第14卷 第2期
2007年6月
寄生虫与医学昆虫学报
Acta Parasitol. Med. Entomol. Sin.
Vol.14, No.2
Jun., 2007

ASSOCIATION BETWEEN LAND COVER AND HABITAT PRODUCTIVITY OF MALARIA VECTORS IN CENTRAL KENYAN RICELANDS*

Benjamin G. JACOB[1**] Ephantus J. MUTURI[1] Jose E. FUNES[1]
Joseph I. SHILILU[2] John I. GITHURE[2] Robert J. NOVAK[1]
(1. *Illinois Natural History Survey, Center for Ecological Entomology, 607 East Peabody Dr. Champaign IL 61820*;
2. *Human Health Division, International Centre of Insect Physiology and Ecology (ICIPE), P.O.Box 30772, Nairobi, Kenya*)

Abstract This research covers the current status of rice land malaria mapping with particular reference to recent developments in spaceborne data availability. A land cover map was generated in Erdas *Imagine* V8.7® using Quickbird 0.6 m and Ikonos 4.0 m visible and near infrared (NIR) data acquired July 2005, for Kangichiri, Kiuria and Rurumi agro-village complexes within the Mwea Rice Scheme, Kenya. Field sampling data was acquired from the three study sites during July 2005 to July 2006. We performed a maximum likelihood unsupervised classification on the satellite datasets. Each paddy and canal habitat in the three study sites was digitally traced in Arc Info 9.1® which served as a grid. A unique identifier was placed in each grid cell. All habitats in each study site were stratified based on levels of rice stage (1=ploughed, 2=flooded, 3=post-transplanting, 4=tillering, 5=flowering/maturation, 6=fallow). Differentially corrected global positioning systems (DGPS) ground coordinates of rice land *Anopheles* oviposition sites were overlaid on the satellite datasets. An analyses of variance test between aquatic habitat, strata and study site was performed. The Ikonos data and the QuickBird data identified every rice land aquatic habitat by village and strata. Ikonos and QuickBird visible and NIR data of geo-referenced riceland *An. arabiensis* aquatic habitats can develop and implement an Integrated Vector Management (IVM) program based on larval productivity.

Key words QuickBird; Ikonos; *Anopheles arabiensis*; Agro-village complex

1 Introduction

Previous research has shown specific land use land cover change (LULC) can cause a cascade of factors that exacerbate malaria transmission in rice environments (Diuk-Wasser *et al.*, 2004; Jacob *et al.*, 2006). LULC in a rice ecosystem can occur through deforestation, road construction, dam building, irrigation, wetland modification, and other activities (Patz *et al.*, 2004). For example, in Cameroon forest clearance for rice cultivation was associated with invasion of malaria vector: *Anopheles gambiae* s.s. Giles compared with an adjacent area of undisturbed land (Livadas *et al.*, 1958). In Uganda clearance of papyrus swamps at the bottom of highland valleys for rice agriculture has created suitable conditions for *An. gambiae* and *An. funestus* Giles (Steyn, 1946), and marsh clearance has had similar effects in Rwanda (Vincke and Jadin, 1946). Irrigation dam construction has had demonstrable effects on local levels of malaria transmission, as evidenced in Kenya (Khaemba *et al.*, 1994) and Rwanda/Burundi (Meyus *et al.*, 1962). In Kenya, there was a 70 fold increase in the population of *An. gambiae* in the Ahero rice irrigation scheme as compared with an adjacent area of undisturbed land (Surtees, 1970). In Madagascar the association

Received: 2006-11-21
* National Institute of Health Grant (U01A1054889)
** Corresponding author: bjacob@uiuc.edu

between rice fields which support *An. funestus* and malaria risk has been clearly demonstrated (Lepers *et al*., 1991). Vector density was four times higher in a Tanzanian rice field village than in a nearby sugarcane or savanna village (Ijumba *et al*., 2002). In Ethiopia, people that used rice-irrigated land were exposed to a higher risk of malaria as measured by incidence (Ghebreyesus *et al*., 2000). Night time landing bite collections revealed significantly higher adult anopheline densities in rice communities as compared to non-rice agricultural communities in the city of Kumasi, Ghana (Afrane *et al*., 2004). 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 (Faye *et al*., 1993). Significantly higher biting rates and an increase in malaria transmission has recently been documented in an newly irrigated sub-arid rice ecosystem of Madagascar (Marrama *et al*., 2004). Keiser *et al*. (2005) states that the introduction of rice irrigation can place non-immune populations at a high risk for malaria by altering transmission from mesoendemic to hyper endemic as they observed in Rosso in the Senegal River Basin.

Remote sensing and GIS technologies have been successfully used in many vector disease studies to detect LULC and mosquito breeding habitats (Hayes *et al*., 1985; Hay *et al*., 1998; Jacob *et al*., 2003, 2005, 2006; Keating *et al*., 2003, 2004; Sithiprasasna 2003, 2005; Eisele *et al*., 2004; Mushinzimana *et al*., 2006), predict the densities of anopheline vectors (Wood *et al*., 1991; Pope *et al*., 1994; Roberts and Rodriguez 1994; Washino and Wood, 1994; Rodriguez *et al*., 1996) and classify the risk of urban malaria transmission (Beck *et al*., 1994, Carter *et al*., 2000). However previous research has demonstrated limitations of remotely sensed data for providing visual and quantitative confirmation of the abundance and distribution of rice land LULC. For example, Landsat TM at 30 m spatial resolution has been used to estimate paddy rice field land cover (Tennakoon and Murty, 1992; Okamoto and Fukuhara, 1996; Fang *et al*., 1998; Okamoto and Kawashima, 1999). Coarse resolution data and frequent cloud cover in rice growing areas make it difficult to acquire multi-temporal cloud-free images for identifying the flooding and rice transplanting at paddy fields (Xiao *et al*., 2002). Satellite data are commonly used to monitor changing ecological conditions over multiple years using an inter-calibrated Normalized Difference Vegetation Index (NDVI) (Anno *et al*., 2000), however NDVI data from most platforms cannot generate LULC classifications in a rice land area using lower resolution data. Given that many LULC classification of interest to rice land mosquito ecologists occur over large extents but at local scales' the level of spatial detail provided by most past satellite systems is likely to be sufficient for rice land LULC classification.

Recently there has been a significant advance in high resolution polarimetric satellite platforms. The most well-known of the fine spatial resolution satellite sensors, and regarded widely as the first of this new 'era' of remote sensing is Ikonos, launched in 1999. The Ikonos satellite uses a multispectral sensor to collect blue, green, red, and near-infrared (NIR) bands with 4.0 m spatial resolution, providing natural-color imagery for visual interpretation and color-infrared applications (www.spaceimaging.com). A significant event occurred in 2001, with the launch of QuickBird, comprising the finest spatial resolution imagery available currently (0.61 m and 2.44 m spatial resolution panchromatic and multispectral imagery, respectively) (www.digitalglobe.com) Ikonos and QuickBird satellite data can be used to display LULC data associated with the mapped features for identification and characterization of urban larval anopheline mosquito habitats (Sithiprasana *et al*., 2005).

Given that Ikonos and QuickBird observations are at a spatial scale equivalent to rice field measurements, the implications for rice land mosquito control strategies are significant. A quantitative LULC assessment using fine resolution satellite data may spatially target highly productive anopheline aquatic habitats and help direct resources for developing an integrated vector management (IVM) based on habitat variability. Therefore the objective of our study was to compare

Ikonos and QuickBird data for identification of *An. arabiensis* Patton aquatic habitats in three rice agro-village ecosystems using several remotely measured rice land LULC classifications.

2 Material and methodology

2.1 Study sites

The studies were conducted 100 km north east of Nairobi, in Kangichiri, Kiuria and Rurumi village within the Mwea Rice Scheme, Kenya. Mwea occupies the lower altitude zone of 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 about 13 640 ha. More than 50% of the scheme area is used for rice cultivation. The remaining area is used for subsistence farming, grazing and community activities or remains close to its original state. The mean annual precipitation is 950 mm with maximum rainfall occurring in April/May and October/November. The average temperatures range from 16~26.5℃. Relative humidity varies from 52%~67%. Rurumi is located at the central-west region of the scheme and has 225 homesteads and 900 residents. Kangichiri and Kiuria are located in the north east of the scheme and have approximately 150 and 222 homesteads respectively with over 650 residents in each village. Cows, goats, chickens, and donkeys are the primary domestic animals which are generally kept within 5 m of most houses. Over 90% of the houses have mud walls with iron roofing.

The drainage systems of the study sites are divided into three parts. The first is the Nyamindi drainage system consisting of three main canals of which the parent drainage river is the Murubara. The second is the Thiba drainage system comprising five main canals and two branch canals of which the parent river is the Kiruara, a branch of the Tana River. The third is a drainage system composed of some collector drains which evacuate the drainage water directly into the parent Nyamindi and Thiba rivers. In addition, some small streams also run through the study sites. These small streams constitute minor irrigation water sources and natural drains. All irrigated soils in the three study sites are typical black cotton soils (i.e. vertisoils). The land slopes in the direction of northwest to southwest with an average gradient of about 1:140. The discharge measurement of water resources is carried out at the gauging stations located 5 km upstream from the Thiba head works. The farm roads are developed well along main and branch canals allowing transportation of agricultural inputs and products and human habitants. Existing networks of irrigation and drainage systems are separated in each study site.

2.2 Paddy cultivation

As in many East African farm areas, rice cultivation is not synchronous in the three sites. The rice plants in the study sites usually take 3~6 months from germination to maturity, depending on the variety and the environment under which it is grown. It is convenient to regard the life history of Mwea rice plants in terms of three growth stages: vegetative reproductive and ripening. The vegetative stage refers to a period from germination to the initiation of panicle (primordial) and is preceded by the reproductive stage, from panicle primordial initiation to heading, and later by the ripening period, from heading to maturity. A 120-day variety includes 60 days in the vegetative stage, 30 days in the reproductive stage and 30 days in the ripening period.

2.3 Land preparation

The paddy field is pre flooded with about 12 cm of water before rotation. Farmers prepare their own nurseries within their paddy plots. For transplanting, the number of seeding is 3~4 per hill, and planting density is 20~30 hills per m^2. Some crop seasons the density of 100 hills per m^2 (10 cm × 10 cm) is used. Ammonium sulphate and triple super phosphate are applied at a rate of 50 kg/ha and 125 kg/ha, respectively as basal fertilizers about 5 days before transplanting. The actual amount of water used by farmers for land preparation and during the crop growth period is much higher than the actual field requirement. Paddy farmers often store water in their fields as a back-up safety measure against unreliability in water supply. Also, there is often field-to-field irrigation. This leads to a high amount of surface runoff, seepage and percolation accounting for about 50~80 percent of the total water input to the field.

2.4 Larval sampling data

Paddies and canals located within a 1 km buffer in the three study sites were identified and mapped using a CSI-Wireless differentially corrected global positioning systems (DGPS) Max receiver with an Omni Star L-Band satellite signal which has a positional accuracy of less than 1 m (Advanced Computer Resources Corp (ACR), 100 Perimeter Road Nashua, NH, USA). Water bodies were inspected for mosquito larvae using standard dipping techniques with a 350 mL dipper to collect the mosquito larvae (Service, 1993). The number of dips per habitat was a function of habitat size (e.g. paddies 0.3~1.0 hectare) and ranged from 15 to 25. The larvae were preserved placed in whirl pack bags and transported to the Mwea. Research Station for further processing. Anopheline larvae were separated from culicine larvae, preserved in absolute ethanol and later identified microscopically to species (Gillies and Coetzee, 1987). The characteristics of each aquatic habitat as shown in Table 1 were also recorded. A subset of the larvae of the *An. gambiae* complex were identified to sibling 31 species using Polymerase Chain Reaction (PCR) technique (Scott *et al*., 1993).

2.5 Habitat base-mapping

Base maps for this study including major roads and hydrography for the three study sites were created using the DGPS data in ArcInfo 9.1® (Earth Systems Research Institute Redlands, CA, USA) from DGPS

Tab.1 Categories of habitat descriptions and mosquito data used for the Kangichiri, Kiuria and Rurumi Study sites

Items	Abbreviation	Classification
Habitat type	HABTYP	1=paddy, 2=canal, 3=pool, 4=marsh, 5=hoof print, 6=ditch, 7=seep
Habitat nature	HABNAT	0=natural, 1=man made
Distance to nearest house	DISTHSE	1=0~20 m, 2=21~40 m, 3=41~60 m, 4=>60
Distance domestic animals	DOMAN	1=0~20 m, 2=21~40 m, 3=41~60 m, 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=post transplant, 2=tillering, 3=boot, 4=flower/maturation, 5=fallow, 6=flooded, 7=ploughed
Rice height	RICEHGT	measured in cm=
#tillers	TILLER	Count =
Organic matter	ORGMAT	0=none, 1=plant, 2=animal
Turbidity	TURB	0=no, 1=low, 2=high
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=chironomus, 12=midges
Pollution	POLL	measured as a %=
Substrate	SUBS	1=mud, 2=sand, 3=gravel/rock, 4=concrete, 5=rubber, 6=plastic
Azolla	AZOL	0=none, 1=1%~25%, 2=26%~50%, 3=51%~75%, 4=76%~100%
#Dips	DIPS	#=
Anopheles larvae	ANOPH	L1=L2=L3=L4=
Pupae	PUPAE	#=

(Plate Ⅲ). Each rice land *An. arabiensis* larval habitat with its associated land cover attributes from each study site were entered into a Vector Control Management System® (VCMS) (Advanced Computer Resources Corp (ACR), 100 Perimeter Road Nashua, NH, USA) database. VCMS supported the mobile field data acquisition in each study site through a Microsoft PocketPC™. All two-way, remote synchronizing of data, geocoding, and spatial display were processed using the embedded GIS Interface Kit™ that was built using ESRI's MapObjects™ 2 technology. The VCMS database plotted and updated DGPS ground coordinates of aquatic larval habitat seasonal information and supported exporting data to a spatial format whereby any combination of rice land larval habitats and supplementary field data in the three study sites were exported in a GIS as a shape file format.

2.6 Remote sensing data

The information obtained from Ikonos encompassed wavebands 1 (0.45～0.53 μm), 2 (0.54～0.61 μm), 3 (0.64～0.72 μm) and 4 (0.76～0.83 μm) was acquired July 21, 2005. Ikonos visible and near-infrared (NIR) bands data were collected in an 8-bit format. The sun-synchronous Ikonos orbit provides global coverage, consistent access times, and near-nadir viewing angles (Table 2) (www.spaceimaging.com). QuickBird multispectral products provide four discrete non-overlapping spectral bands covering a range from 0.45 to 0.72 μm with an 11-bit collected information depth. The QuickBird image encompassing the visible and NIR band and was acquired July 15, 2005. Information from visible and NIR channels can distinguish mosquito aquatic habitats (Wood *et al*., 1991). DigitalGlobe's QuickBird satellite provides the largest swath width, largest on-board storage, and highest resolution of any currently available or planned commercial satellite (www.digitalglobe.com) (Table 2). Only the data from the cloud free clearest contiguous sub areas of the rice-village complex were used. Both satellite datasets were classified using the Iterative Self-Organizing Data Analysis Technique

Tab.2 Characteristics of QuickBird and Ikonos orbital sensor systems

Satellite	QuickBird	Ikonos
Launch date	October 18, 2001	September 24, 1999
Launch vehicle	Boeing Delta 11	Boeing Delta 11
Launch location	Vandenberg Air Force Base Ca USA	Vandenberg Air Force Base Ca USA
Orbit altitude	450 km	681 km
Orbit inclination	97.2 degree, sun synchronous	98.1 degree, sun synchronous
Speed	7.1 km/s	7.5 km/s
Equator crossing time	10:30 a.m. (descending node)	Nominally 10:30 a.m. solar time
Orbit time	93.5 minutes	98 minutes
Revisit time	1～3.5 days depending on latitude (30° off-nadir)	Approximately 3 days at 40° latitude
Swath width	16.5 km at nadir	11.3 km at nadir 13.8 km at 26° off-nadir
Metric accuracy	23-meter horizontal (CE 90%)	23-meter horizontal (CE 90%)
Digitization	11 bits	11 bits
Resolution	Pan: 61 cm (nadir) to 72 cm (25° off-nadir)	Nadir: 0.82 meters panchromatic 3.2 meters multispectral
	MS: 2.44 m (nadir) to 2, 88 m (25° off-nadir)	26° Off-Nadir, 1.0 meter panchromatic; 4.0 meters multispectral
Image Bands	Pan: 450～900 nm; Blue: 450～520 nm; Green: 520～600 nm; Red: 630～690 nm	Blue: 455～516 nm; Green: 506～595 nm; Red: 632～698 nm
	Near Infra-Red (NIR) 760～900 nm	Near Infra-Red (NIR): 0.757～0.853 nm

(ISODATA) unsupervised routine in ERDAS *Imagine* V 8.7™ (Atlanta, USA). The supervised classification assigned the signatures automatically generated by the ISODATA algorithm (Huang, 2002) for remote identification of mosquito aquatic habitats (Jacob *et al*., 2005). The geographic projection used for all of the spatial datasets is the Universal Transverse Mercator (UTM) Zone 37S datum WGS-84 projection.

2.7 LULC habitat characterization

LULC classification used for assessing the satellite data of the paddy habitats in the three study sites was based on the rice stage of development. (1) Ploughing: field preparation prior to transplanting of rice seedlings. (2) Flooding: comprised of areas of intensive use with much of the land covered by water. (3) Post transplanting: A period following rice seedlings transplanting. (4) Tillering: extends from the appearance of the first tiller until the maximum tiller (5~9) number is reached. Stem elongation occurs and the tillers continue to increase in number and height, with increasing ground cover and canopy formation. (5) Flowering and maturation: the stage plants stop growing and orient towards the development of the panicles and grains (water is drained), and in which plants senesce and their water content drops. The flowering/maturation phase includes the panicle initiation, booting, heading and flowering stages. Harvesting occurs 120~150 days post transplanting when the grains fill, turn yellow and the plants senesce. (6) Fallow/post-harvest: After harvesting, the land is left bare waiting the next crop cycle.

2.8 Digitized grid

A digitized custom grid tracing each riceland for *An. arabiensis* aquatic habitats were generated in Arc Info 9.1®. A unique identifier was placed in each grid cell (i.e. polygon). The digitized grid extended out to a 1 km distance from the external boundary of each village providing a 1 km radial area.

2.9 Canal vegetation spectral analyses

Additionally, canal habitats were examined for abundance and distribution of *Anopheles* aquatic habitats using QuickBird and Ikonos visible and NIR data. The digitized grid overlaid on the satellite data was used to calculate the measure of spatial complexity and configuration of vegetation within each canal habitat. Rice land habitats frequently comprise a mixture of vegetation soil and water each of which may have a different spectral response (Huang, 2002). Using variations in canal habitat vegetation in each study site were assessed into smaller subsets.

2.10 Data analyses

Due to the variation in the number of dips collected per habitat based on the size, we based our results on the number of larvae collected per dip. The entomological variable was total rice land anopheline larvae. We performed an ANOVA test to compare the differences in larval abundance between different paddy categories in each study site. An independent sample *t* test was used to compare differences in larval abundance between paddies and canals as well as between vegetated and non-vegetated canals. We examined each QuickBird and Ikonos grid cell unit in each study site to determine the amount of grid cell variation for rice land *An. arabiensis* aquatic habitats. Robust standard errors were used because data were collected at both the 0.61 m and 4.0 m pixel level. An alpha level of 0.05 was used to indicate significance. All data management and calculations were performed using SAS 9.1.3® (SAS inc. Carey, NC, USA).

3 Results

We 'screened' the QuickBird and Ikonos images to determine location of rice land all paddy and canal habitats. The QuickBird visible and NIR data captured each paddy by study site and strata (Plate Ⅳ-2). The Ikonos visible and NIR data was also able to identify any rice land aquatic habitat by study site or strata (Plate Ⅳ-1). QuickBird and Ikonos visible and NIR bands were able to spatially distinguish levels of canals and their surrounding vegetation in the study sites.

The QuickBird and Ikonos visible and NIR data identified each paddy habitat by study site and strata. The abundance of 1st instar larvae/dip collected in Rurumi and Kangichiri study sites was 0.99 and 1.95, respectively and significantly lower than 4.81 in the Kiuria study site ($F = 5.16$, $df = 2$, 751, $P < 0.01$). Similarly, the abundance of 2nd instar larvae differed significantly among villages with that of 0.66 in the Rurumi study site being significantly lower than 1.09 or 2.11 in Kangichiri and Kiuria study sites, respectively ($F = 3.79$, $df = 2$, 751, $P < 0.05$). The abundance of 3rd and 4th instar larvae as well as that of pupae did not differ significantly among villages ($F = 1.64$, 0.97 and 1.04, $df = 2$, 75, $P > 0.05$). Table 3 shows the abundance of rice land *An. arabiensis* larvae/20 dips collected in the paddy and canal habitats at the 3 study sites. In the Kangichiri study site, the difference in the abundance of pupae and 1st, 2nd and 3rd instar larvae collected in paddy and canal habitats was not significant ($P > 0.05$) while that of 4th instar larvae was significantly higher in the paddy habitats than in the canals ($F = 5.19$, $df = 1$, 179, $P < 0.05$). In the Kiuria study site, significantly higher abundance of 3rd instar larvae were collected in the canals ($F = 4.68$, $df = 1$, 179, $P < 0.05$) while the other immature stages did not differ significantly between canal and paddy habitats. In the Rurumi study site, paddy habitats had significantly higher abundance of 1st and 2nd instar larvae compared with the canals ($F = 5.60$ and 3.94, $df = 1$, 188, $P < 0.05$) but the other immature stages did not vary significantly between paddy and canal habitats.

The distribution of larvae in rice fields at different stages of the rice cycle is shown in Table 3. Six stages of rice growth were identified in each of the three study sites by the QuickBird and Ikonos visible and NIR data. An analysis of variance test indicated the relative abundance of immature stages of *An. arabiensis* at the three study sites to be significantly higher during the post transplanting and the tillering stages of the rice growth ($P < 0.05$). In the other rice stages, the immature stages of *An. arabiensis* were either absent or occurring in low numbers (Table 4).

Tab.3 Abundance of *An. arabiensis* larvae in paddies and canals identified using QuickBird 0.61 m and Ikonos 4.0 m visible and near infra-red (NIR) data

Village	Habitat type	No. of habitat	Proportion positive for *Anopheles* larvae	1st instars	2nd instars	3rd instars	4th instars	Pupae
Kangichiri	Paddy	160	57.10	1.64±0.38	1.18±0.25	0.24±0.13	0.00±0.00	0.40±0.13
	Canal	135	42.90	2.28±1.16	0.99±0.25	0.17±0.10	0.07±0.03	0.17±0.05
Kiuria	Paddy	122	62.80	5.50±2.00	1.83±0.59	0.14±0.07	0.37±0.35	0.27±0.11
	Canal	69	37.20	3.66±0.85	2.59±0.85	0.40±0.10	0.04±0.03	0.19±0.09
Rurumi	Paddy	106	68.60	1.42±0.34	1.12±0.45	0.08±0.04	0.05±0.03	0.16±0.11
	Canal	98	31.40	0.59±0.12	0.23±0.07	0.11±0.04	0.01±0.01	0.04±0.02

The relative abundance of rice land *An. arabiensis* larvae in vegetated and non-vegetated canal habitats identified by the QuickBird and Ikonos visible and NIR data and the statistical comparisons of larval abundance between the two categories are represented in Tables 5 and 6 in the Kangichiri study site, the relative abundance of 1st and 2nd instar larvae was significantly higher in non-vegetated than vegetated canals while the differences in the other aquatic stages was not significant. In the Kiuria study site, the abundance of all the 4 larval instars of *An. arabiensis* was significantly higher in non-vegetated canals whereas in the Rurumi study site, the same trend was observed for the 2nd and 3rd instar larvae.

4 Discussion

Results of this study demonstrated QuickBird 0.61 m and Ikonos 4.0 m data can be used for identification of LULC stages Anopheles aquatic habitats in a rice land environment. QuickBird and Ikonos visible and NIR bands visualized the study sites with great details, and facilitated identification of all rice land LULC classification. The canal habitats vegetation cover was easily distinguished in the Ikonos and QuickBird image (Plate Ⅳ-1a and Plate Ⅳ-2a) · Spectral regions of paddies were separated by color differences (e · g · flooded (dark blue tone) and (Plate Ⅳ-1b and Plate Ⅳ-2b) · In both satellite datasets canal vegetation generates shades of green in the rice fields · The spatial resolution of newer satellites can allow for exact recognition of broad vegetative types (Thenkabail *et al* ·, 2004) · Post transplanting LULC had the most habitats positive for *An* · *arabiensis* larvae in the three study sites ·

Tab ·4 Immature stages of *An* · *arabiensis* sampled in paddies containing different stages of rice growth using a QuickBird 0.61 m and Ikonos 4.0 m visible and near infra-red (NIR) data

Village	Paddy category	No · of habitats	1st instars	2nd instars	3rd instars	4th instars	Pupae
Kangichiri	Ploughed	25	1.41	0.95	0.09	0.00	0.36
	Flooded	23	1.67	1.10	0.30	0.00	0.36
	Post transplanting	30	6.02	3.00	1.89	1.20	0.99
	Tillering	28	8.00	6.67	2.00	3.22	0.67
	Flowering/maturation	27	0.01	0.00	0.02	0.01	0.00
	Fallow	27	1.00	0.67	0.00	0.00	0.01
Kiuria	Ploughed	22	0.00	0.00	0.00	0.00	0.00
	Flooded	23	1.23	0.65	0.07	0.01	0.0
	Post transplanting	21	5.58	1.63	0.17	0.51	0.19
	Tillering	22	8.50	5.25	0.25	0.25	1.25
	Flowering/maturation	20	0.02	0.00	0.01	0.0	0.00
	Fallow	14	0.03	0.01	0.0	0.01	0.00
Rurumi	Ploughed	18	0.00	0.00	0.00	0.00	0.00
	Flooded	21	1.56	1.28	0.09	0.06	0.19
	Post transplanting	20	5.73	3.37	1.17	1.03	0.47
	Tillering	20	4.91	4.67	1.19	1.11	1.00
	Flowering/maturation	15	0.00	0.00	0.00	0.00	0.00
	Fallow	12	1.17	0.00	0.00	0.00	0.00

QuickBird 0.61 m and Ikonos 4.0 m visible and NIR data provided critical LULC information for characterizing highly productive rice land aquatic habitats in the three study sites · We found mosquito numbers increased as soon as the paddies were flooded, rising to a peak when the rice plants were small, before declining when the rice plants cover the surface of the water generally in the late tiller stage · Similar findings have been reported previously (Surtees 1970; Snow 1983; Lindsay *et al* ·, 1991) · The open sunlit pools created by rice workers during transplanting have been hypothesized to favor the breeding of *An* · *arabiensis* (Mutero *et al* ·, 2000) · In addition, as the rice canopy cover expands following tiller formation and increase in rice height, the paddy habitat become unsuitable for this species · Increased rice canopy cover may reduce the amount of sunlight reaching the water surface resulting in lower temperatures · Reduced temperature causes a decline in microbial growth upon which mosquito larvae depend on (Rao, 1984) · In addition rice plants may obstruct this species from ovipositing considering its preference for open sunlit habitats (Rajendran and Reuben, 1991; Shililu *et al* ·, 2004) ·

Tab.5　Average number (±*SE*) of *An*. *arabiensis* larvae in vegetated and non-vegetated canals identified using a QuickBird 0.61 m and Ikonos 4.0 m visible and near infra-red (NIR) data

Village	Vegetation	1st instars	2nd instars	3rd instars	4th instars	Pupae
Kangichiri	Present	1.20±0.31	0.87±0.21	0.00±0.00	0.00±0.00	0.00±0.00
	Absent	24.50±24.50	3.50±3.50	0.18±0.10	0.07±0.03	0.17±0.05
Kiuria	Present	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00	0.00±0.00
	Absent	3.83±088	2.71±0.89	0.72±0.11	0.5±0.03	0.20±0.09
Rurumi	Present	0.4±0.17	0.10±0.10	0.00±0.00	0.00±0.00	0.00±0.00
	Absent	0.64±0.14	0.27±0.08	0.14±0.05	0.01±0.01	0.05±0.03

Tab.6　Statistical values comparing the differences in *An*. *arabiensis* larval densities between the vegetated and non-vegetated canals

Stage	Kangichiri			Kiuria			Rurumi		
	df	*t*	Sig.	*df*	*t*	Sig.	*df*	*t*	Sig.
1st instars	134	22.22	0.00	68	0.86	0.03	97	0.87	0.35
2nd instars	134	4.97	0.03	68	0.43	0.04	97	3.75	0.05
3rd instars	134	0.15	0.70	68	0.68	0.04	97	0.02	0.04
4th instars	134	0.23	0.64	68	0.08	0.06	97	0.01	0.93
Pupae	134	0.60	0.44	68	0.22	0.64	97	0.35	0.55

Determining spatial heterogeneity in larval habitat distribution can have important operational significance because vector control operations can be designed to target zones where high densities of malaria vectors are found. Treatments or habitat perturbations should be based on surveillance of larvae in the most productive areas of the agro ecosystem and adjacent village (Gu *et al*., 2005). The spatial pattern of larval productivity within a rice-village complex can dictate where microbial larvicides are applied. 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 rice land LULC sites. Laboratory studies should test Aquabac® or Vectobac® (*Bacillus thuringiensis* var. israelensis-Bti) and Vectolex® (*Bacillus spaericus*-Bsph) ratios to determine lethal concentration parameters on all highly productive rice-related Anopheline aquatic habitats. 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 immatures, i.e. treated habitats produce zero contribution to the total productivity.

An unsupervised algorithm using QuickBird and Ikonos visible and NIR data in ArcInfo 9.1® provided informative LULC data for rice land Anopheline habitat suitability in the three study sites. However, one of the most important considerations of satellite data is the increased error in geo-referencing on a pixel-by-pixel basis. ArcInfo 9.1® overlay operations involving adding and ratioing map values which requires application of the operation to each pixel; in turn, the problem of error propagation such as location errors through the use of these operations may be relevant to ArcInfo 9.1®. 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 indeed their simultaneous presence are capable of generating spatially complex maps of propagated error (Jacob *et al*., 2003; Jacob *et al*., 2005). Inadequate geographic registration could have resulted in misclassification and subsequent underestimation or overestimation of the extent of satellite data coverage in the three study site. 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 the satellite data may have failed to capture all spatio-temporal topographic cover. Also, seasonal variation in water level can alter land/water interface depiction, which can lead to mis-registration of LULC at those sites. For example, the homogeneity of the LULC can affect a particular pixel if an area of high reflectivity, such as flooded, is next to an area of low reflectivity, such as fallow, creating an 78 average value that may be confused with 79 another LULC. As such, the actual relationship between LULC and rice land mosquito larval habitats deserves further clarification through continued field and satellite studies.

In conclusion, the QuickBird 0.61 m and Ikonos 4.0 m visible and NIR data identified every paddy and canal habitat by rice land LULC in the three study sites. An LULC classification of a multispectral QuickBird and Ikonos rice land image can clearly identify highly productive riceland *An. arabiensis* aquatic habitats. Mosquito surveillance systems based on QuickBird and Ikonos data can provide early warning as well as crucial LULC and larval abundance data for targeting effective prevention efforts. QuickBird and Ikonos visible and NIR data can be used to develop and implement a rice land IVM program based on habitat productivity. In the presence of either genotypic or behavioral adaptation of the anopheline to rice land environments, oviposition preferences and larval development strategies may change (Khambea *et al*., 1994; Chinery, 1995). Therefore it is crucial to continue to determine further accurate rice land LULC and aquatic habitat information using QuickBird 0.61 m and Ikonos 4.0 m visible and NIR data to determine rice land habitats which are more likely to produce a greater abundance of vectors and promote vector-host interactions. Continued exploitation of QuickBird and Ikonos data can reduce the standard error of estimates and increase the power of LULC models generated to detect correlations and relationships between man-made activity and entomologic factors in a rice-village agro-ecosystem.

Acknowledgement We would like to thank the data collection efforts of the ICIPE Mwea Rice Mosquito Team; provided by and Simon M. Muriu, Enock Mpanga, James Wauna, Peter Barasa, Nelson M. Muchiri, Glady Kamari, Irene Kamau, Charles C. Kiura, Peter M. Mutiga, Paul K. Mwangi, Nicholus G. Kamari, William M. Waweru, Christine W. Maina, Martin Njigoya and Naftaly Gichuki at the Mwea Divison in Kenya for conducting the study. We would also like to thank Dr Clifford Mutero for providing data for the various base maps of the three study sites. This research was funded by the National Institute of Health Grant U01A1054889 (Novak Robert) University of Illinois, Urbana-Champaign.

References

Afrane, Y. A., A. Klinkenberg, P. Eveline *et al*. 2004 Does irrigated urban agriculture influence the transmission of malaria in the city of Kumasi, Ghana? *Acta Trop*., **89**: 125～134.

Anno S., M. Takagi, Y. Tsuda *et al*. 2000 Analysis of relationship between *Anopheles subpictus* larval densities and environmental parameters using Remote Sensing (RS), a Global Positioning System (GPS) and a Geographic Information System (GIS). *Kobe J. Med. Sci*., **46**: 231～243.

Beck, L. R., M. H. Rodriguez, S. W. Dister *et al*. 1994 Remote sensing as a landscape epidemiologic tool to identify villages at high risk for malaria transmission. *Am. J. Trop. Med. Hyg*., **51**: 271～280.

Carter, R., K. Mendis and D. Roberts 2000 Spatial targeting of interventions against malaria. *Bull. World Health Organ*., **78**: 1 401～1 411.

Chinery, W. 1995 Impact of rapid urbanization on mosquitoes and their disease transmission potential in Accra and Tema, Ghana. *Afr. J. Med. Med. Sci*., **24**: 179～188.

Diuk-Wasser, M. A., M. Bagayoko, N. Sogoba *et al*. 2004 Mapping rice field anopheline breeding habitats in Mali, West Africa, using Landsat ETM+ sensor data. *Int. J. Remote Sens*., **25** (2): 359～376.

Eisele, T. P., J. Keating, C. Swalm *et al*. 2004. Linking field-based ecological data with remotely sensed data using a geographic information system in two malaria endemic urban areas of Kenya. *Mal. J*., **10**: 36～44.

Fang, H., B. Wu, H. Liu *et al*. 1998 Using NOAA AVHRR and Landsat TM to estimate rice area year-by-year. *Int. J. Remote*

Sens., **19**: 521～525.

Faye, O., D. Fontenille and J. P. Herve 1993 Malaria in the sahelian zone of Senegal. 1. Entomological data concerning transmission. *Annales de la Société Belge de Médecine Tropicale*, **73**: 21～30.

Ghebreyesus, T., M. Haile, K. Witten *et al*. 2000 Household risk factors for malaria among children in the Ethiopian Highlands. *Trans. R. Soc. Trop. Med. Hyg.*, **94**: 17～24.

Gillies, M. T. and M. Coetzee 1987 A supplement to the Anophelinae of Africa south of the Sahara (Afrotropical region). *Johannesberg. Pub. South Afr. Ins. Med. Res.*, **55**: 1～143.

Gu, W. and R. Novak 2005 Habitat-based modeling of impacts of mosquito larval interventions on entomological inoculation rates, incidence, and prevalence of malaria. *Am. J. Trop. Med. Hyg.*, **73**: 546～552.

Hay, S. I., R. W. Snow and D. J. Rogers 1998 From predicting mosquito habitat to malaria seasons using remotely sensed data: practice, problems and perspectives. *Parasitol. Today*, **14**: 306～313.

Hayes, R. O., E. L. Maxwell, C. J. Mitchell *et al*. 1985. Detection, identification and classification of mosquito larval habitats using remote sensing scanners in earth-orbiting satellites. *Bull. WHO*, **63**: 361～374.

Huang, K. Y. 2002 A synergistic automatic clustering technique (Syneract) for multispectral image analysis. *Photogrammetric Engineering & Remote Sensing*, **68**: 33～40.

Ijumba, J. N., F. C. Shenton, S. E. Clarke *et al*. 2002 Irrigated crop production is associated with less malaria than traditional agricultural practises in Tanzania. *Trans. R. Soc. Trop. Med. Hyg.*, **11**: 476～480.

Jacob, B., J. Regens, C. Mbogo *et al*. 2003 Occurrence and distribution of *Anopheles* (Diptera: Culicidae) larval habitats on land cover change sites in urban Kisumu and urban Malindi, Kenya. *J. Med. Entomol.*, **40**: 777～784.

Jacob, B., K. Arheart, D. A. Griffith *et al*. 2005 Evaluation of environmental data for identification of *Anopheles* (Diptera: Culicidae) aquatic larval habitats in Kisumu and Malindi, Kenya. *J. Med. Entomol.*, **42**: 751～755.

Jacob, B. G., E. Muturi, J. M. Mwangangi *et al*. 2006 Spatially targeting *Culex quinquefasciatus* aquatic habitats on modified land cover for implementing an Integrated Vector Management (IVM) program in three villages within the Mwea Rice Scheme, Kenya. *Int. J. Health Geogr.*, **12**: 5～18.

Keating, J., K. Macintyre, C. Mbogo *et al*. 2003 A geographic sampling strategy for studying relationships between human activity and malaria vectors in urban Africa. *Am. J. Trop. Med. Hyg.*, **68**: 35～47.

Keating, J., K. Macintyre, C. Mbogo *et al*. 2004 Characterization of potential larval habitats for Anopheles mosquitoes in relation to urban land-use in Malindi, Kenya. *Int. J. Health Geogr.*, **15**: 3～9.

Keiser, J., M. C. de Castro, M. F. Maltese *et al*. 2005 Effect of irrigation and large dams on the burden of malaria on a global and regional scale. *Am. J. Trop. Med. Hyg.*, **72**: 92～406.

Khaemba, B. M., A. Mutani and M. K. Bett 1994 Studies of anopheline mosquitoes transmitting malaria in a newly developed highland urban area: a case study of Moi University and its environs. *East Med. Afr. J.*, **59**: 164～171.

Lepers, J. P., D. Fontenille, M. D. Rason *et al*. 1991 Transmission and epidemiology of newly transmitted falciparum malaria in the central highland plateaux of Madagascar. *Ann. Trop. Med. Parasitol.*, **85**: 297～304.

Lindsay, S. W., H. A. Wilkins, H. A. Zieler *et al*. 1991 Ability of *Anopheles gambiae* mosquitoes to transmit malaria during the dry and wet seasons in an area of irrigated rice cultivation in The Gambia. *J. Trop. Med. Hyg.*, **94**: 313～324.

Livadas, G., J. Mouchet and R. Chastang 1958 Peut-on envisager l'éradication du paludisme dans la région forestière du Sud Cameroun? *Estratto dalla Rivista di Malariologia*, **37**: 228～256.

Marrama, L., R. Jambou and I. Rakotoarivony 2004 Malaria transmission in southern Madagascar: influence of the environment and hydro-agricultural works in sub-arid and humid regions. *Acta Trop.*, **89**: 193～203.

Meyus, H., M. Lips and H. Caubaugh 1962 L'et actuel du problème du paludisme d'altitude au Rwanda-Urundi. *Annales de la Societe Belge de Medecine Tropicale*. **42**: 771～782.

Mushinzimana, E., S. Munga, N. Minakawa *et al*. 2006 Landscape determinants and remote sensing of anopheline mosquito larval habitats in the western Kenya highlands. *Mal. J.*, **5**: 5～13.

Mutero, C. M., H. Blank, F. Konradsen *et al*. 2000 Water management for controling the breeding of Anopheles mosquitoes in rice irrigation schemes in Kenya. ICIPE, Nairobi. *Acta Trop.*, **76**: 253～256.

Okamoto, K. and M. Fukuhara 1996 Estimation of paddy field area using the area Anopheles rice breeding mapping using the area ratio of categories in each mixel of Landsat TM. *Int. J. Remote Sens.*, **17**: 1 735～1 749.

Okamoto, K., S. Yamakawa and H. Kawashima 1998 Estimation of flood damage to rice production in North Korea in 1995. *Int. J. Remote Sens.*, **19**: 365～371.

Patz, J. A., P. Daszak, G. M. Tabor *et al*. 2004 Unhealthy landscapes: Policy recommendations on land use change and infectious disease emergence. *Environ. Health Perspect.*, **112**: 1 092～1 098.

Pope, K. O., E. Rejmankova, H. M. Savage *et al*. 1994 Remote-sensing of tropical wetlands for malaria control in Chiapas, Mexico. *Ecol. Appl.*, **4**: 81～90.

Rajendran, R. and R. Reuben 1991 Evaluation of water fern Azolla microphylla for mosquito population management in the rice land agro-ecosystem of South India. *Med. Vet. Entomol.*, **5**: 299～310.

Rao, R. 1984 The Anophelines of India. Revised edition. ICMR, New Delhi.

Roberts, D. R. and M. H. Rodriguez 1994 The environment, remotes sensing, and malaria control. *Ann. N. Y. Acad. Sci.*, **74**: 396～402.

Rodriguez, A. D., M. H. Rodriguez, J. E. Hernandez *et al.* 1996 Landscape surrounding human settlements and *Anopheles albimanus* (Diptera: Culicidae) abundance in Southern Chiapas, Mexico. *J. Med. Entomol.*, **33**: 39～48.

Scott, J., W. G. Brogdon and F. H. Collins 1993 Identification of single species specimens of the *Anopheles gambiae* complex by the polymerase chain reaction. *Am. J. Trop. Med. Hyg.*, **49**: 520～529.

Service, M. W. 1993 Mosquito ecology: field sampling methods, 2nd ed. Essex, UK: Elsevier Publishers.

Shililu, J., T. Ghebremeskel, F. Seulu *et al.* 2003 Larval habitat diversity and ecology of anopheline larvae in Eritrea. *J. Med. Entomol.*, **40**: 921～929.

Sithiprasana, R., W. J. Lee, D. M. Ugang *et al.* 2005 Identification and characterization of larval and adult anopheline mosquito habitats in the Republic of Korea: potential use of remotely sensed data to estimate mosquito distributions. *Int. J. Health Geogr.*, **4**: 17～24.

Sithiprasasna, R., K. J. Linthicum and G. J. Liu *et al.* 2003 Use of GIS-based spatial modeling approach to characterize the spatial patterns of malaria mosquito vector breeding habitats in northwestern Thailand. *Southeast Asian J. Trop. Med. Public Health*, **34**: 517～528.

Snow, W. 1983 Mosquito production and species succession from an area of irrigated rice fields in The Gambia, W. Africa. *J. Trop. Med. Hyg.*, **86**: 237～245.

Surtees, G. 1970 Effects of irrigation on mosquito populations and mosquito-borne diseases in man, with particular reference to rice field extension. *Int. J. Environ. Stud.*, **1**: 35～42.

Tennakoon, S. B., V. N. Murty 1992 Estimation of cropped area and grain yield of rice using remote sensing data. *Int. J. Remote Sens.*, **13**: 427～439.

Thenkabail, P. S. 2004 Inter-sensor relationships between IKONOS and Landsat-7 ETM＋NDVI data in three ecoregions of Africa. *Int. J. Remote Sens.*, **25**: 389～408.

Vincke, I. H. and J. B. Jadin 1946 Contribution a l'e tude de l'anophelisme en pays d'altitude Annales de la Societe Belge Medicne Tropicale, **26**: 483～500.

Washino, R. K. and B. J. Wood 1994 Application of remote sensing to arthropod vector surveillance and control. *Am. J. Trop. Med. Hyg.*, **50**: 134～144.

Wood, R., R. K. Washino, L. Beck *et al.* 1991 Distinguishing high and low anopheline-producing rice fields using remote sensing and GIS technologies. *Prev. Vet. Med.*, **11**: 277～288.

Xiao, X., S. Boles, S. Frolking *et al.* 2002 Observation of flooding and rice transplanting of paddy rice fields at the site to landscape scales in China using VEGETATION sensor data. *Int. J. Remote Sens.*, **23**: 3 009～3 022.

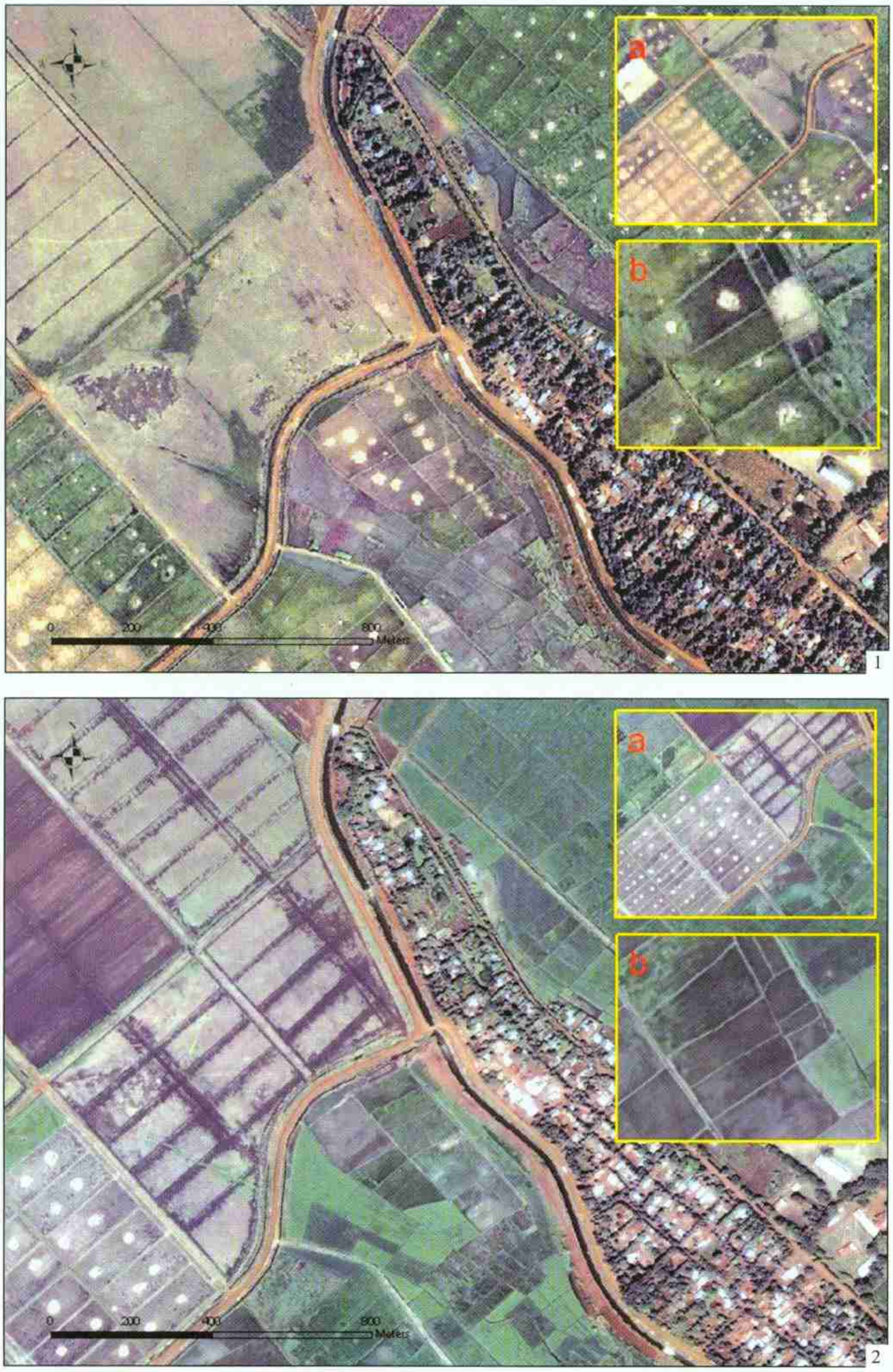
水稻种植区疟疾媒介环境生产力与地面植被覆盖的关系

Benjamin G·JACOB[1] Ephantus J·MUTURI[1] Jose E·FUNES[1]
Joseph I·SHILILU[2] John I·GITHURE[2] Robert J·NOVAK[1]

(1. *Illinois Natural History Survey, Center for Ecological Entomology*, 607 *East Peabody Dr. Champaign IL* 61820;
2. *Human Health Division, International Centre of Insect Physiology and Ecology (ICIPE), P.O.Box* 30772, *Nairobi, Kenya*)

摘要 本文选择了肯尼亚Mwea 水稻种植区中Kangichiri、Kiuria 和Rurumi 3个村庄-农田交错地区为观察区，分析并比较了2种卫星数据对水稻种植区疟疾媒介分布的指示情况。首先运用2005年7月获取的Quickbird（分辨率0.6 m）和Ikonos（分辨率4 m）卫星数据在Erdas *Imagine* V8.7® 中生成观察区的地面植被覆盖图；并于2005年的7月至2006的7月观察相应地区地面蚊虫消长情况。通过对观察区的卫星数据的最大似然法监测分类，并于分类后对每一田块与灌溉渠道都用Arc Info 9.1® 进行栅格矢量化处理（每一栅格设置唯一的标识）。所有调查的蚊虫滋生点，依照水稻的生育期的不同分为6层进行分析。然后将经差分GPS 定位的每一处水稻田及按蚊产卵点都叠加到该地区的卫星底层数据上，并对不同的水体、水稻生育期、调查地点的蚊虫滋生情况进行了方差分析。结果显示，由于Ikonos 只有可见光和近红外光谱分辨能力，单一的Ikonos 卫星数据难以区分不同样点和分层的生境，而QuickBird 具有全光谱分辨能力，可区分所有的稻田生境。因此，可根据QuickBird 0.6 m 卫星数据的土地利用和覆盖指数和阿拉伯按蚊滋生点幼虫的增殖特性，在当地建立和应用媒介综合防治系统（IVM-Integrated Vector Management）。

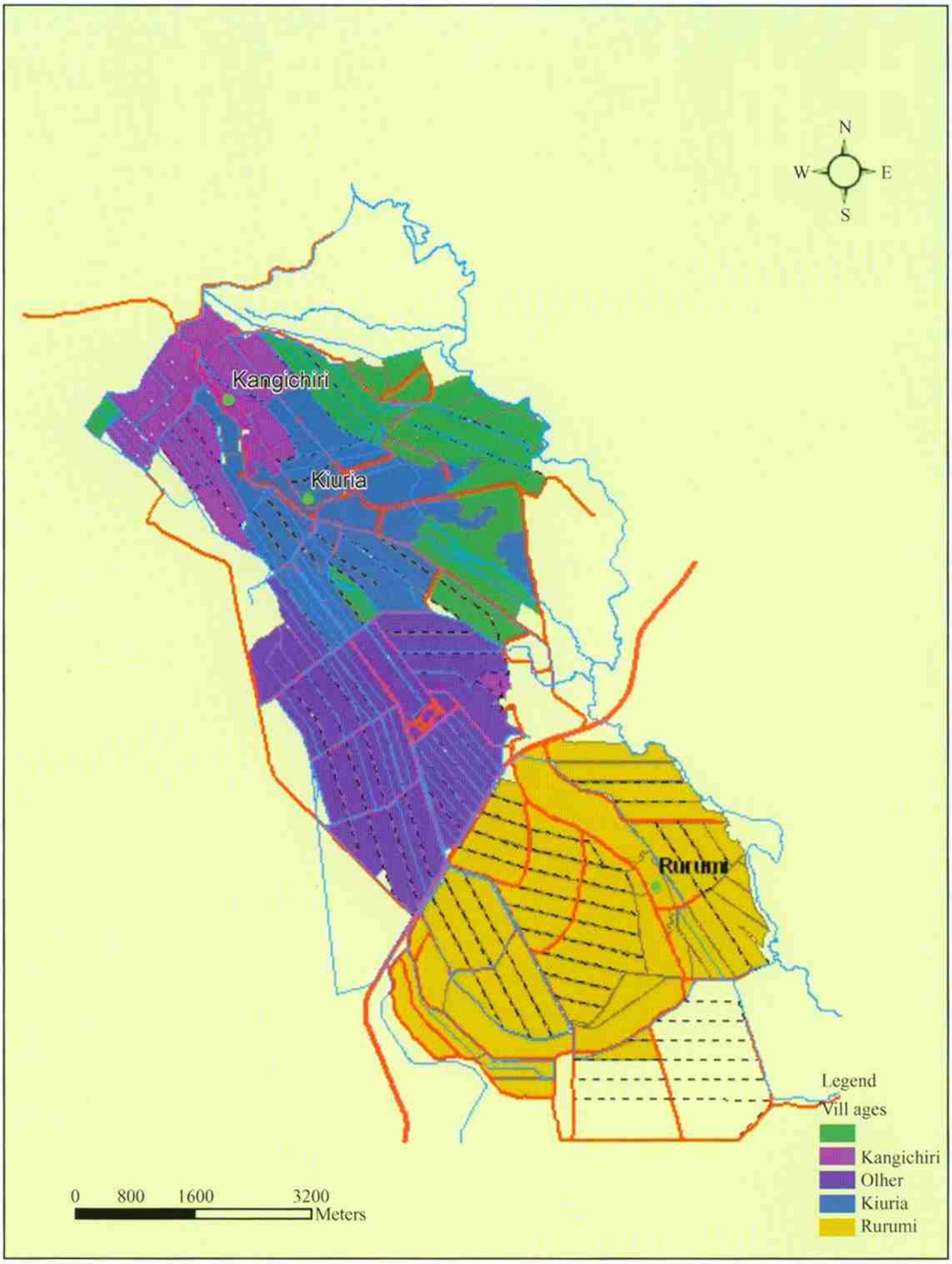
关键词 QuickBird；Ikonos；阿拉伯按蚊；农田-村庄交错区



1. Ikonos 4.0 m image of Kangichiri rice-village complex;

2. QuickBird 0.61 m mage of Kangichiri rice-village complex.

a: Canal vegetation with land preparation LULC; b: Flooded paddies.



Base map of the Kangichiri, Kiuria and Rurumi study sites in the Mwea Rice Scheme, Kenya