NIH Public Access
Author Manuscript
J Med Entomol. Author manuscript; available in PMC 2009 April 27.

Published in final edited form as:
J Med Entomol. 2005 September ; 42(5): 751–755.

Evaluation of Environmental Data for Identification of *Anopheles* (Diptera: Culicidae) Aquatic Larval Habitats in Kisumu and Malindi, Kenya

BENJAMIN G. JACOB[1], **KRISTOPHER L. ARHEART**[2], **DANIEL A. GRIFFITH**[3], **CHARLES M. MBOGO**[4], **ANDREW K. GITHEKO**[5], **JAMES L. REGENS**[6], **JOHN I. GITHURE**[7], **ROBERT NOVAK**[1], and **JOHN C. BEIER**[8]

1 *Illinois Natural History Survey-CEE, 1910 Griffith Dr., N 104 Annex, Champaign, IL 61820.*

2 *Department of Epidemiology, 1801 NW 9th Ave., Suite 300 Highland Professional Bldg. (D-93), University of Miami, Miami, FL 33186.*

3 *Department of Geography and Regional Studies, P.O. Box 248067, University of Miami, Coral Gables, FL 33124–2221.*

4 *Centre for Geographic Medicine Research, Coast, Kenya Medical Research Institute (KEMRI), P.O. Box 428, Kilifi, Kenya.*

5 *Centre for Vector Biology and Control Research, KEMRI, P.O. Box 1578, Kisumu, Kenya.*

6 *Department of Occupational and Environmental Health, University of Oklahoma Health Sciences Center, Oklahoma City, OK 73104.*

7 *Human Health Division, International Centre of Insect Physiology and Ecology (ICIPE), P.O. Box 30772, Nairobi, Kenya.*

8 *Global Public Health Research Group, Department of Epidemiology and Public Health, 12500 SW 152nd St., Bldg B, University of Miami, School of Medicine, Miami, FL 33177.*

Abstract

This research evaluates the extent to which use of environmental data acquired from field and satellite surveys enhances predictions of urban mosquito counts. Mosquito larval habitats were sampled, and multispectral thermal imager (MTI) satellite data in the visible spectrum at 5-m resolution were acquired for Kisumu and Malindi, Kenya, during February and March 2001. All entomological parameters were collected from January to May 2001, June to August 2002, and June to August 2003. In a Poisson model specification, for *Anopheles funestus* Giles, shade was the best predictor, whereas substrate was the best predictor for *Anopheles gambiae*, and vegetation for *Anopheles arabensis* Patton. The top predictors found with a logistic regression model specification were habitat size for *An. gambiae* Giles, pollution for *An. arabensis*, and shade for *An. funestus*. All other coefficients for canopy, debris, habitat nature, permanency, emergent plants, algae, pollution, turbidity, organic materials, all MTI waveband frequencies, distance to the nearest house, distance to the nearest domestic animal, and all land use land cover changes were nonsignificant. MTI data at 5-m spatial resolution do not have an additional predictive value for mosquito counts when adjusted for field-based ecological data.

Keywords

multispectral thermal imager; land use land cover; *Anopheles gambiae*

Expansion of cities to rural peripheral areas and increasing land cover changes in cities produces dramatic differences in mosquito larval habitats, and this expansion necessitates modifications in strategies for controlling aquatic stages of anopheline mosquitoes. Conventional methods for monitoring larval habitats involve identification of ecological variables through extensive field sampling. However, recent studies have shown that a landscape-based approach using remote sensing and geographic information system technology can offer an objective and innovative way to improve assessments of spatial and temporal distributions of vector populations by generating regional maps and environmental variables of localized malaria risk (Wood et al. 1991; Beck et al. 1994, 1997; Pope et al. 1994; Rejmankova et al. 1995; Anno et al. 2000; Jacob et al. 2003, 2004; Keating et al. 2003, 2004). Higher resolution passive satellite systems may provide detailed spectral and thermal images of the earth's surface from which surrogate ecological indicators of complex processes can be measured.

Multispectral thermal imager (MTI) was launched 12 March 2000 from Vandenberg Air Force Base in California. It carries advanced technology for resolving visible, near infrared (NIR), infrared (IR), and thermal signals, and it sends these data to the Sandia National Laboratory in Albuquerque, NM. The superior resolution may be used to survey urban areas to identify potential aquatic habitats and predict spatial patterns of mosquito production. This research evaluates whether MTI data at 5-m spatial resolution have an additional predictive value for mosquito counts when adjusted for field-based ecological data. This assessment is particularly important for African urban environments, where larval control should be feasible (Robert et al. 1998).

Two cities, Kisumu and Malindi, in Kenya were chosen as study areas to conduct ecological investigations about anopheline larval development and productivity. This study is part of an ongoing investigation of Afrotropical mosquitoes and their relationship to malaria transmission in urban environments (McIntyre et al. 2002; Eisele et al. 2003; Keating et al. 2003, 2004; Jacob et al. 2003, 2004). The entomological variable was *Anopheles* abundance (Table 1). The field sampling strategy used for the collection of larval site was geocoded with global positioning system data that was developed from a previous research project and has already has been described in detail (Keating et al. 2003), including all land use land cover (LULC) change parameters and remotely sensed wavelength ranges from the visible band and near infrared region of the MTI satellite (Jacob et al. 2004) to determine which environmental parameters covary with urban aquatic larval habitat development for *Anopheles gambiae* s.l. in Kisumu and Malindi.

The MTI satellite carries a sophisticated telescope that collects day and night images of the Earth in 15 spectral bands ranging from the visible to long-wave infrared. MTI data were acquired for Kisumu and Malindi districts for the dates of 20 February 2001 and 4 March 2001, respectively. The MTI data were georeferenced to the Universal Transverse Mercator (UTM) coordinate system and then cross-referenced with control points from existing TM data that were already projected to UTM coordinates. The projection used for all of the spatial data sets is the UTM Zone 38 datum WGS-84 projection.

The LULC change parameters are derived from Jacob et al. (2003) and are generated from Landsat TM data. MTI data encompassing visible wavebands 3 (0.45–0.52 μm), 4 (0.52–0.60 μm), and 5 (0.62–0.68 μm) were selected to synthesize images containing positive *An. gambiae* larval habitats that ranged from swamps to tree holes (Jacob et al. 2004). The MTI visible bands at 5-m spatial resolution correspond closely to the Landsat Thematic Mapper visible bands (Clodius et al. 2003), with only minor variations in spectral response and focal plane position.

A data set of all field-based ecological data and satellite parameters were compiled. Multivariable analyses were performed with the GENMOD procedure of SAS 8.01 (SAS Institute, Cary, NC) on all data sets of Kisumu, Malindi, and the combined data set of both towns. Moran's *I* and Geary's c were created from ground-based and remote-sensed ecological databases by using SpaceStat 1.80 (Anselin 1994) for the mosquito counts from the data sets of Kisumu, Malindi, and the combined data set of Kisumu and Malindi. Global measures depend on a spatial structural specification such as a spatial weights matrix or a distance related decline function (Griffith et al. 2003). Autocorrelated data may determine whether map patterns underlie the geographic distributions of the habitat counts.

For Kisumu, there was a total of 329 anopheline and 1,022 culcine larvae (Table 2). Of the 329 *Anopheles,* all were *An. gambiae* s.l. of which 88.8% (189 of 213 specimens) were polymerase chain reaction (PCR) identified as *Anopheles arabiensis* and 6.6% (14 specimens) as *An. gambiae* s.s. For Malindi, there was a total of 459 anopheline and 4,651 culicine larvae. Of the 459 total *Anopheles,* 22.1% were identified as *Anopheles funestus and* 77.9% were identified as *An. gambiae* s.l., of which 88.3% (95 of 108 specimens) were PCR identified as *An. gambiae* s.s., 4.3% (five specimens) as *An. arabensis,* and 1% (two specimens) as *Anopheles merus* (Table 2).

Poisson and logistic regression models were generated with the counts of *Anopheles* mosquitoes for the aquatic larval habitat data sets of Malindi, Kisumu, and for a combined data set of both cities. In all models, predictor variables were added in a stepwise manner, beginning with the one that explained the most variation. For the Poisson regression this included shade for both Malindi and the combined data set for the Kisumu and Malindi, and domestic animals for Kisumu. The final model explained 52% of the variation in Malindi, 36% in Kisumu, and 41% in the combined data sets of Malindi and Kisumu (Table 3). In the logistic regression models, habitat size for Malindi, domestic animals for Kisumu, and shade for the combined data set of Kisumu and Malindi were significant. The final model explained 34% of the variation in Malindi, 5% in Kisumu and 21% for the combined data sets of Kisumu and Malindi (Table 4).

The R^2 of the final model for Kisumu was 0.35 ($P < 0.001$); for the validation set, it was 0.14 ($P = 0.052$). The R^2 of the final model for Malindi was 0.52 ($P < 0.001$); for the validation set, it was 0.44 ($P < 0.001$) (Table 5). In Kisumu, the Moran's *I* was 0.075 (> −1/184) and for Malindi the Moran's *I* was 0.295 (> −1/144) (Table 5). The Moran's *I* implies a weak tendency for values of larvae counts to cluster geographically in each urban town. Geary's c for the Malindi data corroborated its corresponding Moran's *I,* whereas for the Kisumu data the Geary c's statistic is somewhat less consistent with its corresponding Moran's *I* value. These calculations were made for different distance intervals and then tabulated into a correlogram table (Table 6).

All significant determinants of larval distribution and abundance for Kisumu and for Malindi, and for the combined data sets of both urban sites, were from field-collected data. For Malindi alone, the satellite parameter LULC to urban was significant. The MTI bands were unable to predict either counts or presence or absence of anopheline in both cities.

The Poisson regression with the actual counts estimated the frequencies and their variation for all multivariable models in Kisumu, Malindi, and the data set of both cities, with greater explanatory power than the parameter estimates from the logistic regression. The validation for the Poisson model for Malindi was significant and fit the data moderately well. The validation data demonstrated that the model for Kisumu needs improvement. The Kisumu data did not contain many observations with a positive anopheline count. The model for Malindi is general enough to make predictions for future observations. We were not able to validate the combined model, perhaps due to extreme ecological differences between the two cities. The model was overparameterized for the validation data set (i.e., we had too many predictors for the small sample size in the validation set). Seasonal restrictions may have affected *Anopheles* densities in both urban sites. Regression assumes that the predictor variables are noncollinear. To test for collinearity, we used the design matrix from a Poisson regression and ran it through SAS's PROCREG procedure, which indicated the absence of problematic correlation among the predictors.

The logarithmic versions of Kisumu and Malindi mosquito counts, which are reasonably well approximated by a bell-shaped curve, display weak to very weak positive spatial autocorrelation; similar numbers of log-counts tend to cluster in geographic space. A value of $-1/(n-1)$ indicated no spatial autocorrelation; in these two cases, this value was $-1/(23-1) = -0.05$. Generally, the extremes are $+1/-1$, but unlike a conventional correlation coefficient, they are not exactly these values. The magnitude of influence of adjacent aquatic larval habitat effects tended to decrease with distance.

In conclusion, MTI at 5-m spatial resolution lacks the sensitivity for detailing aquatic larval habitats of mosquitoes in urban environments, and it should not replace field-collected ecological data in terms of planning for public health disease control operations. Higher resolution imagery, such as IKONOS with 1-m black-and-white (panchromatic) and 4-m multispectral (red, blue, green, and near infrared) band resolution, may hold potential to supplement field-collected ecological data and georeferenced surveys from urban areas.

Acknowledgments

We are grateful to Samuel Kahindi, Lucy Atieli, and Eunice Odhiambo for data collection efforts and to Joseph Keating for critical review. This research was supported by National Institutes of Health Grants U19 AI45511 and FO6 TWO5588. This paper has been drafted with the permission of the Director of the Kenya Medical Research Institute.

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Table 1

Characterization of aquatic larval habitats in urban Kisumu and urban Malindi

Environmental parameter	Variable name	Classification
Habitat size	HBTSIZE	1, small (<3 m^2); 2, medium (>3 m^2–<10 m^2); 3, large (>10 m^2)
Vegetation	VEGE	1, none; 2, some; 3, thick
Nearest domestic animal	DOMANIM	1, 0–20 m; 2, 21–40 m; 3, 41–60 m; 4, >60 m
Shade	SHADE	1, no shade; 2, partly shaded; 3, shaded
Emergent plant	EMERG	1, 0–33.3%; 2, 33.3–66.6%; 3, 66.6–100%
Turbidity	TURBIDIT	0, no; 1, slight; 2, medium; 3, heavy
Depth	DEPTH	1, 0–20 m; 2, 21–40 m; 3, 41–60 m; 4, >60 m
Aquatic animals	AQUANIM	1, dragonflies; 2, backswimmers; 3, tadpoles/frogs; 4, flies, wrigglers/ maggots; 5, small mite-like red insects; 6, fish; 7, none
Pollution	POLLUTIO	0, none; 1, some; 2, thick
Substrate	SUBSTRAT	1, mud; 2, sand; 3, gravel/rock; 4, concrete; 5, rubber; 6, plastic
Algae	ALGAE	1, none; 2, some; 3, thick
Multispectral thermal imager	MTI	(MTI) bands 3 (MTI3), 4 (MTI4), and 5 (MTI5) measured as wavelength frequency
Land use/land cover change	LULC	0, no change; 1, LULC to urban; 2, LULC nonurban
Canopy/plant coverage	CANOPY	1, 0–33.3%; 2, 33.3–66.6%; 3, 66.6–100%
Organic material	ORG	1, 0–33.3%; 2, 33.3–66.6%; 3, 66.6–100%
Debris	DEBRIS	1, 0–33.3%; 2, 33.3–66.6%; 3, 66.6–100%
Permanency	PERM	1, temporary; 2, semipermanent; 3, permanent

Table 2

An. gambiae complex mosquitoes collected and identified by PCR, by ecological strata for the urban areas of Kisumu and Malindi, and the proportion of sites positive for larvae

Site	Strata	No. of habitats sampled	% (*n*) Identified by PCR			
			An. gambiae	*An. arabensis*	*An. funetus*	*An. merus*
Kisumu	1	53	3.1 (7)	22.4 (48)	6.7 (0)	0.0 (0)
	2	33	1.2 (2)	7.6 (6)	0.0 (0)	0.0 (0)
	3	15	0.0 (0)	1.7 (4)	0.0 (0)	0.0 (0)
	4	84	2.3 (5)	56.3 (121)	3.3 (0)	0.0 (0)
Malindi	1	38	12.1 (13)	1.2 (1)	1.3 (6)	1.0 (2)
	2	36	100.1 (11)	0.0 (0)	0.0 (0)	1.0 (0)
	3	8	5.5 (6)	0.0 (0)	0.0 (0)	0.0 (0)
	4	63	60.6 (65)	3.1 (4)	20.7 (95)	1.0 (2)
Kisumu validation[a]	1	11	1.6 (1)	92.9 (12)	0.0 (0)	0.0 (0)
	2	6	0.0 (0)	3.8 (2)	0.0 (0)	0.0 (0)
	3	2	3.2 (2)	5.5 (3)	0.0 (0)	0.0 (0)
	4	29	3.2 (2)	61.4 (32)	0.0 (0)	0.0 (0)
Malindi validation[a]	1	13	4.5 (5)	0 (0)	25.0 (3)	0 (0)
	2	12	7.2 (8)	0 (0)	25.0 (3)	0.0 (0)
	3	6	0 (0)	0 (0)	0.0 (0)	0.0 (0)
	4	5	13.5 (15)	1.8 (2)	50.9 (6)	3.2 (1)

[a]Larval habitats sampled in 2003 for statistical validation. 1, planned-well drained; 2, planned-poorly drained; 3, unplanned-well drained; and 4, unplanned-poorly drained.

Table 3

Significance level of the environmental and satellite parameter predictors in a Poisson regression model of *Anopheles* mosquito counts for Malindi, Kisumu, and the combined data set of Malindi and Kisumu

Variable[a]	*Malindi*			*Kisumu*			*Malindi* and *Kisumu*		
	Initial	**Final**	**%**	**Initial**	**Final**	**%**	**Initial**	**Final**	**%**
HBTSIZE	<0.001	<0.001	9.0	<0.001			0.075	<0.001	3.1
HBTNATUR	0.002			0.002			0.497		
PERMANEN	<0.001			<0.001			0.105		
LULC	0.197	0.023	2.5	0.197			0.503		
NEARHSE	<0.001			<0.001			0.104	0.005	1.8
VEGE	0.002			0.002			0.215	<0.001	2.5
SHADE	<0.001	<0.001	14.7	<0.001	0.020	2.0	<0.001	<0.001	10.8
CANOPY	<0.001			<0.001			0.007		
ALGAE	<0.001	<0.001	5.0	<0.001	0.057	1.6	0.041	<0.001	2.9
DEBRIS	0.086			0.086			0.759		
EMERGENT	<0.001	0.004	4.7	<0.001	0.014	9.6	0.002	0.005	2.4
DEPTH	<0.001	0.001	2.8	<0.001			0.001	<0.001	2.2
SUBSTRAT	<0.001	0.001	12.0	<0.001			0.022	<0.001	5.1
TURBIDIT	<0.001			<0.001	0.005	6.6	0.690	0.012	2.7
DOMANIM	0.499			0.499	<0.001	13.1	0.033	0.010	2.0
AQUANIM	0.224	0.067	1.5	0.224			0.003	<0.001	2.6
ORGANIC	<0.001			<0.001			0.568		
POLLUTIO	0.002			0.002	0.069	2.7	0.004	0.026	2.7
MTI3	<0.001			<0.001			0.821		
MTI4	<0.001			<0.001			0.931		
MTI5	<0.001			<0.001			0.931		
Pseudo-R^2		0.52			0.36			0.41	

See Table 1 for variable definitions.

Table 4

Significance level of the environmental and satellite parameter predictors in a logistic regression model of the presence of *Anopheles* mosquitos for Malindi, Kisumu, and the combined data set of Malindi and Kisumu

Variable	***Malindi***			***Kisumu***			***Malindi* and *Kismu***		
	Initial	**Final**	**%**	**Initial**	**Final**	**%**	**Initial**	**Final**	**%**
HBTSIZE	<0.001	<0.001	27.1	0.112			<0.001	<0.001	5.9
HBTNATUR	0.624						0.641		
PERMANEN	0.696			0.276			0.099		
LULC	0.181	0.030	4.2	0.650			0.206		
NEARHSE	0.934			0.151			0.189		
VEGE	0.210			0.771			0.482		
SHADE	<0.001			0.597			<0.001	0.001	7.4
CANOPY	0.165			0.397			0.006		
ALGAE	0.979			0.636			0.742		
DEBRIS	0.461			0.785			0.645		
EMERGENT	0.906			0.626			0.064		
DEPTH	0.752			0.527			0.001	0.002	3.0
SUBSTRAT	0.004			0.183			0.026		
TURBIDIT	0.010			0.072			0.003		
DOMANIM	0.409			0.013	0.013	4.9	0.604		
AQUANIM	0.005	0.077	2.4	0.784			0.476		
ORGANIC	0.956			0.186			0.112		
POLLUTIO	0.095			0.574			<0.001	<0.001	5.1
MTI3	0.497			0.169			0.724		
MTI4	0.545			0.115			0.773		
MTI5	0.470			0.617			0.773		
Pseudo-R^2		0.34			0.05			0.21	

See Table 1 for variable definitions.

Table 5

Numver and R^2 for Malindi and Kisumu and the combined data for Malindi and Kisumu model and validation data sets

	Malindi		Kisumu		Kisumu/Malindi	
	n	**Pseudo-R^2**	***n***	**Pseudo-R^2**	***n***	**Pseudo-R^2**
Model	116	0.52	160	0.35	276	0.41
Validation	54	0.44	24	0.14	48	−1.39

Table 6

Spatial autocorrelation correlogram-type statistics including Moran coefficient and Geary ratio on mosquito counts, number of neighbors, and log (counts) for Kisumu and Malindi

Relative distance	Kisumu					Malindi				
	Counts		No. of neighbors	Log-(counts + 0.15)		Counts		No. of neighbors	Log-(counts + 0.02)	
	MC	GR		MC	GR	MC	GR		MC	GR
0.05	−0.08	1.95	20	0.07	1.26	−0.07	1.14	48	0.29	0.76
0.10	−0.05	1.64	24	0.05	1.14	−0.05	0.82	84	0.12	0.83
0.15	−0.06	0.87	60	−0.05	1.09	−0.01	1.19	156	0.03	1.02
0.20	−0.05	0.82	64	−0.06	1.07	0.01	1.01	192	0.07	0.93
0.25	−0.06	0.87	114	−0.05	0.97	−0.05	1.23	244	−0.04	1.07
0.30	−0.07	0.90	164	−0.08	0.97	−0.04	1.15	262	−0.03	1.05
0.35	−0.06	0.78	194	−0.08	0.92	−0.06	1.25	270	−0.03	1.06
0.40	−0.04	0.76	232	−0.05	0.91	−0.05	1.17	288	−0.01	1.00
0.45	−0.08	0.90	276	−0.09	0.99	−0.04	1.11	304	0.00	0.97
0.50	−0.09	0.99	318	0.09	1.02	−0.03	1.01	344	−0.01	0.95
Relevant statistics	E(MC)	E(GR)	Max	S-W: 0.51→0.69		E(MC)	E(GR)	Max	S-W: 0.38→0.70	
	−0.045	1	506			−0.045	1	506		