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Application of geographic information systems to the study of the ecology of mosquitoes and mosquito-borne diseases

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Abstract

Geographic information systems (GIS) are powerful computer mapping and analysis systems for studying spatial patterns and processes; they are applicable to numerous disciplines, including the study of mosquito ecology. The distribution of mosquitoes is largely dependent upon the spatial distribution of their larval breeding sites, their flight range and the spatial distribution of their preferred hosts. These are all heterogeneous in space and time and GIS therefore has many potential applications to the study of mosquitoes and the diseases they transmit. GIS may be used to map and analyse the spatial distribution of mosquitoes and to assess the ecological factors that contribute to observed distributions. A detailed understanding of what drives heterogeneities in the distribution of mosquitoes and mosquito-borne diseases can help to design better, more efficient control programmes that maximize the use of limited resources.
Keywords: geographic information systems; remote sensing; mosquitoes; malaria

Introduction

Geographic information systems (GIS) are computerized systems capable of integrating, displaying and analysing large quantities of spatial data (Vine, Degnan and Hanchette 1997). A GIS is a powerful tool for elucidating spatial patterns and processes. In addition, GIS is able to link spatial and non-spatial data, allowing for a wide range of display and analysis capabilities. GIS has applications in numerous fields of study, including marketing, agriculture, forestry, animal ecology, transportation planning and public heath (Clarke, McLafferty and Tempalski 1996). Applications in public health include the estimation of spatial variation of disease, determination of risk factors of disease, and improved delivery of health services (Briggs and Elliott 1995; Tanser and Le Sueur 2002; Vine, Degnan and Hanchette 1997).

The use of GIS has increased dramatically in recent years due to several factors. One is the recognition of its application to a wide range of disciplines. However, its widespread appeal was made possible mainly by increasing technological developments. The advent of powerful, inexpensive personal computers and the development of easy to use, menu-driven GIS software made it possible for persons with little or no expertise to design and conduct spatial studies. Lastly, the acquisition of spatial data has become easier. Global positioning systems (GPS) have become less

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expensive and easier to use with increased capabilities for rapidly collecting both spatial and non-spatial data. For many applications, spatial data already exist and public-domain digital maps can be downloaded from the Internet (Clarke, McLafferty and Tempalski 1996; Moore and Carpenter 1999).

GIS has many applications to the study of vector-borne diseases, as many of the underlying processes influencing the distribution of insect vectors of disease are spatially heterogeneous. Mosquitoes require pools of water in which to breed and the short flight range of many species limits the adult populations to areas surrounding their breeding sites. Recently, there has been interest in applying GIS to study the continental and global distribution of malaria and the mosquitoes that transmit malaria (Coetzee, Craig and Le Sueur 2000; Craig, Snow and Le Sueur 1999; Omumbo et al. 1998). These continent-scale studies have also been used to estimate the impact of global warming on the distribution of mosquitoes and malaria.

On a smaller scale, GIS has several applications to the study of mosquito biology and ecology. In many cases, GIS is the best or the only available method to answer questions regarding mosquito ecology. Studies of risk as a function of distance from known breeding sites are one common application of GIS. This is particularly useful in areas with a small number of discrete breeding sites around urban or highland areas where mosquitoes exhibit strong spatial patterns over short distances. Using knowledge of the distribution of adult mosquitoes and the distribution of larval breeding sites, average flight distances of malaria vectors may be inferred using GIS. GIS, in combination with remote-sensing (RS) technology, has also been employed to predict areas of high productivity of mosquitoes and potential malaria epidemics based on the detection of proxy ecological variables (Hay et al. 2000; Thomson et al. 1996). Other factors affecting the distribution of mosquitoes, such as the distribution of available hosts, have been investigated with GIS. The rapid decline of adult mosquitoes at the onset of the dry season and the rapid increase at the onset of the rains has puzzled mosquito biologists. Various hypotheses to explain the rapid changes in adult numbers include aestivation of adults through gonotrophic dissociation, extended survival of eggs and larvae on wet or damp soil, or survival in focal refugia where breeding may occur year-round. Through repeated measures of mosquito abundance over time, GIS may be applied to identify the location of potential dry-season refugia of mosquitoes. GIS has been applied to estimate the impact of insecticide-treated nets (ITNs) on the spatial distribution of malaria vectors. The results suggest that ITNs derive some of their benefit from an area-wide impact on adult mosquito populations and that this benefit may extend into areas where ITNs are not used. Lastly, GIS has application in the design and implementation of control activities that target the vectors of disease. In this paper we describe the development and application of GIS technology to the study of mosquitoes and malaria.

Development of a GIS

The development and application of a GIS includes 3 components: data acquisition and management, visual presentation and statistical analysis. The first factor to take into consideration is the scale that is relevant to the questions being addressed (Clarke et al. 2002; Moore and Carpenter 1999). The selection of scale is critically important as biologically relevant spatial patterns may be masked if the scale is not appropriate. The scale should take into consideration the question being addressed and the biological processes underlying the topic under study. Continental- or regional-scale models may help further define the relationship between climate and the risk of

malaria, better quantify risk over large geographic regions and assess the potential impact of climate change on malaria distribution. However, these models mask local-scale variation. For studies of mosquito ecology, the appropriate scale is likely just a few kilometres as the relevant underlying biological process (flight range) is usually less than 1 kilometre.

The acquisition of spatial data may be done by several means. First, existing maps or aerial photographs may be digitized and imported into a spatial database. This has already been done for many areas and public-domain maps may be available on the Internet for many areas of developed countries (Clarke et al. 2002; Moore and Carpenter 1999). In addition to Cartesian coordinates, other geo-referenced information such as postal codes or even specific addresses may be available in these countries. Unfortunately, reliable maps, aerial photos and other geo-referenced information often are not available in developing countries. Also, for the study of mosquito ecology, it is often necessary to map features that do not appear on existing maps (e.g. small bodies of water). In these cases, one may develop maps using GPS technology. Simple hand-held GPS units have become increasingly affordable and easy to use and may be employed to rapidly generate accurate maps. Many GPS units even allow for data entry so that non-spatial data, linked to a geographical feature, may be recorded at the same time as the geographical position. Simple GPS is often adequate for many spatial studies as there are many sources of error that may reduce its accuracy. If more accurate readings are desired, differential GPS may be employed. This approach can generate positional data that are accurate to within one metre (Hightower et al. 1998). Additional, non-spatial data may also be linked with positional data for incorporation into statistical models.

Numerous software packages make presentation and simple analysis of spatial data easier than ever. The use of maps showing spatial patterns may be regarded as a simple, straightforward approach to data analysis as many spatial patterns are evident when simply presented on a map. Spatial patterns may be presented using contours, sized symbols and shading. In addition, a GIS can estimate distances, conduct buffer analysis, perform a spatial query on data from multiple sources and perform polygon overlay analysis. While simple visual presentation is often sufficient to discern spatial patterns, it is often necessary to perform formal data analysis. Data analysis methods for spatial data are numerous and varied. Detailed description of spatial-data analysis methods is beyond the scope of this paper (for more detailed discussion, see Moore and Carpenter 1999), however, they may be grouped into exploratory analysis and modelling. Exploratory analytic techniques are generally used to identify clusters and determine whether these occur by chance. Many of these methods do not account for underlying distribution of populations but are a quick way to assess 'hot spots' that may deserve further investigation. Other exploratory techniques include kriging and Bayes methods for data smoothing and interpolation. Results can easily be presented in the form of surface maps employing colour shading to indicate areas of high or low risk. Overlaying these interpolated maps on other geographic features is an informal approach to identifying potential risk factors. More formal data analysis can also be done by modelling, integrating GIS data with standard statistical models. Unfortunately, many entry-level GIS software packages do not allow for advanced analytic techniques but these may usually be done in existing statistical packages.

Applications in mosquito ecology

GIS has many applications to the study of mosquitoes and mosquito-borne diseases. The distribution and abundance of mosquitoes and other vectors of human disease are often determined by factors that exhibit clear spatial heterogeneity. The most obvious factor influencing the distribution of mosquitoes is the distribution of breeding sites. The distribution of available hosts and the distribution of vector-control interventions may also affect mosquito abundance and distribution. Below, we review some of the applications of GIS technology to the study of malaria vectors, with an emphasis on the vectors in sub-Saharan Africa.

Mosquito abundance and distance from breeding sites

There have been numerous studies demonstrating the spatial distribution of malaria vectors as a function of distance from known or suspected breeding sources. Larval mosquitoes are usually highly aggregated in pools of waters with specific characteristics. The distribution of adults is largely dependent upon the distribution of these larval habitats and the flight range of the adults. Using this information it is possible to estimate and even predict the risk of exposure (i.e. infectious bites) based upon the distance to known breeding sites.

Smith et al. (1995) described the small-scale spatial and temporal variation in the abundance of malaria vectors in a single village near Ifakara, Tanzania. They mapped the houses in the village using GPS and performed CDC light-trap collections from a subset of houses every two weeks for one year. Mosquito abundance was modelled using several statistical methods to adjust for spatial and temporal effects as well as the effect of non-spatial variables such as the presence of windows or animal sheds. Contour maps were generated based upon the models and overlaid on maps of the study area. Areas of high mosquito abundance within houses tended to correlate with low-lying areas near streams and rice fields. However, after accounting for housing density, it was observed that the average number of *Anopheles gambiae s.l.* per hectare was highest on densely populated ridges at the centre of the village. This demonstrates that the underlying distribution of houses may affect apparent spatial patterns and that the unit of measure (number per house vs. number per hectare) must be selected carefully. For ecological studies assessing overall population densities, the number of mosquitoes per hectare may be the more appropriate unit of measure. However, studies of malaria epidemiology are usually interested in estimating the exposure of individual persons and the number of mosquitoes per house may be the more appropriate unit of measure for these studies. This effect of different units of measure was less pronounced in *An. funestus*, which had the highest density per house and the highest density per hectare in the low-lying areas of the village.

Ribeiro et al. (1996) studied the distribution of malaria vectors in a single village in Ethiopia. Existing maps of the village were digitized and converted to Cartesian coordinates for data analysis. Mosquitoes were collected monthly by mouth aspiration or pyrethrum spray catch. An average of 54 houses were sampled by mouth aspiration each month. Aggregation of mosquitoes was estimated using Taylor's power regression plot and Iwao's mean crowding plots. In addition, kriging was performed to estimate the number of mosquitoes throughout the village for each month. Mosquitoes were highly aggregated, particularly during the dry season. For most months, fewer than 20% of houses accounted for 50% of all collected mosquitoes. Maps based upon kriging analysis showed that clusters of mosquitoes tended to segregate around the edges of villages. It was hypothesized that the distribution of

mosquitoes was largely affected by the distribution of breeding sites around the village. It was also suggested that selective targeting of areas of high mosquito abundance could maximize the effectiveness of vector control, particularly when mosquito densities are low.

Two studies in urban areas clearly demonstrate the strong effect of distance to breeding sites on adult mosquito populations and the risk of malaria infection. In Dakar, Senegal, the dispersion of adult mosquitoes (*An. arabiensis*) from a permanent swamp and the prevalence of antibodies to *Plasmodium falciparum* in children residing near the swamp were investigated (Trape et al. 1992). Mosquito abundance within houses varied by distance from the swamp. In the rainy season, there were an average of 414 *An. arabiensis* per house within 160 m of the swamp while there were only 21 per house at distances 785-910 m from the swamp. During the dry season the effect of distance was even more pronounced. The average number of *An. arabiensis* was 84 per house at distances <160 m from the swamp, 40 per house at distances of 160-285 m from the swamp and <10 per house at distances >285 m from the swamp. There was also a decrease in proportion of children with antibodies to *P. falciparum* at increasing distances from the swamp. The prevalence of children without antibodies rose from 17% in children residing within 160 m of the swamp to 73% in children residing 785-910 m from the swamp. Similar observations were made in Maputo, Mozambique (Thompson et al. 1997). Entomological inoculation rates (EIR), malaria prevalence and clinical malaria were observed over 2.5 years in a suburb of Maputo adjacent to mosquito breeding-sites. Malaria prevalence in areas adjacent to the breeding sites ranged from 40 to 60% but was as low as 5-11% just 500 m from the breeding sites. The risk of clinical malaria was estimated to be 6.2 times higher in individuals living within 200 m of the breeding site compared to persons living >500 m away. EIRs were estimated to be as high as 20 infectious bites per person per year in areas adjacent to the breeding site but were too low to measure in areas more distant from the breeding site.

Clarke et al. (2002) studied the relationship between distance from mosquito breeding-sites and entomological and clinical malaria indices in 48 villages along the River Gambia in West Africa. Distances from villages to the nearest edge of the alluvial plain of the River Gambia were estimated from 1:50,000 maps. Mosquitoes were collected every 2 weeks throughout the transmission season from 2 houses in each of the 48 villages. A cross-sectional survey was conducted in 1996 in which children from sentinel houses and their neighbours were tested for malaria and anaemia. EIRs, the prevalence of parasitaemia and the prevalence of enlarged spleens were all lower in villages ≥3 km away from main breeding sites along the river. However, among infected children, rates of high-density parasitaemia, fever and anaemia were all higher in villages ≥3 km from the breeding sites. Furthermore, older children in these villages did not experience a decline in clinical illness. These data suggest that the lower transmission in villages further from mosquito breeding-sites results in a reduced acquisition of natural immunity to *P. falciparum*. In a similar study in the same area, Thomas and Lindsay (2000) correlated exposure to adult mosquitoes in 10 villages with distance to breeding sites. Using multispectral SPOT satellite imagery with 20 m resolution to detect larval breeding sites within 2 km of a village, they were able to estimate the exposure to adult mosquitoes in 26 villages where clinical surveys had been conducted but entomological data were unavailable. Similar to the study of Clarke et al. (2002), the estimated exposure rates for each village were positively correlated with parasite prevalence and negatively correlated with high density parasitaemia and splenomegaly.

The use of RS in conjunction with GIS to predict areas of high mosquito density is illustrated in several studies from Central America. Rejmankova et al. (1995) used RS to estimate land-cover elements in Belize and then predict areas with high/low densities of *An. albimanus*. Land cover was classified using SPOT satellite imagery with a resolution of 20 m x 20 m. Areas identified as contact zones between the fresh water and the sparse emergent-vegetation zones on the SPOT image were considered predictors of *An. albimanus* densities. Villages within 500 m of a larval habitat were predicted to be high-risk villages while villages located >1500 m from a larval habitat were predicted to be low-risk villages. The SPOT classification was verified by human landing catches made for one night during the dry season in each of 16 villages. Villages were defined as having high mosquito densities if there were ≥0.5 mosquitoes/human/minute; villages with <0.5 mosquitoes/human/minute were considered to have low mosquito densities. There was good agreement between densities predicted by the SPOT image and those observed in the human-landing collections. All sites predicted to have low densities had landing rates <0.5 mosquitoes/human/minute while one village predicted to have high densities by SPOT imagery was found to have low densities in the human-landing collections. Similar studies with *An. albimanus* have been done in other areas of Central America. Beck et al. (1994) used SPOT imagery to classify land cover and then used a GIS to create 1-km buffers around 40 villages in southern Mexico. The proportion of each land-cover classification was estimated within the 1-km buffer surrounding each village. Vector abundance was measured using light traps in each village over 4 months in 1992. Discriminant function and linear regression analyses both showed *An. albimanus* densities to be correlated with the proportion of land cover surrounding villages classified as transitional swamp or unmanaged pasture. Additional studies using SPOT imagery have been used with somewhat less accuracy to predict areas with high densities of *An. psuedopunctipennis* (Roberts et al. 1996) and the larval breeding sites of *An. vestitipennis* (Rejmankova et al. 1998).

Spatial distribution of hosts and mosquito community structure

Many mosquito species feed on a restricted range of available hosts. Members of the *An. gambiae* complex in East Africa exhibit distinct host-choice behaviour with *An. gambiae* being strongly anthropophilic and *An. arabiensis* usually being strongly zoophilic. It is well known that the location of sampling of adult females will strongly affect the proportion of each of these sibling species. Recent studies suggest that the spatial distribution of hosts may also affect the spatial distribution of the larvae of these species. Charlwood and Edoh (1996) and Minakawa et al. (1999) both found that *An. gambiae* larvae were more prevalent near human habitation while *An. arabiensis* larvae were more common near animals. Several studies have shown little or no discriminating physical or chemical characteristics between habitats with *An. gambiae* vs. those with *An. arabiensis* (Minakawa et al. 1999; Gimnig et al. 2001). In the study by Minakawa et al. (1999), the only variable that was predictive of *An. gambiae* and *An. arabiensis* was proximity to human habitation.

To expand on this finding, Minakawa, Seda and Yan (2002) used a GIS to compare the proportions of *An. gambiae* and *An. arabiensis* larvae in relation to proximity to human and animal habitation in western Kenya. Surveys of larval habitats were conducted in the early and late rainy season of 1999. Anopheline larvae were collected and preserved in ethanol for identification by polymerase chain reaction. All houses, cowsheds and larval habitats were mapped by GPS and distances from larval habitats to the nearest house and cowshed were calculated. The densities of humans

and cattle around each larval habitat were estimated by taking the average numbers of humans and cattle in the 5 nearest houses and cowsheds. The ratio of human density to cow density and the ratio of the distance from larval habitats to houses and from larval habitats to cowsheds were modelled using linear regression to assess their effect on the proportion of *An. gambiae* in each larval habitat. Both measures indicated that the proportion of *An. gambiae* was higher in habitats near houses while the proportion of *An. arabiensis* was higher near cowsheds. Analysis of adult densities in houses in the study area indicated that only proximity to larval habitats was a significant predictor of adult densities – the densities of humans and cows and the distance to the nearest cowshed were not significantly associated with adult *An. gambiae* or *An. arabiensis* densities within houses. This study highlights the importance of the availability of hosts on the spatial distribution of larval mosquitoes and the community structure within larval habitats. Additional research employing GIS is necessary to further assess how the spatial distribution of human hosts within villages may affect the spatial distribution of adult mosquitoes.

Identification of dry-season refugia

In areas of sub-Saharan Africa with highly seasonal transmission, malaria vectors are often absent for much of the year. How mosquitoes survive dry periods has been a subject of conjecture. It has been hypothesized that mosquitoes may aestivate through some form of gonotrophic dissociation, that eggs or larvae may survive on damp or even dry soil for short periods (Beier et al. 1990; Minakawa et al. 2001), or that mosquito populations persist year-round in localized refugia. By applying a GIS over time, seasonal foci of mosquitoes may be identified that would suggest refugia where mosquito breeding continues during extended dry periods.

Evidence from a study in western Kenya suggested that malaria vectors in this region survive dry seasons by retreating to refugia around the beds of streams and rivers (Hightower et al. 1998). The entire 70-km^2 study area in western Kenya was mapped by differential GPS. Geographic features mapped included hospitals, clinics, medicine shops, major shopping centres, schools, churches, boreholes, burrow pits and all 1,169 compounds (clusters of houses belonging to one family). Also mapped were roads, streams and the shore of lake Victoria, which bordered the study area. Mosquitoes were collected from a subset of houses in June and September of 1995, representing the end of the rainy season and the dry season, respectively. Bed-net trap collections were made from 394 houses in June and from 416 houses in September. At least 3 collections were made for each house and were averaged for each month. Linear regression was used to assess the relationship between mosquito density and the distance from potential larval habitats, defined as the lakeshore, streams and burrow pits.

For *An. gambiae*, average density decreased with increasing distance from potential larval habitats during the dry season (P=0.0039). This relationship was not evident during the rainy season (p=0.153). These results were interpreted to indicate that *An. gambiae* breeding continues year round, but is restricted to areas around streams and the lakeshore where receding waters likely leave pools of water that are suitable for developing larvae. For *An. funestus*, the average number of adults actually increased with increasing distance from larval habitats during the rainy season (p=0.0191) but not the dry season (p=0.6608). The somewhat surprising results observed for *An. funestus* highlight our lack of knowledge of *An. funestus* breeding habits.

This study demonstrates how a GIS may be used to identify areas where mosquitoes may survive extended dry periods. This is not definitive proof that these areas act as refugia. Nor does it exclude the possibility that other survival mechanisms contributed to the dry-season survival of *An. gambiae*, particularly in other regions of Africa. However, as is often the case, GIS may generate hypotheses or indicate additional avenues of research. In this case, surveys of larval mosquitoes during the dry season may provide further evidence that *An. gambiae* is breeding in isolated areas during the dry season. The poor correlation between distance from suspected breeding sites and the abundance of *An. funestus* adults indicates additional research is necessary to characterize the larval habitats of this mosquito properly.

Spatial impact of vector control interventions

Insecticide-treated mosquito nets and curtains (ITNs) have been shown to reduce malaria morbidity and all-cause mortality (Snow et al. 1988; Phillips-Howard et al. 2003) in sub-Saharan Africa, and the World Health Organization's Roll Back Malaria Initiative has advocated their use for the prevention of malaria. Despite their obvious benefits, one concern about ITNs has been that pyrethroid insecticides have strong excito-repellent properties and that incomplete coverage will result in diversion of mosquitoes from households with nets to those without nets (Lines, Myamba and Curtis 1987). This could result in even higher exposure to infected mosquitoes among persons who do not own nets. This is a particular concern as most ITN distribution programmes in Africa rely on private markets or partially subsidized, targeted distribution through the public sector. If diversion of malaria vectors does occur, current distribution systems are likely to increase malaria exposure among the poorest and most vulnerable populations.

We tested the hypothesis that widespread distribution of ITNs affects the spatial distribution of malaria vectors as part of a large-scale trial of ITNs conducted in western Kenya (Gimnig et al. 2003). The study area, west of Kisumu along the shores of Lake Victoria, had been mapped previously using differential GPS (Hightower et al. 1998). The 19 villages located in the southern part of the study area were included in the entomological evaluation. Weekly bed-net trap collections were conducted in households where children had been enrolled in a study of malaria epidemiology and the development of natural immunity since 1992. Nine of the 19 villages were randomly allocated to receive ITNs, and in December of 1996, ITNs were distributed to cover all the sleeping spaces (beds and mats) in the intervention villages.

Entomological collections continued through October of 1997 in the control villages only. These data provided an opportunity to determine whether ITNs in the intervention villages affected the distribution of malaria vectors in the control villages. Control households were categorized by distance to the nearest intervention village as 0-299 m, 300-599 m, 600-899 m or $\geq$900 m. The effect of distance from the intervention village on the number of mosquitoes collected was modelled by Poisson regression. Distance to intervention villages was included in the models either as a categorical variable or as a continuous categorical variable to test for trends. Models were constructed for *An. gambiae s.l.* and *An. Funestus* and each model controlled for pre-intervention trends. Other variables controlled for in the models were rainfall, temperature and distance to the lakeshore. For *An. gambiae*, there was a pre-existing trend of increasing numbers with increasing distance from the intervention area (p=0.027). However, this trend was exacerbated in the intervention year (p=0.002) and the difference between years was statistically significant (p=0.05). For *An. funestus*, no trend was observed in the pre-intervention year (p=0.373), while a strong

trend of increasing numbers with increasing distance from intervention villages was observed after the introduction of ITNs (p=0.014). Categorical analysis indicated that the effect on *An. gambiae* could be detected up to 600 m from an intervention village. For *An. funestus*, the effect was strongest within 300 m from an intervention village and was not statistically significant at distances further than 300 m. These results indicated that populations of *An. gambiae* and *An. funestus* were depressed in the areas surrounding ITNs and suggested that high coverage of ITNs has a community-wide impact on these malaria vectors.

These results were confirmed by spatial analysis of clinical indicators of malaria (Hawley et al. 2003). Malaria-specific indicators were measured in 2 cross-sectional surveys conducted in 60 villages located north of the entomological study area. The surveys were conducted in February-March of 1997 and November-December of 1998. Approximately 900 children under 3 years of age were examined in each cross-sectional survey for malaria parasitaemia, high-density parasitaemia, clinical malaria and anaemia. Logistic regression was used to assess the effect of distance to the nearest intervention or control village for each health indicator. The distance variable included 8 categories. For ITN villages, distances to control villages were categorized as 0-299 m, 300-599 m, 600-899 m. and >900m. For control villages, distances to intervention villages were categorized using the same distance categories. Models controlled for age, sex, weight for age, cross-sectional number and distance to nearest health clinic. For all malaria-specific outcomes, the spatial patterns were similar. Children residing in intervention villages experienced a protective effect for malaria-specific disease outcomes compared to children in control villages. This protective effect extended into adjacent control villages with children residing within 300 m of the intervention villages receiving a similar protective effect as children residing within the intervention villages. Analysis of the spatial pattern of child mortality within the whole of the study area yielded similar results. The spatial pattern of geohelminth infections, which should not be affected by ITNs, was also modelled. No apparent pattern of geohelminth infections was observed indicating that the results for malaria-specific outcomes were not the result of study/model design.

Additional models were constructed to assess what proportion of households must be covered with ITNs to observe this community effect. Three-hundred-metre buffers were created around each household in the control villages and coverage – defined as the proportion of households using ITNs within the 300-m buffer zone – was calculated for each household. The effect of coverage on malaria-specific indicators was modelled using logistic regression with households in areas of 0% coverage used as the reference group. Rates of high-density parasitaemia and anaemia decreased with increasing coverage of ITNs surrounding a control household. Children living in control households in areas where coverage with ITNs was >50% were significantly less likely to have high-density parasitaemia or anaemia compared to children living in areas where coverage with ITNs was 0%.

These studies, employing GIS, indicated that the spatial distribution of ITNs affects the spatial distribution of malaria vectors as well as the spatial pattern of clinical illness. These findings are in agreement with other studies that suggest that high coverage of ITNs may reduce morbidity (Howard et al. 2000) and mortality (Binka, Indome and Smith 1998) among neighbours who do not own ITNs. One drawback in these studies is that the distribution of ITNs was artificial, with villages having either very high or very low coverage. In practice, the distribution of ITNs will be more random. The effect of incomplete coverage in these situations may be evaluated using the buffer analysis approach described above.

Designing vector control interventions with GIS

Given the spatial heterogeneity in the distribution of anopheline vectors of malaria, GIS has potential applications in designing and monitoring interventions. Studies demonstrating the rapid decline in vector abundance and malaria prevalence at increasing distances from known vector breeding-sites suggest that spatial targeting of interventions to areas nearest breeding sites could have a substantial impact upon malaria prevalence in communities, at least in certain situations. A targeted approach would be a more cost-effective use of limited resources than complete coverage when malaria risk varies substantially and predictably within a community. RS could also be used as a tool for rapidly identifying potential vector breeding-sites to supplement a GIS approach to targeted vector control.

The use of GIS has been already been applied for surveillance for malaria as well as targeting of vector control interventions for malaria prevention. In Israel, a national database of vector breeding-sites and population centres was created (Kitron et al. 1994). Distances between breeding sites and population centres were calculated and the risk of malaria transmission was estimated based upon different vector species, their vector capacity and their flight ranges. Although malaria is not endemic to Israel, the surveillance system ensures that localized epidemics can rapidly be associated with probable vector species, likely breeding sites and potential human source of infection. Appropriate control measures can then be rapidly implemented.

In South Africa, GIS was used to better define malaria risk in two districts within Mpumalanga province (Booman et al. 2000). The reporting system for malaria was strengthened and modified to include address in case reports. Data collected from 1995 through 1999 were used to estimate the incidence of malaria in each village and town in Barberton and Nkomazi districts and the data were analysed visually by creating thematic maps displaying malaria risk throughout the two districts. A clear decline in malaria incidence was observed from west to east, with the highest rates in villages and towns along the border with Mozambique. Statistical analysis indicated that persons living within 5 km of the Mozambique border had a 4-fold higher risk of malaria compared with persons residing in villages more distant. This finding allowed district managers and the Mpumalanga Malaria Control Programme managers to limit indoor residual spraying to villages closer to the Mozambique border.

Targeting of vector control interventions requires detailed knowledge of vector biology and ecology, particularly breeding habits and flight range. While targeting can greatly increase the effectiveness of interventions, exclusion of locations where transmission occurs may cause targeted interventions to fail. Furthermore, the level of transmission may also determine whether spatially targeted interventions are appropriate (Carter, Mendis and Roberts 2000). In areas of low to moderate transmission, spatial aggregation of vectors and malaria cases is common and spatial targeting may be appropriate. In areas of high transmission, spatial aggregation in the level of transmission still occurs but low-level transmission likely occurs throughout much of these areas. In addition, the high prevalence of asymptomatic carriers makes it difficult to identify spatial clustering. However, spatial variation in malaria risk among the young may still exist and targeted interventions may have some roll to play in high-transmission areas.

Summary

GIS has numerous applications to the study of the ecology of mosquitoes and malaria. GIS is useful for studying the spatial distribution of mosquitoes and the

factors that contribute to heterogeneities in their distribution. It has been used in the past to investigate the relationship between the distribution of larval habitats and the density of adult mosquitoes in houses. These studies contribute to our understanding of the biology of adult mosquitoes (i.e. flight ranges) and suggest targeted approaches to the control of mosquitoes and the diseases they transmit. Other studies demonstrate the importance of host availability and control measures in determining the distribution of both larval and adult mosquitoes. Studies employing GIS indicate that the population dynamics of strongly anthropophilic (or zoophilic) mosquitoes is partly driven by access to the preferred hosts. Additional areas where GIS technology may contribute to the study of mosquitoes and mosquito-borne disease include studies of landscape architecture to assess how elevation, slope and land-use patterns influence the formation of larval breeding sites and the generation of interpolated measures of transmission as predictors to understand better the relationship between malaria transmission and disease outcomes. Further studies using RS in conjunction with GIS will help identify gaps in our knowledge of the characteristics of larval biology and may even be used as a predictor of areas of high disease transmission. As GIS technology becomes more affordable and more user-friendly, it will also have increasing applications in designing control and surveillance programmes for malaria and other diseases in developing countries.

References

Beck, L.R., Rodriguez, M.H., Dister, S.W., et al., 1994. Remote sensing as a landscape epidemiologic tool to identify villages at high risk for malaria transmission. *American Journal of Tropical Medicine and Hygiene,* 51 (3), 271-280.

Beier, J.C., Copeland, R., Oyaro, C., et al., 1990. *Anopheles gambiae* complex egg-stage survival in dry soil from larval development sites in western Kenya. *Journal of the American Mosquito Control Association,* 6 (1), 105-109.

Binka, F.N., Indome, F. and Smith, T., 1998. Impact of spatial distribution of permethrin-impregnated bed nets on child mortality in rural northern Ghana. *American Journal of Tropical Medicine and Hygiene,* 59 (1), 80-85.

Booman, M., Durrheim, D.N., La Grange, K., et al., 2000. Using a geographical information system to plan a malaria control programme in South Africa. *Bulletin of the World Health Organization,* 78 (12), 1438-1444.

Briggs, D.J. and Elliott, P., 1995. The use of geographical information systems in studies on environment and health. *World Health Statistics Quarterly,* 48 (2), 85-94.

Carter, R., Mendis, K.N. and Roberts, D., 2000. Spatial targeting of interventions against malaria. *Bulletin of the World Health Organization,* 78 (12), 1401-1411.

Charlwood, J.D. and Edoh, D., 1996. Polymerase chain reaction used to describe larval habitat use by *Anopheles gambiae* complex (Diptera: Culicidae) in the environs of Ifakara, Tanzania. *Journal of Medical Entomology,* 33 (2), 202-204.

Clarke, K.C., McLafferty, S.L. and Tempalski, B.J., 1996. On epidemiology and geographic information systems: a review and discussion of future directions. *Emerging Infectious Diseases,* 2 (2), 85-92.

Clarke, S.E., Bøgh, C., Brown, R.C., et al., 2002. Risk of malaria attacks in Gambian children is greater away from malaria vector breeding sites. *Transactions of the Royal Society of Tropical Medicine and Hygiene,* 96 (5), 499-506.

Coetzee, M., Craig, M. and Le Sueur, D., 2000. Distribution of African malaria mosquitoes belonging to the *Anopheles gambiae* complex. *Parasitology Today,* 16 (2), 74-77.

Craig, M.H., Snow, R.W. and Le Sueur, D., 1999. A climate-based distribution model of malaria transmission in sub-Saharan Africa. *Parasitology Today,* 15 (3), 105-111.

Gimnig, J.E., Kolczak, M.S., Hightower, A.W., et al., 2003. Effect of permethrin-treated bed nets on the spatial distribution of malaria vectors in western Kenya. *American Journal of Tropical Medicine and Hygiene,* 68 (4 Suppl.), 115-120.

Gimnig, J.E., Ombok, M., Kamau, L., et al., 2001. Characteristics of larval anopheline (Diptera: Culicidae) habitats in Western Kenya. *Journal of Medical Entomology,* 38 (2), 282-288.

Hawley, W.A., Phillips-Howard, P.A., Ter Kuile, F.O., et al., 2003. Community-wide effects of permethrin-treated bed nets on child mortality and malaria morbidity in western Kenya. *American Journal of Tropical Medicine and Hygiene,* 68 (4 Suppl.), 121-127.

Hay, S.I., Omumbo, J.A., Craig, M.H., et al., 2000. Earth observation, geographic information systems and *Plasmodium falciparum* malaria in sub-Saharan Africa. *In:* Hay, S.I., Randolph, S.E., Rogers, D.J., et al. eds. *Remote sensing and geographical information systems in epidemiology.* Academic Press, San Diego, 173-215. Advances in Parasitology no. 47.

Hightower, A.W., Ombok, M., Otieno, R., et al., 1998. A geographic information system applied to a malaria field study in western Kenya. *American Journal of Tropical Medicine and Hygiene,* 58 (3), 266-272.

Howard, S.C., Omumbo, J., Nevill, C., et al., 2000. Evidence for a mass community effect of insecticide-treated bednets on the incidence of malaria on the Kenyan coast. *Transactions of the Royal Society of Tropical Medicine and Hygiene,* 94 (4), 357-360.

Kitron, U., Pener, H., Costin, C., et al., 1994. Geographic information system in malaria surveillance: mosquito breeding and imported cases in Israel, 1992. *American Journal of Tropical Medicine and Hygiene,* 50 (5), 550-556.

Lines, J.D., Myamba, J. and Curtis, C.F., 1987. Experimental hut trials of permethrin-impregnated mosquito nets and eave curtains against malaria vectors in Tanzania. *Medical and Veterinary Entomology,* 1 (1), 37-51.

Minakawa, N., Githure, J.I., Beier, J.C., et al., 2001. Anopheline mosquito survival strategies during the dry period in western Kenya. *Journal of Medical Entomology,* 38 (3), 388-392.

Minakawa, N., Mutero, C.M., Githure, J.I., et al., 1999. Spatial distribution and habitat characterization of anopheline mosquito larvae in Western Kenya. *American Journal of Tropical Medicine and Hygiene,* 61 (6), 1010-1016.

Minakawa, N., Seda, P. and Yan, G., 2002. Influence of host and larval habitat distribution on the abundance of African malaria vectors in western Kenya. *American Journal of Tropical Medicine and Hygiene,* 67 (1), 32-38.

Moore, D.A. and Carpenter, T.E., 1999. Spatial analytical methods and geographic information systems: use in health research and epidemiology. *Epidemiologic Reviews,* 21 (2), 143-161.

Omumbo, J., Ouma, J., Rapuoda, B., et al., 1998. Mapping malaria transmission intensity using geographical information systems (GIS): an example from Kenya. *Annals of Tropical Medicine and Parasitology,* 92 (1), 7-21.

Phillips-Howard, P.A., Nahlen, B.L., Kolczak, M.S., et al., 2003. Efficacy of permethrin-treated bed nets in the prevention of mortality in young children in an area of high perennial malaria transmission in western Kenya. *American Journal of Tropical Medicine and Hygiene,* 68 (4 Suppl.), 23-29.

Rejmankova, E., Pope, K.O., Roberts, D.R., et al., 1998. Characterization and detection of *Anopheles vestitipennis* and *Anopheles punctimacula* (Diptera: Culicidae) larval habitats in Belize with field survey and SPOT satellite imagery. *Journal of Vector Ecology,* 23 (1), 74-88.

Rejmankova, E., Roberts, D.R., Pawley, A., et al., 1995. Predictions of adult *Anopheles albimanus* densities in villages based on distances to remotely sensed larval habitats. *American Journal of Tropical Medicine and Hygiene,* 53 (5), 482-488.

Ribeiro, J.M., Seulu, F., Abose, T., et al., 1996. Temporal and spatial distribution of anopheline mosquitos in an Ethiopian village: implications for malaria control strategies. *Bulletin of the World Health Organization,* 74 (3), 299-305.

Roberts, D.R., Paris, J.F., Manguin, S., et al., 1996. Predictions of malaria vector distribution in Belize based on multispectral satellite data. *American Journal of Tropical Medicine and Hygiene,* 54 (3), 304-308.

Smith, T., Charlwood, J.D., Takken, W., et al., 1995. Mapping the densities of malaria vectors within a single village. *Acta Tropica,* 59 (1), 1-18.

Snow, R.W., Lindsay, S.W., Hayes, R.J., et al., 1988. Permethrin-treated bed nets (mosquito nets) prevent malaria in Gambian children. *Transactions of the Royal Society of Tropical Medicine and Hygiene,* 82 (6), 838-842.

Tanser, F.C. and Le Sueur, D., 2002. The application of geographical information systems to important public health problems in Africa. *International Journal of Health Geographics,* 1 (1), 4.

Thomas, C.J. and Lindsay, S.W., 2000. Local-scale variation in malaria infection amongst rural Gambian children estimated by satellite remote sensing. *Transactions of the Royal Society of Tropical Medicine and Hygiene,* 94 (2), 159-163.

Thompson, R., Begtrup, K., Cuamba, N., et al., 1997. The Matola malaria project: a temporal and spatial study of malaria transmission and disease in a suburban area of Maputo, Mozambique. *American Journal of Tropical Medicine and Hygiene,* 57 (5), 550-9.

Thomson, M.C., Connor, S.J., Milligan, P.J., et al., 1996. The ecology of malaria-as seen from Earth-observation satellites. *Annals of Tropical Medicine and Parasitology,* 90 (3), 243-264.

Trape, J.F., Lefebvre-Zante, E., Legros, F., et al., 1992. Vector density gradients and the epidemiology of urban malaria in Dakar, Senegal. *American Journal of Tropical Medicine and Hygiene,* 47 (2), 181-189.

Vine, M.F., Degnan, D. and Hanchette, C., 1997. Geographic information systems: their use in environmental epidemiologic research. *Environmental Health Perspectives,* 105 (6), 598-605.