Effect of bendiocarb based (Ficam® 80% WP) Indoor Residual Spraying on feeding patterns of malaria vectors in Burkina Faso, West Africa.

HIEN S. Aristide (aristide.hien@yahoo.fr)
IRSS/Centre Muraz
Dieudonné Diloma Soma
Institut de Recherche en Sciences de la Sante
Simon Pengwende Sawadogo
Institut de Recherche en Sciences de la Sante
Serge Bèwadéyir Poda
Institut de Recherche en Sciences de la Sante
Moussa Namountougou
Universite Nazi Boni
Georges Anicet Ouédraogo
Universite Nazi Boni
Abdoulaye Diabaté
Institut de Recherche en Sciences de la Sante
Roch Kounbobr Dabiré
Institut de Recherche en Sciences de la Sante

Research

Keywords: Indoor residual spraying, bendiocarb, malaria vectors, mosquito feeding patterns, Burkina Faso

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Abstract

Background : Vector control is a key component in malaria prevention strategies in many malaria endemic countries in Africa. In Burkina Faso, malaria transmission is seasonal in most parts of country, so a single round of spraying should provide effective protection against malaria, provided the insecticide remains effective over the entire malaria transmission season. The primary effects of IRS towards curtailing malaria transmission are : i) to reduce the life span of vector mosquitoes and ii) to reduce the density of the vector mosquitoes.

Methods : CDC light trap and pyrethrum spray catches were carried out monthly to determine the change in malaria vector indices in sprayed (Diebougou) and unsprayed sites (Dano). The females malaria vectors collected by CDC light trap and PSC were used to determine their blood feeding and sporozoites rate using enzyme-linked immunosorbent assay (ELISA) and their biting rate and entomological inoculation rate

Results: Three species belonging to the *Anopheles gambiae* complex (*Anopheles gambiae* s.s., *Anopheles coluzzii* and *Anopheles arabiensis*) are present throughout the transmission season, but *An. gambiae* s.s.was the most frequent species of the complex (P =0.0005), comprising 88% of the total collected and the most infected species. Malaria vectors densities were significantly lower in sprayed villages (n=4,303) compared with unsprayed villages (n=12,569) during post-spraying period (P = 0.0012). In addition, mean human biting rate of *An. gambiae* sl and *An. funestus* ss were significantly lower in sprayed areas compared to unsprayed areas (P<0.05). Overall, malaria vector transmission risk was significant lower in villages which received IRS (P=0.0001) whatever the malaria vectors species (*An. gambiae* sl and *An. funestus* ss).

Conclusion: The results showed that in the sprayed area (Diebougou), vector densities, human biting rates and malaria transmission risks were very lower than unsprayed areas (Dano). The findings also showed a change in vector behavior especially within *An. funestus* which became more zoophagic following IRS. The indoor residual spraying could be recommanded as control tool in areas where malaria transmission occured throughout the year.

Keywords: Indoor residual spraying, bendiocarb, malaria vectors, mosquito feeding patterns, Burkina Faso.

Background

Vector control is a key component in malaria prevention strategies [1]. In Africa, it relies primarily on two effective and complementary tools: long-lasting insecticidal nets (LLINs) and indoor residual spraying (IRS) [2]. Several studies have demonstrated the effectiveness of both tools in reducing the incidence of malaria [3, 4] morbidity and mortality in Africa [5–9]. However, these interventions, especially LLINs, rely on the use of pyrethroid insecticides. Unfortunately, the recent evolution and spread of pyrethroid resistance in West Africa in Anopheles gambiae s.s. is a major concern for the sustainability of malaria prevention in Africa [10, 11]. For this reason, the research of alternate solutions using a non-pyrethroid insecticide has become a priority [12]. Indeed, since 2006, the World Health Organization (WHO) encouraged a scale-up of IRS for vector-borne disease control, using one of several classes of insecticide that are suitable for IRS [13]. In 2008, of 108 malaria-endemic burdened countries, 44 reported the use of IRS [14]. The primary effects of IRS towards curtailing malaria transmission are: i) to reduce the life span of vector mosquitoes and ii) to reduce the density of the vector mosquitoes [15]. There are several insecticide formulations currently prequalified by WHO for IRS; namely organophosphates, carbamates, pyrethroids and neonicotinoids. In addition, the effectiveness of IRS depends on many factors, including residual efficacy of IRS formulations, indoor resting behaviour of malaria vectors and local vector susceptibility to the insecticide used for IRS [16]. Residual efficacy of IRS formulations and local vector susceptibility to the insecticide used for IRS were discussed in a separate manuscript about bendiocarb efficacy on walls. The monitoring of behavioral responses of mosquitoes to insecticides is critical to the understanding of how chemicals function in the control of disease transmission [17]. Indeed, in northern Nigeria [18], IRS led to a considerable decrease in the total vector population and reduction in the incidence of malaria among children, the plasmodic index and fever, and an apparent effect on mortality of 1–4-year-old children. In Kenya, IRS with fenitrothion in Kisumu [19] and the use of LLINs in the south coast of Kenya [20], showed a decline in populations of An. funestus s.l. and An. gambiae s.l. by the IRS, while the high bed net coverage was followed by a much reduced human biting rate and a diminishing role of An. gambiae s.s. in malaria transmission.

In Burkina Faso, malaria was the most common cause of outpatient consultations (41.3%), hospitalizations (21.4%) and death (16.4%) in 2018 [21]. According to WHO [22], resistance to at least one insecticide had been identified in 64 malaria-endemic countries, including Burkina Faso [23–27]. Pyrethroid resistance is particularly widespread in Burkina Faso, with high frequency of voltage gated sodium channel mutations reported as long ago as 2006 [28]. However, susceptibility tests performed in 2010–2012 with insecticides belonging to carbamates class (such as 0.1% bendiocarb) have shown a high mortality rate of the local population of malaria vectors and low allelic frequencies of gene ace-1^R [29] throughout the country including the southwest (Diebougou). This insecticide molecule was chosen to be applied on walls during pilot study as described in the previous article. Indeed, the preliminary results from this study have shown a short persistence and a vectors resistance to this insecticide. As the international community has now prioritized national and regional elimination with a long-term ultimate goal of malaria eradication [30], the need to understand the biological implications of IRS is paramount. It is important to understand its impact on the behavior of malaria vectors in contact with walls treated with insecticide. In this context, the present study aims to evaluate the effect of a large scale IRS using a non pyrethroid insecticide (bendiocarb) on the behavior of malaria vectors, in the intervention areas (Diebougou district) compared to untreated areas used (Dano district) as controls.

Methods

Study area

Entomological surveys were conducted in the health district of Diebougou (intervention or sprayed area) and covered four villages (or agglomeration) including Diebougou center (N10.96741; W 003.24580), Bagane (N10.96397; W003.23422), Loto (N10.96871; W003.23477) and Bapla (N10.87638; W 003.26145). Dano (control or unsprayed area) is situated 42 km from Diebougou and was utilized as an unsprayed control area. Four villages were sampled,

including Dano sector 1 corresponding to the center of Dano (N11.14288; W 003.05969), Dano sector 2 (N11.13802; W 003.06216), Dano sector 3 (N11.16464; W 003.06374) and Dano sector 4 (N11.14541; W 003.05141) (Fig. 1). Villages chosen in Diebougou and Dano districts were selected to be representative of the different settings of the areas (peripheral, central, sub-urban, presence of water source, etc) and had the same type of walls such as “banco” (a mixture of mud and water) and cement.

Implementation of intervention

Indoor Residual Spraying was introduced in 2010 with funding from PMI/USAID, and continued through 2011 in conjunction with the NMCP. During the 2010 spray round, 33,897 structures were sprayed (98.9 percent of the target area), protecting 118,691 persons including nearly 25,000 children under five years of age and more than 2,000 pregnant women. In the 2011 spray campaign, 33,897 structures were sprayed protecting 118,691 people. IRS was implemented in accordance with President’s Malaria Initiative Best Management Practices (PMI, 2010) to ensure a high quality of spraying and the safety of the residents, spray operators and the environment. Spray operators were provided with full personal protective equipment including coveralls, gloves, boots and helmet with face visor. Spray operators used either Hudson X-Pert or Goizper IK Vector Control compression sprayers fitted with flat fan nozzles to spray the interior walls and non-metal ceilings of eligible structures in IRS-targeted areas. All spray operators, team leaders and spray supervisors were trained prior to spray operations. Ficam 80%WP (wettable powder) was selected for spraying onto the walls in Diebougou district. The formulation was applied at 400 mg of bendiocarb active ingredient/m^2 on walls of houses as recommended by the World Health Organization Pesticide Evaluation Scheme (WHOPES) [31, 32]. Spray operation staff informed residents to stay out of the structure for at least two hours after IRS application.

Mosquito sampling and identification

Following IRS, the Institut de Recherche en Sciences de la Santé (IRSS) monitored the efficacy of IRS on entomological indicators of malaria transmission. Monthly collections were conducted to determine mosquito species composition, biting rates and indoor resting densities. Malaria vector population dynamics were monitored in each of the eight selected villages (four sprayed and four unsprayed controls) using indoor and outdoor CDC light trap collection (CDC LT) and pyrethrum spray catch (PSC). Two months of baseline collections were conducted, before IRS was performed, in June and a week before IRS application in July 2012 in Dano and Diebougou. The relatively short baseline period of data collection was due to the long dry season in the study area from November until May, during which Anopheles densities and malaria transmission is low. Subsequent monthly entomology surveys were conducted until December 2012.

Indoor CDC LT were installed approximately 1.5 m above the ground next to an occupied (bait) untreated mosquito net (usually in the living room, although many houses have only a single room). Unbaited light traps were also hung outdoors at the same height, approximately 10-20m away from the houses. CDC LT was the preferred trapping method due to concerns about potential disease transmission risks during human landing catch. Moreover, several studies [33, 34, 35] showed a comparability of CDC LT catch size compared with HLC for different Anopheles species. In each village, CDC LT collections were conducted (indoors and outdoors) from 20:00 pm to 06:00 am for a total of four nights per month. Four randomly selected houses were sampled each month, resulting in 16 trap-nights indoors and 16 trap-nights outdoors per month, per site. In addition, indoor resting mosquitoes were collected by pyrethrum spray catches (PSC) in four randomly selected houses in each village. PSC was conducted by laying white sheets on the floor and furniture before spraying a commercial aerosol consisting of 0.64% Pyrethrum EC and 0.75% chlorpyrifos ethyl. PSC was conducted between 06:00 and 09:00 am. The sampling of mosquitoes was carried out in the same bedroom and at the same frequency during the intervention periods.

Laboratory processing

All anophelines were sorted and assigned to species based on morphological characters using standard identification keys [36]. An. gambiae s.l. females caught in CDC LT were to be dissected to determine the parity rate. Unfortunately, parity rates could not be assessed as females died while in traps and were too dry for dissection. Legs of each female from mosquitoes collected by CDC LT and PSC were tested in PCR for molecular identification of species [37]. The heads and thoraces of host-seeking females were tested by enzyme-linked immunosorbent assay (ELISA) for the detection of Plasmodium falciparum circumsporozoite protein (CSP) using the procedure of Wirtz et al., [38]. The blood meals from freshly fed females collected using PSC were used to assess host preference for blood meal source. A random selection of 30 specimens per month and per district were tested by a direct ELISA [39] using anti-host immunoglobulin G (IgG) conjugated against human, bovine, pig, donkey and sheep blood. All the mosquito samples collected were stored individually in numbered vials with desiccant.

Data analysis

Measured parameters

The mean human-biting rate (HBR) was calculated for each species collected by CDC light trap by dividing the total number of captured specimens by the total person-nights for the collection period. The mean indoor resting density was defined as the total number of mosquitoes (per species) collected by PSC divided by the total number of rooms sampled. The circumsporozoite rate was calculated as the proportion of mosquitoes infected with P. falciparum sporozoites. The anthropophilic rate was calculated as the proportion of female malaria vectors with human blood out of the total tested for blood-meal source. The entomological inoculation rate (EIR) was calculated by multiplying the HBR indoor/outdoor and the CSP rate.

All the measured parameters were computed and analysed using the free software GraphPad 5.0 version. Data were compared with the Pearson chi^2 or Fisher exact tests and odds ratio were calculated to determine the impact of IRS in study sites. All calculations were expressed with the statistical significant threshold set at $P \leq 0.05$.

Ethical consideration

Ethical approval for this study was granted by the Ethical Committee of the Ministry of Health in Burkina Faso. The mosquito collectors gave prior informed consent and they were vaccinated against yellow fever. An agreement with health facilities close to sites was also obtained for the free anti-malarial treatment of mosquito collectors who may suffer from malaria.

Results

Malaria vector densities and species composition

A total of 26.276 mosquitoes (13.555 anopheline and 12.721 other culicines) were collected from June to December 2012 using both CDC LT (9158 mosquitoes) and PSC collection methods (17.118 mosquitoes). In addition, 9.404 mosquitoes were collected in Diebougou (sprayed area) between June and December (Table 1) whose 3040 mosquitoes collected in baseline (June-July 2012) and 6.364 mosquitoes during post-spraying period (Augut-December) compared to unsprayed area with 16.872 collected mosquitoes whose 4303 mosquitoes at baseline and 12569 mosquitoes in post-spraying period (P = 0.0012). a significant difference was observed between the total number collected in sprayed and unsprayed areas. According to species composition, An. gambiae sl (69.34%) and An. funestus ss (24.16%) were the most predominant Anopheline species collected in sprayed area (Diebougou) compared to 45% An. gambiae s.l., 19% An. funestus s.s., and 36% other culicines (Culex sp, Aedes sp., Anopheles sp etc) (Additional file 1: Figure S1). Their proportion were significantly reduced between sprayed and unsprayed areas (P = 0.039). In addition, there was a greater number of culicids collected in sprayed areas compared to unsprayed areas certainly due to impact of IRS. Overall, the total number of collected mosquitoes in sprayed areas (6364 mosquitoes) compared to unsprayed area (12569 mosquitoes) was significant (P = 0.001) after spraying period.

Table 1
Seasonal variation of major vectors densities in sprayed (Diebougou) and unsprayed (Dano) sites

Samples	CDC indoor collections							CDC outdoor collections							Pyrethrum indoor collections				
Sprayed area	June	July	Aug	Sept	Oct	Nov	Dec	June	July	Aug	Sept	Oct	Nov	Dec	June	July	Aug	Sept	
An. gambiae s.l.	33	76	213	106	76	40	22	8	35	28	2	3	2	18	234	317	338	335	
An. funestus	0	0	27	47	33	28	31	5	15	62	9	31	36	41	10	11	8	11	
Other culicids	256	220	678	246	309	206	92	15	131	433	37	203	183	135	809	865	667	149	
Total	289	296	918	399	418	274	145	28	181	523	48	237	221	194	1053	1193	1013	495	
Unsprayed area	June	July	Aug	Sept	Oct	Nov	Dec	June	July	Aug	Sept	Oct	Nov	Dec	June	July	Aug	Sept	
An. gambiae s.l.	74	218	640	244	72	36	14	17	31	21	14	2	2	4	469	777	1926	1160	
An. funestus	15	98	94	109	158	110	50	7	25	2	3	3	4	26	118	244	256	547	
Other culicids	150	263	413	198	172	159	170	128	77	25	20	28	17	74	1145	447	839	844	
Total	239	579	1147	551	402	305	234	152	133	48	37	33	23	104	1732	1468	3021	2551	

During the post IRS study period, indoor resting densities of malaria vectors were significantly lower in sprayed villages (n = 1,798) compared with unsprayed villages (n = 8,607) P = 0.0051 (Table 1). There was also a significant difference for total Anopheline catch by indoor CDC LT, with 1,527 in the untreated area compared with 623 in the IRS area (P = 0.0069). When broken down to species, An. funestus indoor resting (PSC) and host-seeking (CDC LT) densities (CDC LT: sprayed = n = 166 vs unsprayed n = 521 with P = 0.004; PSC: sprayed n = 99 vs unsprayed n = 2,136; P = 0.0079) and An. gambiae s.l. indoor resting densities (PSC: sprayed n = 1,076 vs unsprayed n = 4,944 11; P = 0.0005 were significantly lower in sprayed sites compared with control villages (Table 1).

Monthly biting and resting behaviour of Anopheles gambiae sl and An. funestus ss following IRS

Baseline data

In Dano (unsprayed), in June 2012, the An. gambiae s.l. indoor human biting rate was estimated at 4.6 bites per person per night by CDC LT collection and 13.6 bites/person/night in July 2012 (Fig. 3A). However, in Diebougou the An. gambiae s.l. human biting rates by indoor CDC LT were found to be lower at 2 and 5 b/p/n indoors in June and July respectively. The An. funestus indoor human biting rate was less than 1 b/p/n (Fig. 4A). A similar trend was recorded for indoor resting densities, with Dano having approximately double the catch size of Diebougou (Fig. 5A&B). The highest resting densities by indoor PSC

collection with a mean value in July reaching 49 An. gambiae s.l. per house per night in Dano (Fig. 5A). The catch size was generally low in outdoor CDC collections in both sites (Fig. 3B & 4B).

Post-spraying data

A summary of mean biting rates is presented in Fig. 3 for An. gambiae s.l. and Fig. 4 for An. funestus ss In addition, the number of mosquitoes collected by month and by site is summarized in Table 2&3.

Table 2
Monthly An. gambiae s.l.sporozoite rate and entomological inoculation rate from Dano unsprayed area and Diebougou (sprayed area) from June to December, 2012.

	June	July	August	September	October	November	December	2012 Total
Dano (unsprayed area)								
Total An. gambiae s.l. (CDC-LT) collected	91	249	661	258	74	38	18	1389
CDC trap-nights	32	32	32	32	32	32	32	224
(indoors + outdoors)								
HBR per night	2.84	7.78	20.66	8.06	2.31	1.19	0.56	6.2
Total An. gambiae s.l. tested by CSP	78	45	44	14	21	27	13	242
Sporozoites rate	0	6.7	13.6	14.2	09.5	11	30.8	7
EIR p/night	0	0.521	2.809	1.145	0.219	0.131	0.173	0.714 (mean)
EIR p/month*	0	15.64	84.28	34.35	6.591	3.92	5.19	21.42 (mean)
Dano 5-month EIR post-IRS August-December 2012 = 134 infectious bites per person								
Diebougou (sprayed area)								
Total An. gambiae s.l. (CDC-LT) collected	41	111	241	108	79	42	40	662
CDC trap-nights	32	32	32	32	32	32	32	224
(indoors + outdoors)								
HBR per night	1.28	3.47	7.53	3.38	2.47	1.31	1.25	2.95
Total An. gambiae s.l. tested by CSP	42	49	56	25	114	62	30	378
Sporozoites rate	0	6.1	5	8	14	3.2	0	0.052
EIR p/night	0	0.212	0.377	0.27	0.346	0.042	0	0.1778 (mean)
EIR p/month*	0	6.35	11.29	8.1	10.36	1.26	0	5.34 (mean)
Diebougou 5-month EIR post-IRS August-December 2012 = 31 infectious bites per person								

Table 3
Monthly An. funestus ss sporozoite rate and entomological inoculation rate from Dano (unsprayed area) and Diebougou (sprayed area) from June to December, 2012.

	June	July	August	September	October	November	December	2012 Total
Dano (unsprayed area)								
Total An. gambiae s.l. (HLC) collected	22	123	96	112	161	114	76	704
CDC trap-nights	32	32	32	32	32	32	32	224
(indoors + outdoors)								
HBR per night	0.69	3.84	3	3.5	5.03	3.56	2.38	3.14
Total An. gambiae s.l. tested by CSP	18	78	77	24	58	23	26	304
Sporozoites rate (%)	0	1.3	1.3	4.2	5.2	0	0	1.7
EIR p/night	0	0.05	0.039	0.147	0.262	0	0	0.071 (mean)
EIR p/month*	0	1.5	1.17	4.41	7.85	0	0	2.13 (mean)
Dano 5-month EIR post-IRS August-December 2012 = 13 infectious bites per person								
Diebougou (sprayed area)								
Total An. gambiae s.l. (HLC) collected	5	15	92	56	64	64	72	368
CDC trap-nights	32	32	32	32	32	32	32	224
(indoors + outdoors)								
HBR per night	0.16	0.47	2.88	1.75	2	2	2.25	1.64
Total An. gambiae s.l. tested by CSP	8	11	50	44	43	37	16	209
Sporozoites rate (%)	0	9.1	0	0	2.3	2.7	0	2
EIR p/night	0	0.043	0	0	0.046	0.054	0	0.02 (mean)
EIR p/month*	0	1.2796875	0	0	1.38	1.62	0	0.61 (mean)
Diebougou 5-month EIR post-IRS August-December 2012 = 3 infectious bites per person								

In the period post-IRS (August to December) the mean indoor biting rate per person per night (bpn) was significantly different for An. gambiae s.l. females between the two areas, with the highest mean biting rate observed in the unsprayed sites (mean = 6.55 bites per person per night from August to December) compared to sprayed sites (mean = 3.18 bites per person per night). A significant difference was observed (P = 0.015)

The peak from indoor biting density of An. gambiae sl occurred in August with about 40 bites/person/night in Dano (unsprayed) and decreased progressively to December, when it was less than 5 b/p/n at the end of the rainy season (Fig. 3A). The same pattern was observed in the intervention area but with less than 15 An. gambiae sl bites per person per night. The human biting rate and mean number of An. gambiae sl per house from indoor collections (CDC LT and PSC) in sprayed sites was half a time lower compared to unsprayed sites (Odds ratio $_{(CDC\ LT)}$ = 0.51, 95% CI= [0.34–0.67] with P = 0.001 and Odds ratio $_{(PSC)}$ = 0.30, 95% CI= [0.21–0.43]. Outdoor biting rates were particularly low in both sites, with a mean of < 3 bites per person per night (Fig. 3B). But, the exposure to mosquito bites outdoors was slightly, but more increased in Diebougou (sprayed area) after treatment compared to Dano, the unsprayed area but the difference was not significant (P > 0.05).

Similar results were observed in An. gambiae s.l. and An. funestus ss biting rates (Fig. 4) in PSC collection (Fig. 5B) with a mean biting rate of 2.00 bpn in Diebougou compared with 4.00 in Dano during the post-spraying period August-December (Odds ratio $_{(CDC\ LT\ indoors)}$ = 0.28, 95% CI= [0.11–0.35] with P = 0.035 (Table 3).

Plasmodium falciparum circumsporozoite and entomological inoculation rates (EIR) in An. gambiae sl and An. funestus ss

The results of CSP-ELISA assays and entomological inoculation rate of An. gambiae s.l. and An. funestus ss are presented in Table 2 and 3 respectively. Overall, 2051 An. gambiae sl and 1072 An. funestus ss specimens were screened for the circumsporozoite protein from June to December 2012 in the two areas. The sporozoites and entomological inoculation rate (EIR) were calculated by grouping indoor and outdoor collections of An. gambiae s.l. and An. funestus ss due to low number sampled in indoor and outdoor collection (Additional file 2: Table S1; Additional file 3: Table S2). So, during the post-IRS period (August-December), the mean CSP rate differed between unsprayed and sprayed areas for CDC LT method. The average sporozoites rates were significantly different (more than 2-fold) between the unsprayed areas (average sporozoite rate = 15.82%; 95% CI: [8.94–23.49]) and the sprayed areas (average sporozoites rate = 6.05%; 95% CI: [3.509–12.59]) (t = 2.475; df = 9 with P = 0.022) (Table 2). The highest sporozoites rates were observed in Dano in August (average sporozoite rate = 13.6%; 95% CI: [9.68–17.33]) and September reaching an average of 14.2%. The similar trends were also observed in An. funestus ss

sporozoites rate (Table 3) but in lowest proportions (average sporozoite rate = 2.14%; with 95% CI: [0.25–3.15] in unsprayed areas and average sporozoites rate = 1% with 95% CI: [0.33–1.8] in sprayed area) with a significant difference (P = 0.035).

The major contributor to the EIR, both in the control and intervention areas, was An. gambiae s.l. (70%). The indoor EIR reached 134 infective bites/person during the five-month post-IRS in the unsprayed area Dano. IRS appears to have reduced the EIR four-fold in the sprayed area (31 infective bites /person) after spraying with P = 0.0001. An. funestus ss contributed also to the transmission in the two areas, with the similar results (EIR reduced 4-fold in sprayed area) compared to An. gambiae sl after spraying (mean EIR in Dano = 13 bi/p/n vs mean EIR in Diebougou = 3 bi/p/n with P = 0.003).

An. gambiae sl and An. funestus ss blood meal sources

The results presented in Figs. 8 and 9 include data from indoor and outdoor CDC collections and indoor PSC collections, for An. gambiae sl and Anopheles funestus ss from the two areas. Irrespective of the sampling month, the proportion of An. gambiae sl. blood- fed on human was highest, reaching more than 80% of the total of 335 females analysed, both in the sprayed and unsprayed areas. No female was recorded blood-fed only on animals. For An. funestus ss the feeding patterns were quite different, especially in the sprayed area (Diebougou) where females showed a large range of hosts. Out of 132 females analysed for their blood-fed origin, about 20–40% of An. funestus ss females had taken a mixed blood meal (human, bovine, and goat). A potential effect of the IRS on An. funestus ss is that the proportion of human blood meals decreased being replaced by animal and mixed blood meals.

Discussion

The study showed that two species An. gambiae s.l. and An. funestus ss are predominant vectors of malaria transmission in study areas [28] collected by CDC light trap and pyrethrum spray catches. the results aslo indicated that the An. gambiae sl entomological inoculation rate was 4-fold lower in sprayed area compared to the unsprayed area, after the implementation of the IRS primarily due to a lower indoor biting rate and a significant decrease of malaria vectors sporozoite rates. However, the indoor resting density of vectors declined in the sprayed houses following IRS, but increased slightly in October, probably due to the relatively short residual duration of bendiocarb indicated in a separate manuscript. This drastic drop could be also due to the lethal effect of bendiocarb on the anophelines resistant to pyrethroids [40]. The biting rates observed outdoors were slightly higher in intervention areas compared to control areas and may be an early sign of biting behavior change. In conclusion IRS did not reduce the endophily behaviour from that of the baseline but had significantly reduced the density of mosquitoes resting indoors in sprayed area compared to the unsprayed area. In addition, EIR might have been impacted by the observed outdoor biting behaviour, and the reduced residual efficacy of the insecticide after September. The overall indoor biting rate of An. funestus ss was twofold greater in the unsprayed area. Indeed, the susceptibility status, taxonomy, and the role of An. funestus in malaria transmission was well documented in this area at west (Lena) and southwestern Burkina Faso (Soumousso) [44].

The use of vector control tools and behaviors of the host would be the main factors that modify the behavior of human blood feeding observed on An. gambiae s.l.. Indeed, recent studies [41, 42] showed that the long-term indoor application of residual insecticides contributes towards an increased tendency for outdoor feeding among malaria vector populations. The treatment had a great positive impact within An. funestus decreasing the human host-seeking in interventions sites compared to control sites. It is probably due to behavior change that this species is opting to go outside to seek a bloodmeal. It is important to highlight the exophagic host seeking activities and the exophilic behaviour that resulted in the search for blood in animals and mixed meals analyzed which more developed by An. funestus in the intervention area than in the control area where this vector remains mainly endophagic and endophilic. Indeed, after treatment there is less of An. funestus collected in intervention area compared to control area. Moreover, the exophagic host seeking recorded in intervention area was more pronounced than that obtained with An. gambiae s.l. Gillies and De Meillion [36] stated "…Funestus shows a closer adaptation to human dwellings than any other African anopheline. In many areas it spends the greater part of its adult life in houses, which has made it one of the most vulnerable of species to attack with residual insecticides". This statement is clearly valid in this case. Such a clear response to indoor insecticides makes the emergence of insecticide resistance in this species all the more likely [43]. Moreover, the results of impact of IRS on malaria transmission by An. gambiae s.l. indicated that the transmission was lower compared to the control area, after the implementation of the IRS, where the biting rate of Anopheles dropped drastically. This drastic drop is due to the lethal effect of bendiocarb on the anophelines resistant to pyrethroids [40] even though such efficacy did not last more than three months (discussed in a separate manuscript). The biting rates observed in outdoors were higher in intervention areas compared to control areas assuming a less pronounced behavior change of vectors.

In conclusion IRS did not reduce the endophily behavior from that of the baseline though it had significantly reduced the density of mosquitoes resting indoors compared to the control area. In addition, the findings have also shown An. gambiae s.l. were particularly anthropophilic in the two areas with few cases of mixed blood meals and no pure animal blood meals identified. This feeding pattern was the inverse for An. funestus in the intervention area where more females showed a large plasticity of the host range (zoo-anthropophilic). The results have shown that An. gambiae s.s. S-form was the major malaria vector species biting in the southwestern region in Burkina Faso. This corroborates previous reports [28–29] of the anopheline distribution in Burkina Faso, which explained the abundance of the S molecular form by the ecological characteristics of this region.

Conclusion

The pilot study of IRS with bendiocarb appeared to have a significant impact on malaria transmission in the sprayed areas, as measured by EIR. Indeed, the results illustrated that IRS was strong enough to reduce mosquito abundance, sporozoite rate, and EIR in pyrethroids resistance areas. However, the baseline period indicated intrinsic differences in biting rates between Dano and Diebougou before IRS.

The findings also showed a change in vector behavior, with An. funestus becoming more zoophagic after IRS. Furthermore, the residual efficacy of IRS did not last more than three months. In areas of high transmission, other insecticides with a longer life span covering the malaria transmission season need to be

explored, in combination with LLINs.

Declarations

Availability of data and materials

All relevant data and material are available upon request.

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Affiliation

Institut de Recherche en Sciences de la Santé, Direction Regionale, 399, Avenue de la liberté, 01 BP 545, Bobo-Dioulasso 01, Burkina Faso;

Université Nazi Boni,01 BP 1091 Bobo-Dioulasso 01, Burkina Faso.

Authors' contributions

KRD designed the study and drafted the manuscript. ASH, DDS and SPS participated in the field study, the sample collection, the laboratory and data analysis and the drafting of the manuscript; DDS and ASH participated in the data analysis; SP and DDS participated in the laboratory analysis. ASH and RKD participated in the study design. MN, SP, GAO and AD corrected the first draft of the manuscript and participated to data analysis. All authors read and approved the final version. KDR is guarantor of the paper.

Corresponding author

Correspondence to dabireroch@gmail.com

Ethics approval and consent to participate

Ethical approval for this study was granted by the Ethical Committee of the Ministry of Health in Burkina Faso. The mosquito collectors gave prior informed consent and they were vaccinated against yellow fever. They were also subjected to regular medical check-ups with preventive treatments of malaria.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Supporting Information

Additional file 1 : Figure S1. A) overall density of mosquitoes per species and B) proportion of species composition from June to December 2012 in unsprayed and sprayed

Additional file 2: Table S1. Infection rate for *P. falciparum* calculated by circumsporozoite protein (CSP) ELISA from the head and thoraxes of *An. funestus*

Additional file 3: Table S2. Infection rate for *P. falciparum* calculated by circumsporozoite protein (CSP) ELISA from the head and thoraxes of *An. gambiae* sl

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Figures

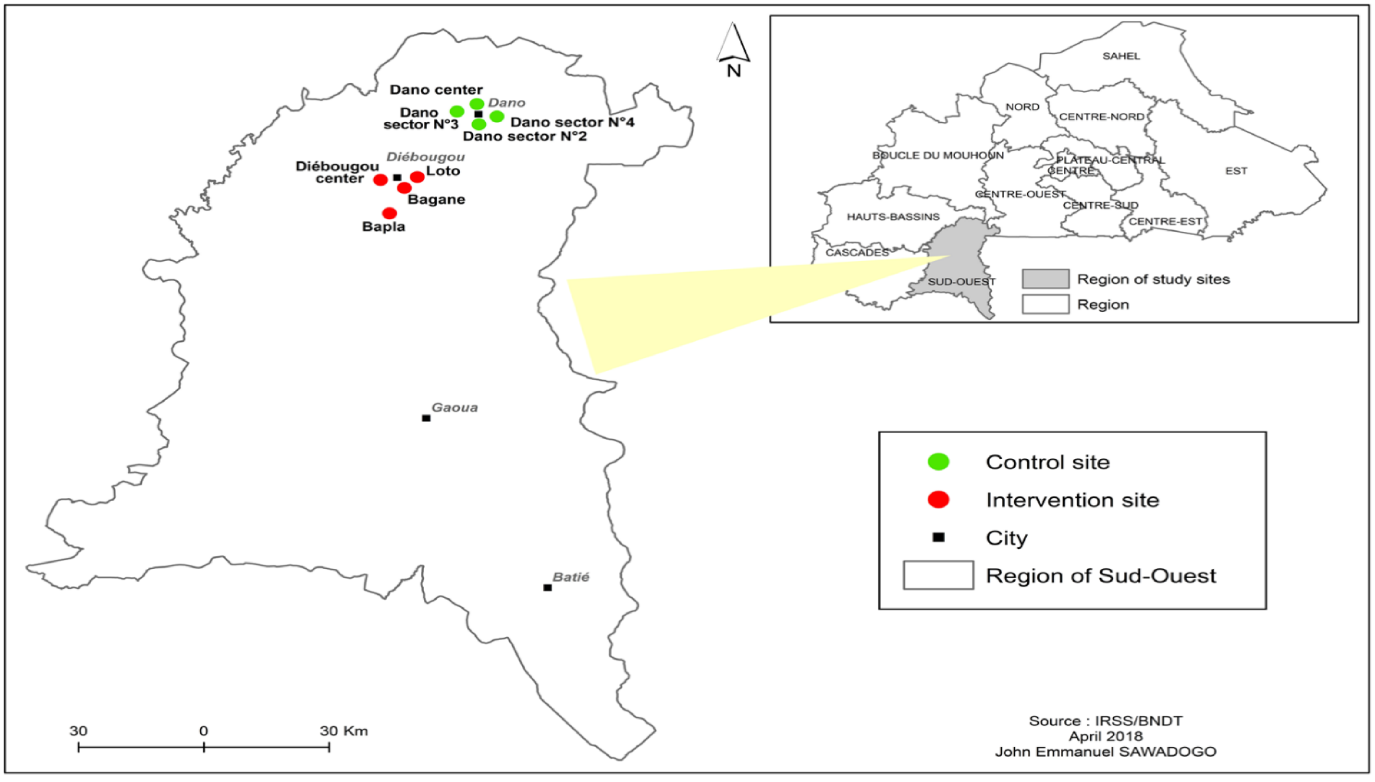

Figure 1

Location of study sites

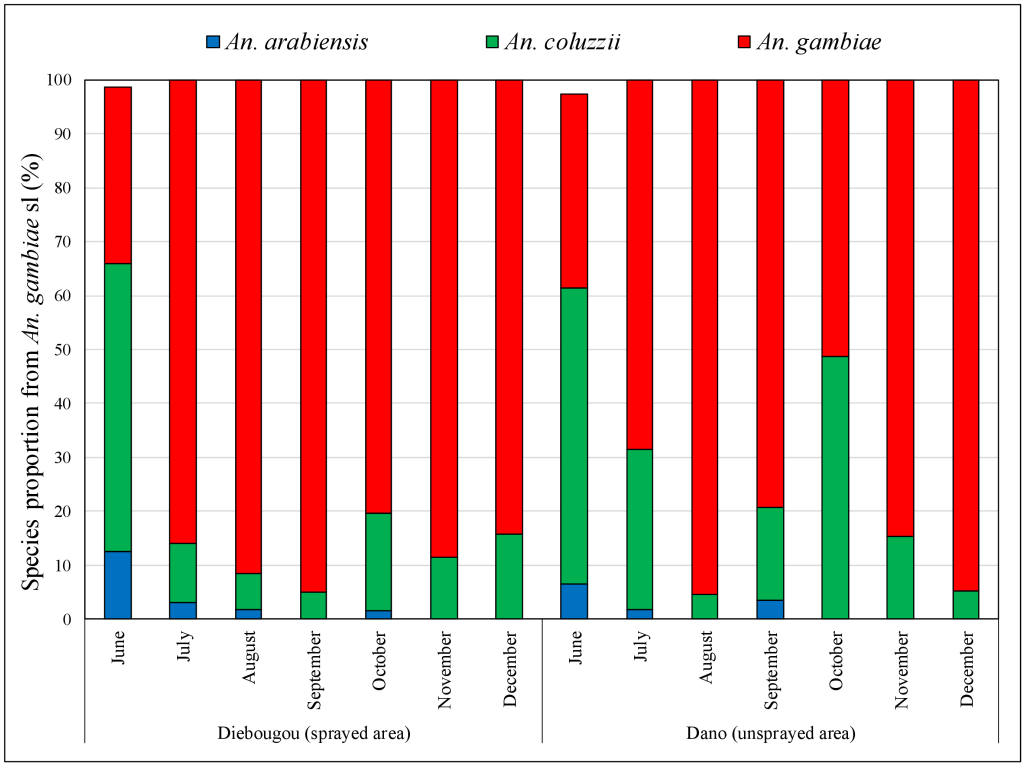

Figure 2

Species composition within the An. gambiae complex collected by CDC light-traps in sprayed (Diebougou) and unsprayed areas (Dano).

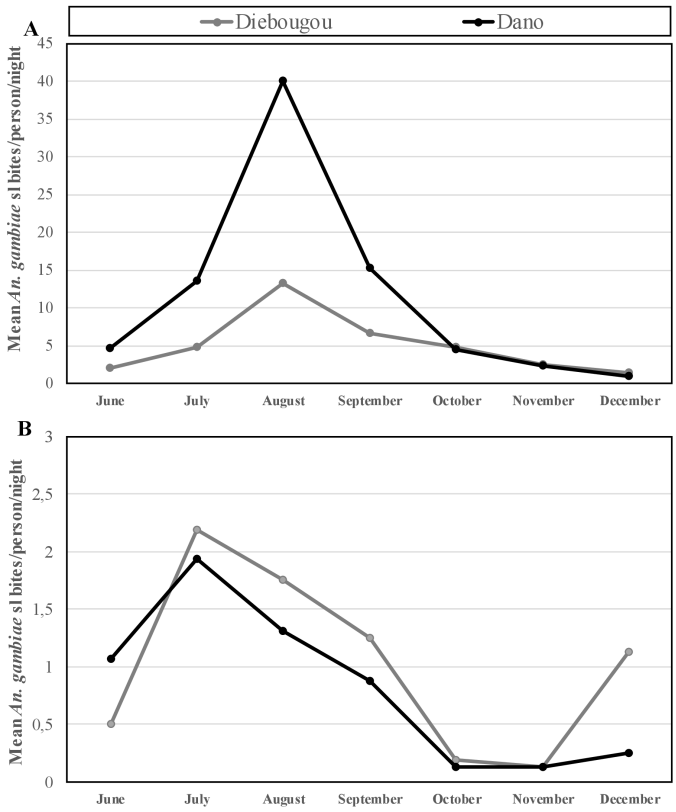

Figure 3

Mean An. gambiae sl bites per person per night collected by CDC light-traps in sprayed (Diebougou) and unsprayed areas (Dano) in A) Indoor collection and B) Outdoor collections before and after spraying

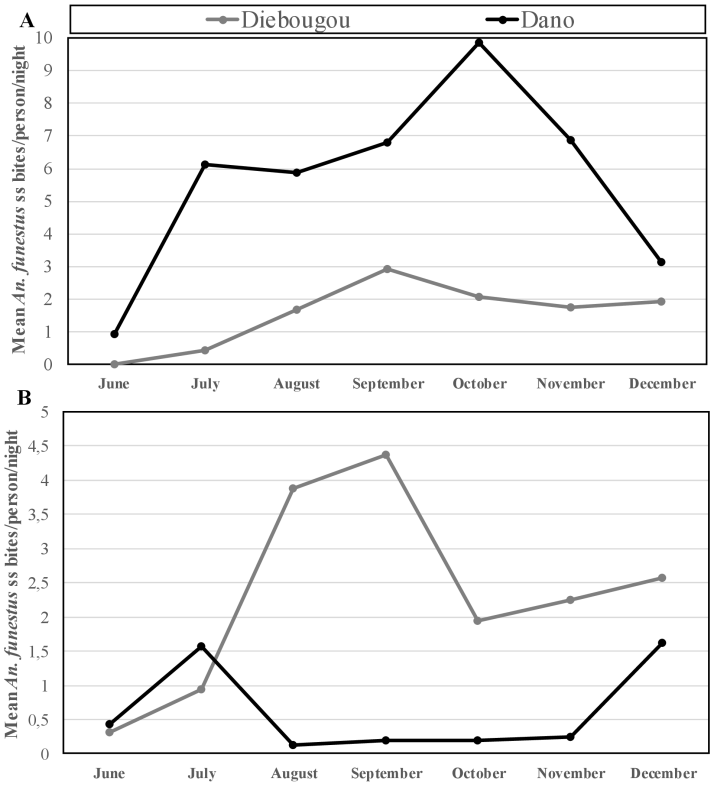

Figure 4

Mean An. funestus ss bites per person per night collected CDC light-traps in sprayed (Diebougou) and unsprayed areas (Dano) in A) Indoor collection and B) Outdoor collections before and after spraying.

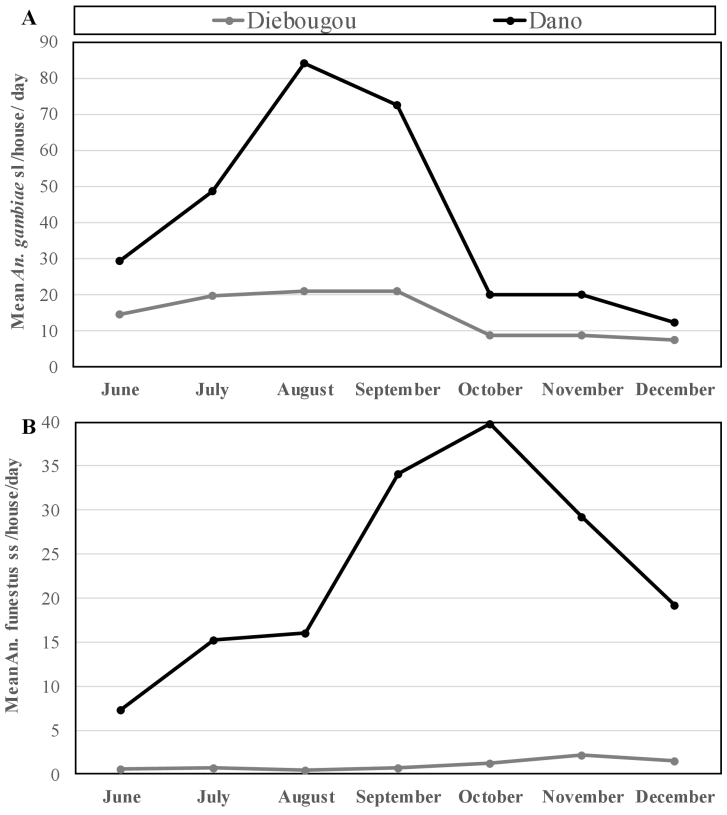

Figure 5

Mean number of mosquitoes /houses from indoor PSC collection in sprayed (Diebougou) and unsprayed areas (Dano) in A) An. gambiae sl and B) An. funestus ss before and after spraying

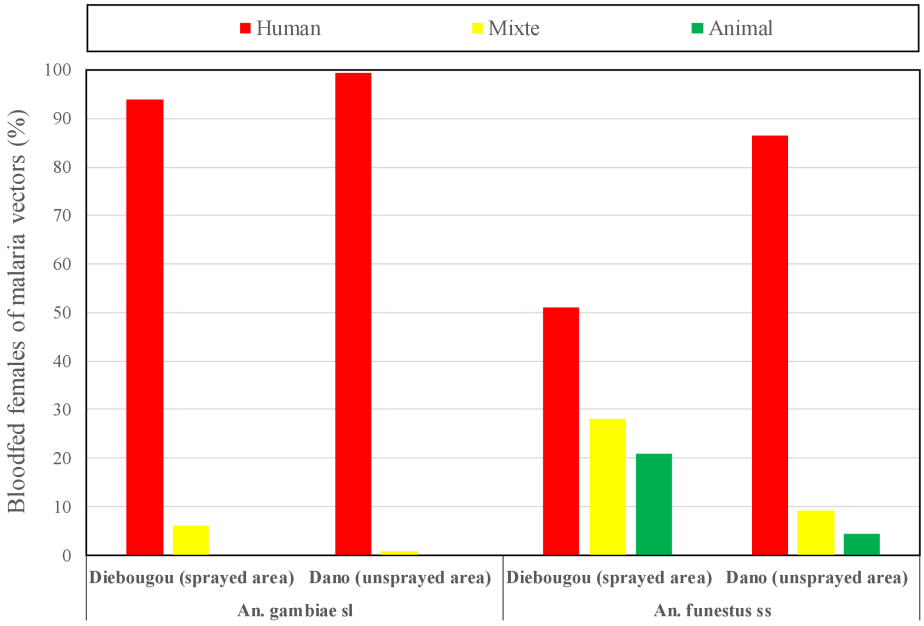

Figure 6

Proportion of An. gambiae sl and An. funestus ss blood-fed on humans, animals or mixed from sprayed area (Diebougou) and unsprayed area (Dano).

Supplementary Files

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- Additionalfile1.xlsx
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