volume 8 no 5 pp 439–448 may 2003

The relationship between *Anopheles gambiae* density and rice cultivation in the savannah zone and forest zone of Côte d'Ivoire

Olivier J. T. Briët[1], Joel Dossou-Yovo[2], Elena Akodo[1], Nick van de Giesen[3] and Thomas M. Teuscher[1]

1 *West Africa Rice Development Association, Bouaké, Côte d'Ivoire*
2 *Institut Pierre Richet, Bouaké, Côte d'Ivoire*
3 *Center for Development Research (ZEFc), Bonn, Germany*

Summary In 13 villages in the savannah zone and 21 villages in the forest zone of Côte d'Ivoire, the biting density of the principal malaria vector, *Anopheles gambiae*, was studied as a function of rice cultivation in the inland valleys in a 2-km radius around each village. In the savannah villages, during the main season cropping period, surface water on rice-cultivated and to a lesser extent on uncultivated inland valleys seems to contribute strongly to the *A. gambiae* population density. For the off-season cropping period (which starts after the first light rains in the savannah zone), correlations were weaker. Breeding sites other than in inland valleys may play an important role in the savannah zone. In the forest zone, however, the *A. gambiae* population density was strongly correlated with the surface water availability (SWA) in the rice-cultivated inland valleys, whereas the correlation with the SWA in other (uncultivated) inland valleys was weak. The requirement of sunlit breeding sites for *A. gambiae* might explain this difference between zones. In the forest zone, only inland valleys cleared for rice cultivation meet this requirement, whereas all other inland valleys are covered with dense vegetation. In the savannah zone, however, most undergrowth is burnt during the dry season, which permits sunlight to reach puddles resulting from the first rains.

keywords *Anopheles gambiae*, population density, rice cultivation, flooding, savannah, forest, Côte d'Ivoire, inland valley, irrigation

Introduction

Human health is often considered as a major constraint to sustainable intensification of rice cultivation in lowland areas, and alleviating this constraint may contribute to reduced land pressure in the upland areas (Garrity 1988; Service 1989a,b; Windmeijer & Andriesse 1993). Lowland or irrigated rice cultivation enhances population development of many mosquito species, many of which transmit human diseases (Lacey & Lacey 1990). In the absence of mosquito control, this occurs worldwide. In Africa, irrigated rice cultivation (with full or partial water control) is associated with higher densities of the main vectors of malaria (the mosquito species *Anopheles gambiae s.s.*, *A. arabiensis, A. funestus* and *A. pharoensis*) than neighbouring areas without irrigated rice cultivation (Chandler *et al.* 1975; Coosemans 1985; Robert *et al.* 1985; Faye *et al.* 1993, 1995; Dossou-Yovo *et al.* 1994; Marrama *et al.* 1995). Often, irrigated rice cultivation leads to extension of the breeding season of malaria vectors (Chandler *et al.* 1975; Mwangi & Mukiama 1992).

The major limitations of most studies that try to measure the impact of irrigated rice on vector-borne diseases is that often few villages are used in the analyses, and that villages with irrigated rice cultivation might be fundamentally different from villages without rice cultivation, in terms of hydrology and natural breeding sites, even before the introduction of rice cultivation. In villages in areas subject to flooding, a large part of the anopheline population might be breeding in sites other than rice fields, especially when the rice cultivated surface is limited.

This study focuses on the relationship between rice cultivation in inland valleys and populations of *A. gambiae*, the major malaria vector in the savannah and forest zone of West Africa, which breeds in sunlit water bodies. The transmission of malaria in the savannah zone is further discussed by Dossou-Yovo *et al.* (unpublished) and Henry *et al.* (2003). We assessed the correlation of flooded area (with or without rice cultivation) with the seasonal *A. gambiae* population size.

Materials and methods

Selection and description of study sites

We assigned villages to three agro-ecosystem classes according to the surrounding inland valleys within a 2-km radius: (R0) villages with inland valleys without rice cultivation, (R1) villages with inland valleys with no or partial water control, suitable for one rice-cropping cycle during the rainy season, and (R2) villages with inland valleys with partial or full water control that permits two cycles of rice cropping per year. In both the savannah zone in the north, and the forest zone in the west of Côte d'Ivoire, a geographical area was sought with a population density of 20–40 people per square kilometre, in which villages of all three classes were present. Areas with villages that practised either one or more cycles of rice cropping were found in both zones, but villages with uncultivated inland valleys were found in areas close by. In the savannah zone, the area around Korhogo (between 9°10′ and 9°40′ N and between 5°20′ and 5°60′ W) was selected for villages with rice cultivation (R1/R2), and the area between Niakara and Katiola (between 8°00′ and 8°55′ N and between 4°50′ and 5°13′ W) was selected for R0 villages. In the forest zone, the area between Danane and Zouan-Hounien and Bin-Houyé (between 6°47′ and 7°09′ N and between 8°03′ and 8°18′ W) was selected for villages with rice cultivation, and the area between Guiglo and Toulépleu (between 6°32′ and 6°35′ N and between 7°34′ and 7°57′ W) was selected for R0 villages. For each of the four areas a sampling frame was constructed of villages that had inland valleys within a 2-km radius and a population of more than 300 with the help of topographic maps and field visits. In the savannah zone, the size of the sampling frame was 11 villages for R0, 108 villages for R1 and nine villages for R2. In the forest zone, the size of the sampling frame was 15 villages for R0, 74 villages for R1 and eight villages for R2. The villages of each agro-ecosystem class were listed in random order, and the first eight (savannah zone) or seven (forest zone) villages of each group were selected. These villages are presented in Tables 1 and 2 and Figure 1.

In northern Côte d'Ivoire, in the area around Korhogo, the savannah vegetation consists of an open forest of trees, shrubs and grassland. The dry harmattan wind blows for 3–5 months during the dry season, which is usually from November to March/April. In this period, drought is almost absolute with the exception of some rare rains. During this period, the grassland is burned over large areas. From April to June, light rains fall in large intervals. The rainy season generally starts at the end of June or beginning of July and ends in October. Rainfall is monomodal, and the vegetative period is 220 days. Erosion is a problem in large deforested areas. During the dry season, rice can only be cultivated with the help of irrigation water from man-made reservoirs. In the region of Korhogo, there are 13 dams, built in the 1970s for irrigation purposes, of which eight are rehabilitated or in the process of rehabilitation. All double-cropping villages in our study had access to water from such reservoirs. The dams/irrigation structures of the villages Nambekaha and Zemongokaha were deteriorated, and therefore only a relatively small proportion of their inland valleys could be used for off-season cropping. Without irrigation, only one crop per year is possible, during the rainy season.

In the more southern savannah around Katiola, deforestation is less of a problem than in the region of Korhogo. The Harmattan only blows 1–3 months, and the rainfall is pseudo-bimodal. The vegetative period is 240 days. In the inland valleys of the R0 villages, according to local farmers, rice is no longer cultivated because of insufficient rainfall. In this area, however, other villages do cultivate rice.

In western Côte d'Ivoire, in the area south of Danané, the natural vegetation is semi-deciduous forest, but most of the natural forest has been replaced by coffee and cocoa plantations. The rainfall pattern is long-monomodal, and the vegetative period is 290 days. In the 1970s, numerous inland valleys were improved for rice cultivation by the Société pour le Développement de la Riziculture, but after this organization was dissolved, most of the infrastructure deteriorated because of lack of maintenance. Therefore, water control is only partial in the inland valleys, and as a result, the agricultural calendar is strongly dependent on rainfall. This is one reason why little rice is cultivated during the dry season, besides problems of bird pests and presence of leeches.

In the region west of Guiglo, the natural forest is dense, but here also, most of the natural forest has been replaced by coffee and cocoa plantations. The dry season lasts 3–4 months from December to February. The rainfall is pseudo-bimodal, and the vegetative period is 270 days. Rice is not cultivated in the inland valleys by local farmers, and only small patches of inland valley are cultivated by immigrants. However, upland rice cultivation is well-developed. The local farmers believe that farming the inland valleys causes male sterility.

Environmental, weather and agronomic data collection

The villages were visited by an agronomist who measured the surface of inland valleys (including rivers, lakes and

Table 1 The surface and surface water availability of rice land and valley land by season for the villages of study in the savannah zone

District	AES	Village	Latitude (degrees)	Longitude (degrees)	Population (1988)	Surface of valleys (ha)	Surface of riceland OSCP (ha)	Surface of riceland MSCP (ha)	SWA of valleys OSCP (ha.days)	SWA of valleys MSCP (ha.days)	SWA of riceland OSCP (ha.days)	SWA of riceland MSCP (ha.days)	*A. gambiae* OSCP (b/p.n)	*A. gambiae* MSCP (b/p.n)
Katiola	R0	Angolokaha	8.520	−5.176	377	21.9	0	0	552	1059	0	0		
		Doussoulokaha	8.905	−5.141	300	17.7	0	0	121	245	0	0		
		Folofonkaha	8.577	−5.208	632	37.8	0	0	1159	2480	0	0	1.4	3.5
		Kabolo	8.187	−4.988	838	31.6	0	0	846	3437	0	0	1.7	2.1
		Ounandiekaha	8.362	−5.173	557	42.0	0	0	1613	1586	0	0	5.7	1.8
		Petionara	8.432	−5.115	652	38.0	0	0	1713	2031	0	0	21.2	3.2
		Serigbokaha	8.447	−5.150	368	24.6	0	0	265	1582	0	0		
		Timorokaha	8.502	−5.204	311	21.5	0	0	41	107	0	0		
Korhogo	R1	Binguebougou	9.526	−5.812	960	42.5	0	33.6	1353	4556	395	2654	8.4	9.3
		Fapaha	9.489	−5.830	1163	72.0	0	58.6	2020	8208	365	5367	8.6	19.8
		Kaforo	9.294	−5.671	379	37.5	0	34.1	952	4842	130	2983	64.0	55.6
		Karakpo	9.224	−5.678	352	26.2	0	24.8	0	2861	0	2203		
		Kassoumbarga	9.563	−5.750	481	30.3	0.7	28.1	551	3732	137	2907		
		Katiorkpo	9.235	−5.739	329	25.1	0	19.1	570	2623	65	1485		
		Kombolokoura	9.333	−5.885	1392	34.5	0	24.8	2499	5313	587	2669	3.5	6.7
		Tioroniaradougou	9.357	−5.638	1976	69.8	0	42.6	4736	7620	76	1947	15.6	34.7
	R2	Gbahouakaha	9.499	−5.412	600	88.6	35.0	70.4	5121	8159	3137	5281	4.2	27.7
		Kohotcheri	9.620	−5.622	919	158.6	80.9	130.1	16 787	22 964	9709	17 492		
		Koumbolikaha	9.261	−5.607	280	48.4	29.2	42.2	1678	3579	1289	3054		
		Lamekaha	9.270	−5.643	836	72.0	25.4	54.2	4998	7626	2698	5277		
		Nambekaha	9.291	−5.687	732	267.8	19.2	109.5	14 537	37 154	2401	12 016	119.2	79.6
		Nombolo	9.412	−5.826	300	100.7	58.3	77.1	7684	8582	5296	6313	42.4	21.0
		Nongotchenekaha	9.519	−5.398	451	68.2	28.9	49.7	3835	6080	2716	3748	54.1	37.3
		Zemongokaha	9.643	−5.620	527	149.6	18.6	95.7	12 785	21 916	3502	11 934		

AES, agro-ecosystem classification of village; SWA, surface water availability; OSCP, off-season cropping period; MSCP, main season cropping period; b/p.n, bites per person and per night.

Table 2 The surface and surface water availability of rice land and valley land by season for the villages of study in the forest zone

District	AES	Village	Latitude (degrees)	Longitude (degrees)	Population (1988)	Surface of valleys (ha)	Surface of riceland OSCP (ha)	Surface of riceland MSCP (ha)	SWA of valleys OSCP (ha.days)	SWA of valleys MSCP (ha.days)	SWA of riceland OSCP (ha.days)	SWA of riceland MSCP (ha.days)	*A. gambiae* OSCP (b/p.n)	*A. gambiae* MSCP (b/p.n)
Guiglo	R0	Beoue	6.548	−7.872	1593	78.1	0.3	3	1395	4019	5	142	0.0	4.8
		Douandrou	6.540	−7.920	1247	86.5	0	0.5	1869	4041	0	37	0.0	1.5
		Douedy-Guezon	6.565	−7.752	821	79.1	0	0	1399	3906	0	0	0.1	4.0
		Glopaoudy	6.545	−7.632	581	105.6	0	0.5	1562	5307	0	28	0.1	15.3
		Pohan	6.545	−7.927	356	83.3	0	0	2093	3594	0	0	0.0	6.1
		Ziglo	6.566	−7.799	570	92.3	0	0	9071	5712	0	0	0.7	12.7
		Zouan	6.543	−7.598	830	137.2	0	0	12 625	178	0	0	0.1	0.3
Danane	R1	Bepleu	6.999	−8.047	702	290.1	0	132.4	10 197	25 750	0	11 261	6.6	71.4
		Bietouo	6.904	−8.130	504	174.6	0	79.1	10 121	17 373	0	7729	0.9	34.9
		Danta	7.020	−8.157	328	213.0	0	140.2	8386	18 280	0	12 071	0.1	45.8
		Gbontegleu	6.975	−8.237	352	193.3	0	123.8	5371	12 454	0	8059	1.1	41.5
		Meantouo	6.886	−8.143	885	186.8	0	122.8	7550	15 626	0	10 176	1.4	20.5
		Seileu	7.097	−8.173	1531	122.0	0	91.7	4281	8012	0	6088	0.0	5.2
		Yotta	7.152	−8.186	438	110.1	0	84.6	5275	9489	0	7207	0.2	26.3
	R2	Batouapleu	6.786	−8.323	4346	191.4	62.6	138.9	13 684	15 692	5740	11 346	48.1	52.9
		Bouenneu	6.926	−8.227	690	217.7	9.2	150.9	17 385	15735	975	11 026	20.6	71.4
		Finneu	6.993	−8.152	1133	206.7	1.5	127.2	13 689	15955	117	9693	1.9	25.1
		Pepleu	6.951	−8.195	272	216.5	7.1	135.9	7908	15230	610	9890	13.2	26.7
		Vetouo	6.963	−8.116	1137	153.3	0	53.7	6836	3548	0	1257	0.2	17.5
		Zeale	6.988	−8.161	3219	224.6	1.5	133.5	6716	5560	69	2938	0.9	19.6
		Zoleu	6.814	−8.308	261	204.8	10	128.2	10 128	11 744	206	5388	4.9	35.9

AES, agro-ecosystem classification of village; SWA, surface water availability; OSCP, off-season cropping period; MSCP, main season cropping period; b/p.n, bites per person and per night.

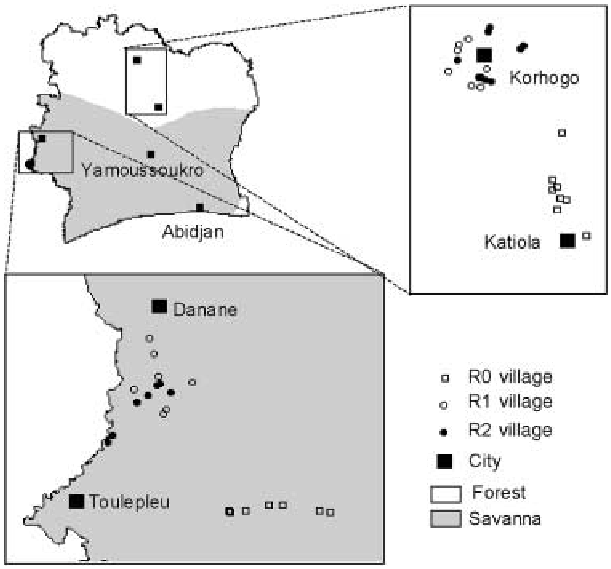

Figure 1 Study villages in the savannah and forest zone of Côte d'Ivoire.

swamps) and the rice-cultivated surface during the off-season and main season cycles in the area within a 2-km radius around each village. With the help of locally recruited assistants, daily rainfall was recorded at village level from January 1997 until March 1998 in the savannah zone and from May 1998 until May 1999 in the forest zone. The agricultural calendar of inland valley rice cultivation, marking the presence or absence of tilling, nursery, transplanting and harvesting, and flooded surfaces at various observation points in the inland valleys were recorded on a weekly basis.

Entomological data collection

In the savannah zone, entomological data were collected in four villages per agro-ecosystem (five in R1) (Table 1[1]). Nine *trans*-sectional entomological surveys were held at 6-week intervals, from December 1996 to November 1997. For the village Binguebougou, the first survey was missing. The entomological study is described in detail in Dossou-Yovo *et al.* (unpublished). In the forest zone, entomological data were collected in all selected villages listed in Table 2, following the same method as Dossou-Yovo *et al.* (unpublished). The entomological surveys in the villages Batouapleu, Bietouo, Bouenneu, Douedy-Guezon, Gbontegleu, Glopaoudy, Meantouo, Vetouo and Zouan were funded by the Multilateral Initiative for Malaria (MIM). In the forest zone, in most villages, nine entomological surveys were held at 6-week intervals, from March 1998 to March 1999. The first survey of March 1998 was missing for the villages Beoue and Seileu and for the MIM villages with the exception of Vetouo. In the MIM villages and the villages Pepleu, Pohan, Yotta and Ziglo, an additional survey was held in April 1999. In the forest villages, mosquitoes were collected from 21.00 to 06.00 h, whereas in the savannah, collections were from 18.00 to 06.00 h. Only catches within the 21.00–06.00 period of the species *A. gambiae s.l.* are considered in the present study.

Data analysis

Poisson regression analysis (with logarithmic link function) was performed in the statistical package R, with *A. gambiae* human biting catches (HBC) as a proxy for *A. gambiae* population density[2] during the respective cropping seasons as response variable with the villages as units of analysis.

Because of a relatively small number of villages per agro-ecosystem (four in the savannah zone and seven in the forest zone), all villages in a zone were analysed together without using the agro-ecosystems classification as a categorical variable in the model. Such a variable would have been appropriate in the regression model, because the R0 villages were in geographically different areas and the R2 villages in the savannah had access to controlled irrigation water from man-made lakes, unlike R1 villages, but we had too few data points for the inclusion of such a stratification. In a quantitative analysis, it is difficult to incorporate mosquito population dynamics (e.g. height and timing of population peaks) and environmental events such as rainfall and agricultural activities. For this reason, and to avoid problems of serial correlation of temporal data, *A. gambiae s.l.* HBC were averaged for the surveys during the respective cropping period. In the savannah, surveys 2, 3, 4 and 5 (January–June) were averaged as a proxy for the mosquito density during the off-season cropping period, and surveys 1, 6, 7, 8 and 9 (July–December) as a proxy for the mosquito density during the main season cropping period. The first survey in Binguebougou, which was missing, was estimated by the average of the first surveys of the villages Fapaha and Tioroniaradougou. In the forest,

[1] The villages without entomological data are listed here for cross-reference with other articles in this issue.

[2] This with the assumption that anthropophily and feeding rhythm were stable over the year (Dossou-Yovo *et al.* unpublished). As the overall use of bed nets was low in the villages (Geneau *et al.* unpublished), this measure was not expected to be biased (Dolo *et al.* 2000).

surveys 7, 8 and 9 (November–March) were averaged as a proxy for the mosquito density during the off-season cropping period, and surveys 2, 3, 4, 5 and 6 (April–October) as a proxy for the mosquito density during the main season cropping period.

As explanatory variable we used, a measure of surface water availability (SWA) (on both rice-cultivated and uncultivated inland valley area in a 2-km radius around the villages) for the respective cropping season. The SWA measure was calculated as follows: the flooded surfaces of each inland valley were interpolated for each day during the study period. The sum of the flooded surfaces of all inland valleys per village yielded an estimate for the total of flooded surface each day in the 2-km radius of each village. The sum of the flooded surfaces over the periods of the respective cropping cycles or agricultural activities was then used as a measure for SWA.

For the SWA calculation in the savannah, 1 July to 31 December 1997 was chosen for the main season cropping period, and 1 January to 30 June 1997 for the off-season cropping period. In the forest, these periods were 9 July to 31 October, and 1 November to 31 March, respectively (in the forest zone we did not have data for the beginning of the main season cropping cycle). In univariate regression analysis, the SWA on all inland valleys, the SWA on rice cultivated land and the SWA on inland valley land without rice cultivation, were tested for correlation with biting density. In multivariate analysis, the proportion of SWA on rice cultivated inland valleys out of the SWA on all inland valleys (representing the effect of cultivation of the flooded land), together with the SWA on all inland valleys were tested as covariates. Testing both the SWA on rice cultivated land and the SWA on inland valley land without rice cultivation were computed together in multivariate analysis would not separate out the effect of cultivation from the effect of flooding, since it was unknown how much of the flooding of land was caused by agricultural activities. The regression analysis was performed for each season and zone combination separately.

Results

The surface of inland valleys including water bodies, the cultivated surface of rice fields, the SWA measure, and the average density of *A. gambiae* bites per night for each village are presented for both the off-season and the main season cropping periods in Tables 1 and 2.

In the savannah zone, the village Kassoumbarga (classified as R1) had some off-season rice cultivation, but this was very little (0.7 ha) compared with the villages classified as R2 (on average 37 ha). In the forest zone, three villages classified as R0 had main season rice cultivation, but the surface was negligible compared with that of the villages classified as R1 and R2. The villages Vetouo, Finneu and Zoleu in the forest zone, classified as R2 (based on previous years), had little or no off-season rice cultivation during the study.

Entomological curves

In most villages in the savannah zone, two population peaks of *A. gambiae* were observed: the first at the end of April, following the first (light) rains of end March and April, the second at the end of September. This made it convenient to divide the year into two periods: a period from the beginning of the year (before the first rains) to the end of June and a second period from the beginning of July to the end of the year. These periods correspond to the off-season cropping cycle and main season cropping cycle, respectively, in the rice-cropping villages. The *A. gambiae* population dynamics are described in detail by Dossou-Yovo *et al.* (unpublished).

In the R0 villages, *A. gambiae* densities were not significantly different between periods. However, in two of the R0 villages, the rainy-season density peak was markedly lower than the dry-season density peak. In the R1 villages, with the exception of Kaforo, the *A. gambiae* density peaks were significantly higher during the rice-growing period than during the dry season (Mann–Whitney *U*-test, $\alpha = 0.05$). The *A. gambiae* population in Kaforo was comparable with that of the double-cropping village Nambekaha. Double-cropped fields of Nambekaha and Lamekaha were situated just outside the 2-km radius of Kaforo. For this reason, Kaforo was excluded from the regression analysis (see below). In three of the four double-cropping villages, the *A. gambiae* density peak was significantly higher during the off-season cropping period than during the main season rice cropping period. In the village of Gbahouakaha, the mosquito densities were very low during the off-season rice cycle. This was surprising, as this village shared a large part of the double-cropped inland valley with the neighbouring village of Nongochenekaha, which had a high population density of *A. gambiae* during the off-season rice cycle.

In the forest zone, over the period of 1 year, one population peak of *A. gambiae* was observed in the villages of R0 and R1. In R2, a peak of *A. gambiae* occurred in villages that had more than 1.5 ha of off-season rice. This peak fell during the dry season from December to March, in which there was very little or no rain. During this period, no peak was observed in the R0 and R1 villages, or in the savannah zone. The *A. gambiae* density during the off-season rice cycle was lower than that of the main season rice cycle in the R2 forest villages.

Table 3 Explained variation [pseudo $R^2 = 1 -$ (null deviance/residual deviance)] by Poisson regression analyses of *Anopheles gambiae* seasonal density per person with Surface Water Availability (SWA) in rice land and inland valleys in a 2-km radius around villages

		Savannah zone				Forest zone	
		Off season		Main season			
Model	Variables	Inc. Nam. ($n = 12$)	Exc. Nam. ($n = 11$)	Inc. Nam. ($n = 12$)	Exc. Nam. ($n = 11$)	Off season ($n = 21$)	Main season ($n = 21$)
Univariate	ln(SWA on all valley land)	0.74	0.44	0.78	0.75	0.54	0.74
	ln(SWA on rice cultivated valley land)	0.38	0.32	0.69	0.69	0.85	0.58
	ln(SWA on other valley land)	0.52	NS	0.55	0.20	0.20	0.37
Multivariate	ln(SWA on all valley land) ln(Proportion of SWA on rice cultivated land + 0.01)	NS	NS	NS	NS	0.91	NS

n, number of villages tested; Nam., Nambekaha; Inc., included; Exc., excluded; ln, natural logarithm; NS, not significant ($\alpha = 0.05$).

Regression analysis

In the following section, the regression results of the *A. gambiae* density per person with the SWA explanatory variables are presented (Table 3).

In univariate Poisson regression analysis, for the savannah during the off-season cropping period, the SWA of all inland valleys irrespective of rice cultivation showed a strong correlation with the *A. gambiae* density per person (pseudo $R^2 = 0.74$) (Figure 2). The SWA on rice cultivated land was only weakly correlated (pseudo $R^2 = 0.38$), whereas the SWA in the uncultivated inland valleys was more strongly correlated (pseudo $R^2 = 0.52$). However, when the village of Nambekaha, which had extreme values for surface, SWA and *A. gambiae* density per person, was excluded from the analysis, the SWA of all inland valleys irrespective of rice cultivation showed a weaker correlation (pseudo $R^2 = 0.44$). The effect of SWA on rice cultivated land, was similar (pseudo $R^2 = 0.32$), but the effect of the SWA of uncultivated inland valleys became insignificant. In multivariate analysis, the effect of the cultivation of the flooded land was not significant.

In the savannah during the main season cropping period, results were similar to those of the off-season cropping period, except that correlations with the SWA on rice cultivated land were higher (pseudo $R^2 = 0.69$) and a high correlation of the SWA of all inland valleys, irrespective of including Nambekaha in the analysis (Figure 3).

In the forest during the off-season cropping period, the SWA of the total inland valley area (irrespective of rice cultivation) showed a significant but weak correlation with the *A. gambiae* density per person (pseudo $R^2 = 0.54$). In contrast, the SWA of the area cultivated with rice had a strong correlation with the *A. gambiae* density per person (pseudo $R^2 = 0.85$). In the multivariate regression analysis, the proportion of SWA on rice cultivated inland valleys of

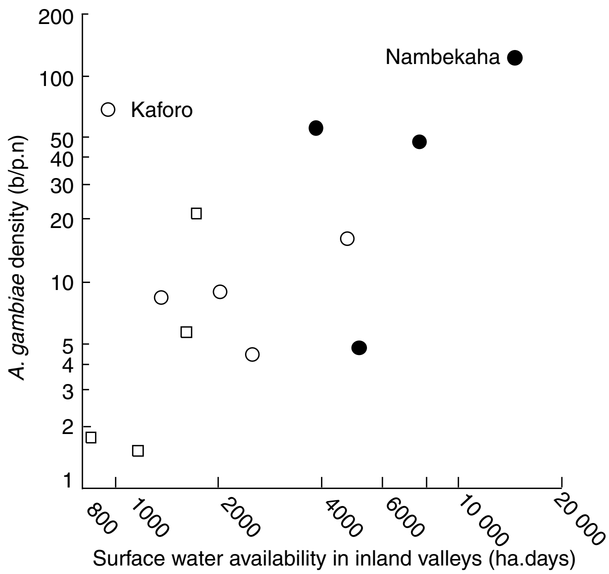

Figure 2 Scatter plot of the average *Anopheles gambiae s.l.* density (bites per person-night) against the surface water availability in all inland valleys in a 2-km radius around a village (irrespective of rice cultivation) for villages without inland valley rice cultivation (□), single-cropping (○) and double-cropping (●) villages in the savannah studied during the off-season cropping period. The outlying village Kaforo was excluded from the regression analysis. The effect of inclusion of the village Nambekaha was studied in the regression analysis.

the SWA on all inland valleys was significant (pseudo R2 for the full model, 0.91) (Figure 4).

In the forest during the main season cropping period, the SWA of the total inland valley area (irrespective of rice cultivation) showed a strong positive correlation with the *A. gambiae* density per person (pseudo $R^2 = 0.74$) (Figure 5), comparable with the correlation found in the

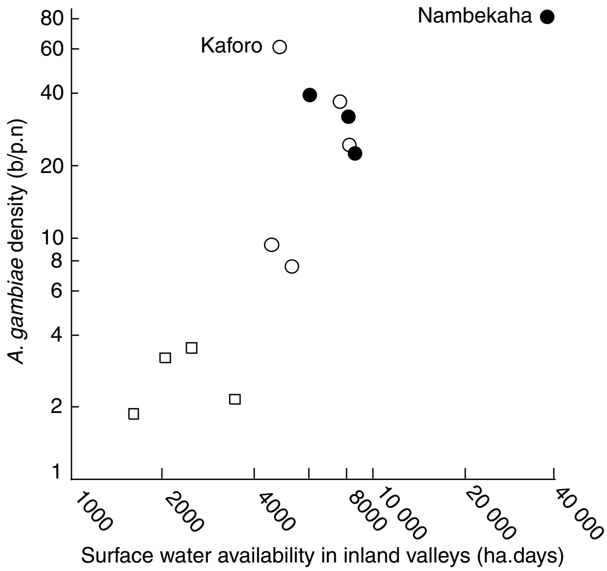

Figure 3 Scatter plot of the average *Anopheles gambiae s.l.* density (bites per person-night) against the surface water availability in all inland valleys in a 2-km radius around a village (irrespective of rice cultivation) for villages without inland valley rice cultivation (□), single-cropping (○) and double-cropping (●) villages in the savannah studied during the main season cropping period. The outlying village Kaforo was excluded from the regression analysis. The effect of inclusion of the village Nambekaha was studied in the regression analysis.

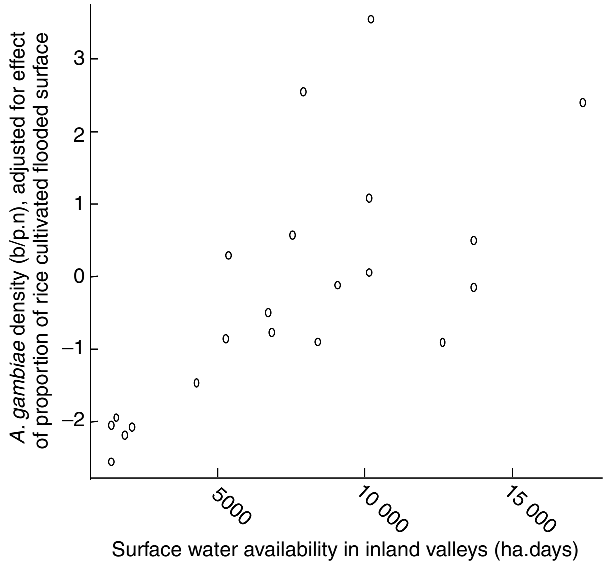

Figure 4 Partial regression plot (added variable plot) of the average *Anopheles gambiae s.l.* density (bites per person-night) against the effect of the surface water availability in inland valleys in a 2-km radius around a village for villages in the forest studied during the off-season cropping period, corrected for the effect of cultivation of the inland valleys.

savannah. The SWA of the land cultivated with rice had a somewhat weaker correlation with the *A. gambiae* density per person (pseudo $R^2 = 0.58$), whereas the correlation of the SWA on land without rice cultivation was weak (pseudo $R^2 = 0.37$). In multivariate analysis, the effect of the cultivation of the flooded land was not significant, as in the savannah.

Discussion

In this study, it was difficult to quantify the flooding of inland valleys attributable to rice cultivation activities, because it was unknown how much of the flooding would occur naturally. However, in general (except for the case of the off-season rice cropping period in the savannah zone, with the outlying village Nambekaha included), in univariate regression analysis the correlations with the *A. gambiae* population density per person were higher for the SWA on rice cultivated land than on uncultivated inland valleys. However, correlations for the SWA on all inland valleys irrespective of rice cultivation were generally higher than for rice cultivated land, except for the case of the off-season cropping period in the forest zone, indicating that both types of flooded land contribute to mosquito

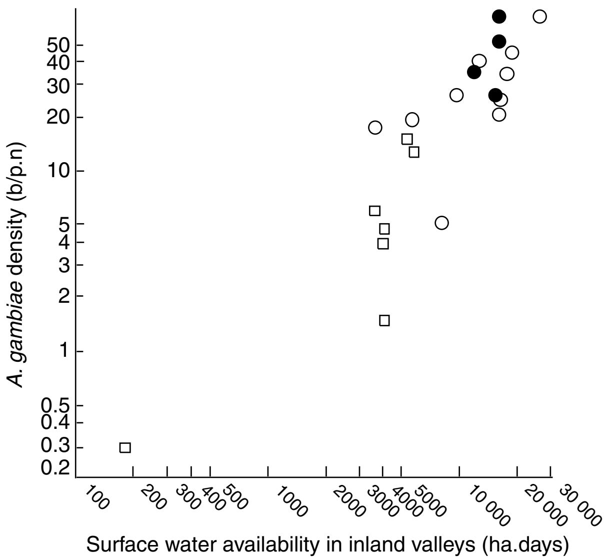

Figure 5 Scatter plot of the average *Anopheles gambiae s.l.* density (bites per person-night) against the surface water availability in rice-cultivated inland valley area during transplanting in a 2-km radius around a village for villages without inland-valley-rice cultivation (□), single-cropping (○) and double-cropping (●) villages in the forest studied during the main season cropping period.

breeding. The correlation of biting density with SWA on all inland valleys irrespective of rice cultivation is particularly strong during the main cropping season. During the off-season cropping period, in the savannah zone, other breeding sites such as rain puddles and stagnant water in beds of seasonal rivers, which were not taken into account for the calculation of the SWA, might have been responsible for a large part of the unexplained variation. In the savannah zone, rain puddles and flood-prone areas receive ample sunlight as compared with the forest zone, especially at the beginning of the rainy season, due to the clearing of the undergrowth during the dry harmattan season by bush fires. During the main season cropping period, there is much less direct sunlight, due to growth of annual grasses. This could explain why in the R2 savannah villages, the *A. gambiae* population density was generally higher during the off-season cropping period, even with lower SWA, than during the main season cropping period with higher SWA. The fact that in the R1 villages, the *A. gambiae* population density was lower during the off-season cropping period could be explained by the very low SWA.

In the forest zone during the off-season cropping period, a very strong correlation existed of rice-cultivated inland valley with the *A. gambiae* density per person, whereas the uncultivated inland valley variables had a very weak correlation with the *A. gambiae* density per person. The fact that the proportion of SWA on rice cultivated land was a significant covariate in the multivariate regression model indicates that the cultivation of flooded land does enhance mosquito breeding. These results are best explained by the requirement of sunlight for breeding of *A. gambiae*. In the forest zone, the – often naturally flooded – uncultivated inland valleys are covered with dense vegetation. The clearing of this vegetation for rice cultivation might create potential breeding sites. The fact that the correlation of *A. gambiae* population density with rice-cultivated inland valleys being higher for the off-season cropping cycle than for the main season cropping cycle is explained by the absence of other suitable breeding sites of minor importance such as rain puddles on dirt roads or other open areas around villages during the off-season cropping cycle. We conclude that in the forest zone, rice cultivation is a major variable in enhancing *A. gambiae* population density during the main season. During the off-season, rice plots in inland valleys even seem to provide the only suitable breeding sites for *A. gambiae*. The surface of the off-season rice-cultivated land is currently small in the forest zone. We predict that further clearing of inland valleys or rehabilitation of irrigation works for off-season rice cultivation will result in increased vector populations.

Particularly in the forest zone, the linear relationship of the seasonal *A. gambiae* density per person with SWA on rice-cultivated land is stunning. Apparently, in these rural settings, surface water on inland valleys is the major factor limiting population size, and not adult density-dependent mechanisms, at least up to an average of 20 bites per person-night over the season. It was unfortunate that we did not have access to recent data on the human population of the villages, to check whether the relationship is as clear between the total biting population and the surface of inland valleys around a village. Nevertheless, an analysis (results not shown) with the *A. gambiae* density per village (i.e. the *A. gambiae* density per person multiplied by the human population size), calculated with the 1988 census data (Anonymous 1988) as response variable, showed broadly the same relationships with rice land and inland valleys, as the analysis with the *A. gambiae* density per person as response variable.

It has to be kept in mind that high mosquito densities do not necessarily result in high transmission of malaria. Density-dependent mechanisms might affect the proportion of sporozoite-infected mosquitoes, even resulting in reduced transmission at higher densities (Dolo *et al.* 2000). In a preliminary binomial regression analysis with the proportion of infective mosquitoes over a rice cropping season as response variable and the seasonal *A. gambiae* density per person as explanatory variable with villages as unit of analysis, we observed significant negative correlations for all seasons and zones, except for the off-season cropping period in the forest zone (analyses not shown). In the savannah, no significant correlation of seasonal entomological inoculation rate was observed with SWA on inland valleys. However, in the forest zone, positive correlations were found for both cropping seasons.

It is generally assumed that the flight range of *A. gambiae* is within 1–2 km from suitable breeding sites (Birley 1989; Thomson *et al.* 1995; Dolo 1996). Usually, highest mosquito densities are found close to breeding sites, such as rice fields (Faye *et al.* 1993; Lindsay *et al.* 1995). Therefore, the 2-km radius around villages seems sufficient to include the major breeding sites of the mosquitoes biting in the village. However, as the dry season *A. gambiae* density in Kaforo (without off-season rice cultivation) was very similar to that of the nearby double-cropping village of Nambekaha, and as in the other R1 villages the dry-season densities were very low, we suspect that during the dry season, the mosquitoes biting in Kaforo were bred in the rice fields just outside the 2-km radius. This indicates that the 2-km radius might not be appropriate, and that observations in geographically close villages might not be independent. Conversely, a reverse effect was observed with the two neighbouring villages of Gbahouakaha and Nongochenekaha which shared double-cropped inland valleys within their radius.

Acknowledgements

This study was undertaken within the framework of the WARDA/WHO-FAO-UNEP PEEM/IDRC/DANIDA/Norway Health Research Consortium on the Association between Irrigated Rice Ecosystems and Vector-borne Diseases in West Africa. The Consortium received financial support from the International Development Research Center (IDRC), Ottawa, Canada, the Danish International Development Agency (DANIDA) and the Royal Government of Norway.

References

Anonymous (1988) *Recencement de la population et de l'habitat 1988. Resultats provisoires, ensemble Cote d'Ivoire.* Comité National du Recencement, Secretariat Géneral du Recencement, Ministère de l'Industrie et du plan, Direction de la statistique et de la compatabilité, Abidjan.

Birley MH (1989) *Guidelines for Forecasting the Vector-Borne Disease Implications of Water Resources Development.* PEEM Guidelines, Series 2. WHO Geneva.

Chandler JA, Highton RB & Hill MN (1975) Mosquitoes of the Kano plain, Kenya 1. Results of indoor collections in irrigated and nonirrigated areas using human bait and light traps. *Journal of Medical Entomology* **12**, 504–510.

Coosemans MH (1985) Comparison of malarial endemicity in a rice-growing zone and in a cotton-growing zone in the Rusizi Plain, Burundi. *Annales de la Société Belge de Médecine Tropicale* **65**, 187–200.

Dolo G (1996) *Etude des populations d'An. gambiae s.l. par marquage, lâcher et recapture à Banambani en 1993 et 1994 (Arrondissement central de Kati, Mali).* Mémoire de DEA en Entomologie et Parasitologie médicales, ISFRA, Bamako.

Dolo G, Briët OJT, Dao A *et al.* (2000) The relationship between rice cultivation and malaria transmission in the irrigated Sahel of Mali, West Africa. *Cahiers Agricultures* **9**, 425.

Dossou-Yovo J, Doannio J, Riviere F & Duval J (1994) Rice cultivation and malaria transmission in Bouake city (Cote d'Ivoire). *Acta Tropica* **57**, 91–94.

Faye O, Fontenille D, Gaye O *et al.* (1995) Malaria and rice growing in the Senegal river delta (Senegal). *Annales de la Société Belge de Médecine Tropicale* **75**, 179–189.

Faye O, Fontenille D, Herve JP *et al.* (1993) Malaria in the sahelian zone of Senegal. 1. Entomological data concerning transmission. *Annales de la Société Belge de Médecine Tropicale* **73**, 21–30.

Garrity DP (1988) Tropical rice agroecosystems: characteristics, distribution, and future trends. In: *Vector Borne Disease Control in Humans Through Rice Agroecosystem Management.* Proceedings of a workshop jointly sponsored by International Rice Research Institute and the WHO/FAO/UNEP Panel of Experts on Environmental Management for Vector Control. International Rice Research Institute, Manila, pp. 13–28.

Henry MC, Rogier C, Nzeyimana I *et al.* (2003) Inland valley rice production systems and malaria infection and disease in the savannah of Côte d'Ivoire. *Tropical Medicine and International Health* **8**, 449–458.

Lacey LA & Lacey CM (1990) The medical importance of riceland mosquitoes and their control using alternatives to chemical insecticides. *Journal of the American Mosquito Control Association* **6**, 1–93.

Lindsay SW, Armstrong Schellenberg JR, Zeiler HA *et al.* (1995) Exposure of Gambian children to *Anopheles gambiae* malaria vectors in an irrigated rice production area. *Medical and Veterinary Entomology* **9**, 50–58.

Marrama L, Rajaonarivelo E, Laventure S & Rabarison P (1995) *Anopheles funestus* and rice culture on the Plateau of Madagascar. *Cahiers d'Etudes et de Recherches Francophones Santé* **5**, 415–419.

Mwangi RW & Mukiama TK (1992) Irrigation scheme or mosquito hazard: a case study in Mwea Irrigation Scheme. *Hydrobiologia* **232**, 19–22.

Robert V, Gazin P, Boudin C *et al.* (1985) The transmission of malaria in a wooded savanna zone and a rice-growing zone in the vicinity of Bobo Dioulasso (Burkina Faso). *Annales de la Société Belge de Médecine Tropicale* **65**, 201–214.

Service MW (1989a) Rice, a challenge to health. *Parasitology Today* **5**, 162–164.

Service MW (1989b) Irrigation: boon or bane? In: *Demography and Vector Borne Diseases* (ed. MW Service) CRC Press, Inc., Boca Raton, FL, pp. 237–254.

Thomson MC, Connor SJ, Quinones ML *et al.* (1995) Movement of *Anopheles gambiae s.l.* malaria vectors between villages in The Gambia. *Medical and Veterinary Entomology* **9**, 413–419.

Windmeijer PN & Andriesse W (1993) *Inland Valleys in West Africa: an Agro-Ecological Characterization of Rice-Growing Environments*, 52. ILRI, Wageningen.

Authors

Elena Akodo, West Africa Rice Development Association, Bouaké, Côte d'Ivoire. Tel.: +225 3163 8983.

Olivier J. T. Briët, International Water Management Institute, PO Box 2075, Colombo, Sri Lanka. Tel.: +94 1787 404; E-mail: o.briet@cgiar.org, obriet@zonnet.nl (corresponding author).

Thomas M. Teuscher, 25 Route de Chenes, 1208 Geneva, Switzerland. Tel.: +41 22 7913741; E-mail: teuschert@who.int

Nick van de Giesen, Center for Development Research (ZEFc), Walter-Flex-Str. 3, 53113 Bonn, Germany. Tel.: +49 228731 720; Fax: +49 228731 889; E-mail: nick@uni-bonn.de

Joel Dossou-Yovo, Institut Pierre Richet, 01 BP 1500, Bouaké 01, Côte d'Ivoire. Tel.: +225 3163 3746; Fax: +225 3163 2738; E-mail: dossou@ipr.ird.ci