosquito dispersal to the smallest possible resolution, while at the same time considering the logistically possible options with regard to the extents of the study area.

To avoid excessive heterogeneities resulting from differences in house designs [2, 24], or differences in number and attractiveness of household members to mosquitoes [10], the mosquito sampling was conducted outdoors as opposed to inside houses. For this purpose, we used an exposure free version of the Ifakara Tent trap, recently developed for sampling exophagic and endophagic mosquitoes [25, 26]. A total of 20 traps were positioned in the target area according to the prepared mapping plan (Fig. 1). Each trap was baited with single adult male human volunteer (aged 18-35 years) who slept inside them. Sampling was conducted for 16 days during which the volunteers in each transect rotated nightly to the different traps but within the same transects, such that at the end of the sampling period, each volunteer had been in each trap four times. Each morning the different taxa of trapped female mosquitoes were identified and counted.

2.5 Determining the safest distance from human dwellings

The odour-baited stations (OBS) used to exemplify this model uses synthetic attractants which are more attractive to host seeking mosquitoes at long range than humans but less attractive than the humans at short range, for example within households. It was previously reported that the number of mosquitoes that come to houses occupied by humans significantly increased whenever the synthetic attractants were added into those houses, but that once the mosquitoes were inside the houses, they preferred to go towards the humans as opposed to the synthetic lure [12]. In their publications, the authors further indicated that it would be inappropriate to use this or similar attractants close to human dwellings as it would increase the risk of mosquito bites and thus pathogen transmission to occupants of such dwellings. They also proposed that in real life operations, 30m was the safest distance from occupied households, at which technologies based on this attractant could be located. For the purposes of this model, we therefore conducted further field experiments to determine the actual distance-exposure gradient within this 30m cut off, and thus establish how this risk of exposure is affected by varying the distance between humans and the OBS.

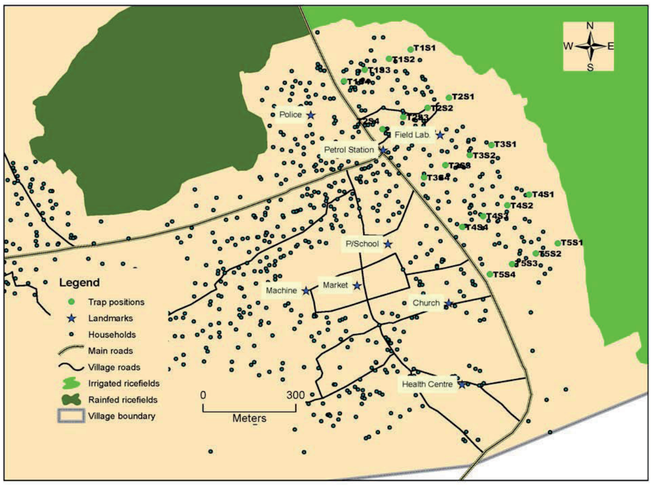

Figure 1. ***Outdoor mosquito sampling plan depicting breeding habitats, landmarks, human dwellings and trap positions.*** *The trap locations represented by letters T&S (T refers to "transect" and S refers to "station"). Therefore T1S1 represents a trap on Transect 1, position 1 whereas T1S2 represents a trap on Transect 1 and position 2 and so forth. Only dry season larval breeding sites are shown.*

The experimental design was as follows: Two sites were identified 200m apart along the edge of the study village and one OBS was located at each of the two sites. Ifakara Tent traps [25] in which human volunteers slept, were set up in a semi-circular formation around each of the two OBS, at different distances 5m, 15m and 30m from the OBS. To minimise directional bias resulting from wind effects, the traps at the three different distances were set up in three different directions respectively relative to the OBS. This arrangement ensured that the OBS was always between the tent traps and the front line of the larval habitat, and was therefore representative of geographical conformation of our study village with the rice fields at its edge. Each night, one of the OBS sites was used as a control (*i.e.* no bait added to the OBS) while the other acted as treatment (*i.e.* the OBS was baited with the synthetic lure). The treatment and control were rotated nightly between the two locations. The trap directions were rotated every six days such that at the end of the experiment, which lasted a total of 18 nights, each trap direction had been tested at each distance three times; and also both the treatment OBS and the control OBS had been at each site in nine different occasions. Each morning, female mosquitoes captured in each of the tent traps were sampled, identified and recorded by taxa.

2.6 Analysis of the entomological data

The entomological data was analyzed using SPSS version 16 (SPSS Inc. Chicago). To assess how mosquito densities varied with distance from rice fields, the average numbers of mosquitoes caught at each trap location were compared for different transects and also for all transects together. Correlation coefficients were calculated to describe the trends of distance versus mosquito density relationship. Regarding the experiment in which we attempted to determine the safest distances from the OBS, the number of mosquitoes caught per night was compared between the control site and the treatment site and also between the different distances from the OBS. The data was first split by distances so that controls and the treatments could be compared at any of the three distances (5m, 15m and 30m) separately. For each distance, the data was therefore fitted in Generalized Linear Models (GLM), log-transformed (using log-link function in SPSS) to normalize its distribution and then mosquito catches modeled as a function of whether the OBS had been baited or not (*i.e.* control vs. treatment).

By using control data as the reference and calculating the best fit regression between the control catches and the treatment catches at each of the distances one at a time, an intercept was obtained for each of the regressions, and this was exponentiated to obtain the relative rate of mosquitoes being caught in the treatment relative to the rate of mosquitoes being caught in control at any given distance. This allowed for the estimation of the number of mosquitoes caught in treatment (y) as a function of the number caught in control (x) at similar distances, while correcting for other factors such as site and day of experiment. The associated confidence intervals of the relative rates were also calculated. The exponential of the intercept is mathematically equivalent to the number of mosquitoes caught in a tent trap near a baited OBS whenever a single mosquito was caught in the tent trap at the same distance near a control OBS. Therefore, if the value of the exponential was found to be significantly higher than 1, it meant that the synthetic lure (treatment) increased the number of mosquitoes at that distance (and thus there was increased risk of mosquitoes biting anyone at that distance). On the contrary, if the exponential was equal to or significantly lower than 1, it meant that the treatment did not increase risk of mosquito bites to anyone at that distance.

2.7 Mosquito identification

The *Anopheles gambiae s.l.* were distinguished morphologically from Culicine species and Mansonia species. Malaria vectors in the study area comprise primarily of the *Anopheles gambiae* complex, though there is also a small population of *Anopheles funestus*. In a recent assessment we have previously determined that 99% of sibling species within the *An. gambiae* complex were *An. arabiensis*, the remaining being *An. gambiae sensu stricto* [13] and as such, no attempts were made to distinguish further the sibling species within this complex.

2.8 GIS location analysis and associated parameter values

The location model was implemented in a computer based GIS environment, using ArcGIS Desktop 9.2 (ESRI Inc. USA). A conceptual model showing all the procedures undertaken is shown in Fig. 2, with the associated legend briefly describing each of the steps followed. All the analyses were restricted to the extents of the study area. The following criteria were used to determine if any given location was suitable or not suitable for locating the lure and kill stations by ranking suitability of any selected location within the study area. Firstly, it was decided that the devices must be at least 10 meters from existing roads to avoid blocking the passageways and to minimise any likelihood of vandalism. Therefore all areas within 10m from the edge of the roads were considered unsuitable (attribute value = 0) for OBS locations and the rest considered suitable (attribute value = 1).

Secondly, we had originally set up a basic constraint that the devices must be placed at least 30 meters from nearest households, as the odour blend used attracts many mosquitoes and may therefore increase the risk of mosquito bites to inhabitants both when they are inside and when they are outside their houses [12]. However, based on the results of the experiment to determine safest distances from OBS (see details in results section), a gradient was introduced to this constraint as follows: areas within 10m from houses were considered completely unsafe for placing the OBS (attribute value = 0), areas 10 to 30m from houses were considered moderately safe (attribute value = 2), and areas further than 30m away from the houses were considered completely safe (attribute value = 3). Moderately safe distances represent areas where the OBS may still be used but with certain conditions for example ensuring that all persons living in nearby houses are provided with personal protection measures like bed nets and mosquito repellents. These attribute values included 0, 2 and 3 but not 1, simply because this model was multiplicative and therefore the value, 1 would mean no change on the output variable.

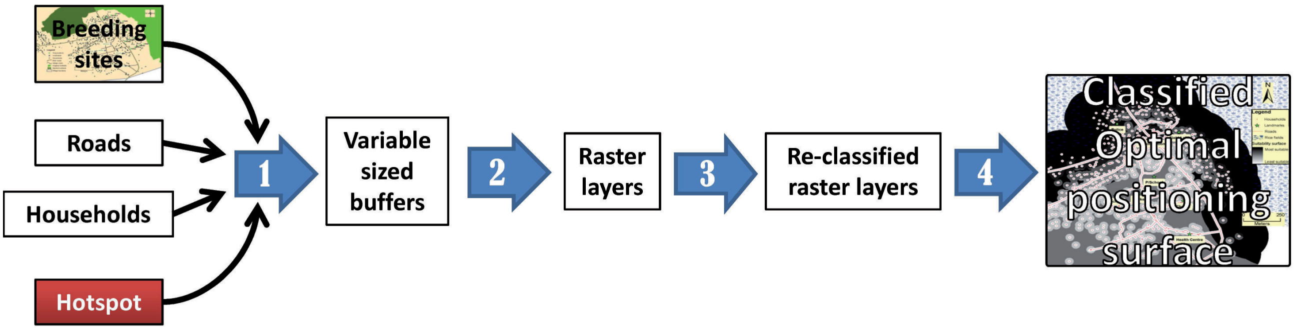

Figure 2. ***A schematic presentation of the GIS location modelling and analysis to determine suitable areas for locating odour-baited lure and kill stations.*** *In Step 1, buffers with customised dimensions specific for each layer were created around mosquito breeding habitats, roads, households and the hotspot within the village. The buffers were converted from polygon shapefiles to raster files in step 2. In step 3, the raster layers created in the step 2 were classified by introducing values to represent relevant characteristics unique for each raster layer. Finally using raster calculator tool ArcGIS (ESRI Inc. USA) in a single equation all layers were multiplied to give the model output.*

Thirdly, mosquito distribution relative to the larval habitats was classified using a 5-point suitability gradient derived from the data collected during the field experiment in which we conducted outdoor adult mosquito sampling. This experiment revealed that generally, the closer one gets to larval habitats (which in this case were at the edge of the village) the more likely one is to encounter mosquito bites (see details results section). Thus a uniform gradient of attribute values 5, 4, 3, 2 and 1 respectively was used, where 5 represents the highest likelihood of mosquito bites. However, during the same survey we also observed an abnormal increase in the number of catches of *Anopheles gambiae s.l.* in one particular location i.e. Trap 4 of Transect 2 (Fig. 1). Through direct observation, we linked this increase to a unique daily congregation of people around this particular location (which was at road junction where shops and a gas station were located and where many people come in the early hours of the night, thus attracting large numbers of mosquitoes towards this location).

We therefore added a separate feature layer with parameters representing gradually increasing mosquito densities with reducing distances from this particular hotspot. The parameter values for this new layer were as follows: areas within 50m of the road junction hotspot were considered to have highly increased mosquito densities (attribute value = 3) while areas between 50 and 100 metres from the junction were considered to have moderately increased densities (attribute value = 2). All areas beyond 100m were considered to experience no change specific to this human congregation phenomenon (attribute value = 1). These distances were considered reasonable estimates and were guided by the nearness of the place where the abnormally high densities of *An. gambiae s.l.* mosquitoes were caught to the place where there was the unique daily aggregation of people.

2.9 Community approximation of areas where mosquitoes are most abundant

For small scale operations such as implementing the OBS technology in a single village or in a small number of villages, the GIS based location modelling incorporating entomological data collection may be considered suitable and accurate. However, we envisaged that the actual process of geographical and entomological data collection as we have conducted in this small scale operation would be too cumbersome and time consuming to be feasible in large scale operations; for example where the technology is to be implemented in several districts at the same time. We therefore sought to test a cheaper, quicker and easier method of determining where mosquitoes are most abundant, and which would potentially be used to guide large scale implementation of OBS or similar technologies. This new concept was based on simply asking resident community members to point out where they think, based on their own personal experiences, the mosquitoes would most likely be.

Focused group discussions and participatory map-reading sessions were conducted during which community members were guided and asked to study maps representing their own village and then to point out different areas where they expected to find the highest mosquito densities based on their own experiences. The village map (Fig. 3), was prepared in ArcMap (ESRI, Inc. USA) and depicted important landmarks including schools, households' GPS points, a health centre, a police post, a petrol filling station, a market and surrounding rice fields. It was overlaid with equal sized square grids measuring (grid size =120m $\times$ 120m, total number of grids=266), also shown in Fig. 3. This grid size was selected so as to be able to communicate information clearly on a small (A4) paper map to community mem-

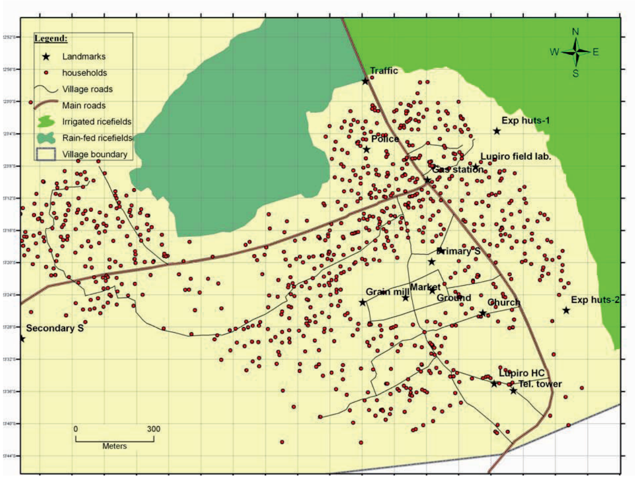

Figure 3. ***A map of the study area overlaid with grids, used to guide discussion and approximation of mosquito densities with community members.*** *Important landmarks (indicated in the map legend) were used to guide participants in a focus group discussion session where they were asked to rank the grids to depict the relative density of mosquitoes they would expect to find in each grid.*

bers, so that the participants could visually differentiate one place to another, but also to obtain the smallest possible yet most workable resolution map of the study area. A total of 57 community members from the study village participated in the map reading sessions. The participants were in three groups as follows: 20 adult villagers, 20 primary school children and 17 secondary school children and the sessions were conducted separately for each group as follows: Firstly, a brief introductory remark aimed at priming the session was provided by the facilitator focusing on: 1) the purpose of the study, 2) the life cycle of mosquitoes particularly malaria vectors, and 3) the role of mosquitoes in disease transmission. This was followed by a session on discussions, questions and answers with the participants.

Secondly, the gridded maps were handed to each individual participant and this was also followed by a brief discussion about map reading, including village orientation (East, West, North and South) and the identification of important landmarks within the study area. Once the participants were conversant with the map reading exercise and could identify important landmarks based on the map key, each participant on his/her own was asked to select 10 grids and rank the likely mosquito densities using numbers 1-10 (1 for most abundant and 10 for least abundant) and thus depict which grids they expected to find the largest number of mosquitoes based on their knowledge and experience.

Once all the data was collected, weights representing mosquito abundance were assigned such that grids with rank of 1 were assigned an arbitrary weight of 10 whereas grids with rank of 2 were assigned a weight of 9 and so forth. For purposes of analysis, grids that were not selected by the respondents were considered to missing values, but not as zero values. The final value (representing mosquito abundance) for each individual grid (g_i) was calculated as the sum of the products of rank assigned by the respondents and the number of respondents assigning that particular rank to that particular grid as follows:

$$g_i = (r_1 \times f_{r1}) + (r_2 \times f_{r2}) + ... + (r_{10} \times f_{r10})$$

Where g_i refers to the value for the $_i$th grid; f_{r1}, f_{r2}, ... f_{rn} refer to the number of times a rank has been assigned to the $_i$th grid and r_1, r_2, ... r_{10} refer to the ranks in the scale of 1-10.

For each grid, the centroid (latitude and longitude) was used as the reference GPS point to enable creation of a community approximation map file containing values for all grids with their corresponding coordinates.

2.10 Comparison of mosquito distribution maps

To enable direct comparison, two GIS interpolated maps covering the same geographical extents of the study area were produced based on the outdoor mosquito sampling and the community approximation technique as follows:

A worksheet was prepared with trap locations and corresponding data on cumulative number of mosquitoes of different species collected over the 16 trapping nights. The mosquito species collected were *Anopheles gambiae s.l*, *Culex* species, *Mansonia* species, *Coquilletidia* species, and *Aedes* species. The point data were imported to ArcGIS and displayed using the ArcMap application (ESRI, Inc. USA). Based on the assumption that geographical features near each other are likely to be more related than features that are distant apart [27, 28], mosquito distribution outdoors was determined using inverse distance weighted (IDW) method of interpolation. This is a deterministic interpolation model that assigns values to locations where no measurements have been taken, based on how far those locations are to sentinel locations where measurements have been taken. This way, the interpolation surface was therefore used to make predictions from the trap catches, for all locations in a raster dataset representing the study area.

Similarly, the community approximation data obtained from the focused group discussion and map reading sessions was subjected to GIS interpolation using the same method, restricting the study area to that covered by the outdoor trapping exercise. During the community approximation procedure there were some grid cells that had not been selected by any member and which therefore had no data.

This interpolation therefore enabled us to predict likely values for these grid cells and thus obtain a uniform interpolated map covering the entire target area. It should be noted therefore that even though the input data for this interpolation was limited, the interpolations enabled us to generate values even for locations that were not originally sampled, based on how far those particular locations were from the sampled sites.

The two interpolation maps were then visually inspected to identify similarities in the location of distinctive hotspots (areas with highest mosquito abundance). We also examined if by targeting interventions on the basis of the hotspots depicted in the interpolated community approximation map, it would be possible to also protect the hotspots depicted in the interpolated traps map (the trapping data being considered the field reference). We envisioned that if it was possible to target interventions on the basis of community knowledge and experience, and still achieve the necessary coverage in the field, then this would be a more readily replicable method for large scale or multiple operations in future.

2.11 Ethics statement

Prior to the entomological experiments conducted during this study, a full explanation of the risks involved and the objectives of the study was provided, after which written informed consent was obtained from the volunteers sleeping in the tent traps, all of whom were male and aged between 18-35 years old. The tent traps used here were exposure free, meaning that the trapped mosquitoes would not possibly reach and bite the volunteer inside the traps. All participants were guaranteed access to treatment including weekly screening for malaria parasites by light microscopy and treatment with artemether-lumefantrine; however no participant was affected during the study.

In addition all the other activities including the focus group discussions and the map reading sessions were conducted with the full knowledge and permission from the village leaders and the participants themselves. Ethical approval for the study was obtained from both the Ifakara Health Institute's Institutional review board and the Medical Research Coordination Committee of the National Institute for Medical Research of the United Republic of Tanzania.

3 Results

3.1 Breeding habitats

The main malaria mosquito breeding habitats were the irrigated rice fields on the eastern and north-eastern part of the village and a rain-fed rice field on the northern part of the village (Fig. 1). These habitats are principally large chunks of land sub-divided into small plots for individual farmers and used primarily for rice cultivation. Habitats were mapped as a single block since the individual plots were contiguous with each other.

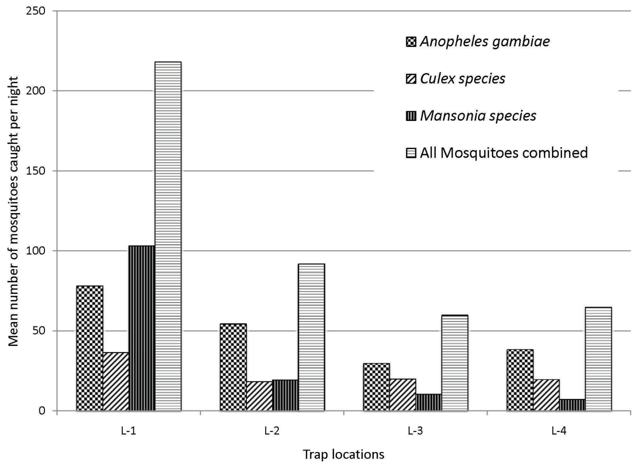

Figure 4. ***Relationship of mosquito densities in the study area and distance from larval breeding sites.*** *The tent traps were located such that trap 1 (L-1) in each transect was at the edge of residential areas and closest to the main breeding sites and trap 4 (L-4) was near the centre of the study area as illustrated also in Fig. 1.*

3.2 Mosquito density gradients relative to larval breeding habitats

Mosquito catches (*An. gambiae s.l.*, *Culex* species and *Mansonia* species) were higher in traps closer to the rice fields (Fig. 4), as compared to those closer to centre of the village. Generally, there was a strong relationship between distance from breeding sites and number of mosquitoes trapped; *An. gambiae* (R^2 =0.875, P = 0.007), *Culex* species (R^2 = 0.713, $P < 0.001$), *Mansonia* species (R^2 = 0.861, $P < 0.001$) and total mosquitoes (R^2 = 0.884, $P < 0.001$). However, an increased number of *An. gambiae s.l.* was observed at the location of trap 4 along transect 2 compared to the other traps at the same position in other transects. Other mosquito species caught (albeit in small numbers) included *Coquilletidia* species, *Aedes* species as well as *An. coustani*.

3.3 Risk of mosquito bites at different distances from odour-baited lure and kill stations

The average (and 95%CI) number of mosquitoes caught per night at the control site (where the OBS was not baited) and treatment site (where the OBS was baited with the synthetic lure), were 22.94 (19.45-26.44) and 24.35 (19.57-29.53) respectively. Of these there were 2.56 (2.09-3.02) *An. gambiae s.l.* per night at the control site and 4.47 (2.99-6.35) *An. gambiae s.l.* per night at the treatment site. The other mosquitoes included 2.56 (1.63-3.49) *Culex* mosquitoes at the control site and 4.67 (1.44-7.89) of the same genera at the treatment site, 11.13 (6.93-15.33) *Mansonia africana* at the control site and 9.31 (6.28-12.35) of the same species at the treatment site and also 6.70 (4.39-9.02) *Mansonia uniformis* mosquitoes at the control site and 5.70 (4.22-7.19) of the same species at the treatment site.

Considering data for the malaria vector *An. gambiae s.l.* only, we observed that at 5m from the OBS, the number of mosquitoes caught in human baited tent traps was increased in the treatment sites relative to the control sites. The relative rate of catching *An. gambiae s.l.* at a distance of 5m from the baited OBS was 2.403 (1.787-3.232) times higher than the rate of catching the same mosquito species at the same distance from the unbaited OBS ($P < 0.001$). However no increase in *An. gambiae s.l.* catches was observed at 15m or at 30m distances. When the data for all mosquito species were combined (indicating all potential bites from all mosquito species in the area), we observed that there was also increased exposure at 5m distance (relative rate = 1.321 (1.180-1.479), $P < 0.001$) and at 15m distance (relative rate = 1.281(1.167-1.415), P = 0.002) but not at 30m distances (relative rate = 0.952 (0.821-1.105), P = 0.520).

Based on these results, it was clear that the synthetic lure would increase the likelihood of being bitten by *An. gambiae s.l* at 5m distances and by all mosquito species at 15m distances. However, at 30m, no increased exposure to the mosquitoes was evident. For the purposes of the GIS model, 10m distance was therefore considered the cut off point to represent distances around human houses within which the synthetic lure should never be used. This 10m distance was considered a reasonable estimate for two reasons: firstly it was the mean of the two safe distances *i.e.* 5m as calculated for *An. gambiae s.l* and 15m as calculated for all mosquitoes, and secondly because in practice, if an OBS were to be located 15m away (being the furthest safe distance from any human), then considering the local houses in our study village, it would actually be approximately 10m from the outside wall of the house and an additional average of 5m away from a person inside the house.

Thus the GIS modelling and analysis (see details in the methods section) was based on the argument that areas within 10m from houses are completely unsafe for placing the OBS (attribute value = 0) and areas further than 30m away from the houses were considered completely safe (attribute value = 3). All areas between 10m and 30m from houses are considered moderately safe and are only considered for placing OBS if residents in surrounding houses are provided with additional protection such as insecticidal bednets and mosquito repellents (attribute value = 2).

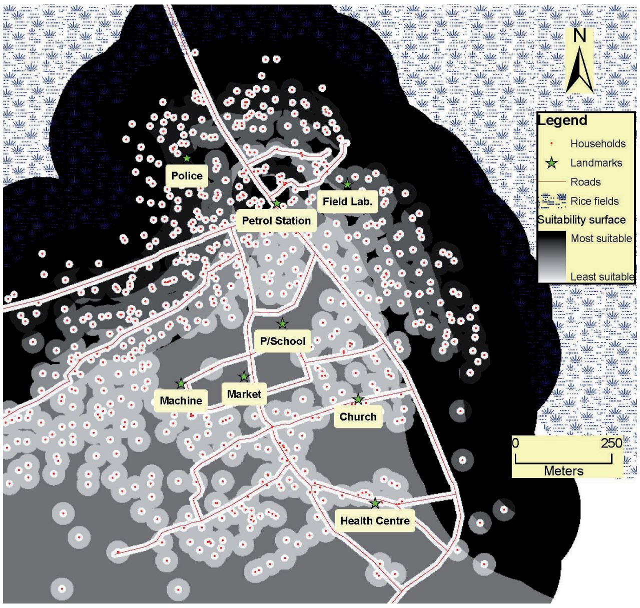

Figure 5. ***GIS location model output showing suitability of different areas of the study areas for locating the OBS.*** *The map shows most suitable to least suitable areas for positioning the candidate odour-baited lure and kill stations (OBS) for controlling mosquitoes.*

3.4 Optimal locations for the odour-baited stations

The GIS generated optimal location map surface and its associated keys and legend is presented in Fig. 5. It shows the most suitable areas where our selected candidate outdoor intervention (the OBS) could be stationed, and also surfaces that are determined to be least suitable for locating the OBS. Since the model incorporated parameters from different input features some of which were negatively correlated to the suitability for locating the OBS, some households appear in the middle of the most suitable location sites with exception of the 10m radius (which according to this multiplicative model, were considered to be unsafe for locating the devices as this would increase exposure to mosquito bites and were assigned an attribute value of zero). Similarly, all areas within 10 metres of the road are depicted as being unsuitable surfaces for the OBS.

Generally, it is apparent from this analysis that the best locations for the devices would be at the edge of the study village, or between the larval breeding habitats and human settlements. However, the optimal surface map shows also that there are areas within the village (for example areas around the Petrol Station in Fig. 5) that are suitable for the OBS and which would need to be targeted for outdoor mosquito control as well. Though not expressly delimited

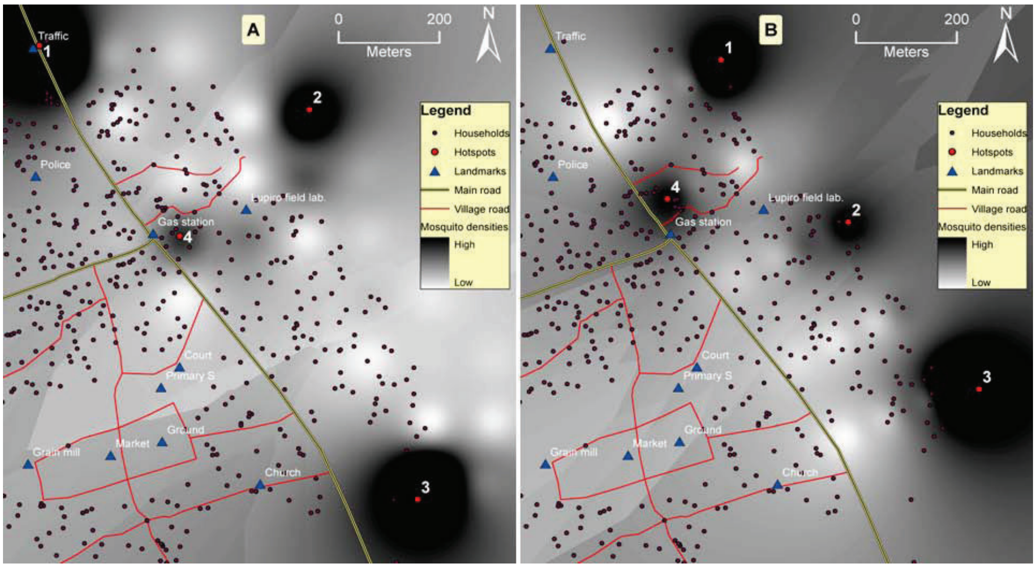

Figure 6. ***Mosquito densities derived from inverse distance weighted (IDW) interpolation model.*** *Panel A (left) represents an interpolated map derived from the community approximation of mosquito densities in their environments based on their knowledge and experience. Panel B (right) represents approximation of mosquito densities derived from the data obtained during outdoor mosquito sampling conducted in the same study area. Comparison of the interpolation results is likely to have higher accuracy where sampling sites were located (north eastern part of the study area), than in the south western part where there were no actual sampling sites.*

in our map (Fig. 5), it would be unreasonable to locate any OBS far away from the village and in the middle of the rice fields. Instead, such devices would better be located between the rice fields and the human settlements as depicted in the figure.

3.5 Visual interpretation and comparison of mosquito densities

The community members indicated their opinion about mosquito densities within their environment on the gridded A4 paper map with different ranks assigned. Due to limited knowledge on differences between malaria vectors and other mosquito species, they identified the densities of total mosquito population as any species and not necessarily as malaria vectors. Some of the cells were picked more frequently than others, and there were also grid cells that were left blank. The choices by the three different community groups were comparable, indicating a common knowledge of mosquito distribution among community members.

When the final grid values calculated using equation 1, were input into ArcGIS and analysed using the Inverse Distance Weighted interpolation method, the resulting mosquito distribution surface (Fig. 6A) was comparable to the distribution surface obtained from interpolation of mosquito trapping data (Fig. 6B). By visual interpretation, it can be observed that both community approximation and empirical outdoor traps information produced four distinct hot spots (representing areas of highest mosquito densities) in comparatively the same geographical areas (Fig. 6).

Interpolation of the outdoor mosquito trapping data revealed three hotspots along the edge of the village (spots 1, 2 and 3 in Fig. 6B) and an additional hotspot at the centre of the village (spot 4 in Fig 6B), somewhere close to the gas station where we had also observed the large human aggregation. Similarly, interpolation of the community approximation data revealed three hotspots also at the edge of the village (spots 1, 2, and 3 in Fig. 6A) and an additional hotspot in the middle of the village (spot 4 in Fig. 6A) also close to the gas station. Even though the geographical positions of these spots in the two different maps are not exactly congruent, the extents of displacement were generally small except for spots 1 and 2 in both maps which seemed to be slightly over-displaced, approximately 200m northwestwards and thus occupied different positions.

4 Discussion

Owing to the expense, logistical and technical challenges involved in undertaking vector control, it is necessary to have prior information to guide the operations and thus maximise the potential benefits while minimising costs of implementation [29-32]. The purpose of this study was to develop a model planning tool in form of a location model necessary for deploying odour-baited lure and kill technologies for the control of disease transmitting mosquitoes in rural Africa. It was intended that this GIS model would help to classify all areas within a given study village in terms of how suitable or unsuitable they are for locating the OBS; and therefore to determine optimal surfaces to locate the outdoor devices in relation to: 1) the distribution patterns of both mosquito populations and human populations, 2) characteristics of the intended lure and kill technology, 3) the location of the main breeding sites and 4) other factors such as the road infrastructure network. Obviously, some of the results we report here may not have been unexpected, for example the fact that mosquito densities generally decreased with increasing distances from larval breeding sites. Nevertheless, one other important objective of this work was to demonstrate how such ecological parameters could be used in GIS-based models to plan the positioning of outdoor lure and kill stations.

By applying this technique to our study village in rural Tanzania, we determined that the devices would best be placed at the edge of the village, such that they are between the breeding sites and the people and in a few locations in the middle of the village where mosquito densities were found to be high. This way, the newly emerged host seeking female mosquitoes would easily get lured into the devices and either trapped or contaminated by agents such as toxicants, insect growth regulators or even biological agents such as mosquito killing fungi [14, 33-35].

Even though this model was exemplified using a specific lure and kill device that was recently developed and tested in rural Tanzania [13, 14], different characteristics may be incorporated in the model to represent any other outdoor intervention used for targeting adult disease-transmitting mosquitoes. These may include mass trapping devices [36, 37], or other odour-based sites where mosquitoes would be attracted then passively contaminated with larvicides which the mosquitoes can then transfer back to their own breeding habitats [35]. Moreover, even though we applied this approach to a specific study village, the principles of the technique and its associated arguments may be used to perform the same exercise for any other area selected for a study or an actual intervention. The results in such cases would therefore depend on the input parameters representative of that study area and the selected outdoor intervention technology.

Currently, the most commonly used interventions against disease-transmitting mosquitoes, indoor house spraying with residual insecticides (IRS) or insecticide treated nets (ITNs) are intra-domiciliary in nature and target only mosquitoes that attempt to enter or those that enter human dwellings. It may be argued that one disadvantage of such strategies is that they do not consider the actual geographical distribution of the mosquitoes and therefore cannot control transmission that occurs outside human houses. The odour-baited lure and kill devices that are used to test this approach were developed to target mosquitoes outside human dwellings and are designed in such a way that they can be easily positioned and even moved to different areas predetermined to have most of the mosquitoes. This geographical model therefore provides the necessary planning and implementation tool that would ensure the desired success of the OBS or similar technologies.

To accurately approximate the outdoor distribution pattern of the mosquitoes, data used in the model was collected using outdoor traps [25, 26] as opposed to indoor mosquito collections which would otherwise be amenable to several intra-house variations potentially caused by differences in number of house occupants, differences in house design [1, 2, 24, 38] and perhaps even the differential attractiveness of humans to mosquitoes [10, 39]. The geo-location analyses were thus based on outdoor distribution of mosquitoes as opposed to indoor distribution and did not consider any characteristics of human dwellings other than their geographical locations.

By considering the most obvious factors affecting distribution of disease transmitting-mosquitoes and then modifying these factors with additional data obtained from field experiments in the study area, established information on ecological and epidemiological heterogeneities [15, 40] was supplemented with empirical data describing actual patterns in the study village. One advantage of this approach was that it enabled identification of important discrepancies specific to the study area and which needed to be incorporated so as to maximise the accuracy of the model and thus improve effectiveness of any intended intervention. For example even though it was previously known that mosquito densities decrease with increasing distance from their larval breeding sites [15], we observed from the direct outdoor mosquito density survey, that there was an abnormally high density of the malaria vector *An. gambiae s.l* at a location near the road junction and petrol station (Figs.1 and 5). When investigated further, it was observed that people spend a lot of time around the junction during the early hours of the night as it is a main business area, a phenomenon that would expectedly increase anthropophagic mosquito densities [15]. Depending on village characteristics, as well as time and place-related behaviour of people, it can be expected that such human aggregations and the resulting effects on mosquito densities may be observed in different spots in different villages, for example around open-air markets, in villages where people stay there until the early hours of the night. Also, in places where mosquito species are known to be zoophilic and where residents keep cattle, it might be important to include cattle aggregations as well in the models. The village within which the current work was done was purely agronomist, with chicken as the only livestock kept, thus it was not important to consider aggregations of cattle in addition to human aggregations.

We propose that the determined OBS locations in relation to the human dwellings must be considered as a trade off between the desired protection and the safety of the house dwellers. The synthetic lure used in the OBS is a long range attractant and would concentrate biting mosquitoes to areas closer to the households. A distance of 30m is considered safe here while distances within 10m are considered unsafe, therefore in situations where it is necessary to place an OBS 10-30 meters from nearest households, the inhabitants of those houses must be provided with the other protection measures such as insecticide treated bed nets or insect repellents for personal protection. Nevertheless, we propose also that the OBS or any similar outdoor intervention should always be used only to supplement rather than to supplant existing vector control interventions like the ITNs and IRS.

One other likely application of this model is that it could be used in combination with other models to compute the required number of units for outdoor intervention and also to compute the cost of covering any given area. For example if odour-baited traps are known to have capacity to lure mosquitoes from a given acreage, it would be possible to compute how many such devices would be necessary to cover the locations deemed suitable using this model. Since transmission of most infectious pathogens including mosquito-borne diseases is known to occur heterogeneously, such that most transmission results from only about a fifth of the entire extent of populations or geographical areas [40], this paper was focused primarily on determining places where mosquitoes are most abundant and where interventions should therefore be targeted, to address most of the biting exposure, it may be important to determine thereafter how many such devices would be required to actually address this need. Our earlier estimates using deterministic mathematical models show that where breeding sites are easily identifiable, and depending on various epidemiological characteristics of an area, such as the mosquito species and human/animal population densities, 20-130 odour-baited stations per 1000 people may be required to match the benefits of 50% coverage with insecticide treated nets, currently the primary malaria vector control strategy [41].

The true value of OBS proposed in this model present some challenges in deployment as an intervention due to its dependency on industrial carbon dioxide from pressurised cylinders [13]; however some efforts are under way to do away with this dependency [14] and to develop cheap and more readily available mosquito lures. Although the GIS-based map model is seen as precise and important planning tool in deployment of the lure and kill stations against adult mosquito vectors, in some situations it may be economically, logistically and technically challenging, and thus impractical for large scale operations. As an attempt to address these potential challenges, this work also examined if knowledge and experience of community members may be exploited to approximate mosquito densities within their environments, especially in rural and remote areas. The results of the comparative interpretation of the empirical mosquito survey data versus the data gathered through community approximation provided promising evidence that community members could near accurately estimate the densities of disease transmitting mosquitoes albeit with minor errors. Indeed it can also be argued that even though there were minor positional displacements as shown in Fig. 6, the proximity of the hotspots identified in the two maps and the likely mosquito dispersal patterns could still ensure that effects of outdoor interventions deployed on the basis of the community approximation map, could also be experienced in the actual spots as depicted in the map generated from empirical data.

Unlike regular entomological sampling, such community based approaches may not be useful to distinguish between mosquito species, or to distinguish nuisance biters from actual disease vectors, since community members may not have this expertise. However, because most mosquitoes that are nuisance biters for example *Culex* and *Mansonia* species in rural Tanzania, may also transmit diseases like filarial worms and arboviruses, and based on our observations in the rice growing area that these species often have their breeding sites in close proximity to the breeding sites of major malaria vectors, the community based approach would remain an appropriate means of mapping mosquito densities, especially for purposes of targeted and integrated control of mosquito-borne diseases.

Another important aspect of this methodology is that in our survey, the responses from community members were not restricted to 'yes or no' answers. Instead, the respondents were provided with a gridded map and asked to rank different locations on the basis of how many bites they would expect to find in each location relative to any other location in the study area. We argue that such ranking (as opposed to asking people to simply select one place where they would expect mosquitoes to be most abundant) combined with the lifelong experiences of community members would produce a fairly consistent picture of mosquito distribution in an area. Moreover, our methodology also involved initial sensitization and guided map reading sessions, both of which were aimed at obtaining a more accurate map surface which could be obtained by respondents simply selecting one preferred location. Though this participatory technique was tested here only as a small component of the main study and thus still needs additional field evaluation, it is a highly promising technique which would be cheap, easy-to-perform, readily replicable and highly scalable. We therefore propose that it should be considered a potential new way, to be developed further for use in large scale operations involving similar outdoor interventions. Perhaps most importantly, this approach was tested for the first time here and it will therefore require further experimentation in different geographical settings to determine its sensitivity.

5 Conclusion

The renewed interest in elimination and eradication of mosquito borne diseases such as malaria requires the development of new vector control interventions to complement existing ones such as the ITNs, IRS and larval control. This study demonstrates the feasibility of identifying the most suitable locations of prototype complementary outdoor interventions, so as to maximise benefits through appropriate targeting and also to minimise logistical challenges and costs of implementation. Though the geographical location model has been implemented with parameter values descriptive of one study village and one type of outdoor intervention, it has the potential to be used for different study areas and for different outdoor lure and kill interventions. For example, the approach may be used to improve malaria prevention by geographically targeting outdoor adult mosquito control (using odour-baited lure and kill technologies or similar interventions that require optimal positioning). Finally, we recommend that the use of community based approximation method tested here for determining areas where mosquito densities are highest and where outdoor interventions should be targeted, need to be investigated further in multiple geographical areas to determine if it would hold true in different settings, as it could potentially be a cheap, easy-to-perform, readily replicable and scalable way of planning and implementing outdoor interventions in future operations.

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