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MOSQUITO LARVAL HABITATS IN A SEMIARID ECOSYSTEM IN ERITREA: IMPACT OF LARVAL HABITAT MANAGEMENT ON *ANOPHELES ARABIENSIS* POPULATION

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Abstract. This study investigated the impact of larval management and the temporal variation in larval productivity in Eritrea, a semiarid ecosystem. Results of this study show that mosquito breeding persists throughout the year mainly in stream bed pools. *Anopheles arabiensis* production in the ephemeral natural aquatic habitats such the streambed pools was high throughout the year and negatively associated with rainfall ($r = -0.288$, $P = 0.047$). High densities of *An. arabiensis* larvae were also recorded from canals and drainage channels at wells and communal water supply points. The numerous water supply locations and wells help sustain malaria transmission by serving as sources of anophelines where people aggregate. There was a strong association between larval production and adult emergent densities ($r = 0.365$, $P = 0.011$). The results of this study further show that implementation of larval control strategies in the study villages significantly reduced vector productivity as measured by both larval ($F = 24.919$, df = 1,178, $P < 0.001$) and adult *An. arabiensis* densities ($F = 3.052$, df = 1,119, $P = 0.014$) in the treated sites over the 24-month study period. The results of this semiarid larval management model suggests that 1) larval management backed by habitat identification, mapping, and surveillance is a feasible tactic for managing malaria vectors, 2) a special focus in such semiarid ecosystems should be targeted to the highly productive larval habitats along stream beds and others of periodic importance derived from human activities, and 3) public information and sensitization of communities to participate in controlling the pre-adult stages of anopheline mosquitoes is central for success.

INTRODUCTION

Malaria is a major vector-borne disease in sub-Saharan Africa whose increase can be attributed to environmental changes, leading to the expansion of its geographical limits.[1] The disease is the leading cause of morbidity and mortality, and it is a major threat to socio-economic development to poor countries of Africa, where 15% of all disability life-years are lost to malaria.[2,3] The situation is worsening with the spread of drug resistance in the parasite and insecticide resistance in the vector.[4,5] In Eritrea, malaria accounts for ~30% of outpatient morbidity and 28% of all hospital admissions, with a 7.2% mortality rate and 1.2% case fatality rate in all age groups (Ministry of Health, unpublished data, 2003). Malaria transmission is driven by *Anopheles arabiensis*, the major vector of malaria in the country.[6,7] Eritrea stands out as a success story alongside Brazil, India, and Vietnam, where the burden of malaria has been successfully reduced[8] through an integrated program involving the implementation of habitat source management, application of larval insecticides, use of insecticide-treated nets (ITNs), and indoor residual spraying using dichloro-diphenyl-trichloroethane (DDT). This positive trend in malaria reduction is further facilitated by the almost predictable short period of malaria transmission coinciding with the short rainy season.[6] The country receives only scanty and highly seasonal rainfall, ranging from 400–650 mm/yr in the highlands to 200–300 mm/yr in the lowlands.[9]

In defining its long-term vector control strategies for the country, Eritrea's Malaria Control Program (MCP) has put renewed interest in larval control as a critical component of the program's integrated vector management policy. The semiarid climatic conditions and the seasonal incidence of malaria make it ideal for implementation of larval control as one of the principal interventions for reducing the burden of malaria in the country. Given the semiarid conditions experienced in the country, with < 3 months of rain per year, mosquito control through larval management remains a feasible option because larval sites are discrete and limited in time and space. Therefore, managing of water-filled harborages that provide sustainable habitats especially in the dry season becomes a viable option in vector management in such dry land ecosystems. These larval management strategy would likely clear "seed populations" that form critical sources of the enormous and rapid increases in the adult population that occur after the onset of the rainy season when aquatic habitats are created.

This study was undertaken to assess the impact of larval (source) control or management in a semiarid ecological system in selected treated and untreated villages in Eritrea. The underlying principle of the larval (source) management plan was to locate, map, monitor larval mosquito production, and implement targeted larval control based on field-collected data.

MATERIALS AND METHODS

Country profile. The country of Eritrea is situated in the horn of Africa. It is bordered by The Sudan to the north and west, Ethiopia to the south, Djibouti on the southeast, and the Red Sea to the east. The country is divided into six administrative regions referred to as zones and has a total of 56 subzones with ~1,500 villages. The estimated population is ~3.5 million, with ~10% of the population being urban. It has an area of ~124,000 km^2, including the Dahlak Archipelago and the islands in the Red Sea. The average rainfall ranges from 400 to 650 mm/yr in the highlands and from 200 to 300

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mm/yr in the lowlands. Rainfall is highly seasonal in the country. In the central highlands and the western lowlands, the rainy season falls between July to September, and from October to April in the coastal plains. Daytime temperature ranges from 16.3°C to > 40°C in different parts of the country. *An. arabiensis* is the major vector of malaria, and recent studies have shown that it predominates in aquatic habitats in the country, whereas other species, *An. cinereus*, *An. pretoriensis*, *An. d'thali*, *An. funestus*, *An. squamosus*, *An. adenensis,* and *An. demeilloni*, comprise only a very small proportion.[6,9]

Study sites. The study was conducted in two villages in each of four of six zones (provinces) in Eritrea: Anseba zone (western escarpments, 1,600 m above sea level), Gash-Barka zone (western lowlands, 570 m), Debub zone (highlands, 1,540 m), and North Red Sea (NRS) zone (eastern escarpment, 295 m). The four zones were chosen based on previous malaria morbidity data and the presence and abundance of anopheline mosquitoes based on the countrywide vector distribution survey.[6,7] The study villages in each zone were chosen based on similarities in ecology, human population densities, house types, and accessibility. In the highlands, the houses in the sampled villages are predominantly stone-walled with tin roofs (76–81%), with a few having mud walls and grass thatch (Agudo, 19–24%). In the western lowlands, 91% of the houses in the sampled villages are mud-walled with a grass thatch (Agudo). In the eastern escarpments the houses in the villages sampled have walls made of stones or cement blocks (34%), mud (16%), and mats (46%), with either tin or thatch roofs in equal proportion. The population density in the sampled villages in the highlands, western lowlands, and the eastern escarpment was similar (four to five persons per household). One of the villages selected was randomly designated as the treated village and the other as untreated or control village. Both villages were treated in the same manner in terms of mapping of larval sites, monitoring larval productivity, and adult surveillance. Only in the treated village was larval control implemented using commercial granular formulations of *Bacillus thuringiensis israelinsis* (Bti), *B. sphaericus* (Bsph), and Temephos 50% EC on a rotational basis or by source elimination through environmental management. Other malaria control practices such as use of bed nets or clinical interventions were not altered in any of the selected villages. The paired village design was used with the key assumption that the level of implementation or changes in the other interventions between the treated and untreated village was the same over the 24-month study period and that larval control had no drastic effect on the implementation of the other control interventions applied between study villages.

Larval habitat mapping and management plan. At each of the study sites, an area of ~0.5–1 km around the perimeter of the village was divided into workable sections based on the geography, size, and the number of potential larval habitats. Two types of maps were developed: the village operational map and section map. The village map showed the extent/boundaries of the study village showing key landmarks and broad location of the sections and larval habitats (Figure 1). The section maps included in great detail location and type of all larval habitats found within the predetermined section boundaries. This map also included major landmarks, such as roads, wells, and clusters of houses. Each site was inspected for the presence of new larval habitats and presence of mosquito larvae weekly for the duration of the study (24 months). All new larval habitats were added to the section map and given unique identifiers. If at some time the size of the section became too large to manage (numerous larval habitats present), the section was divided into smaller workable subsections. A larval habitat database was developed showing both temporal and spatial distributions and habitat productivity.

Environmental management. Community mobilization and awareness campaigns through village meetings were organized by Village Health Agents (VHAs) and the local administration in each of the treated study villages. Community participation in environmental management activities such as filling and draining of breeding sites was organized once weekly over the period of the study. Rain pools, puddles at water supply points, and some stream bed pools were either filled or drained. A record of habitats eliminated, filled, or drained was kept and entered in the habitat data base.

Larvicidal application. Granular formulation of Bti serotype H-14 (200 ITU/mg, VectoBac G) and Bsph serotype H5a5b, strain 2362 (670 Bs ITU/mg, VectoLex CG) were applied at the label application rates to positive larval habitats that were not amenable to environmental management in the treatment sites whenever such sites were available based on the weekly surveillance. Both larvicides were supplied by Valent BioSciences (Chicago, IL). Temephos (Abate 50% EC., 500 g AI/L) was also used. The larvicides were applied at label rates as follows: VectoBac G, 11.2 kg/ha; VectoLex CG, 22.4 kg/ha; Abate, 112 mL/ha.[10] The three larvicide types were used in rotation. Calibration of Maruyama granular spreader was made for 5/8 Mesh VectoBac granules and the 10/14 Mesh VectoLex CG granules. Clean Hudson Liquid Sprayers (H.D. Hudson Manufacturing, Chicago, IL) were used for the application of temephos.

Larval and adult mosquito sampling. Mosquito larvae and pupae were sampled using standard dipping techniques and 10–20 dips taken in each larval habitat using a standard mosquito dipper (350 mL). All larval samples were passed through a 100 mesh sieve and placed with water into labeled whirl bags and returned to the laboratory for further processing. CDC Miniature light traps (LTs) were used to assess the densities of adult mosquito populations to establish the temporal distribution and density. The light trap collections were also used to estimate the impact of larval control efforts on adult vector populations. At each study village, 12 light traps were used (6 treated and 6 untreated) and operated for 12 hours from dusk to dawn on 2 consecutive days every week for the period of the study. The LTs were placed in the following locations: center of the village (1 LT inside + 1 LT outside); periphery of village (1 LT inside + 1 LT outside); edge of study village away from houses but within the mapped perimeter (1 LT outside); and outside the mapped perimeter of the pilot village (1 LT outside). Indoor light traps were placed in rooms where people slept. All family members in the house were required to spend the night under untreated mosquito nets. Outdoor light traps were placed near animal shelters and in locations away from direct sunlight and windy locations. Adult mosquito collections were identified to species based on morphologic characters.

Statistical analysis. Variation in larval and adult densities between treated and untreated villages was analyzed using one-way ANOVA test. Larval densities were expressed as number of larvae per 10 dips because the numbers of larvae

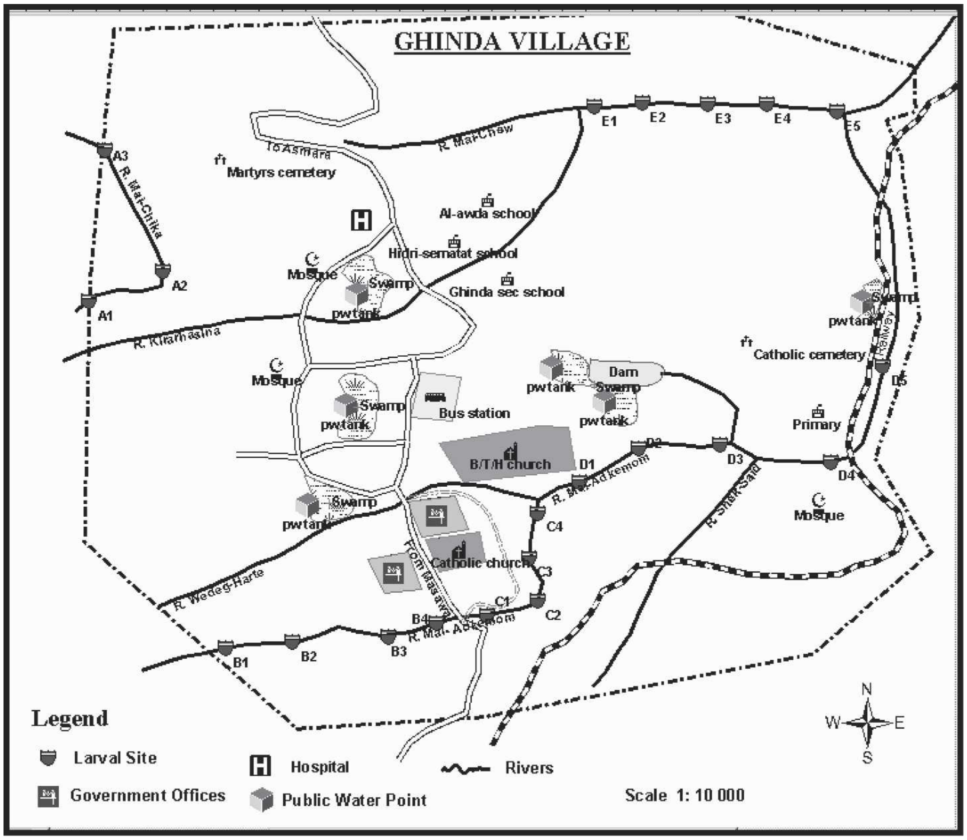

FIGURE 1. Village larval operational map in one of the study sites in Ghinda, North Red Sea, Eritrea. Larval site (A1, B1, C1, D1, etc): represents the center of a section of the river of distance between 20 and 40 m designated as a single habitat for the stream bed pools; the rivers in this site are all seasonal.

sampled was low. Correlation analysis was used to assess the relationship between larval densities and rainfall, and similarly, for assessing the association between larval and adult emergent densities. Log-transformed values ($\log_{10}n + 1$) of larval counts were used in the statistical analysis to normalize the data. Data analysis was performed using the SPSS version 11.5 statistical package.

RESULTS

Larval habitat diversity and productivity. The different types of aquatic habitats encountered in the study sites included canals, rain pools, streambed pools, drainage channels at water supply points, wells, swamps, dams, and ponds. For example, in the Gash-Barka zone alone, larval development was maintained in at least five different larval habitats: puddles associated with streams, rain pools, drainage canals, wells, and drainage channels at communal water supply points. *An. arabiensis* larvae were found abundantly in streambed pools, wells, and dams in the Anseba zone, whereas in Debub, up to five larval habitat types were present, although many except the stream bed pools were of low significance. In the NRS zone, seven different habitats were encountered but yielded few anopheline larvae. The importance of each larval habitat with regard to presence, persistence, and productivity was variable between sites. While canals and wells were the most productive in the Gash Barka zone, contributing 30% (N = 4,284) and 38.9% (N = 5,571) of the total *An. arabiensis* larvae collected, the stream bed pools were the most preferred larval habitat in the NRS (93.3%, N = 15,547), Anseba (99%, N = 82,443), and Debub (96.6%, N = 14,755) zones.

Although the density of the anopheline larvae was low in streambed pools in the Gash Barka zone, they were positive 30.8% of the times sampled. Canals were the highest in this zone with 63.2% positive samples. The proportion of times the stream bed pools were positive for the anopheline larvae in the Anseba (50.8%), Debub (49.2%), and NRS (25.9%) zones were indicative of their role in adult *An. arabiensis* productivity in this semiarid ecosystem. The mean larval density over the 24-month sampling effort differed significantly between sites (F = 21.648, df = 1,166, $P < 0.001$). The Anseba zone recorded the highest anopheline density with 19.6 larvae/10 dips, followed by the Gash Barka (6.2 larvae/10 dips), NRS (3.8 larvae/10 dips), and Debub zones (2.1 larvae/10 dips). The relative importance and diversity of the different larval habitats in the treated and untreated sites with regard to larval presence and *An. arabiensis* productivity is shown in Tables 1 (untreated sites) and 2 (treated sites).

Seasonal productivity patterns of larval habitats. *Anopheles arabiensis* larval production occurred year round in all the study sites, although at a low level during specific times over the study period (Table 3). Larval abundance increased during the wet season and decreased in the dry season. The stream bed pools were the most productive sites, being positive for larvae throughout the year in the high altitudinal sites

TABLE 1

Anopheles arabiensis larval densities in different larval habitats over a 24-month sampling period in the untreated study sites in Eritrea

	Untreated sites											
	Gash Barka			Anseba			Debub			NRS		
Habitat type	No. habitats	Mean *An.* density*	Percent habitat positive	No. habitats	Mean *An.* density	Percent habitat positive	No. habitats	Mean *An.* density	Percent habitat positive	No. habitats	Mean *An.* density	Percent habitat positive
Streambed pools	2	9.9	20.1	21	32.2	61.2	8	11.9	60.8	14	16.8	53.8
Canals	8	28.9	72.6	–	–	–	–	–	–	–	–	
Rain pools	44	4.8	21.1	–	–	–	–	–	–	–	–	–
Water supply	7	5.6	15.1	–	–	–	3	4.2	33.3	–	–	–
Well	2	31.9	66.7	4	27	6.7	39	0.1	1.5	–	–	–
Pond	–	–	–	–	–	–	2	1.7	11.1	–	–	–
Dam	–	–	–	1	0.4	100	3	1.6	7.7	–	–	–
Swamp	–	–	–	–	–	–	–	–	–	–	–	–

* Larval density expressed as number of larvae per 10 dips.

and the eastern escarpments with the exception of the western lowlands. In the Anseba zone, stream bed pools were productive throughout the year (range: 9.8–46.3 larvae/10 dips), with peak productivity falling between September and February. Similarly, the peak productivity for this habitat was between September and February in the Debub zone (range: 0.6–26.5 larvae/10 dips). In the NRS zone, the stream bed pools were also productive throughout the year (range: 0.5–11.4 larvae/dip), with peak activity in March (11.4 larvae/10 dips). In the Gash Barka zone, there was sustained production in streambed pools between September and October. Rain pools and canals were most abundant during the wet season, being only second to the stream bed pools as measured by the duration of productivity.

The significance of the other larval habitats (dams, swamps, ponds) was only sporadic, because positive larval activity was recorded only a few times over the 24 months of the study. For example, the dams were positive only once in Anseba (December: 27 larvae/10 dips) and Debub (August: 2.6 larvae/10 dips). The swamp was productive only in September in the NRS zone (0.6 larvae/10 dips), whereas the ponds were positive only in August (1.1 larvae/dip) in the Debub zone. During the dry season, which lasts > 9 months, larvae were collected mostly in drainage channels at communal water supply points.

Larval densities and control interventions. Larval management through weekly surveillance and application of *Bacillus thuringiensis israelensis*, *B. sphaericus,* and temephos or source reduction, when appropriate, reduced the larval densities drastically in the treated villages compared with the untreated villages over the study period (Figure 2). The mean anopheline larval density recorded in Anseba was 3.168 ± 0.114 and 0.869 ± 0.04 larvae per dip for the untreated and treated villages, respectively. Anopheline larval density in both sampling phases was significantly lower in the treated village compared with the untreated village (F = 394.9, df = 1,4207, $P < 0.001$). Similarly, larval densities were significantly lower in the treated village compared with the untreated village over the two phases of the study in the Debub zone (F = 110.2, df = 1,3372, $P < 0.001$); the Gash Barka zone (F = 52.9, df = 1,1153), and the NRS zone (F = 408.6, df = 1,2201, $P < 0.001$). Overall, the data indicated significant reduction in larval densities by month in the treated sites compared with the control (untreated) sites over the 24 months of the study (Figure 3).

Adult densities and control interventions. Light traps were operated in the treated and untreated villages over 24 months, concurrent with larval surveillance and control. Overall, it was observed that *An. arabiensis* adult densities were significantly lower in the treated villages compared with the untreated villages in both phases of the study (Figure 2). In the Debub zone, low densities of adult *An. arabiensis* mosquitoes were collected in the treated village compared with the untreated site (F = 4.34, df = 1,1353, P = 0.037). Similar trends were observed in the Gash Barka zone (F = 125.36, df = 1,1521, $P < 0.001$), the NRS zone (F = 29.18, df =

TABLE 2

Anopheles arabiensis larval densities in different larval habitats over a 24-month sampling period in the treated study sites in Eritrea

	Treated sites											
	Gash Barka			Anseba			Debub			NRS		
Habitat type	No. habitats	Mean *An.* density*	Percent habitat positive	No. habitats	Mean *An.* density	Percent habitat positive	No. habitats	Mean *An.* density	Percent habitat positive	No. habitats	Mean *An.* density	Percent habitat positive
Streambed	5	3.1	37.5	24	8.6	40.9	7	3.7	32.2	55	3.5	18.9
Canals	3	2.8	14.3	–	–	–	–	–	–	–	–	–
Rain pools	69	4.0	16.9	–	–	–	–	–	–	38	0.5	5.4
Water supply	9	1.1	7.4	–	–	–	2	0	0	31	0.5	2.1
Well	6	3.5	8.8	–	–	6.7	47	0.2	2.2	18	0.3	2.5
Pond	–	–	–	–	–	–	3	0	0	–	–	–
Dam	–	–	–	–	–	–	2	0	0	2	0	0
Swamp	–	–	–	–	–	–	–	–	–	1	0.1	2.0

* Larval density expressed as number of larvae per 10 dips.

TABLE 3

Seasonal variation in *An. arabiensis* larval productivity in diverse larval habitats in four study sites over the 24-month study

Location	Habitat category	No. habitats*	Larval density (number of larvae per 10 dips)												Mean ± SE
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Anseba	Streambed pool	21 (24)	10.4	9.8	5.1	4.1	4.2	1.6	2.2	0.1	13.6	34.9	46.3	31.9	13.7 ± 4.43
	Well	4 (0)	–	–	–	–	0.0	0.0	1.1	–	–	–	–	–	0.4 ± 0.36
	Dam	1 (0)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	27.0	2.3 ± 2.25
Gash Barka	Streambed pool	2 (5)	–	–	–	–	–	–	–	0.0	9.9	4.1	–	–	4.7 ± 2.87
	Canal	8 (3)	21.4	–	–	–	–	–	–	30.4	26.6	26.3	12.7	37.2	25.8 ± 3.38
	Temporary pools	44 (69)	0.0	–	–	–	–	–	–	2.7	6.7	0.0	0.0	0.0	1.6 ± 1.12
	Water supply	7 (9)	0.8	0.4	0.0	0.0	0.0	0.1	0.1	5.5	12.4	18.0	7.8	0.0	3.6 ± 1.74
	Well	2 (6)	–	14.3	13.8	14.8	0.0	1.0	31.4	0.0	0.0	–	–	–	9.4 ± 3.99
Debub	Streambed pool	8 (7)	4.7	6.1	5.8	2.8	0.6	0.6	0.0	0.0	12.4	26.5	15.6	8.8	6.9 ± 3.46
	Dam	3 (2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.6	0.0	0.0	0.0	0.2 ± 0.22
	Pond	2 (3)	–	–	–	–	–	–	0.0	1.1	0.0	–	–	–	0.4 ± 0.36
	Water supply	3 (4)	–	–	–	–	–	–	–	2.4	2.9	0.0	–	–	2.7 ± 0.21
	Well	39 (47)	0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.6	0.2	0.4	0.1	0.0	0.2 ± 0.05
NRS	Streambed pool	14 (55)	4.7	7.7	11.4	5.9	5.2	7.1	0.8	0.5	8.3	4.1	10.8	6.3	6.1 ± 0.97
	Dam	0 (2)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Temporary pools	0 (38)	0.5	0.0	0.0	1.1	0.0	2.9	0.0	0.0	0.0	0.7	0.5	0.4	0.5 ± 0.24
	Swamp	0 (1)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.1 ± 0.05
	Water supply	0 (31)	0.0	2.2	0.0	3.0	0.0	0.0	0.0	0.0	0.5	0.0	0.3	0.4	0.5 ± 0.29
	Well	0 (18)	0.0	0.0	0.2	0.8	0.0	0.0	0.0	0.0	0.0	0.7	0.9	0.0	0.2 ± 0.11

* Number of different larval habitats in untreated and treated (in parenthesis) sites. Minus sign denotes that the habitat was absent, therefore, no sampling done. Larval density expressed as number of larvae per 10 dips.

1,1270, $P < 0.001$), and the Anseba zone in Year 2 of the study ($F = 7.45$, df = 1,1126, $P = 0.006$), indicating the role of habitat management and larviding in keeping the population of malaria vectors low (Figure 4). An unexpected result was, however, observed in Year 1 in the Anseba zone, when high densities of adult anophelines were recorded in the treated compared with the untreated site.

The study further showed that increased number of positive larval habitats was directly associated with rainfall (~1–2 weeks), with peak numbers of adults occurring 2–3 weeks after rain. Anopheline larval densities were negatively correlated with rainfall ($r = -0.288$, $P = 0.047$). Systematic surveillance and subsequent management of breeding habitats in the treated site managed to keep both *Anopheles* larvae and adult densities low.

DISCUSSION

Although larval control is an important component of the malaria control program in Eritrea, little is known about larval habitat productivity and the impact of this strategy on vector population and malaria transmission. Knowledge of larval habitats, their distribution, and productivity is important in planning and implementing larval control strategies effectively in such semiarid ecosystems. The semiarid conditions provide an excellent scenario where larval control would have a critical impact because larval habitats are discrete and can easily be targeted.

Eight larval habitat types were identified in this study, and the productivity of each habitat for *An. arabiensis* larvae, the predominant anopheline species and only vector of malaria in the country,[6,9] was variable in space and time. This variability in larval densities in the different habitats would also be explained by the spatio-temporal differences in food resource and predation pressure in the different habitats and the complex interaction between habitat factors such as water turbidity, depth, temperature, salinity, and dissolved oxygen.[11,12] *An. arabiensis* has been associated with river and irrigation systems in drier the parts of the continent,[13,14] and the species breeds in small, temporary habitats with algae such as foot prints, rain pools, puddles, tire tracks, and garden wells.[15,16]

Larval habitat abundance and productivity tended to track

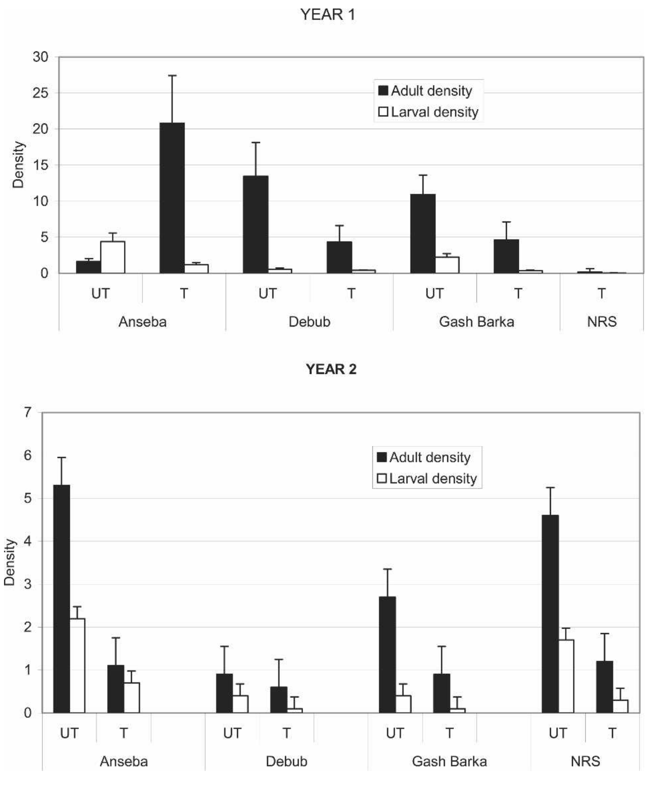

FIGURE 2. Comparison between treated (T) and untreated (UT) villages with reference to *An. arabiensis* larval and adult densities (±SE). Adult densities are estimated as number of *Anopheles* females per light trap night. Larval density is expressed as number of larvae per 10 dips.

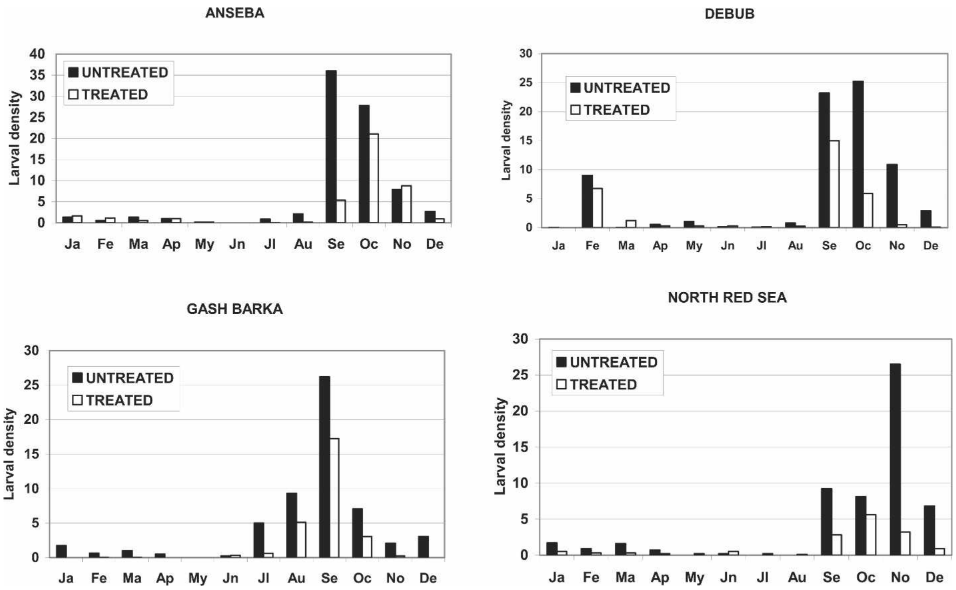

FIGURE 3. *Anopheles arabiensis* larval densities from collections between treated and untreated study villages in Eritrea. Treated (T) denotes larvicides and habitat management applied. Larval density expressed as number of larvae per 10 dips.

rainfall patterns in the study sites. The population of anopheline larvae was high after the rains, but peak densities were achieved at different times. The site-to-site variation could be attributed to the different rainfall patterns experienced in the four zones. Studies have shown that populations of *An. arabiensis* usually increase as the rains recede.[17] The variation in the level of persistence or permanency of larval habitats may also have contributed to the temporal patterns in habitat productivity in this study. While some larval habitat types were important in one zone, they were either absent or of only low significance in another zone at different times of the year, a situation that could be linked to temporal changes in habitat characteristics that may affect larval development.

Our results on the larval management program display the relative significance of each aquatic habitat on a temporal scale as a prerequisite for targeted control by stratifying aquatic habitats with regard to productivity. Much of the larval production goes on in the streambed pools and environmental management through participation of communities would be a rational choice. Despite the semiarid scenario experienced in the study sites, our data show that larval production still persists year-round, although at a generally low level during the dry season in stream bed pools and at water supply points. Studies in Tanzania have similarly shown that focal populations of malaria vectors occur during dry season associated with specific habitats along river valleys.[18] This raises the critical consideration of dry season intervention in the semiarid ecosystems that was tested in this study. It was observed that, during the dry season, larval habitats became

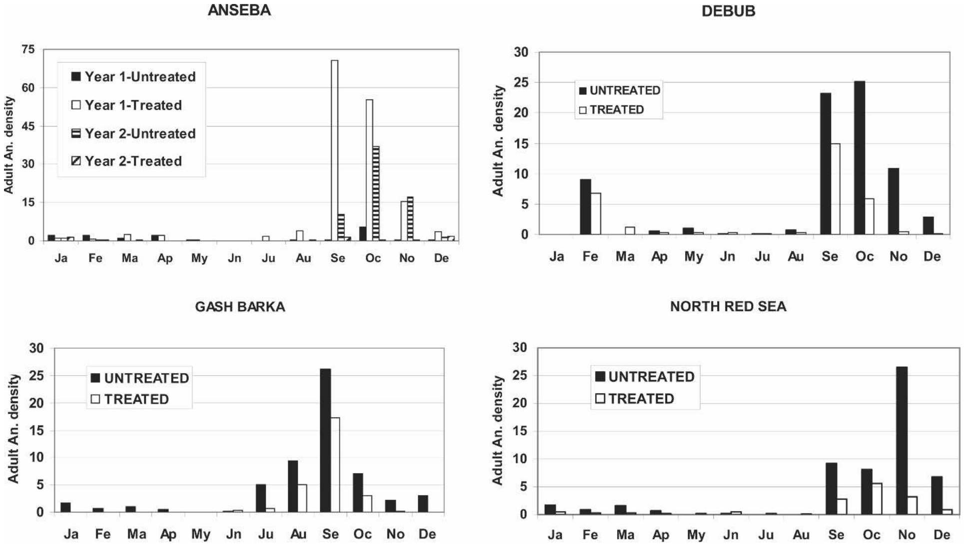

FIGURE 4. *Anopheles arabiensis* adult densities from CDC light trap collections in the treated and untreated study villages in Eritrea. *An. arabiensis* density is expressed as number of mosquitoes per light trap.

discrete, few, and easy to manage with vector production maintained in drainage channels at water supply points and streambed pools. Managing dry season larval sites would have the added impact of limiting adult density during the immediate post-rain period when the number of suitable aquatic habitats increases numerically. Continued pressure through year-round mosquito control will reduce and eventually eliminate dry season anopheline production.

The data gained in the four study sites show that larval management significantly reduced *An. arabiensis* adult populations in the study sites. This provides evidence that anopheline larval control is a potentially important strategy in malaria vector management. Evidence from previous work has shown that source reduction through management of larval habitats was important in malaria eradication efforts in the United States, Italy, and Israel.[19] The suppression and even eradication of malaria from vast areas has been attributed to effective large-scale programs that targeted immature *Anopheles* species or reduced the amount of suitable habitats in proximity to vulnerable human populations.[20] Appropriate management of larval habitats, especially during the dry season, may help suppress vector densities, and consequently, malaria transmission.

While addressing larval control, it was evident from our study that the geographic boundaries of a larval control program are critical for reducing the adult population. The dispersion and movement of adult females must be put into consideration because both major and minor larval breeding sites can make a difference in the abundance of the emerging adult population. In this study, larval surveillance was conducted within a 0.5- to 1-km radius around the study villages. There is possibility of active recruitment of adult anophelines into the study villages from larval habitats outside this area, considering that anophelines may fly up to 2 km away from their aquatic habitats.[21] This can be circumvented through a combination of larval site and adult surveillance both within and outside of the boundaries of the mosquito management area. Surveillance outside of the management boundaries is critical during the post-rain period, because most of the larval producing sites can be located and evaluated for adult productivity at this time.

The data further show that critical surveillance and subsequent management of larval habitats is the prerequisite for effective mosquito control in similar areas in sub-Saharan Africa. Larval habitat surveillance should go beyond the predominant larval habitats into looking for other larval sites that are critical in production of mosquito larvae. Because the larval control program was based on a continuous process of expansion by seeking new larval sites, our studies form a basis for integration of larval control in other sites with similar ecologies. By designing this project with a treated and untreated village with similar ecological conditions, the comparative analysis showed distinct differences between the sites, hence showing the spatial and temporal impact of larval management on the patterns of adult emergence and abundance. This study showed that larval management is a feasible vector control option and an expanded program could play a significant role in reducing malaria in Eritrea and Africa, especially when used in a multi-tactic integrated malaria management program that addresses both the mosquito (vector) and *Plasmodium* (parasite). It is therefore clear that, in semiarid ecosystems, effective vector control relying on active monitoring and subsequent application of anti-larval measures throughout the year to targeted sites would substantially reduce malaria transmission.

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