

Spatio-temporal variation in malaria transmission intensity in five agro-ecosystems in Mvomero district, Tanzania

Leonard E. G. Mboera¹, Kesheni P. Senkoro¹, Benjamin K. Mayala¹, Susan F. Rumisha¹, Rwehumbiza T. Rwegoshora^{2†}, Malongo R. S. Mlozi³, Elizabeth H. Shayo¹

¹National Institute for Medical Research, P.O. Box 9653, Dar es Salaam, Tanzania; ²Amani Medical Research Centre, P.O. Box 81, Muheza, Tanzania; ³Sokoine University of Agriculture, P.O. Box 3002, Morogoro, Tanzania; [†]Deceased

Abstract. In Africa, malaria is predominantly a rural disease where agriculture forms the backbone of the economy. Various agro-ecosystems and crop production systems have an impact on mosquito productivity, and hence malaria transmission intensity. This study was carried out to determine spatial and temporal variations in anopheline mosquito population and malaria transmission intensity in five villages, representing different agro-ecosystems in Mvomero district, Tanzania, so as to provide baseline information for malaria interventions. The agro-ecosystems consisted of irrigated sugarcane, flooding rice irrigation, non-flooding rice irrigation, wet savannah and dry savannah. In each setting, adult mosquitoes were sampled monthly using Centers for Disease Control and Prevention (CDC) light traps from August 2004 to July 2005. A total of 35,702 female mosquitoes were collected. *Anopheles gambiae* sensu lato was the most abundant (58.9%) mosquito species. *An. funestus* accounted for 12.0% of the mosquitoes collected. There was a substantial village to village variation and seasonality in the density of Anopheles mosquito population, with peaks in May towards the end of the warm and rainy season. Significantly larger numbers of *anophelines* were collected from traditional flooding rice irrigation ecosystem (70.7%) than in non-flooding rice irrigation (8.6%), sugarcane (7.0%), wet savannah (7.3%) and dry savannah (6.4%). The overall sporozoite rates for *An. gambiae* and *An. funestus* were 3.4% and 2.3%, respectively. The combined overall sporozoite rate (*An. gambiae*+*An. funestus*) was 3.2%. The mean annual entomological inoculation rate (EIR) for *An. gambiae* s.l. was 728 infective bites per person per year and this was significantly higher in traditional flooding rice irrigation (1351) than in other agro-ecosystems. The highest EIRs for *An. gambiae* s.l. and *An. funestus* were observed during May 2005 (long rainy season) and December 2004 (short rainy season), respectively. The findings support the evidence that malaria transmission risk varies even between neighbouring villages and is influenced by agro-ecosystems. This study therefore, demonstrates the need to generate spatial and temporal data on transmission intensity on smaller scales taking into consideration agro-ecosystems that will identify area-specific transmission intensity to guide targeted control of malaria operations.

Keywords: agro-ecosystem, *Anopheles gambiae*, *Anopheles funestus*, geographical information system, malaria, Tanzania.

Introduction

In Africa, malaria is predominantly a rural disease where agriculture forms the backbone of the econo-

my. Various crop production systems, especially, where irrigation is the practice, are known to provide suitable microhabitats for adult mosquitoes, and hence have an impact on malaria transmission intensity. Generally, higher malaria prevalence has been reported in villages with irrigated than without irrigated agriculture. This is because crop irrigation is known to lead to a sharp rise in mosquitoes, and hence increased malaria transmission (WHO/FAO/UNEP, 2008). Rice, sugarcane, wheat, cotton and

Corresponding author:
Leonard E. G. Mboera
National Institute for Medical Research
P.O. Box 9653, Dar es Salaam, Tanzania
Tel. +255 22 2121400 Fax +255 22 2121360
E-mail: lmbora@nimr.or.tz

vegetables are the major crops under irrigation in Africa. Of these crops rice is considered to pose the greatest danger to health as it is grown in flooded conditions, which provide ideal breeding sites for malaria mosquitoes (Ijumba and Lindsay, 2001).

There is a paucity of data on the impact of other agro-ecosystems on malaria transmission in Africa with only a few studies on malaria among communities in sugarcane plantations and those producing cotton and vegetables (Packard, 1986; Ijumba, 1997; Shililu et al., 2003; Dongus et al., 2009). Studies in Kenya have reported a high sporozoite rate for *Anopheles gambiae* suggesting a high malaria transmission level in the area and low but perennial malaria transmission intensity in sugarcane growing zone (Githeko et al., 1993). In Sudan, an increase in malaria transmission has been reported to be associated with the cotton irrigation scheme in the Gezira-Managil (Oomen et al., 1988). Recently, irrigated, open-spaced, commercial vegetable production has also been associated with malaria in urban areas of Accra, Ghana (Klinkenberg et al., 2005).

Variations in mosquito density and entomological inoculation rate (EIR) in relation to agro-ecosystems have been reported in northern Tanzania and northern Ghana (Ijumba and Lindsay, 2001; Appawu et al., 2004). In Tanzania, Ijumba and Lindsay (2001) observed that the potential risk of malaria due to *An. arabiensis* and *An. funestus* was four-fold higher in rice-field villages than in sugarcane or savannah villages nearby. In the Ghana study (Appawu et al., 2004) a higher intensity of malaria transmission among individuals in irrigated communities than in the non-irrigated ones was reported. However, the study in northern Tanzania showed that improved socio-economic status due to rice growing lead to reduced malaria prevalence, in spite of increased mosquito populations (Ijumba and Lindsay, 2001). Similarly, a study in Kenya has shown that malaria prevalence is lower in irrigated villages, as a result of widespread use of bednets and antimalarial drugs (Mutero et al., 2006).

The enormous heterogeneity in malaria transmis-

sion intensity in Africa calls for targeted malaria control interventions that require an understanding of the forces that drive transmission. The understanding of indices relating to malaria transmission is central to its control through quantifying the potential risk of infection and elucidating the patterns of disease transmission (Githeko et al., 1993). This calls for the need to accurately determine the spatial and temporal variations in malaria transmission within localized areas that will target specific needs in malaria interventions. In this study, we examined the spatial and temporal heterogeneity in malaria transmission in five villages representing different agro-ecosystems in Mvomero district, Tanzania, to provide baseline information for malaria interventions.

Materials and methods

Study area and agro-ecosystems

This study was carried out in Mvomero district (latitudes 5°47'09"-7°23'40"S, longitudes 37°11'09"-38°01'33"E), in Tanzania covering an area of 7,325 km². The district lies on the foothills of Nguru Mountains to the north-west and Uluguru Mountains to the south-east. The study was carried out in five villages namely: Mtibwa, Komtonga, Mkindo, Dakawa and Luhindo. The study area lies at altitudes ranging between 293 and 379 m above sea level (asl) within the Wami River basin. The villages were approximately 8-11 km from one another.

More than 80% of adult population in Mvomero earns their livelihood from agriculture, though mainly at subsistence production. Monoculture, mixed cropping and multiple cropping are common. The average farm size varies with the type of cropping system, which in turn varies from village to village. The locations of the agro-ecosystems and villages were georeferenced using a hand-held global positioning system (GPS) receiver. The coordinates of the variables were imported into a geographical information system (GIS) database in which they were converted into a point map by Arc

GIS software (ESRI, Redlands, CA, USA). The study area was stratified into five agro-ecological systems (Fig. 1) and covered approximately an area of 1,300 km².

Mtibwa village (6°08'20"S, 37°38'16"E; altitude = 379 m asl) forms the furthest north point of the study area and borders the Nguru Mountains. Mtibwa area is relatively more developed compared to many rural areas in Tanzania following the establishment of the sugar-processing factory in the early 1960s. Mtibwa sugarcane scheme is the largest sugarcane estate in Tanzania. The scheme is irrigated by use of overhead sprinklers or by open earth-lined and gravity-fed irrigation canals.

Human houses are within the plantation and surrounded by sugarcane in all sides.

Komtonga village (6°09'54"S, 37°35'06"E; altitude = 305 m asl) is characterised by swampy flatland lying on the tributaries of Wami River. Most of the communities in this village are small-scale farmers of rice using the traditional ground flooding irrigation practice. Human habitations are located at about 50-100 m north-west of the rice fields.

Mkindo (6°14'31"S, 37°33'12"E; altitude = 324 m asl) is a large village in the central part of the study area. Unlike, Komtonga, communities in Mkindo practice improved non-flooding canal rice-irrigation employing gravitational water supply technique.

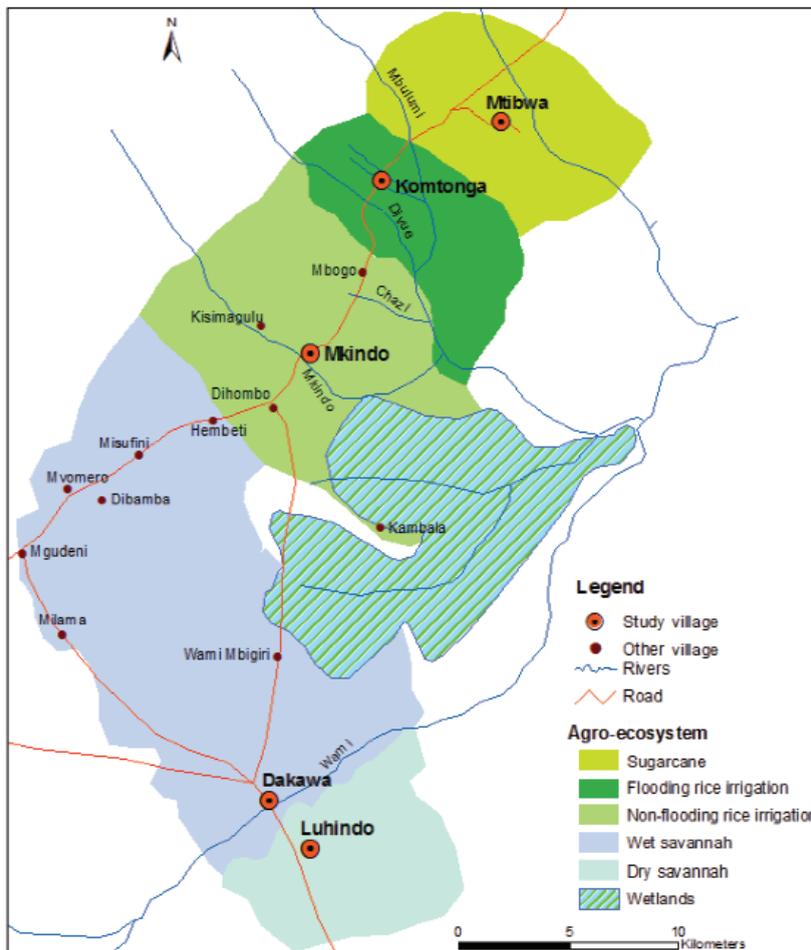


Fig. 1. Distribution of the villages and agro-ecosystems in Mvomero district, Tanzania.

The rice-field canals are open earth-lined and distribute water from the main canal from the Mkindo River. There is a Farmers Field School at Mkindo, which since 1982, has provided farmers training on improved water control, management and agronomic practices. Houses in Mkindo are about 50-100 m from the adjacent rice fields.

Dakawa (6°26'28"S, 37°20'35"E; altitude = 360 m asl) is a big roadside village along the Morogoro-Dodoma highway. The village is characterised by a wet savannah type of ecosystem and maize farming is the predominant agricultural activity. Human settlements are adjacent to their respective maize farms.

Luhindo village (6°27'46"S, 37°33'12"E; altitude = 293 m asl) is located in the south-eastern part of the study area characterised by dry savannah type of ecosystem. Most of the area in the village is covered with short grass, trees and shrubs that provide a wide range of pasture for livestock grazing. The village is inhabited mainly by pastoralists keeping cattle, sheep and goats.

Mosquito collection

Adult mosquitoes were sampled monthly using a total of 15 index houses (three houses per village). Collections were done on three consecutive nights from August 2004 to July 2005. House selection for mosquito collection took into consideration the settlement patterns. The sentinel houses were of similar construction to avoid the effect of variability caused by differences in construction. Mosquito collections were done using Centers for Disease Control (CDC) light traps (J. W. Hock Ltd, Gainesville, Florida, USA). For operation, each light trap was hung at the top of the foot-end of the bed with an adult person sleeping under untreated mosquito net (Mboera et al., 1998). The traps were set at 18:00 hours and collected the following morning at 06:00 hours. Inquiries were made as to whether the trap fan and light had both worked all night, and catches from faulty traps were discounted.

Ethical consideration

The Medical Research Coordination Committee of the National Institute for Medical Research granted ethical clearance for the study (NIMR/HQ/R.8a/Vol.IX/297). A verbal consent was obtained from the owners of the houses where mosquito trapping was done.

Anopheline mosquito identification and processing

Collected mosquitoes were kept in cool boxes and brought to a field laboratory for identification and further processing. At the laboratory, mosquitoes were anaesthetised, sorted, identified morphologically to species level (Gillies and De Meillon, 1968; Gillies and Coetzee, 1987) and counted. Parity of female *An. funestus* and *An. gambiae* s.l. from a sample of unfed mosquitoes were determined using the conventional technique as described by Detinova (1962). The presence of malaria sporozoites was determined by examining the salivary glands under a microscope (WHO, 1975).

Data analysis

Data were entered in EpiInfo database version 6 (Centres for Disease Control and Prevention, Atlanta, GA, USA) and further analysis was done using STATA version 6 (Stata Corp, 2001) and SAS version 9.1 (SAS Institute Inc.). The number of mosquitoes collected per house was transformed to $\log_{10}(n+1)$ before analysis. The parity rates were determined as the proportion of *Anopheles* found to be parous and the sporozoite rates were inferred from the proportion of human biting mosquitoes found to be infected under microscopy. The human biting rates were calculated as the number of mosquitoes biting per person per night using the formula by Lines et al. (1991). Converting the trap catches to estimate bites per person and multiplying by the sporozoite rates gave estimates of the EIR per night. The annual EIR was then determined by multiplying the mean number of human bites per night by the sporozoite rate and by 365 days.

Table 1. Species composition and number (%) of mosquitoes collected in five study villages/agro-ecosystems in Mvomero.

Village	Agro-ecosystem	<i>An. gambiae</i>	<i>An. funestus</i>	<i>Cx. quinquefasciatus</i>	Others	Total
Mtibwa	Sugarcane	1,756 (51.8)	15 (0.4)	1,531 (45.1)	89 (2.6)	3,391
Komtonga	Flooding rice irrigation	14,101(74.0)	3,821 (20.1)	811 (4.3)	315 (1.7)	19,048
Mkindo	Non-flooding rice irrigation	2,105 (42.9)	69 (1.4)	2,551 (52.0)	184 (3.7)	4,909
Dakawa	Wet savannah	1,655 (29.2)	195 (3.4)	3,554 (62.7)	264 (4.7)	5,668
Luhindo	Dry savannah	1,418 (52.8)	195 (7.3)	911 (33.9)	162 (6.0)	2,686
Total		21,035 (58.9)	4,295 (12.0)	9,358 (26.2)	1,014 (2.8)	35,702

Analysis of variance was used to determine differences in biting rates, sporozoite rates, and EIR between agro-ecosystems. All tests were done at 5% level of significance. Repeated measures and multivariate analysis (using Wilk's Lambda) were used to identify any significant differences on the number and proportion of parous and infective mosquitoes between months of collection, villages or the anopheline species. The least square means (LSM) were calculated and the Tukey procedure was used to conduct a multiple pairwise comparisons between months and villages.

Results

Mosquito species abundance and parity rates

A total of 35,702 female mosquitoes were collected. *An. gambiae* s.l. accounted for 58.9% of the mosquitoes collected. Significantly larger numbers of anophelines were collected from traditional flooding rice irrigation (17,922/25,330; 70.7%) than in non-flooding canal rice irrigation (2,174/25,330; 8.6%), sugarcane (1,771/25,330; 7.0%) wet savannah (1,850/25,330; 7.3%) and dry savannah ecosystems (1,613/25,330; 6.4%). Over half of the mosquitoes collected in Mkindo (52.0%) and Dakawa (62.7%) were *Culex quinquefasciatus* (Table 1).

The total mean number of *An. gambiae* s.l. was significantly higher than that of *An. funestus* ($P < 0.001$). The geometric mean density of *An. funestus* and *An. gambiae* s.l. was 3.5 and 5.0 per house per night, respectively. The combined density was 5.1 mosquitoes per house per night.

The overall mean anopheline mosquito density was high during the short rains (October-December 2004) and end of long rains (May 2005). Peak biting density for *An. funestus* was observed during the short rains of November-December 2004 whereas that of *An. gambiae* s.l. was higher throughout the year with a peak during the long rains of April-May 2005 (Fig. 2).

Most (75.0%) parous *An. gambiae* s.l. were collected in the sugarcane ecosystem followed by dry savannah (52.3%) ecosystem. *An. gambiae* s.l. mosquitoes with the lowest parity rate (41.1%) were collected from the non-flooding rice irrigation ecosystem. *An. funestus* with the highest parity rate were collected from the wet savannah (75.0%); followed by sugarcane (62.5%), traditional flooding rice irrigation (55.3%), non-flooding canal rice irrigation (51.3%) and dry savannah (50.0%). On average, a higher parity rate was observed in

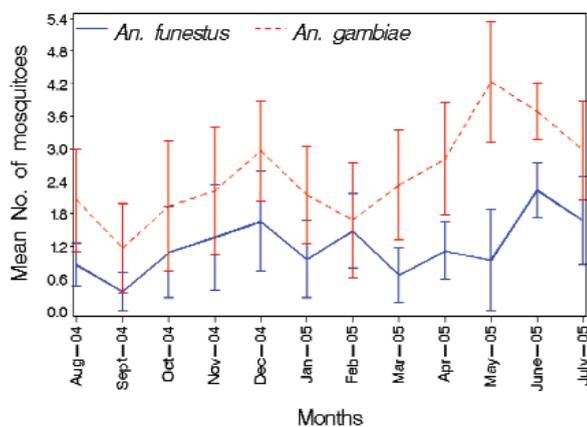


Fig. 2. Monthly geometric mean number of *Anopheles gambiae* s.l. and *An. funestus* in Mvomero district.

An. funestus (55.4%) than in *An. gambiae* s.l. (49.3%). The overall parity rate in *An. gambiae* s.l. differed between months of collection ($P = 0.002$) but not between ecosystems ($P = 0.112$). Likewise, in *An. funestus*, the parity rates differed significantly ($P = 0.045$) between months of collection but not between ecosystems ($P = 0.106$).

Sporozoite and entomological inoculation rates

Overall sporozoite rate in *An. gambiae* s.l. was higher (68/2,025; 3.4%) than that in *An. funestus* (10/434; 2.3%). However, the difference was not significant ($P = 0.165$). Highest mean sporozoite rate (10/236; 4.2%) was recorded in *An. gambiae* s.l. collected in dry savannah ecosystem. None of the *An. gambiae* s.l. collected in sugarcane ecosystem was infected with malaria sporozoite. An overall 81.5% of the difference in sporozoite rate between the villages was observed ($P < 0.001$). Sporozoite-infected *An. funestus* were only collected in flooding rice irrigation ecosystem. In all villages, the biting by *An. gambiae* s.l. and *An. funestus* were experienced throughout the year (Table 2). A larger proportion of *An. gambiae* s.l. infected with malaria sporozoites were collected end of the long rainy season (May 2005). None of the anopheline mosquitoes collected during March 2005 was infective.

In the flooding rice irrigation ecosystem infective *An. gambiae* s.l. were collected throughout the 12-month period, with peaks in August-September 2004 and February 2005. Infective *An. gambiae* in non-flooding rice irrigation were collected in

November 2004, while in the other ecosystems they were collected in May 2005 (wet savannah), May and June 2005 (dry savannah) and June (sugarcane). Infective *An. funestus* mosquitoes were only collected in flooding rice irrigation ecosystem, showing two peaks in October-January and May-June.

Overall human biting rates in *An. gambiae* s.l. and *An. funestus* were 175.3 and 35.8 bites per person per night, respectively. Seasonal pattern in human biting rate was observed in all villages. It was highest during the long rains (March-June) and lowest during the dry season of January and February. The highest human biting rate per person per night in *An. gambiae* s.l. (495.7) and EIR (16.2) were recorded at the end of rainy season in May 2005. In *An. funestus* the highest human biting rate (121.3) and EIR (3.4) were observed during the short rains of December 2004. The average EIR per person per night was estimated at 6.0 and 0.8 for *An. gambiae* s.l. and *An. funestus*, respectively (Table 3).

The daily and annual EIRs varied from one agro-ecosystem to another. The overall annual EIR for the study area was 728 and 12 infective bites (i.b.) for *An. gambiae* s.l. and *An. funestus*, respectively. People living in Komtonga (flooding rice irrigation ecosystem) were receiving the highest annual EIR from either single species (*An. gambiae* = 1,350 infective bites; *An. funestus* = 270 infective bites) or both species combined (*An. gambiae* + *An. funestus* = 1626 infective bites) than their contemporaries in the other ecosystems (Table 4).

Table 2. Sporozoite rate (%) in *Anopheles gambiae* s.l. and *An. funestus* by village and agro-ecosystem in Mvomero district, Tanzania.

Village	Agro-ecosystem	<i>An. gambiae</i> s.l.	<i>An. funestus</i>	Total (<i>An. gambiae</i> + <i>An. funestus</i>)
Komtonga	Flooding rice irrigation	54/1,447 (3.7)	10/399 (2.5)	64/1,846 (3.5)
Mkindo	Non-flooding rice irrigation	3/226 (1.3)	0/20 (0.0)	3/246 (1.2)
Dakawa	Wet savannah	1/107 (0.9)	0/9 (0.0)	1/116 (0.9)
Luhindo	Dry savannah	10/236 (4.2)	0/1 (0.0)	10/237 (0.4)
Mtibwa	Sugarcane	0/9 (0.0)	0/5 (0.0)	0/14 (0.0)
Total		68/2,025 (3.4)	10/434 (2.3)	78/2,459 (3.2)

Table 3. Overall monthly mean number of mosquitoes, estimated human biting rate (HBR) per night and entomological inoculation rate (EIR) per night of *Anopheles gambiae* s.l. and *An. funestus* in Mvomero district, Tanzania.

Month	Mean no. of mosquitoes collected/person/trap		Estimated HBR		Sporozoite rate		EIR	
	<i>An. gambiae</i>	<i>An. funestus</i>	<i>An. gambiae</i>	<i>An. funestus</i>	<i>An. gambiae</i>	<i>An. funestus</i>	<i>An. gambiae</i>	<i>An. funestus</i>
Aug 2004	68.6	4.0	102.9	6.0	1.5	0.0	1.5	0.0
Sep 2004	92.9	6.0	139.4	9.0	4.2	0.0	5.8	0.0
Oct 2004	156.8	42.2	235.2	63.3	3.6	3.2	8.4	2.0
Nov 2004	100.8	49.9	151.2	74.9	1.9	1.1	2.9	0.8
Dec 2004	121.2	80.9	181.8	121.4	2.6	2.8	4.8	3.4
Jan 2005	51.5	15.0	77.3	22.5	5.4	6.9	4.2	1.6
Feb 2005	44.3	10.5	66.5	15.7	12.0	3.5	8.0	0.5
Mar 2005	94.2	3.3	141.3	5.0	0.0	0.0	0	0.0
Apr 2005	171.3	3.3	256.9	5.0	1.1	0.0	2.7	0.0
May 2005	330.5	33.9	495.7	50.9	3.3	1.6	16.2	0.8
Jun 2005	74.5	18.9	111.8	28.3	5.7	4.8	6.4	1.4
Jul 2005	95.7	17.7	143.5	26.6	2.9	0.0	4.1	0.0
Total	116.9	23.9	175.3	35.8	3.4	2.3	6.0	0.8

Table 4. Estimated mean human biting rate (HBR) per night and annual entomological inoculation rate (AEIR) by study village and agro-ecosystem in Mvomero district, Tanzania.

Village	Agro-ecosystem	<i>An. gambiae</i> s.l.		<i>An. funestus</i>		<i>An. gambiae</i> + <i>An. funestus</i>	
		HBR/night	AEIR	HBR/night	AEIR	HBR/night	AEIR
Komtonga	Flooding rice irrigation	195.9	1350.5	53.1	270.1	248.9	1626.3
Mkindo	Non-flooding rice irrigation	30.2	60.6	1.0	0	31.2	58.4
		19.7	159.6	2.7	0	22.4	182.5
Luhindo	Dry savannah	23.0	35.2	2.7	0	25.7	37.5
Dakawa	Wet savannah	24.4	0	0.2	0	24.6	0
Mtibwa	Sugarcane	58.5	727.5	11.9	55.7	70.4	413.5

Discussion

Malaria in Mvomero district, Tanzania, is transmitted predominantly by *An. gambiae* s.l. and *An. funestus*. Indeed, the former species represents more than half of the malaria vectors in the area with variation in density between villages, and hence from one agro-ecosystem to another and between seasons. The variation in monthly mosquito density was less marked in flooding rice irrigation ecosystem (Komtonga), where the two malaria vector species were abundant throughout the year. The all-year round availability of water bodies at Komtonga was providing breeding sites for the two species of mosquitoes.

The variation in the abundance between *An. gambiae* s.l. and *An. funestus* can be explained by their differences in ecological requirements. *An. gambiae* s.l. typically breed in very transient habitats like shallow sunlit fresh water pools or human-made habitats (Shililu et al., 1998), though they may also be common in rice-fields (Robert et al., 1998; Minakawa et al., 1999). In contrast, *An. funestus* breed mainly in marshes and other types of sheltered habitats that contain vegetation (Gillies and De Meillon, 1968; Gillies and Coetzee, 1987), typical of the ecosystem in Komtonga village. The large numbers of *Cx. quinquefasciatus* in Mkindo and Dakawa indicate the availability of favourable

breeding sites, most likely pit latrines, which were very common in both villages (data not shown). *Cx. quinquefasciatus* usually develops mainly in habitats containing highly polluted water rich in organic matter that larvae can use for nourishment (Subra, 1981).

The higher parity rate in *An. gambiae* s.l. population in the sugarcane ecosystem was likely to be due to the low number of mosquitoes collected, indicating a low recruitment rate. However, the mosquitoes were likely to have lived long enough to have taken at least a blood meal. The presence of *An. gambiae* s.l. with low parity rate in non-flooding rice irrigation ecosystem suggests that new emerging mosquitoes were continuously more abundant than the older ones. The monthly variation in parity rate in both *An. gambiae* s.l. and *An. funestus* is most likely to be associated with the seasonal abundance of mosquito breeding sites. The temporal and spatial mosquito abundance and parity rates in Mvomero district is likely to be influenced by environmental variables such as rainfall and availability of either temporary or permanent water bodies.

There were variations in the biting rate and malaria transmission intensity between the five agro-ecosystems. Such variations were clear despite the relative proximity of the villages within short distances. Overall, malaria transmission was highest in rice irrigation ecosystems than in other ecosystems. In the two rice irrigation ecosystems, infective mosquitoes were caught throughout the year except during the start of the long rains in March; indicating a continuous presence of mature female mosquitoes. According to a model by Smith et al. (2004) the human biting rate is highest shortly after the mosquito densities peak, near breeding sites where adult mosquitoes emerge, and around the edges of areas where humans are aggregated. These sources of spatial and temporal heterogeneity in the distribution of mosquito populations are associated with the variability in the human biting rate, the proportion of mosquitoes that are infectious, and in the risk of human infection (Smith et al., 2004).

Similar to mosquito density, the annual EIR esti-

mates at the five sites displayed marked temporal and spatial variations, with likelihood of communities in flooding rice irrigation ecosystem experiencing the highest EIR throughout the year. Similar variations in malaria transmission intensity have been observed elsewhere in Tanzania (Ijumba and Lindsay, 2001), Ghana (Appawu et al., 2004) and Côte d'Ivoire (Koudou et al., 2005; Matthys et al., 2006). In our study, the highest EIR in the flooding rice irrigation and the lowest EIR in sugarcane ecosystem could be explained by differences in the ecological settings of the two sites, and more specifically the availability of favourable breeding sites. It has already been observed that irrigated rice cultivation enhances population development of many malaria mosquito species in sub-Saharan Africa (Chandler et al., 1975; Coosemans, 1985; Robert et al., 1985; Lacey and Lacey, 1990; Dossou-Yovo et al., 1994; Briët et al., 2003) and has been associated with high malaria transmission (Appawu et al., 2004; Dolo et al., 2004; Diuk-Wasser et al., 2005; Koudou et al., 2005). This is because rice irrigation provides ideal breeding sites for the major malaria vectors in Africa (Carnevale et al., 1999; Appawu et al., 2004). The generally low EIR for *An. funestus* compared with *An. gambiae* s.l. in Mvomero suggests that the former species plays a minor role in malaria transmission in the area.

Studies in East and West Africa indicate that communities in irrigated zones are at higher risk of malaria mosquito infective bites than in non-irrigated zones (Ijumba, 1997). Several studies have consequently compared transmission among different ecological zones and even among villages separated only by short distances within the same area (Dolo et al., 2004; Okello et al., 2006). These and the present study confirm that malaria transmission is heterogeneous even at micro-ecological levels, consistent with the high degree of ecological diversity of the area.

Seasonal transmission was observed in almost all ecosystems, with most of the transmission at the end of the long rains in May. It has been observed that vector species behaviour, density and the EIRs are

dependent on seasonal changes in environmental variables (Koudou et al., 2010). However, the seasonal variation was less marked in Komtonga (characterised by permanent swamps), most likely, because, mosquito abundance was not directly associated with rainy season.

The difference in *Anopheles* mosquito densities and transmission intensities in different villages is likely to have been contributed to agro-ecosystems and farming practices. Malaria transmission intensity was lowest in sugarcane ecosystem. A negative impact of large-scale sugarcane cultivation on mosquito productivity and malaria has also been reported in northern Tanzania (Ijumba et al., 2002). Similar to our findings, only a few incidences of increase in malaria has been associated with sugarcane in Africa because it is known that a properly maintained sugarcane irrigation system does not offer appropriate breeding sites for *An. gambiae* s.l. (Packard, 1986). Although sugarcane requires irrigation for optimal growth, the plant is very susceptible to water-logging and therefore needs efficient drainage (Arnon, 1972). During this study irrigation in the sugarcane plantations was either overhead (using sprinklers) or by use of well drained water canals.

Malaria transmission intensity in non-flooding rice irrigation was lower than in flooding rice irrigation villages. This indicates that water management is likely to have an impact on mosquito productivity. Water management such as intermittent irrigation as well as adaptation of farming practices may significantly reduce the number of breeding sites in rice fields (Keiser et al., 2002; Klinkenberg et al., 2005). Contrary to our findings, some other studies in East and West Africa failed to establish a direct association between irrigated fields and transmission intensity (Ijumba et al., 2002; Dolo et al., 2004). For instance, in Côte d'Ivoire, despite high anopheline densities in areas bordering rice cultivation, Dossou-Yovo et al. (1994) reported low sporozoite rates indicating that rice fields did not seem to have increased malaria transmission. More recent investigations in Côte d'Ivoire, however, showed

that irrigated rice farming was strongly associated with malaria transmission, and entomological indicators were tightly linked to changing patterns of irrigated rice farming (Koudou et al., 2005, 2010).

Malaria transmission intensity in Mvomero is closely related to prevalence of malaria in the population. In a series of parallel studies in Mvomero district, the prevalence of malaria parasitaemia was highest in traditional flooding rice irrigation ecosystem where the highest EIR in the current study was observed (Mboera et al., 2007). Similar observations have been reported in north-eastern Tanzania where it was observed that where the mean annual EIR was high, the mean annual parasite prevalence was also high (Ellman et al., 1998). The inoculation rates observed in the present study were generally comparable with records from most entomological surveys carried out across the coastal and north-eastern regions of Tanzania, where transmission is perennial (Temu et al., 1998; Mboera, 2000; Maxwell et al., 2003).

Findings of this study support the evidence that malaria transmission risk varies between regions and even between neighbouring localities (Temu et al., 1998; Ye' et al., 2007). This means, knowledge of malaria risk at a local level is likely to provide more reliable information that is crucial for specific area control strategies. This study therefore, confirms previous studies in demonstrating the need to generate spatial and temporal data on transmission intensity on smaller scales taking into consideration agro-ecosystems that will identify area-specific transmission intensity to guide targeted control of malaria interventions. In conclusion, assessing malaria transmission risk within micro- and agro-ecological zones provides a detailed picture of the spatial distribution of the disease which is likely to require a specific package of interventions.

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