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ENVIRONMENTAL ABUNDANCE OF *ANOPHELES* (DIPTERA: CULICIDAE) LARVAL HABITATS ON LAND COVER CHANGE SITES IN KARIMA VILLAGE, MWEA RICE SCHEME, KENYA

BENJAMIN G. JACOB, EPHANTUS MUTURI, PATRICK HALBIG, JOSEPH MWANGANGI, R. K. WANJOGU, ENOCK MPANGA, JOSE FUNES, JOSEPHAT SHILILU, JOHN GITHURE, JAMES L. REGENS, AND ROBERT J. NOVAK*

Illinois Natural History Survey, Center for Ecological Entomology, Champaign, Illinois; Human Health Division, International Centre of Insect Physiology and Ecology, Nairobi, Kenya; Mwea Irrigation Agricultural Development Centre, Wanguru, Kenya; Department of Occupational and Environmental Health, College of Public Health, University of Oklahoma Health Sciences Center, Oklahoma City, Oklahoma

Abstract. A study was carried out at Karima Village in the Mwea Rice Irrigation Scheme in Kenya to assess the impact of rice husbandry and associated land cover change for mosquito larval abundance. A multi-temporal, land use land cover (LULC) classification dataset incorporating distributions of *Anopheles arabiensis* aquatic larval habitats was produced in ERDAS Imagine version 8.7 using combined images from IKONOS at 4m spatial resolution from 2005 and Landsat Thematic Mapper (TM)™ classification data at 30-meters spatial resolution from 1988 for Karima. Of 207 larval habitats sampled, most were either canals (53.4%) or paddies (45.9%), and only one habitat was classified as a seep (0.5%). The proportion of habitats that were poorly drained was 55.1% compared with 44.9% for the habitats that were well drained. An LULC base map was generated. A grid incorporating each rice paddy was overlaid over the LULC maps stratifying each cell based on levels of irrigation. Paddies/grid cells were classified as 1) well irrigated and 2) poorly irrigated. Early stages of rice growth showed peak larval production during the early part of the cropping cycle (rainy season). Total LULC change for Karima over 16 years was 59.8%. Of those areas in which change was detected, the LULC change for Karima was 4.30% for rice field to built environment, 8.74% for fallow to built environment, 7.19% for rice field to fallow, 19.03% built to fallow, 5.52% for fallow to rice field, and 8.35% for built environment to rice field. Of 207 aquatic habitats in Karima, 54.1 (n = 112) were located in LULC change sites and 45.9 (n = 95) were located in LULC non-change sites. Rice crop LULC maps derived from IKONOS and TM data in geographic information systems can be used to investigate the relationship between rice cultivation practices and higher anopheline larval habitat distribution.

INTRODUCTION

Irrigated rice cultivation in east Africa has been restricted primarily to irrigation schemes planned by irrigation boards. With increasing demand for rice, there has been an upsurge in planned rice cultivation with individual farmers designing their own cropping cycle. However, continuous land cover modification within rice ecosystems creates ideal conditions for malaria mosquitoes throughout the crop season.[1–6] Rice crop ecosystems also use a greater amount of agrochemicals,[7,8] which also effect mosquito populations because *Anopheles arabiensis* Patton rapidly colonize rice fields where land use land cover (LULC) change occurs,[9] underscoring the importance of delineating the relative abundance of habitats suitable for mosquito production.

Past research in African rice ecosystems has demonstrated the primary importance of larval habitats that act as strongholds for smaller focal populations. In Kenya, there was a 70-fold increase in the population of *An. gambiae* s.l. in the Ahero rice irrigation scheme compared with an adjacent area of undisturbed land.[10] In the rice-growing areas of Bobo-Dioulasso, Burkina Faso, the human-biting density of *An. gambiae s. l.* was 10-fold higher than in the nearby savannah areas.[11] Night-time landing bite collections showed significantly higher adult anopheline densities in peri-urban and urban agricultural communities compared with non-agricultural urban communities in the city of Kumasi, Ghana.[12] In Senegal, the biting rate in a village near a rice field was 17-fold higher than that observed in a village located more than 5 km away from rice fields.[5] Significantly higher biting rates and an increase in malaria transmission has recently been documented in an irrigated sub-arid rice ecosystem of Madagascar.[13] Keiser and others[14] reported that the introduction of irrigation can place non-immune population at a high risk by altering transmission from mesoendemic to hyperendemic, as they observed in Rosso in the Senegal River basin.

East African rice management practices such as localized flood control, plowing, and harvesting of rice fields may produce distinctive environmental signatures during certain periods of the crop season. High spatial-resolution satellite-based sensors are able to discriminate land use differences that are important to mosquito production.[15–18] Different surface types such as paddies or canals have distinct spectral signatures that can be distinguished by analyzing their signals in the various bands of the sensor. Since the sensor bands often respond in a strongly correlated manner to different surface features, analyzing imagery using natural or false color may distinguish critical surface features important to mosquito aquatic habitats. Remote sensing estimates derived in this way may prove useful in vector population biology and in improving estimates of exposure-response relationships between the humans, mosquitoes, and the pathogens in east African rice communities.

To evaluate the efficiency of remote sensing mosquito/malaria relationships, we examined whether 1988 Landsat Thematic Mapper™ (TM) (U.S. Geological Survey) at 30-meter spatial resolution and 2005 IKONOS data at 4-meter spatial resolution can be used to map LULC change and rice cohorts over a period of 17 years. The objective of this study was to identify the ecologic, anthropogenic, and LULC factors that influence distribution and abundance of *An. arabien-*

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* Address correspondence to Robert J. Novak, Illinois Natural History Survey, Center for Ecological Entomology, 607 East Peabody Drive, Champaign IL 61820. E-mail: rjnovak@uiuc.edu

sis aquatic larval habitats within the Mwea rice scheme in Kenya. To meet this objective, we created spatial datasets around a typical rice community including entomologic, hydrologic, demographic, and agriculture data to identify all LULC change sites that influence larval anopheline species.

MATERIALS AND METHODS

Study area. The studies were conducted 100 km northeast of Nairobi, in Karima village within Mwea Rice Scheme in Kenya. Mwea occupies the lower altitude zone of the Kirinyaga District in an expansive low-lying, formally wet-savannah ecosystem. The Mwea rice irrigation scheme is located in the west central region of Mwea Division and covers an area of approximately 13,640 hectares. More than 50% of the scheme area is used for rice cultivation. The remaining area is used for subsistence farming, grazing, and community activities. The mean annual precipitation is 950 mm with maximum rainfall occurring in April–May and October–November. The average temperatures range from 16°C to 26.5°C. Relative humidity varies from 52% to 67%. According to the 1999 Kenyan national census, the Mwea Rice Scheme has a population of 150,000 occupying 25,000 households. The study site village Karima has approximately 158 homesteads with more than 650 residents. Cows, goats, chickens, and donkeys are the primary domestic animals and they are kept within 5 meters of most houses. More than 90% of the houses have mud walls with iron roofing. *Anopheles arabiensis* is the predominant vector of malaria in Mwea, and the only sibling species of the *An. gambiae* species complex recorded in the area.[8]

Rice cultivation. In Karima, the beginning of each cropping cycle is scheduled according to the water availability through the irrigation water distribution scheme. The schedule of individual rice husbandry also differs within the water availability time limits from one group of rice fields to another. Most fields are cultivated once a year, although some farmers cultivate a second crop. The typical cultivation cycle includes a sowing–transplanting period (June–August), a growing period (August–November), and an post-harvest period (November–December). The second crop is cultivated prior to the short rainy period between January and May. The duration of the rice cycle varies between 120 and 150 days depending on the rice variety. The cycle includes a flooded vegetative period when plants develop and grow, a reproductive phase with limited water during which plants stop growing and orient towards the development of the panicles and grains, and a ripening phase (water is drained) in which plants senesce and their water content drops. Rice plants are usually transplanted from flooded small seed beds when 20–30 days old, and the vegetative phase lasts 45–60 days, including the seedling transplant, tillering, and stem elongation stages. Tillering extends from the appearance of the first tiller until the maximum tiller number is reached. During stem elongation, the tillers continue to increase in number and height, with increasing ground cover and canopy formation. This stage sometimes overlaps with the tillering stage; its duration depends on rice variety and is highly variable in Karima. The reproductive phase lasts 20–30 days and includes the panicle initiation, booting, heading, and flowering stages. Plants were considered in the reproductive phase when more than 50% of plants have panicles. Finally, the ripening phase lasts 35–65 days, during which the grains fill and turn yellow and the plants senesce. Mosquito numbers increase as soon as the paddies are flooded, rising to a peak when the rice plants are small, before decreasing when the rice plants cover the surface of the water generally in the early tiller stage.[10,19,20] After harvesting, mosquito habitats may persist in the shallow puddles left after harvest.[7]

Larvae sampling. In Karima, 207 temporary, permanent, and semipermanent aquatic habitat sites were located, and mapped using a CSI-Wireless differentially corrected global positioning system (DGPS) Max receiver using a OmniStar L-Band satellite signal with a positional accuracy of less than 1 meter (Advanced Computer Resources Corp., Nashua, NH). Water bodies were inspected for mosquito larvae using standard dipping techniques with a 350-mL dipper to collect the mosquito larvae.[21] The number of dips per habitat was a function of habitat size (e.g., paddies = 0.3–1 hectares) and ranged from 15 to 25. All data from the habitat characterization of each aquatic larval habitat was recorded on a field sampling form (Figure 1). Larvae and a sample of water from each larval habitat were placed in plastic bags and transported to the Mwea Research Station for further processing. Anopheline larvae were separated from culicine larvae and identified to species using the taxonomic keys of Gillies and Coetzee.[22] A subset of the larvae of the *An. gambiae* complex were identified to sibling species using a polymerase chain reaction technique.[23]

Base maps for this study including major roads and hydrography were created using Arc View 9.1® (Environmental Systems Research Institute, Redlands, CA) from DGPS. Each *An. arabiensis* larval habitat with its associated land cover attributes from Karima were entered into a Vector Control Management System® (VCMS) (Advanced Computer Resources Corp.) database. The VCMS database supported the

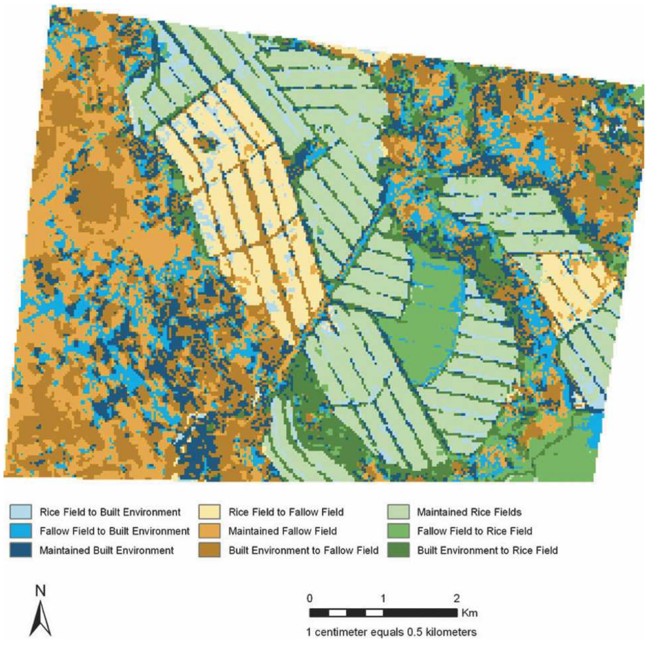

FIGURE 1. Land use land cover change (LULC) and non-LULC map from June 1988 to June 2005 for Karima Village, Mwea Rice Scheme in Kenya. This figure appears in color at www.ajtmh.org.

mobile field data acquisition in Karima through a PocketPC™. All two-way, remote synchronization of data, geocoding, and spatial display were processed using the embedded geographic information system (GIS) Interface Kit™ that was built using MapObjects™ 2 technology (Earth Systems Research Institute). The VCMS database can plot and update DGPS ground coordinates of *An. arabiensis* aquatic larval habitat seasonal information and support exporting data in spatial format whereby any combination of larval habitats and supporting data can be described in a shapefile format (Environmental Systems Research Institute, Redlands, CA) for use in a GIS. The database displayed this information onto a user-defined field base map.

A digitized custom grid tracing for rice paddy was generated in Arc View 9.1® (Environmental Systems Research Institute). This provided for a unique identifier that was placed in each grid cell (paddy). The grid extends to a one-kilometer area extending from the external boundary of Karima village. Stratifying the grid involved assessing the level of drainage in each grid cell and assigning a value of 1 if the grid cell was rice well irrigated and 0 if the rice paddy was poorly irrigated. A grid cell was classified as rice well irrigated if engineered drainage systems, clear of debris, were present; no standing water was visible; or if located on a slope providing gravity driven irrigation. Rice fields were classified as poorly irrigated if irrigation systems had no functional drainage systems or were in dead-end locations in depressions or valleys. The distance between house or spacing, road types, (graded, gravel, foot paths) and networks (i.e. between villages, village to paddy) community water sources, and access to utilities were also noted. Information contained in the 1999 Kenya census and District Development Report, as well as environmental descriptions from field surveys and topographic maps were used to assist with the stratification process. The boundaries of selected grid cells were located in the field using hand-held navigational units from DGPS and base-maps with permanent landmarks, such as car paths, roads, and canals. Latitude and longitude readings were taken at the corners and center of each selected grid cell to confirm the location and extent of grid cell boundaries. Twenty-five grid cells were selected from each stratum (n = 50). A systematic random sample with a random start was used to select rice paddies. This ensured that the probability of selection was equal for each grid cell within the respective strata. We overlaid the sampling unit grid with the larval spatial datasets to identify the LULC pixels within each grid cell of interest. All potential aquatic larval habitat sites were identified, and data relative to species composition and abundance, predators, water quality and environmental parameters were collected longitudinally. The entomologic variable was total *Anopheles* larvae and pupae present (Table 1).

Remote sensing data. The IKONOS image used in this study has 4-meter resolution. The multispectral sensor collects blue, green, red, and near-infrared bands that provide natural color imagery for visual interpretation and color infrared applications. Thematic Mapper™ image data consists of seven spectral bands with a spatial resolution of 30 meters for bands (1–5 and 7). Spatial resolution for the thermal infrared (band 6) during image acquisition is 120 meters, but the delivered TM band 6 was resampled to 30-meter pixel size. The TM imagery was assembled in a mosaic through a photomechanical process that uses a contrast balanced film image. High spatial resolution data (IKONOS at 4 meters) can provide spatio-temporal features important for mosquito larval production,[24–27] local rice cultivation practice,[28] and local variation in planting dates, and several agronomic parameters of the developing rice.[29]

The satellite data were classified using the iterative self-organizing data analysis technique (ISODATA) unsupervised routine in ERDAS Imagine version 8.7 (Leica Geosystems Atlanta, GA). Spectral signatures were used to group classes primarily based on the color configuration. The ISODATA is a widely used clustering algorithm[30] and uses the minimum spectral distance formula to form clusters. The ISODATA utility repeated the clustering of each image until a maximum number of iterations had been performed. The unsupervised classification then assigned the signatures automatically generated by the ISODATA algorithm. Unsupervised classification is used to cluster pixels in a data set based on statistics only, without any user-defined training classes.

The satellite information obtained from IKONOS was obtained February 2005 and encompassed visible wavebands 2

TABLE 1

Total environmental characteristics of mosquito and non-mosquito aquatic habitats measured or sampled at the Karima, Kenya, study site, 2005

Habitat type	HABTYP	1 = paddy, 2 = canal, 3 = pool, 4 = marsh, 5 = hoof print, 6 = ditch, 7 = seep
Habitat nature	HABNAT	0 = natural, 1 = human made
Distance to nearest house	DISTHSE	1 = 0–20m, 2 = 21–40m, 3 = 41–60m, 4 = > 60
Distance to domestic animals	DOMAN	1 = 0–20m, 2 = 21–40m, 3 = 41–60m, 4 = > 60
Vegetation	VEG	0 = none, 1 = present
Shade	SHADE	0 = none, 1 = present
Emergent vegetation	EMERG	0 = none, 1 = present
Paddy category	PADCAT	1 = transplant, 2 = tiller, 3 = boot, 4 = flower, 5 = mature, 6 = harvest, 7 = fallow/unploughed, 8 = flooded, 9 = ratoon, 10 = ploughed
Rice height	RICEHGT	measured in cm
No. of tillers	TILLER	count
Depth	DEPTH	measured in cm
Canopy	CANOP	measured as a %
Aquatic animals	AQUAN	1 = dragonflies, 2 = backswimmers, 3 = tadpoles, 4 = beetles, 5 = flies, maggot/wrigglers, 6 = mites, 7 = fish, 8 = Hemiptera, 9 = none, 10 = snails, 11 = chironomids, 12 = midges
No. of dips	DIPS	Number
Anopheles larvae	ANOPH	L1, L2, L3, L4
Pupae	PUPAE	Number
Irrigation	IRRI	1 = well-irrigated, 2 = poorly irrigated

(0.45–0.53 μm), 3 (0.52–0.61 μm), and 4 (0.64–0.72 μm). The information obtained from the TM included bands 3 (0.63–0.69 μm), 4 (0.76–0.90 μm), and 5 (5 1.55–1.57 μm) in October 1988 was from Landsat 5. The spectral characteristics of the IKONOS multispectral bands are approximately the same as the Landsat TM bands 1 through 4.[31]A single image file of 6 six bands (three IKONOS and three TM), was created for the Karima study site. This dataset enabled a direct pixel-to-pixel comparison of different spatial data layers between sensors. Relationships between images were performed using digital numbers as well as at-satellite exo-atmospheric reflectance obtained by converting image digital number to the temporally comparable surface reflectance factor. Digital numbers were converted to radiance and at satellite reflectance. Land cover was determined from each of the images using ERDAS Imagine version 8.7. Land cover was placed into one of three categories: rice field, fallow, and built environment. The classified images were resampled to a common scale of 30 meters and a change detection analysis was performed to determine how the land cover changed over the time period from 1988 to 2004.

Spatial datasets. Larval sampling information and remotely sensed information were then used to generate spatial datasets. The IKONOS and TM images were registered based on the position of the sensors when the images were generated. We georegistered all the remaining datasets, which involved aligning known control-point locations such as cross roads and hydrologic bodies with exactly the same locations stored in the datasets. The referenced coordinates of the control points were obtained from existing maps that were created from previous ground surveys and from a DGPS. ArcView 9.1® adjusted the datasets so that the control point locations, whose coordinates were entered into the spatial dataset, were correctly positioned relative to each other. The geographic projection used for all of the spatial datasets is the universal transverse mercator zone 38 datum WGS-84 projection. Datasets created for the Karima study site included three LULC classifications: built environment, fallow, and rice field cover classes. Built environment was areas of intensive use with much of the land covered by physical infrastructures. This land cover also included homesteads, holding areas for livestock such as corrals, farm lanes and roads, and ditches and canals (irrigation infrastructure). Fallow was paddies without canopies, e.g., transplant early tiller stage with little canopy covering water. Rice field was paddies where the vegetative growth shades the water and or ground.

The changes in LULC that occurred between 1988 and 2004 were classified into the following classes: rice field to built environment, fallow to built environment, rice field to fallow, and built environment to fallow. Pixels that could not be classified were categorized as maintained built environment, maintained fallow, or maintained rice field. The spatial distribution of the larval mosquito collections was overlaid on the land-use image derived in ArcView 9.1®, and the number of mosquito habitats in each class was calculated.

Data analysis strategy. We examined LULC in each sample unit for the Karima study site to determine the proportion of the land cover in the sample units that changed between 1988 and 2004. All data management and calculations were performed using SAS version 11.0 (SAS Inc., Carey, NC). Statistical significance was determined using a chi-square test at a 95% confidence level to determine if the proportions of paddies positive for anopheline larvae differed by strata and by respective LULC categories.

Normalized difference vegetation index. To evaluate subtle environmental variations for LULC at the Karima study site, a false-color composite was generated based on the normalized difference vegetation index (NDVI) from the IKONOS data. The NDVI expresses the abundance of actively photosynthesizing vegetation[32] and is of particular interest in mapping both spatial and temporal relationships between east African rice environments and malaria incidence and prevalence. The image analysis extension of ArcView 3.3® was used to perform the NDVI calculations of the ERDAS Image formatted files. The NDVI was calculated as (B and D − B and C)/ (band D + band C). The IKONOS band wavelengths ranged from 0.64 μm to 0.72 μm in the red band and from 0.76 μm to 0.86 μm for the infrared (bands D and C). Rice growth stage discrimination has been used to describe the progression of red and infrared reflectance and NDVI throughout a rice growing cycle.[33] The NDVI calculation provided in an ERDAS Imagine floating-point format file, with NDVI values ranging from −1 to 1. To overlay these data on the existing base maps and selected grid cells, the IKONOS data were added to the Arc View 9.1® project file for further processing. The cartographic information for the base map was stored as separate shape files within the Arc View 9.1®. Evaluating remote capabilities can provide spatio-temporal features important for mosquito larval production[24–27,33] using different cultural practices of rice cultivation[28] and local variation in planting dates and several agronomic parameters of the developing rice.[29]

The NDVI classified the data by using a high-gain filter to delete the speckling followed by a reclassification into the three LULC classes. Values for NDVI obtained from the IKONOS satellite were successfully aggregated and overlaid onto georeferenced field-based data for all selected grid cells. A database was created with the mean, minimum, maximum, and standard deviations for NDVI data aggregated to the rice paddy level. To calculate the mean NDVI value per rice paddy, all NDVI pixel values were added within the respective rice paddy and that number was divided by total number of pixels falling within the rice paddy. The NDVI datasets were then merged with the entomologic datasets using the unique identifiers for each selected rice paddy. Raster images were converted to vector polygons. The remaining analysis was conducted in Arc/INFO on the resulting polygons.

RESULTS

The percentage of overall LULC change for 17 years in Karima was 57.7% (Table 2). The most frequent LULC change for Karima was the change from rice field to fallow. The next most frequent LULC change for Karima was fallow to built environment. Transitions from rice field to built en-

TABLE 2

Proportion of overall land cover change over 17 years in Karima, Kenya

No. of pixels	Total area in km^2	Total area in km^2 of land cover change	Percentage of land cover change
1,529	42.81	25.61	59.8

vironment, rice field to fallow, fallow to rice field, and built environment to rice field all were less than 8.5% (Table 3).

A total of 125 paddies were selected from the 1-km study site and all larval habitats associated with each of the selected paddies were sampled for mosquito larvae. Table 4 shows the number of aquatic habitats identified in areas of different LULC change sites. A total of 207 habitats were identified, with most being either canals (53.4%) or paddies (45.9%). Only one habitat was classified as a seep (0.5%), which came from the canals and paddies. Paddies and canals were the most important larval habitats accounting for 95.6% (n = 857) of the total number of larvae collected (Table 5). Of the 857 larvae collected, 568 were first instars, 254 were second instars, 24 were third instars, and 9 were fourth instars. The percentage of aquatic habitats that were classified as poorly drained was 55.1% compared with 44.9% for well-drained habitats.

The proportion of habitats located in LULC change sites was 54.1% compared with 45.9% in the LULC non change sites. In the LULC change sites, 85.5% of the aquatic habitats was positive for anopheline larvae compared with 15.3% in the LULC nonchange sites (Table 6). The proportion of site positive aquatic habitats for anopheline larvae was higher in LULC change sites than for non-LULC change sites. The proportion of total aquatic habitats identified varied across strata in Karima.

DISCUSSION

Both IKONOS and LANDSAT satellite data can display spatial data in the form of geographic coverage and descriptive information in the form of relational databases associated with the mapped features. The unsupervised classification of the imagery permitted good separation between rice field, fallow, and built environment land-use classes. The immature collections of *An. arabiensis* were significantly correlated with LULC change sites at the study site

The most common locale for anopheline larval sites in LULC sites was built environment to fallow field. The higher preponderance of built environment to fallow LULC change sites for Karima is indicative of expansion in urban agricultural activity. Newer urban infrastructure includes sewer systems, dams, canals, and extended roadway networks. The rice field to fallow and fallow to rice field LULC change is assumed to increase the abundance of mosquitoes by increasing standing water. Brick, mud, or stone for housing are replaced by soil and vegetation and by irrigation activities.[7] As anthropogenic settlements extend toward rural areas, new construction activities, excavation sites, and irrigation schemes are introduced, which can provide additional important larval habitats in the presence of precipitation. Rice fields provide more than 90% of the positive mosquito larval habitats versus less than 10% for the nonhuman biotopes.[34] Urban debris has been shown to influence the suitability of aquatic larval habitats.[27,35–37] In the Karima study site, populations are still actively involved in rural-type activities (e.g., urban farming/ gardens). In these areas, waste water is often dumped in the open environment, rainwater pools in the ruts and potholes of unpaved roads, and domestic water is often stored in the open environment.[37] In some poorly drained grid cells, built infrastructures and drainage systems are deteriorating, which can create favorable aquatic larval habitat sites (e.g., potholed roads,). Furthermore, agricultural pollution such as raw sewage often accumulates in common sites creating suitable larval habitats.

Of the non-LULC changes, sites maintained rice field was the most abundant at 53.1%. Dryland tillage practices, use of improved crop varieties, and increases in the amount of fertilizer applied to irrigated crops have helped sustain rice paddies in Karima. The NDVI showed some increase in the early stages of growth in Karima, reaching a peak at the reproductive stage and then decreasing. Although this product was of high resolution, use of the unsupervised classification with a stratified grid was more readily adaptable for the LULC change analysis and did not lead to erroneous interpretations. The use of greenness spectral vegetation indices similar to NDVIs may be problematic in east African rice agrocomplexes because of low vegetation cover and highly reflective and variable soils.

The rice well-drained stratum contained 45% (n = 94) of the total aquatic habitat identified, but the poorly irrigated stratum contained 54 of the total (n = 113) aquatic habitats identified. There was a higher preponderance of well-irrigated paddies positive for *An. arabiensis* larvae. In the well-irrigated rice strata, high densities of mosquitoes may be correlated with lower survival rates and thus decreased sporozoite infection rates. In the poorly irrigated strata, mosquito abundance was much lower, with larval abundance mostly below detection level during the dry season, increasing with the progression of the rainy season.

Most LULC change sites in the Karima study site were predominantly characterized by commercial rice activities and residential sites, and the non-LULC change sites consisted mostly of patches of undeveloped or cultivated land. Stratified grid cells and LULC classification may be measuring anthropogenic-ecological variations in socioeconomic status and community level rice agriculture. Rice paddies are influenced by levels of irrigation, but oviposition behavior may be similar across all LULC sites and strata. Host-seeking females may move to Karima in search of a blood meal, while gravid females may be less selective for oviposition.

As in many east African farm areas, rice cultivation is not synchronous in Karima. Because of variations in water availability, the practice of single or double cropping is common. The existence of rice cohorts planted at different times during the cropping season provides omnipresent aquatic habitats as the most suitable rice growth stages shift from paddy to

TABLE 3

Summary of land use land cover (LULC) and non-LULC change in hectares and percentage of total land cover change for Karima, Mwea rice scheme, Kenya

LULC and non-LULC change	Total hectares of land cover change	Percentage (%) of total land cover change
Built to fallow	917.5	19.0
Built to rice field	402.6	8.4
Rice field to built	207.4	4.3
Rice field to fallow	346.5	7.2
Fallow to built	421.3	8.7
Fallow to rice field	266.1	5.5
Built to built	608.7	12.7
Rice field to rice field	913.1	18.9
Fallow to fallow	737.5	15.3
Total	4,820.7	100

TABLE 4

Summary of aquatic habitats that were identified in areas classified as land cover change and type of land cover change in Karima, Mwea rice scheme Kenya

Strata	Habitat type	No change	Ricefield to built env	Fallow to built env	Rice field to fallow	Built to fallow	Built env to ricefield	Fallow to ricefield	Total
Well irrigated	Paddy	19	5	3	8	8	6	3	52
	Canal	15	2	4	9	4	5	3	42
	Total	34	7	7	17	12	11	6	94
Poorly irrigated	Paddy	24	2	0	7	5	2	3	43
	Canal	36	2	1	14	11	2	3	69
	Seep	1	0	0	0	0	0	0	1
	Total	61	4	1	21	16	4	6	113

paddy. Impacts of cultivation technology for high-yielding variety rice can create LULC change areas in the Karima study site include traditional and power tillers, low-lift irrigation pumps, and chemical fertilizers and pesticides on selected land and soil qualities. Anthropogenically induced LULC changes increase *An. gambaie s.l.* populations and affect malaria transmission patterns through changes in vectorial capacity at those sites.[7]

Identification of temporal distribution of the immature stages of *Anopheles* by rice growth stage should be used in an experimental design as the expected target goals for the implementation of microbial control. A drastic reduction in the number of immature forms between the L1, L2, L3, and L4 (larval) stages can occur on all LULC locations throughout the rice season. Larval densities are affected by changes in plant height and biomass, which are associated with certain microhabitat characteristics, such as light conditions, temperature, mechanical obstruction, and nutritional state of the water.[1,10,20,38] Mosquito larval numbers increase as soon as the paddies are flooded, rising to a peak when the rice plants are small, before decreasing when the rice plants cover the surface of the water.[1,10,20,38] *Anopheles gambiae s.l.* thrives in the shallow inundated fields during tilling, transplanting, the first weeks of the growing period (until canopy closure), and after harvest.[8,9]

The spatial pattern of larval productivity within the rice paddies may dictate where microbial larvicides are applied in LULC areas of the rice-village complex. Since anophelines in rice agriculture are considered to feed primarily on the water surface, it is critical to collect empirical data on this behavior in LULC change and LULC non-change sites. Laboratory studies should test *Bacillus thuringiensis subsp. israelensis*, *B. sphaericus*, and their ratios to determine lethal concentration parameters on all LULC change sites. Overall product design goals may include high efficacy based on feeding behavior and susceptibility to bacteria toxins, minimal impact of ultraviolet radiation on efficacy, ease of use through conventional application equipment, and cost profile similar to other larvicides. Final candidate formulations may be evaluated in village-scale tests. For control, we assume that treatments applied to individual habitats are 100% effective in eliminating all immature forms, i.e., treated habitats produce zero contribution to the total productivity. Treatments or habitat perturbations should be based on surveillance of larvae in the most productive areas of the agroecosystem and adjacent village.[39]

An unsupervised algorithm per pixel based on the information derived directly from IKONOS and TM data in ArcView 9.1® provided favorable habitat data on anopheline larval productivity in Karima. To discriminate rice from other crops, several investigators[40–42] have chosen acquisitions at either plowing or harvesting times or both, which offer windows of spectral contrast between rice fields and the surrounding vegetation. We show that an acquisition at harvesting time (June) allowed a very accurate classification of land uses. Our resampling of the IKONOS and Landsat TM data allowed a high level of detail that enabled GIS to extrapolate and map the occurrence and distribution of LULC change sites with extreme accuracy. As a result, all anopheline larval habitats for LULC change and non-change sites per strata for Karima were identified and recorded.

One of the most important considerations for satellite data

TABLE 5

Number of anopheline larvae collected in Karima, Kenya, in different habitat types within the well and poorly irrigated strata

Drainage	Habitat type	No. of habitats	First instars	Second instars	Third instars	Fourth instars
Well drained	Paddy	51	172	108	5	2
	Canal	42	90	41	3	1
	Total	93	262	149	8	3
Poorly drained	Paddy	44	119	48	7	3
	Canal	69	154	56	9	2
	Seep	1	33	1	2	1
	Total	114	306	105	18	6

TABLE 6

Summary of aquatic habitats showing the proportion of site positive for aquatic habitats per strata in land use land cover (LULC) change sites and LULC non-change sites in Karima, rice scheme, Kenya

Strata	No. of habitats with or without larvae	Habitat type	No. of LULC no change habitats	No. of LULC change habitats	Total
Well irrigated	Larvae absent	Paddy	11	10	21
		Canal	5	12	17
		Total	16	22	38
	Larvae present	Paddy	8	23	31
		Canal	10	15	25
		Total	18	38	56
Poorly irrigated	Larvae absent	Paddy	10	8	18
		Canal	13	10	23
		Total	23	18	41
	Larvae present	Paddy	14	11	25
		Canal	23	23	46
		Seep	1	0	1
		Total	38	34	72

is the increased error in geo-referencing on a pixel-by-pixel basis. The GIS overlay operations involve adding and ratioing map values, which requires application of the operation to each pixel; in turn, however, the problem of error propagation such as location errors through the use of these operations may be relevant to GIS.[27] The presence of location error interacting with the spatial structure in the source maps, the presence of spatial correlation in the errors of the attribute measurement process, or their simultaneous presence are capable of generating spatially complex maps of propagated error. In this study, inadequate geographic registration could have resulted in misclassification and subsequent underestimation or overestimation of the extent of LULC change. Each scene was co-registered to matching scene and the maximum likelihood algorithm used the pixel classification on all the satellite data. However, the bands within Landsat TM may have failed to capture all spatial and temporal topographic cover because of poor atmospheric conditions. Seasonal variation in water level can alter land/water interface depiction, which can lead to misregistration of the LULC at those sites. Finally, the homogeneity of the LULC can affect a particular pixel if an area of high reflectivity, such as soil, is next to an area of low reflectivity, such as forest, creating an average value that may be confused with another LULC.[27] As such, the actual relationship between LULC change and mosquito larval habitats in Karima deserves further clarification through continued field ecologically based research and high resolution satellite surveys.

In conclusion, 57.7% of LULC changes for Karima for our selected time periods contributed to changes in abundance and distribution of anopheline habitats in Karima. There is a positive correlation between larval *An. arabiensis* larval habitat distributions and LULC. In areas in which change was detected, the highest percent of LULC change was built environment to fallow. Anthropogenic perturbation, reductions in open space, and built environment to fallow LULC change can support proliferation of a spectrum of larval mosquito niches in planned east African rice irrigation schemes. Seasonal entomologic data using IKONOS and TM data in ArcView 9.1® can systematically delineate and map significant sources of LULC variation in anthropogenic activity and environmental attributes that affect the risk of encountering potentially infectious mosquitoes and provide relevant information to develop and implement an integrated pest management that focuses on the immature stages of vector *Anopheles* species to reduce the transmission of malaria in rice-village complexes in Karima. Public health workers targeting productive habitats for optimal insecticide application will have to consider all open water bodies on LULC change and non-LULC change sites as potential breeding sites.

As a consequence of continuing rice agriculture, LULC changes are likely to continue to affect anopheline larval habitat species composition, abundance, and distribution. During the data collection phase of this study, some engineered drainage systems and buried water delivery and sewer systems were being installed in Karima. Although the excavation and movement of earth, as well as the machinery tire tracks left in the area, may have a positive effect on the development of potential larval habitat in the short-term, the long-term benefits of access to piped water, covered drainage systems, and improved sanitation service may reduce the propensity of rice paddies to harbor anopheline mosquitoes. The water management cycle is critical throughout the season and an up to date record of paddy flooding cycle and subsequent rice cropping should be kept. There is a great need to increase the productivity of water in rice irrigation systems in a sustainable way in Karima. For multiple-cropping to succeed, farmers in Mwea must follow the cropping calendar strictly and observe set time deadlines for various operations such as nursery preparation, transplanting, channel repairing, weeding, fenitrothion application, and field drainage. Composite manure from straw should be applied to rice plot to improve soil fertility and structure. The mode of land preparation should be shallow plowing and direct ridging. Larval mosquito habitats may be significantly reduced by water management, simultaneous rice planting, harvesting, and proper drainage of fallow and rice fields. If larval management targeting LULC change sites continues to reduce adult populations in Karima, this program should be expanded to other rice irrigation complexes with a focus on remote and field technology transfer.

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Authors' addresses: Benjamin G. Jacob, Ephantus Muturi, Patrick Halbig, Jose Funes, and Robert J. Novak, Illinois Natural History Survey, Center for Ecological Entomology, 607 East Peabody Drive, Champaign IL 61820, E-mail: rjnovak@uiuc.edu. Joseph Mwangangi, Enock Mpanga, Josephat Shililu, and John Githure, Human Health Division, International Centre of Insect Physiology and Ecology, PO Box 30772, Nairobi, Kenya. R. K. Wanjogu, Mwea Irrigation Agricultural Development Centre, PO Box 210, Wanguru, Kenya. James Regens, Department of Occupational and Environmental Health, College of Public Health, University of Oklahoma Health Sciences Center, Oklahoma City, OK 73104.

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