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Case study

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CASE STUDY

Malaria outbreak in Riaba district, Bioko Island, in 2019 – Lessons learnt

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Abstract

A sudden surge in malaria cases was observed in the district of Riaba, Bioko Island, at the start of 2019. Between January and April, confirmed malaria cases and malaria incidence increased about three-fold compared to the same period in 2018. Concurrently, anopheline human biting rate (HBR) increased 2.1-fold. During the outbreak, 82.2% of the district population was tested for malaria with a rapid diagnostic test and 37.2% were found positive and treated according to national guidelines. Vector control interventions, including indoor residual spraying and larval source management were scaled-up in response. After the interventions, the number of confirmed cases decreased by 70% and the overall parasite prevalence in the communities by 43.8%. Observed prevalence in a follow up malaria indicator survey, however, was significantly higher than elsewhere on the island and higher than in previous years. There was no significant reduction in HBR, which remained high for the rest of the year. The surge was attributed to various factors, chiefly increased rainfall and a large number of anthropogenic anopheline breeding sites created by construction works. This case study illustrates the need for sustained vector control interventions and multi-sector participation, particularly in malaria control settings with persistently high receptivity to local transmission.

Keywords: malaria transmission; outbreak; vector control; malaria interventions; breeding sites; Bioko Island

Introduction

Bioko is the largest island of Equatorial Guinea. Administratively, it is divided into four districts: Malabo, Baney, Luba and Riaba (Figure 1). The island has a population of about 270 thousand people, mostly concentrated in Malabo, the main urban centre and country capital. The rural district of Riaba, in the Southeast, has a resident population estimated at 2,560 inhabitants (unpublished data from a household and health population census conducted in 2018).

In 2004, the Bioko Island Malaria Control Project (BIMCP; now the Bioko Island Malaria Elimination Project – BIMEP) was established in order to scale-up malaria interventions on the island. The BIMEP periodically distributes long lasting insecticidal nets (LLINs) through mass-campaigns, implements annual indoor residual spraying (IRS) rounds, conducts annual malaria indicator surveys (MIS) and runs continuous entomological monitoring in sentinel sites across the island. In collaboration with the National Malaria Control Programme (NMCP), the BIMEP provides malaria case management training and supervision as well as anti-malarial drugs and diagnostic tools free of charge in all public health facilities on the island. The project has also supported Bioko's health information system (HIS) through the implementation of the District Health Information System 2 (DHIS2) platform for health facility data in the public sector.

Historically, malaria on Bioko Island was hyper to holoendemic, with year round transmission. The suite of malaria interventions implemented by the NMCP/BIMEP have successfully reduced parasite rate (PR) in the two to 14-year-old age group from 45% in 2004 to around 12% in recent years [1]. This downward trend was interrupted in 2019, when PR was measured at 16.6% [2]. Before control, malaria transmission in Riaba district was particularly intense. An entomological survey conducted in that district between 1998 and 1999 estimated an annual entomological inoculation rate (EIR) of 1,030 infected bites per person per year (ib/p/y), with 242 ib/p/y for *Anopheles gambiae* s.s. and 788 ib/p/y for *An. funestus* [3], an estimate that far exceeded most EIR recorded elsewhere across Sub-Saharan Africa [3, 4, 5]. In 2009, entomological monitoring in Riaba measured an annual EIR of 311 ib/p/y, exclusively due to *An. gambiae* s.s. and *An. melas*; *An. funestus* was not detected in that study and was soon after declared eliminated on the island [6]. In 2018, EIR estimates from one of the entomological monitoring sites in Riaba district (Patio Balboa) were 14.8 ib/p/y (unpublished data).

In this case study, a recent malaria outbreak that developed at the beginning of 2019 in Riaba district is described. The response from the NMCP/BIMEP teams as well as the outcome of this response are documented. Finally, the most plausible drivers for this unexpected outbreak as well as some of the major challenges for malaria control and elimination on Bioko Island are discussed.

The outbreak

In the first third of 2019, records from the Riaba district hospital revealed a 3.8-fold increase in the number of confirmed malaria cases relative to the same period in 2018 (Figure 2A). Health information system data revealed 874 confirmed malaria cases between January and April and a corresponding increase in the ratio of confirmed malaria cases to all outpatient consultations for the period, with mean of 0.55, ranging from 0.38 in February to 0.76 in April. This was significantly higher than the same ratio observed in Riaba for the same period in the preceding four years (mean 0.19, IQR 0.14 - 0.26) as well as between 2015 and 2019 in the other three districts (mean 0.06, IQR 0.04 - 0.08; Figure 2A). The peak in malaria cases was reflected in an incidence of more than 300 cases per 1,000 people in children between 2 and 17 years old in April 2019, significantly higher than any record since 2015. Malaria incidence in adults was also significantly higher, with 155 cases/1,000 in those aged between 18 and 50 years old (Figure 2B).

During concurrent entomological monitoring in the sentinel sites in Riaba, Patio Balboa and Patio López, significant increases in human biting rates (HBR) were particularly notorious in the former. At each site, respectively, 735 and 344 anopheles mosquitoes were captured indoors and outdoors in March and April 2019. Due to logistical constraints, no human landing catches were performed in January and

February. For comparison, the monthly HBR for the same months were determined at 54.9 and 37.0 bites per person per night (b/p/n) in Patio Balboa, and 31.6 and 11.4 b/p/n in Patio López (Figure 2C). The average HBR in these two months was 10.0 b/p/n for the other ten sentinel sites outside Riaba district. Patio Balboa alone contributed 27.5% of the vectors collected in all 12 sites across Bioko. Species composition in Patio Balboa amongst 541 specimens collected between March and December 2019 consisted of 89.6% *An. coluzzii* (n = 485) and 10.4% *An. melas* (n = 56). *Plasmodium falciparum* sporozoites were found in six *An. coluzzii*, representing a sporozoite rate of 1.2%. No sporozoites were found in *An. melas*. In Patio López, *An. melas* represented the majority (62.8%) of 299 specimens collected between March and December 2019. The rest (37.2%) were identified as *An. coluzzii*. No sporozoites were detected in these samples.

The response

In response to the outbreak, the NMCP/BIMEP teams took action reinforcing community sensitisation, malaria diagnosis and treatment, and vector control. First, the communications component mobilized the population in Riaba through community leaders to raise malaria prevention awareness and to promote acceptance of case detection, treatment and IRS. Second, the NMCP/BIMEP engaged 13 community health workers to test the population in Riaba for malaria using rapid diagnostic tests (RDTs; CareStart Malaria, AccessBio). Between 22 and 30 April, a total of 2,105 people (82.2% of the district population) were tested with an RDT, of whom 783 were positive, resulting in an estimated PR of 37.2% (95CI 35.1 - 39.3%); this was significantly higher than prevalence estimates in Riaba district measured during MIS in the four previous years (Figure 3). Investigation by age groups revealed that prevalence was higher in children, with 48.1% (95CI 43.6 - 52.7%) of those between 2 and 10 years old and 56.1% (95CI 46.8 - 65.0%) of those between 10 and 14 years old found infected (Figure 4). All individuals who tested positive were given treatment with artesunate-amodiaquine, according to national treatment guidelines at the time.

Between 22 and 27 April 2019, as part of the annual IRS round, 757 of 871 inhabited households in the district were sprayed, achieving a coverage of 86.9% and effectively providing protection to the entire population of the district. Finally, the entomology team was deployed to search for and treat larval sources across the district. Their main finding was a substantial number of breeding sites created by major construction developments that had established recently (Figure 5). A total of 1,241 breeding sites were mapped during 2019 using global positioning systems (GPS) enabled mobile devices running ArcGIS Collector (Esri, Inc.). Of these, 1,119 (90.2%) were described as anthropogenic: 122 created directly by the construction sites and 997 corresponding to tyre tracks related to these infrastructure development projects. Amongst the mapped anthropogenic breeding sites, 37.8% were found positive for anopheline immature stages upon evaluation. Considerably more anthropogenic breeding habitats were found, but mapping, evaluating and treating all of them proved impossible as this effort overwhelmed the manpower capacity available. Notably, observed malaria prevalence during the cross-sectional survey was higher in communities around these larval habitats (Figures 6 and 7).

The outcome

Following interventions, the incidence of malaria during May 2019 dropped to 54.7 and 88.0 cases per 1,000 inhabitants in the 2-12 and 3-17 years age-groups, and the mean ratio of malaria consultations to all consultations for the remainder of the year was 0.23 (range 0.16 - 0.29; Figures 2A and 2B). The HBR at Patio Balboa, however, remained high for the rest of the year, with a mean of 40.8 b/p/n (range 33.3 - 46.5 b/p/n) between May and December 2019. In contrast, mean HBR at Patio López was 7.6 b/p/n (range 0.4 - 23.1 b/p/n) for the same period (Figure 2C).

Between 12 and 18 August 2019, during the annual MIS, 589 people comprising a representative sample of the whole district population were tested with RDT. This survey served as a follow up to the prevalence survey conducted in April 2019, during the outbreak. A total of 123 individuals were found positive, representing a PR of 20.7% (95CI 17.5 - 24.2%; Figure 3), a significant reduction compared to the previous survey. Importantly, however, this estimate proved significantly higher than that for the rest of the island during the same MIS as well as significantly higher than PR estimates from the previous four years, both for Riaba district and for the rest of the island. The age profile of the 2019 MIS PR showed spikes in the 2-10 and 10-14 years age-groups, similar to those observed during the April 2019 survey (Figure 4). It was possible to disaggregate the PR by community, which showed that, despite the overall decrease, this was more noticeable in the North and South of the district, with a cluster of higher prevalence persisting in communities around the area where the breeding habitats associated with construction sites had been identified (Figures 6 and 7).

Conclusions

The sudden increase in malaria morbidity in Riaba district in the first third of 2019 coincided with a significant increase in rainfall patterns and anopheline HBR that were observed across the island (Figure 2). Despite other areas showed an increase in confirmed malaria cases, namely in Luba district and in certain isolated communities on the West of Malabo district, none showed a spike in cases as dramatic as the one observed in Riaba district. The response from the malaria control teams to diagnose and treat positive individuals with anti-malarials was certainly effective and successfully curbed malaria cases by May 2019. Malaria prevalence and HBR, however, remained significantly high, despite vector control interventions (Figures 2 and 3). Persistently higher malaria prevalence in young children (2-10 years old) measured during the 2019 MIS suggested a higher force of infection in Riaba driven by higher vector densities (Figure 4). The increased rainfall observed in 2019, which favoured the availability of breeding habitats, can explain part of the increase in malaria transmission levels observed in Riaba district, but not all.

Notably, major road and real-state development projects had been ongoing in Riaba for some time before the outbreak. Urban development and construction sites can potentially affect local vector ecology and thus require responsible management by sectors outside health care [7]. In fact, the main finding of the entomology teams during the intervention was the substantial number of anthropogenic mosquito breeding habitats created by these projects. These larval habitats were not only numerous but large and presented a significant challenge for LSM activities (Figure 8). Although efforts were made to treat as many of them as possible, there were simply too many habitats spread over large areas, exceeding the manpower available to tackle them. Following the interventions, malaria prevalence decreased in most communities, but higher PR was seemingly clustered in those in the vicinity of the construction sites (Figures 6 and 7). A notable exception was Patio López, where PR measured during the MIS was higher than during the April survey (35.7% vs. 3.3%), though only 14 people were sampled during the MIS at this community; hence, the confidence limits of this estimate were rather wide (95CI 12.8 - 64.9%) and true prevalence may well had been lower. On the other hand, the HBR estimated in Patio López, despite spiking at the beginning of the year alongside HBR from most of the other entomological monitoring sentinel sites, dropped by May 2019 and remained low thereafter. Conversely, the HBR in Patio Balboa remained high despite the interventions, which could be explained by the fact that this site is located in the surroundings of the anthropogenic breeding habits created by construction projects. Though, historically, Patio Balboa has yielded particularly high vector densities, the current alterations to the local ecology may explain the persistently high HBR observed in this location.

Other, more pernicious drivers may have aggravated the outbreak in Riaba district. First, human mobility and parasite importation from mainland Equatorial Guinea, where malaria transmission is significantly more intense [8], have been identified as important contributors to the parasite prevalence observed on Bioko Island [9, 10]. Apart from the generation of vector breeding habitats, the construction sites in Riaba demanded a high influx of migrant workers from mainland, who could have been malaria infected and, therefore, may have increased the local parasite pool. Also, the presence of military camps in Riaba with highly rotating personnel determines a constant flux of people to and from mainland, potentially resulting in higher parasite importation. Second, the limited uptake of interventions by the population despite universal coverage may have also contributed to the problem. Data from annual MIS indicate that LLIN ownership and access constantly decrease from year to year. The last mass distribution campaign on Bioko took place in 2018, six months before the outbreak. During that campaign, LLINs were distributed to virtually all households on the island. LLIN population access (*i.e.* availability of at least one LLIN for every two people) in Riaba, however, was estimated at 75.2% two months after distribution, during the 2018 MIS, and only at 53.5% in 2019 [2]. Moreover, LLIN use, regardless of access, remains sub-optimal with 49.3% and 48.3% of the population surveyed in Riaba in both years reporting to have slept under a LLIN the night before, decreasing the effectiveness of this vector control intervention. Finally, changes in host-seeking behaviour of anopheline vectors as a response to indoor vector control interventions have been observed on the island [11]. In light of increased vector densities, outdoor biting could have amplified transmission.

In 2019, the malaria control strategy of the NMCP/BIMEP was redefined towards the goal of malaria elimination. Given the local vector ecology, however, the island remains highly receptive to malaria. In 2019, EIR in Patio Balboa was estimated at 174.7 ib/p/y (unpublished data), representing a ten-fold increase from the previous year and mostly attributed to significant increases in vector densities. This suggests that, despite the great reductions in transmission intensity across Bioko in general, and in Riaba district in particular, receptivity to malaria in these areas is indeed important. The outbreak in Riaba exposed several vulnerabilities that probably combined to produce the observed surge in malaria clinical cases. It showed that, if epidemiological or ecological conditions were to change or if interventions were relaxed, malaria will come back hard. The former was proven by the observed increase in HBR following rainfall anomalies and the increased availability of vector breeding habitats driven by the presence of large construction projects, and the latter by logistical constraints at the beginning of 2019 that delayed the start of the malaria control activities, consequently weakening the monitoring and response capacities of the NMCP/BIMEP. The need of sustained malaria interventions with an emphasis on vector control cannot be underscored enough in this context, as cannot be the importance of multi-sector participation as an essential component of integrated strategies when it comes to the fight against malaria. This case study is important because it signals the heavy challenges ahead in the difficult path to malaria elimination on Bioko Island.

Abbreviations
MIS: malaria indicator survey; IRS: indoor residual spraying; LLIN: long-lasting insecticidal net; PR: parasite rate; HIS: health information system; HBR: human biting rate; EIR: entomological inoculation rate.

Ethics approval and consent to participate
All surveys conducted on Bioko Island are approved by the ethics committee of the Ministry of Health and Social Welfare of Equatorial Guinea.

Consent for publication
Not applicable.

Availability of data and materials
The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Competing interests
The authors declare that they have no competing interests.

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Author's contributions
C.A.G. conducted analyses, prepared the figures and wrote the first draft of the manuscript. G.F. collected and assembled entomological data. O.T.D conducted the initial analyses. R.M.A., M.R.R. and W.P.P. supervised fieldwork during the interventions. J.M.S., T.A.O.M., D.E.M.E., C.O.E. and L.A.O. undertook and supported field activities. C.R.J. and M.A.S. assembled the rainfall data. M.A.S. conducted analyses and advised on the entomological data. D.L.S. advised on analyses. G.A.G. supervised all the work. All authors contributed to the final draft.

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References

1. Cook J, Hergott D, Phiri W, Rivas MR, Bradley J, Segura L, et al. Trends in parasite prevalence following 13 years of malaria interventions on Bioko island, Equatorial Guinea: 2004–2016. Malaria Journal. 2018;17:62.
2. The Government of Equatorial Guinea, Medical Care Development International (MCDI). The Bioko Island Malaria Elimination Project Annual Malaria Indicator Survey 2019. Medical Care Development International; 2019.
3. Cano J, Berzosa PJ, Roche J, Rubio JM, Moyano E, Guerra-Neira A, et al. Malaria vectors in the Bioko Island (Equatorial Guinea): estimation of vector dynamics and transmission intensities. J Med Entomol. 2004;41(2):158–61.
4. Hay SI, Rogers DJ, Toomer JF, Snow RW. Annual Plasmodium falciparum entomological inoculation rates (EIR) across Africa: literature survey, internet access and review. Transactions of the Royal Society of Tropical Medicine and Hygiene. 2000;94(2):113–127.
5. Okello PE, Van Bortel WIM, Byaruhanga AM, Correwyn A, Roelants P, Talisuna A, et al. Variation in malaria transmission intensity in seven sites throughout Uganda [Journal Article]. The American Journal of Tropical Medicine and Hygiene. 2006;75(2):219–225. Available from: http://www.ajtmh.org/content/journals/10.4269/ajtmh.2006.75.219.
6. Overgaard HJ, Reddy VP, Abaga S, Matias A, Reddy MR, Kulkarni V, et al. Malaria transmission after five years of vector control on Bioko Island, Equatorial Guinea. Parasit Vectors. 2012;5:253.
7. World Health Organization. Larval source management – a supplementary measure for malaria vector control: An operational manual; 2013.
8. Ncogo P, Herrador Z, Romay-Barja M, Garcia-Carrasco E, Nseng G, Berzosa P, et al. Malaria prevalence in Bata district, Equatorial Guinea: a cross-sectional study. Malar J. 2015;14:456.
9. Guerra CA, Kang SY, Citron DT, Hergott DEB, Perry M, Smith J, et al. Human mobility patterns and malaria importation on Bioko Island. Nature Communications. 2019;10(1):2332.
10. Guerra CA, Citron DT, García GA, Smith DL. Characterising malaria connectivity using malaria indicator survey data. Malaria Journal. 2019;18(1):440. Available from: https://doi.org/10.1186/s12936-019-3078-2.
11. Meyers JI, Pathikonda S, Popkin-Hall ZR, Medeiros MC, Fuseini G, Matias A, et al. Increasing outdoor host-seeking in Anopheles gambiae over 6 years of vector control on Bioko Island. Malaria Journal. 2016;15(1):239. Available from: https://doi.org/10.1186/s12936-016-1286-6.

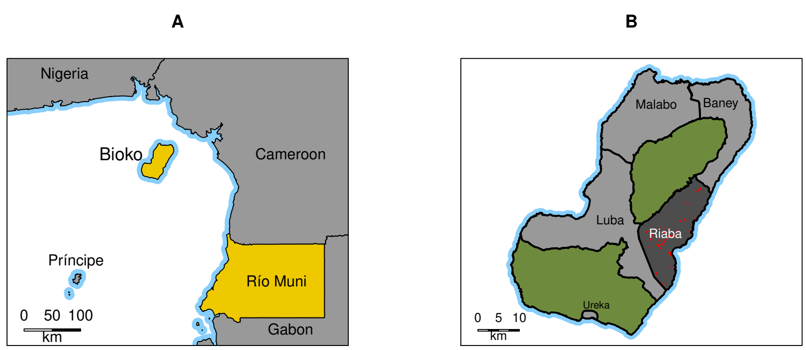


Figure 1 Geographic features of Bioko Island. A. The island is located in the Gulf of Guinea, off the coast of Cameroon. The continental region of Equatorial Guinea (Río Muni) is located to the Southeast. **B.** Administrative divisions of Bioko showing Riaba district in darker grey. The red points indicate communities within the district. The green areas are nature reserves. Ureka is part of Luba district.

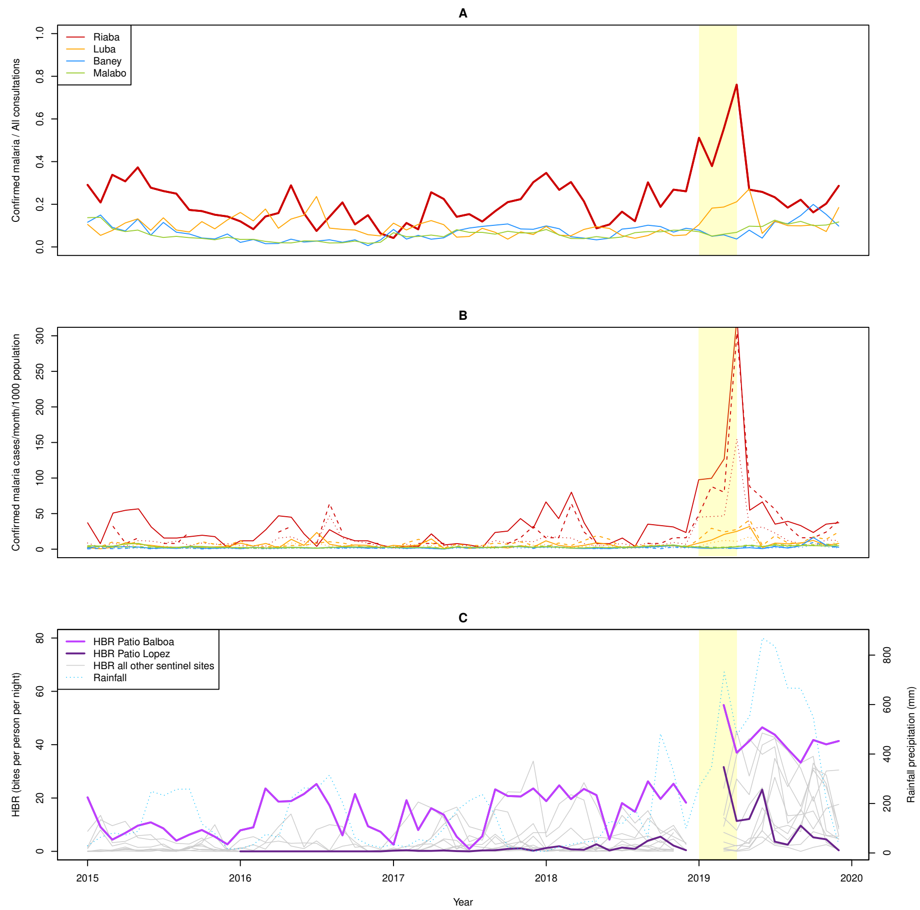


Figure 2 Confirmed malaria cases and HBR on Bioko Island, by district, 2015-2019. The light yellow shade highlights the period January – April 2019. **A.** Ratio of confirmed malaria cases to all outpatient consultations. **B.** Malaria incidence by district and age-group. Solid, dashed and dotted lines represent the 2-12, 3-17 and 18-50 years age groups. **C.** HBR estimates from entomological monitoring sentinel sites and rainfall data for the whole of Bioko Island. Entomological monitoring could not take place in January and February 2019, hence the missing data for these months. Rainfall data were digitised from: https://www.worldweatheronline.com.

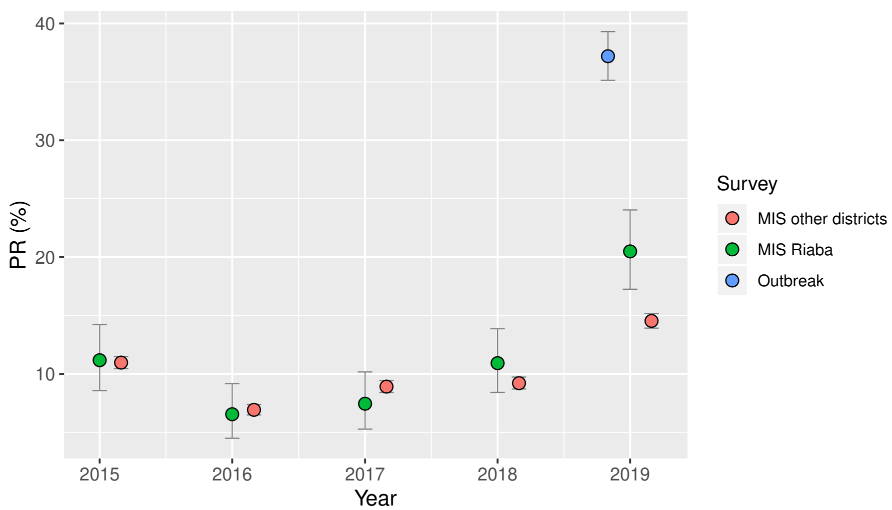


Figure 3 Malaria prevalence estimates from MIS and from the April 2019 survey. Data from MIS were plotted separately for Riaba and for the rest of the island. Error bars illustrate the 95% confidence intervals. Individuals with history of off-island travel in the previous eight weeks were excluded from the MIS to allow for the confounding effects of malaria importation [9].

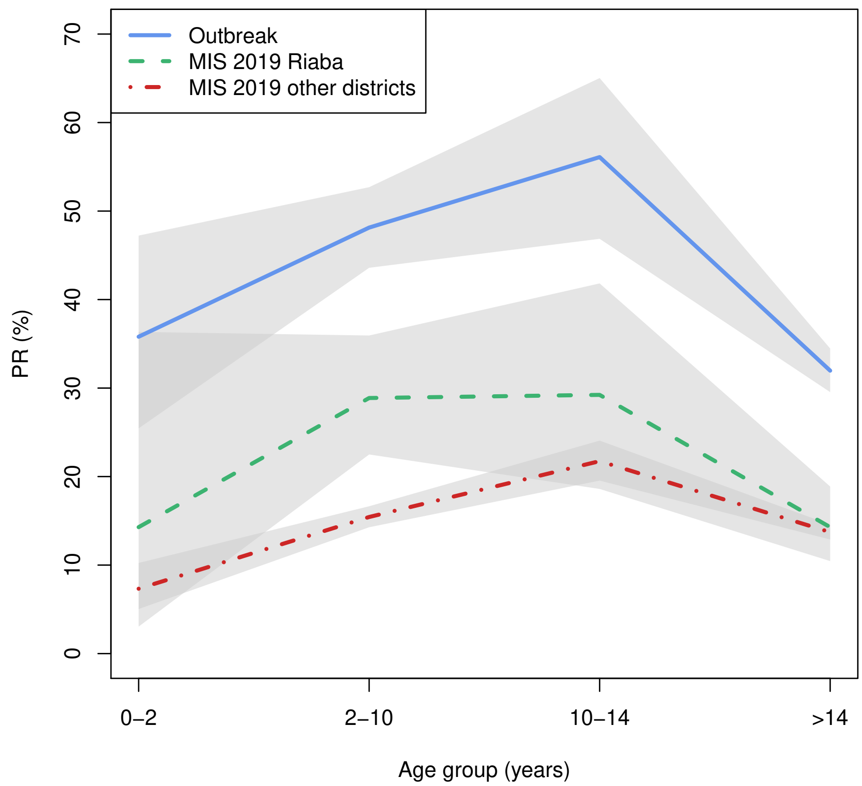


Figure 4 Age profile of malaria prevalence from the 2019 MIS and from the April 2019 survey. The grey polygons illustrate the 95% confidence intervals. Individuals with history of off-island travel in the previous eight weeks were excluded from the MIS to allow for the confounding effects of malaria importation [9].

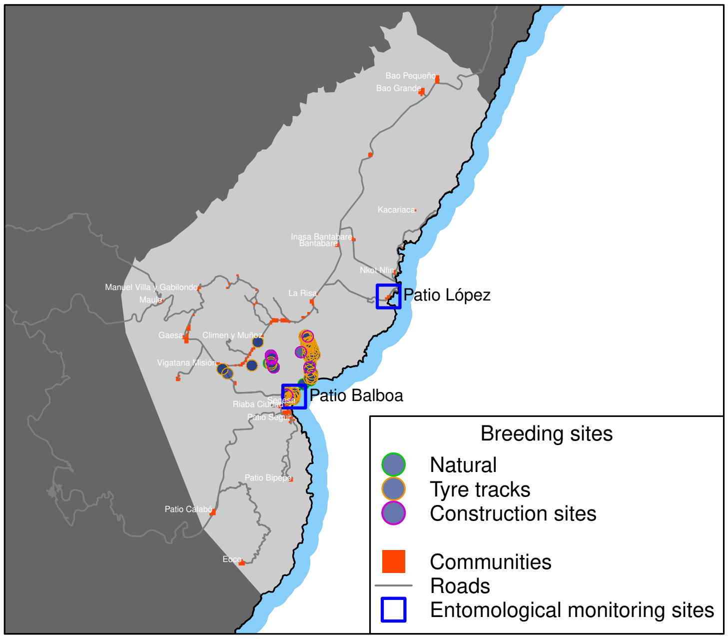


Figure 5 Location of communities and mapped anopheline breeding habitats in Riaba district. Riaba is shaded in lighter grey. Breeding sites are marked according to their type as natural or anthropogenic. Few of those mapped corresponded to the former. Patio López and Patio Balboa are highlighted as they represent sites of longitudinal entomological monitoring.

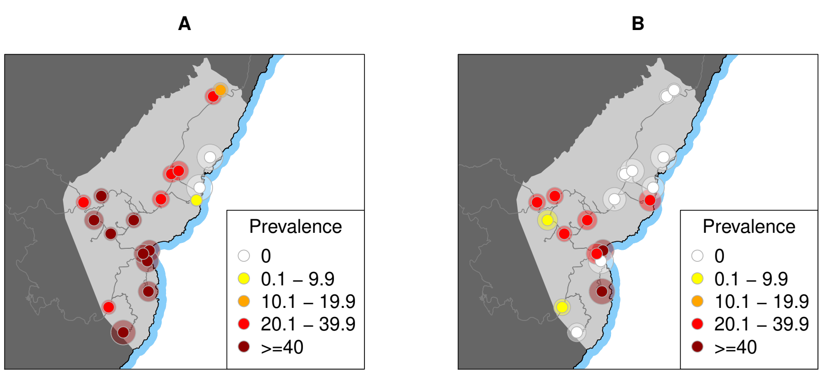


Figure 6 Malaria prevalence estimates by community in Riaba district. Riaba is shaded in lighter grey. **A.** Cross-sectional survey in April 2019. **B.** 2019 MIS. The shaded areas around the mapped points are proportional to the width of the 95% of the confidence intervals of the prevalence estimates.

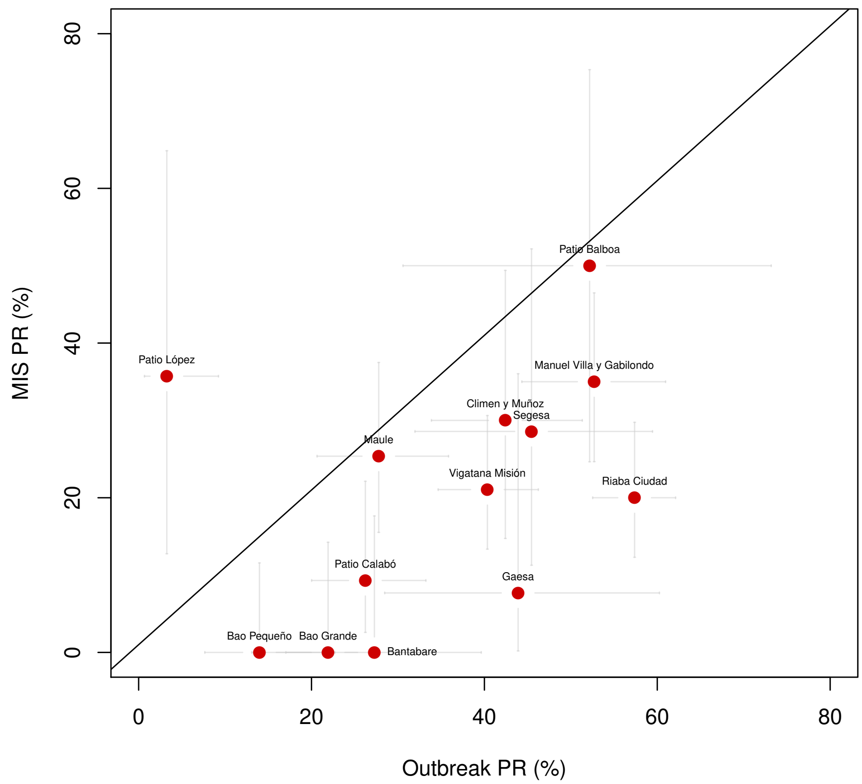
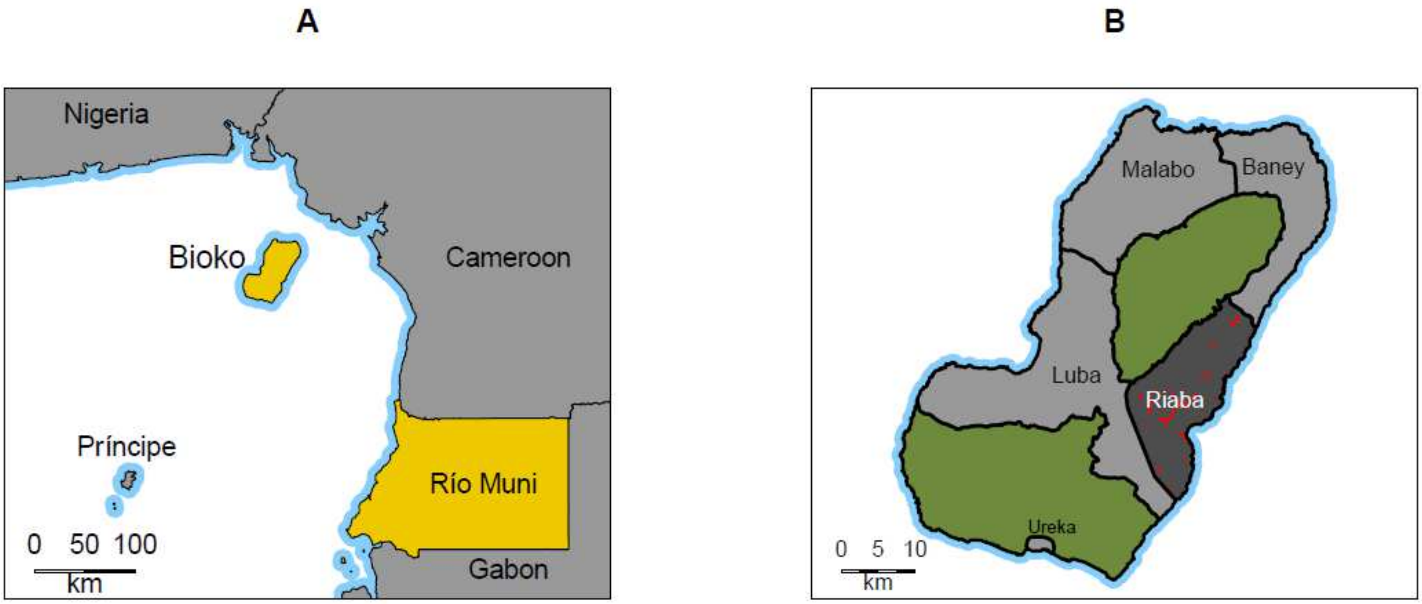


Figure 7 Prevalence estimates in Riaba district during the outbreak against the 2019 MIS. Horizontal and vertical lines illustrate the 95% confidence intervals for the estimates. Sites where less than 10 people were sampled are not shown.

Figure 8 Construction site in Riaba district. Water collections left unattended became active mosquito breeding habitats. In the picture, an entomologist is sampling the site for anopheline larvae. This was one of many such anthropogenic breeding habitats found in Riaba in 2019.

Figures



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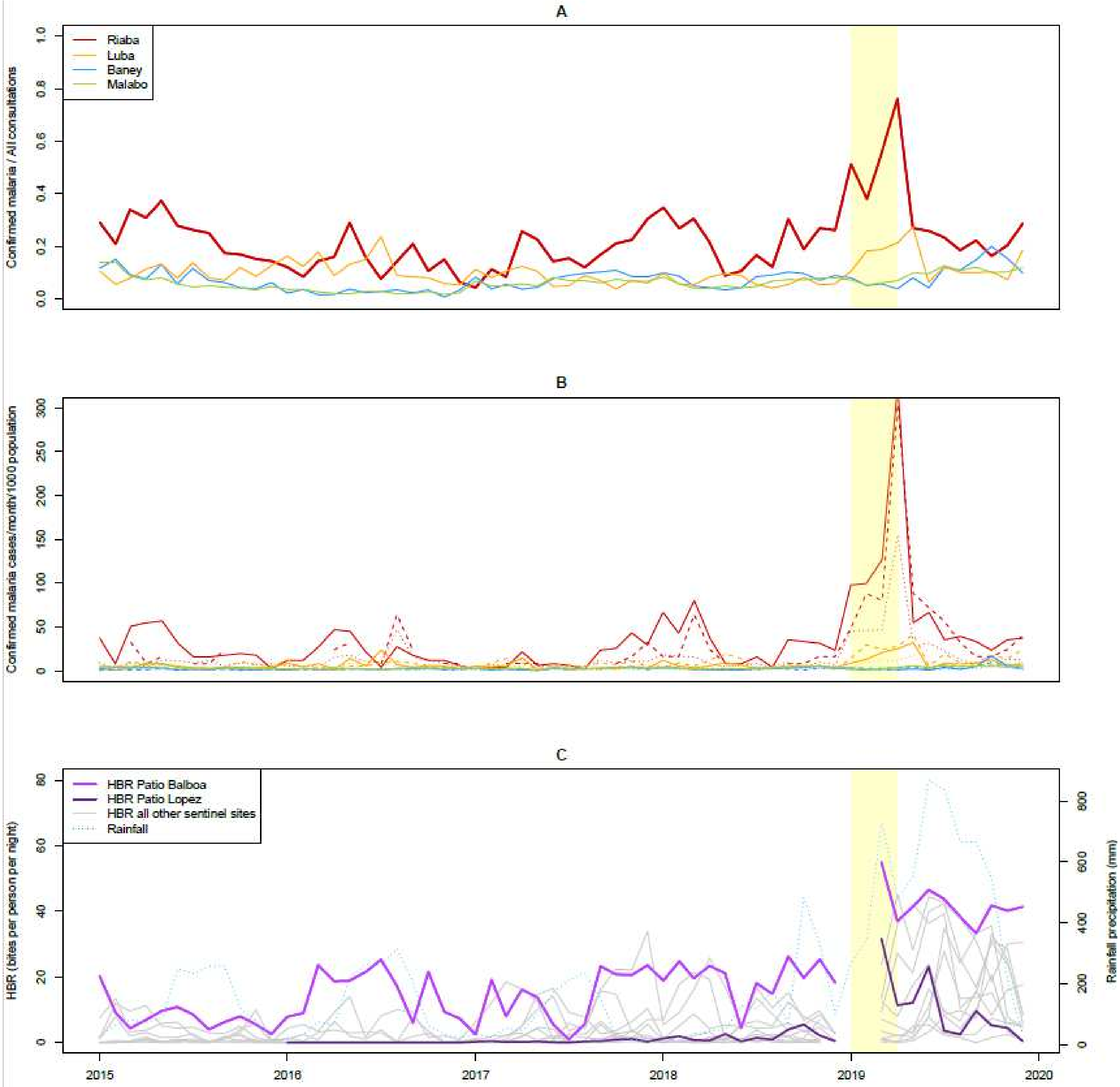

Figure 2

Confirmed malaria cases and HBR on Bioko Island, by district, 2015-2019. The light yellow shade highlights the period January – April 2019. A. Ratio of confirmed malaria cases to all outpatient consultations. B. Malaria incidence by district and age-group. Solid, dashed and dotted lines represent the 2-12, 3-17 and 18-50 years age groups. C. HBR estimates from entomological monitoring sentinel sites and rainfall data for the whole of Bioko Island. Entomological monitoring could not take place in January and February 2019, hence the missing data for these months. Rainfall data were digitised from: https://www.worldweatheronline.com.

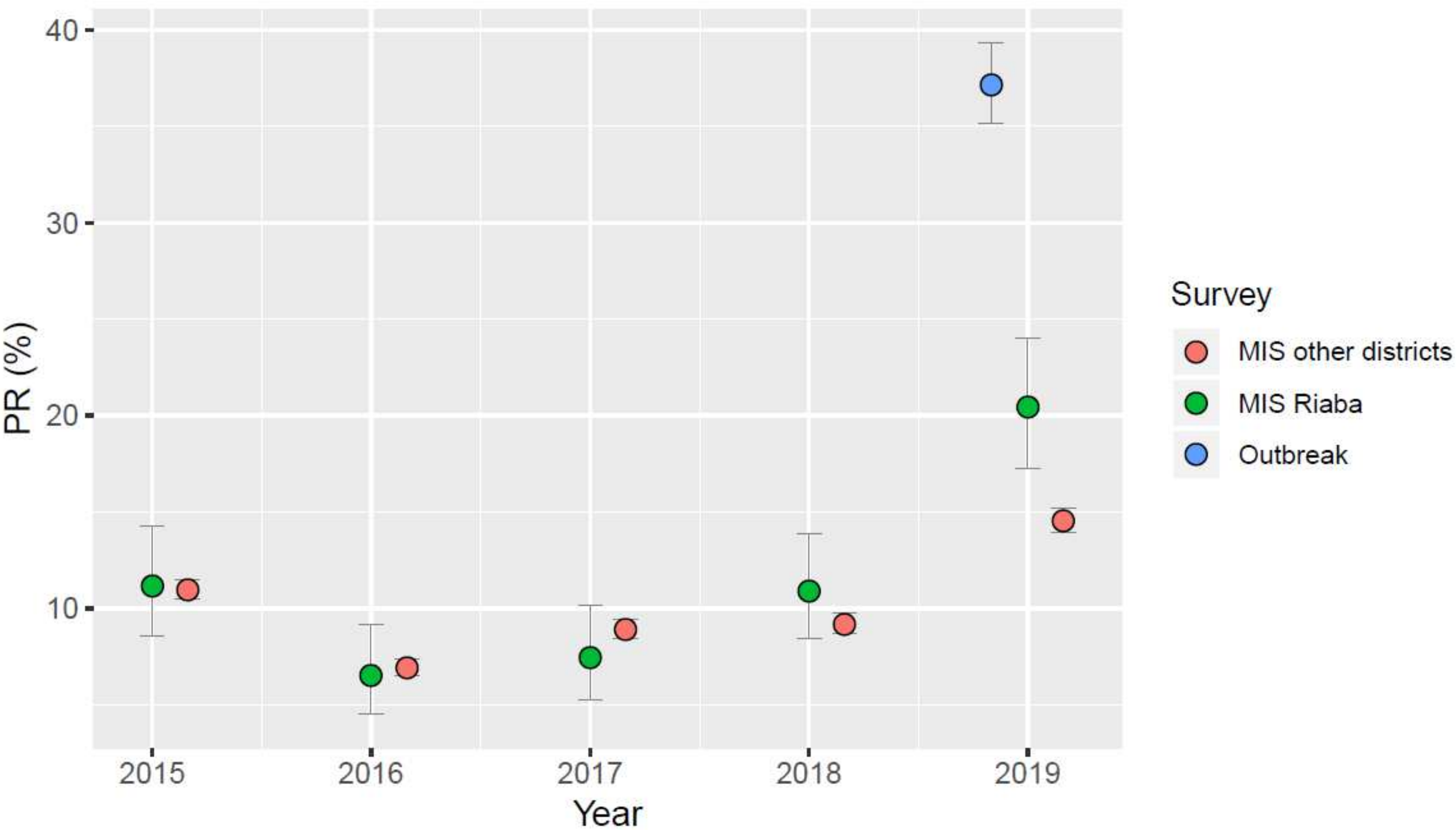

Figure 3

Malaria prevalence estimates from MIS and from the April 2019 survey. Data from MIS were plotted separately for Riaba and for the rest of the island. Error bars illustrate the 95% confidence intervals. Individuals with history of off-island travel in the previous eight weeks were excluded from the MIS to allow for the confounding effects of malaria importation [9].

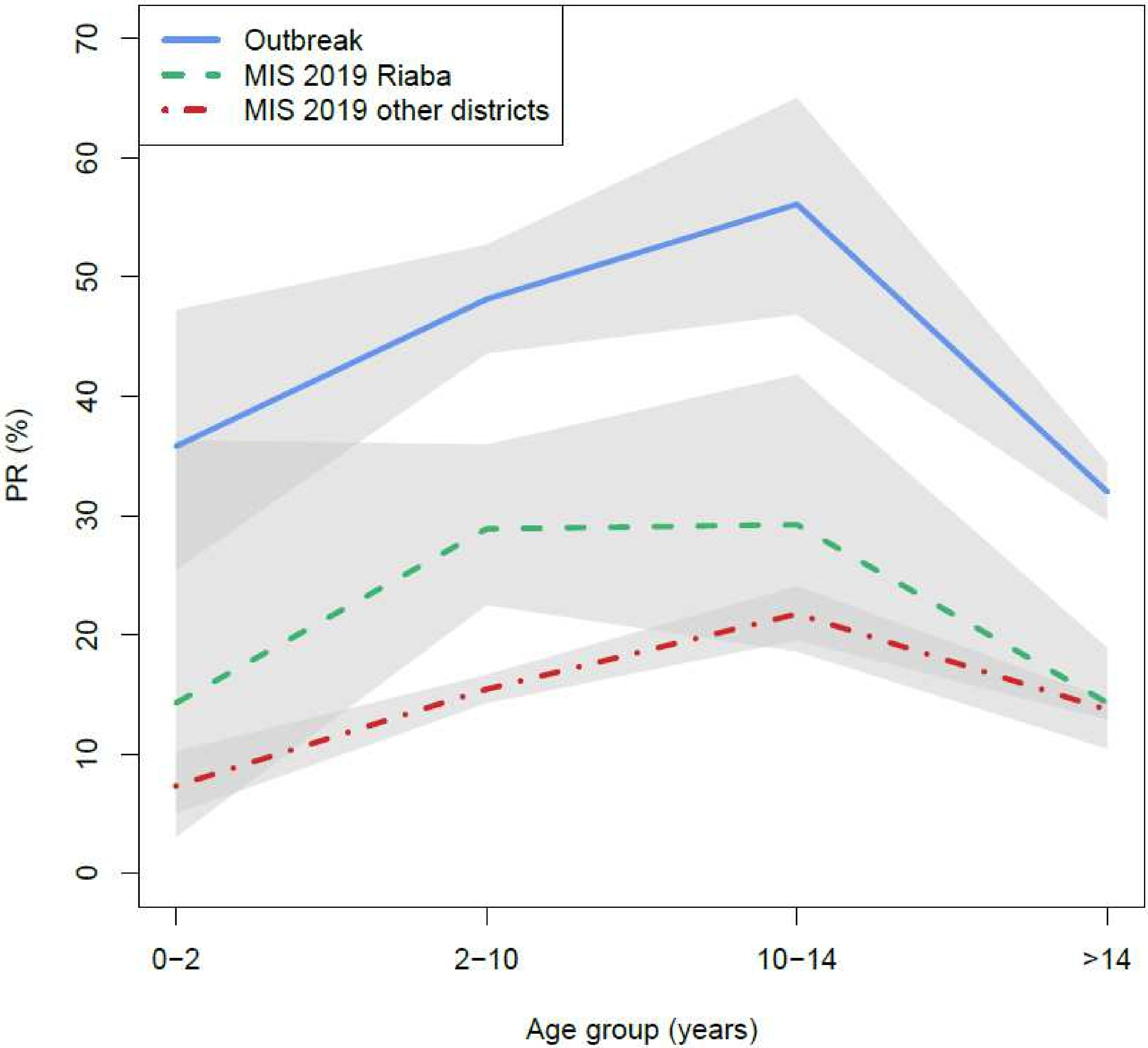

Figure 4

Age profile of malaria prevalence from the 2019 MIS and from the April 2019 survey. The grey polygons illustrate the 95% confidence intervals. Individuals with history of off-island travel in the previous eight weeks were excluded from the MIS to allow for the confounding effects of malaria importation [9].

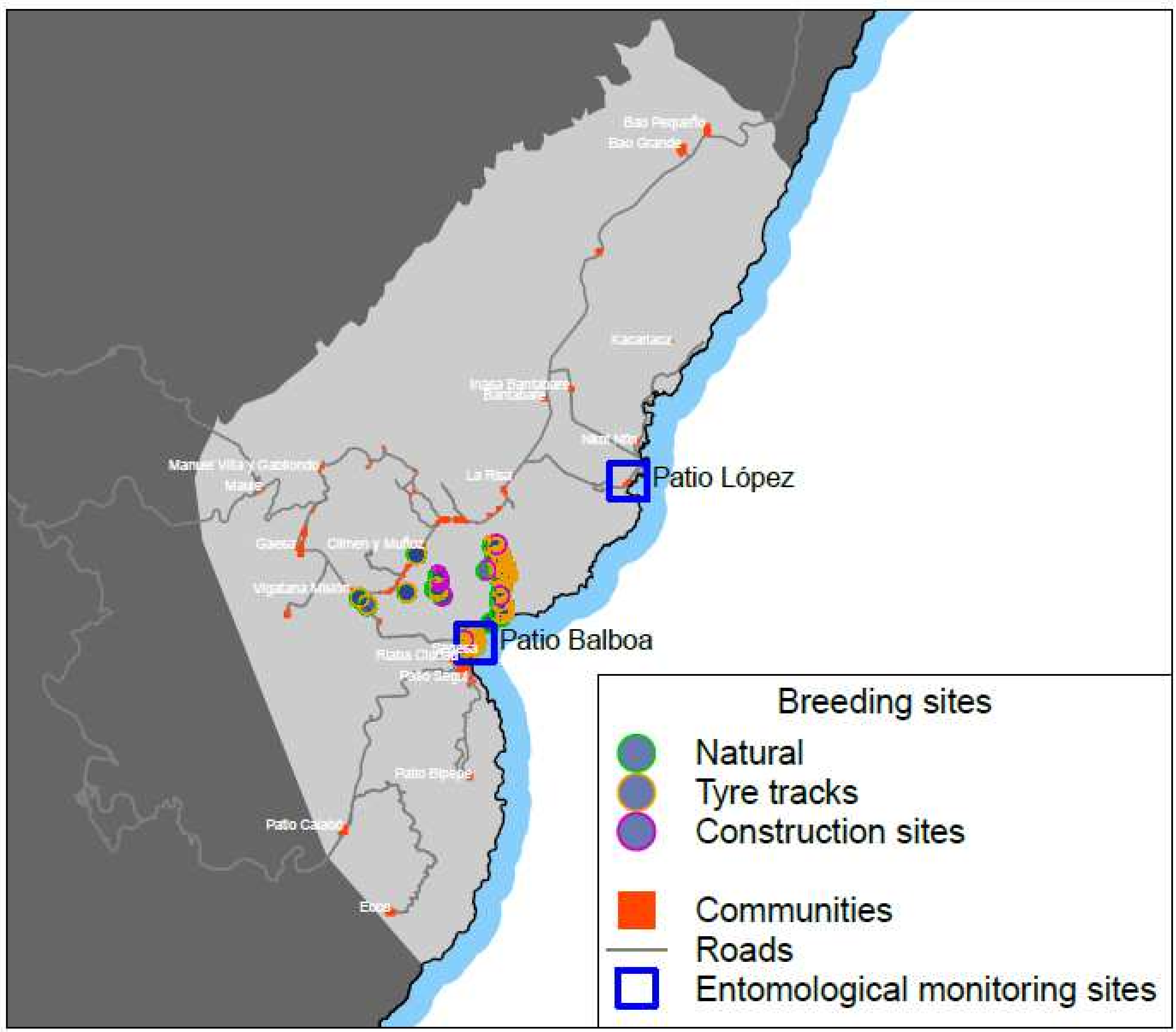

Figure 5

Location of communities and mapped anopheline breeding habitats in Riaba district. Riaba is shaded in lighter grey. Breeding sites are marked according to their type as natural or anthropogenic. Few of those mapped corresponded to the former. Patio L´opez and Patio Balboa are highlighted as they represent sites of longitudinal entomological monitoring.

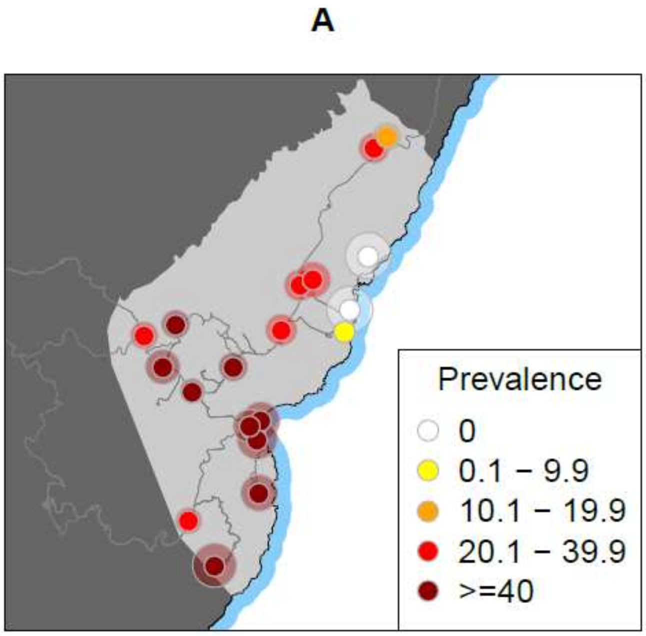

Figure 6

Malaria prevalence estimates by community in Riaba district. Riaba is shaded in lighter grey. A. Cross-sectional survey in April 2019. B. 2019 MIS. The shaded areas around the mapped points are proportional to the width of the 95% of the confidence intervals of the prevalence estimates.

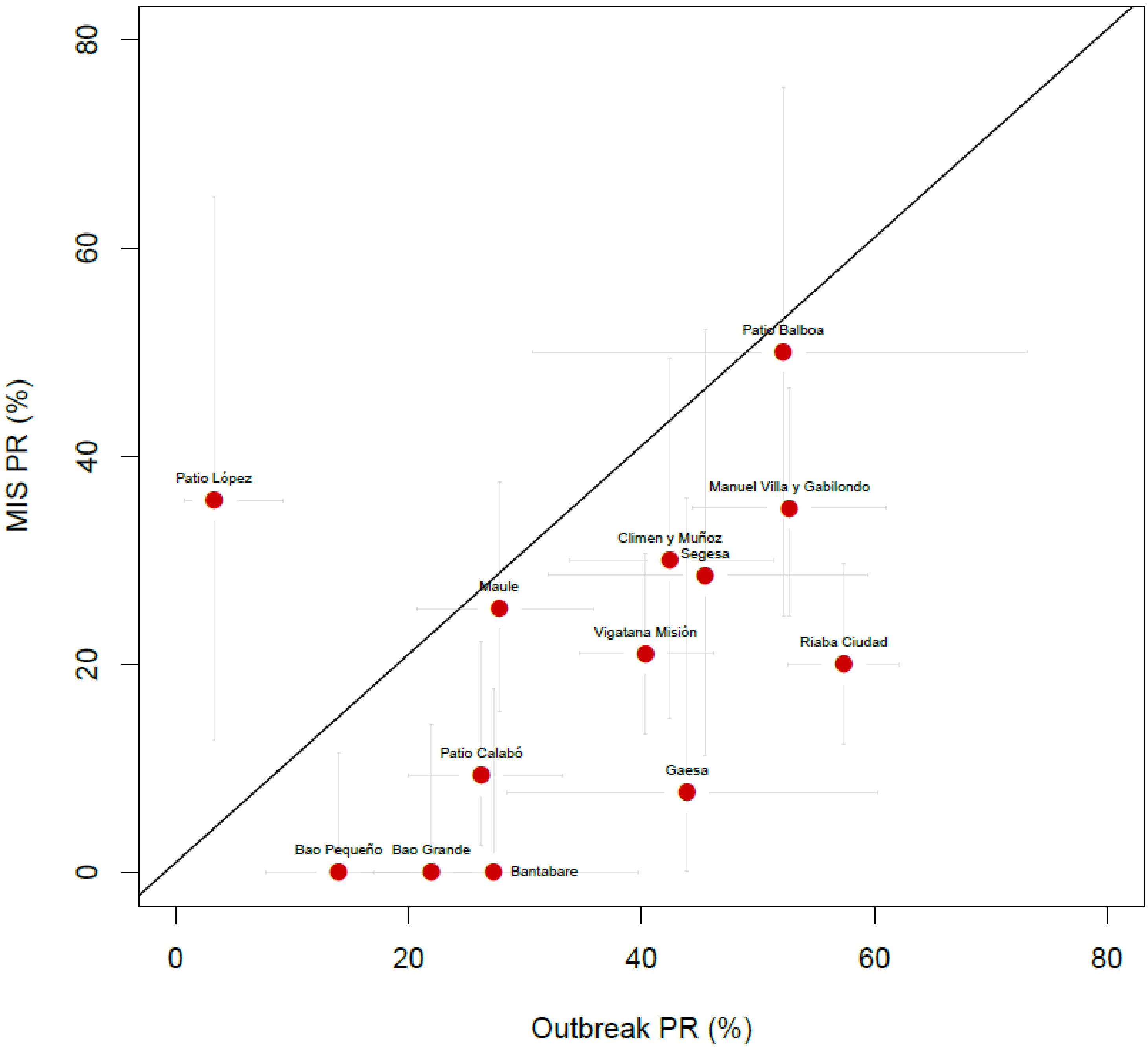

Figure 7

Prevalence estimates in Riaba district during the outbreak against the 2019 MIS. Horizontal and vertical lines illustrate the 95% confidence intervals for the estimates. Sites where less than 10 people were sampled are not shown.

Figure 8

Construction site in Riaba district. Water collections left unattended became active mosquito breeding habitats. In the picture, an entomologist is sampling the site for anopheline larvae. This was one of many such anthropogenic breeding habitats found in Riaba in 2019.