International Journal of Epidemiology, 2025, **54(5)**, dyaf140
https://doi.org/10.1093/ije/dyaf140
Original Article

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Malaria amidst the COVID-19 pandemic in Gabon: an application of autoregressive integrated moving average (ARIMA) models within an interrupted time series (ITS) framework to hospital-based data

Friederike Roeder[1,2], Olouyomi Scherif Adegnika[3,4], Yabo Josiane Honkpehedji[3,4,5], Manuel Huth[6,7], Bertrand Lell[3,8], Ayôla Akim Adegnika[3,9,10], Iris Lopes-Rafegas[1,2,†], Elisa Sicuri[1,2,11,12,†,*]

[1]Facultat de Medicina i Ciències de la Salut, Universitat de Barcelona (UB), Barcelona, Spain
[2]ISGlobal, Barcelona, Spain
[3]Centre de Recherches Médicales de Lambaréné (CERMEL), Libreville, Gabon
[4]Fondation pour la Recherche Scientifique (FORS), Cotonou, Benin
[5]Leiden University Center for Infectious Diseases (LUCID), Leiden University Medical Center, Leiden, The Netherlands
[6]Institute for Computational Biology, Helmholtz Munich—German Research Center for Environmental Health, Munich, Germany
[7]Faculty of Mathematics and Natural Sciences, University of Bonn, Bonn, Germany
[8]Department of Medicine I, Division of Infectious Diseases and Tropical Medicine, Medical University of Vienna, Vienna, Austria
[9]Institute of Tropical Medicine, University of Tübingen, Tübingen, Germany
[10]German Center of Infection Research (DZIF), Tübingen, Germany
[11]LSE Health, London School of Economics and Political Science, London, United Kingdom
[12]Centro de Investigação em Saúde de Manhiça (CISM), Maputo, Mozambique

*Corresponding author. Barcelona Institute for Global Health, Hospital Clínic—Universitat de Barcelona, C/Rosselló 171, 2a, 08036 Barcelona, Spain. E-mail: elisa.sicuri@isglobal.org

[†]Joint senior authors.

Abstract

Background: Coinciding with the SARS-CoV-2 pandemic, malaria cases and malaria-related deaths increased globally between 2020 and 2022. However, evidence linking the pandemic to increased malaria burden remains ambiguous. We assessed the extent to which an observed malaria resurgence in Lambaréné, Gabon, can be associated with pandemic-related disruptions in malaria control programmes.

Methods: Using observational data from two tertiary referral hospitals, spanning 2018 to early 2023, we applied autoregressive integrated moving average (ARIMA) models in an interrupted time series (ITS) framework to test for changes in trends and levels following the onset of the pandemic. The primary outcome is the monthly malaria diagnosis rate (per 1000 all-cause hospital diagnoses). As a sub-analysis, we focused on monthly maternal malaria incidence.

Results: Following an initial drop (–47.32, $P = 0.031$), potentially due to risk-averse behaviours, the malaria diagnosis rate gradually and concavely increased (linear term: 7.32, $P = 0.001$; squared term: –0.19, $P = 0.001$) to a peak above pre-pandemic levels. Additional analyses suggest that this resurgence was likely driven by disruptions to malaria control activities and a waning efficacy of malaria control tools administered pre-pandemic. Conversely, a resurgence in maternal malaria incidence was not estimated.

Conclusion: Findings align with several national and global descriptive reports, but add a more detailed understanding of underlying dynamics, therefore reinforcing the importance of maintaining malaria control in the general population. The absence of a meaningful increase in maternal malaria provides some reassurance that malaria in pregnancy-specific control remained unchanged during the SARS-CoV-2 pandemic. However, observed peaks in post-pandemic maternal malaria incidence should raise concerns given the risks that malaria poses to this group.

Keywords: malaria; COVID-19; Gabon; resurgence; vector control; maternal malaria; time series; ITS; ARIMA.

Key Messages

- We aimed to investigate the link between the SARS-CoV-2 pandemic and malaria resurgence in Lambaréné, Gabon, focusing on both the general population and pregnant women.
- We identified a delayed resurgence in malaria among the general population towards the end of 2021, likely explained by a decrease in malaria control and a waning efficacy of vector control tools administered before the pandemic.
- This case study adds to the scarce evidence on the association of the SARS-CoV-2 pandemic with infectious diseases such as malaria and emphasises the need to maintain malaria control efforts during pandemics or other emergencies.

Received: 14 November 2024; **Editorial Decision:** 1 July 2025; **Accepted:** 22 July 2025

Introduction

The SARS-CoV-2 pandemic has substantially disrupted healthcare services [1, 2], adversely affecting the burden of many diseases. In the case of malaria, severe consequences in terms of incidence and mortality were anticipated at the beginning of the pandemic [3, 4]. Indeed, following a global decline from 2015 to 2019, malaria cases increased throughout 2022 [5]. However, the rise was not solely due to the pandemic, as factors such as population growth, humanitarian crises, and floods also contributed [5]. Therefore, the contribution of the pandemic to the burden of malaria needs to be disentangled from these confounders.

The impact of the pandemic on malaria can be separated into direct and indirect effects. Directly, the common symptoms of SARS-CoV-2 and malaria infection may have hindered accurate diagnosis in malaria-endemic areas, while co-infections possibly led to higher malaria parasitaemia loads and more severe symptoms [6]. Indirectly, the impact of the pandemic was likely two-fold. First, the disruption of malaria control programmes increased exposure to infection; second, delayed diagnosis and treatment resulted in more severe cases and higher mortality rates [5]. Additionally, the pandemic challenged measuring the potential increase in malaria over the peaks of SARS-CoV-2 transmission. Reasons include overwhelmed laboratories, a shortage of rapid tests for malaria, and patients avoiding hospital visits and self-medicating due to fear of SARS-CoV-2 infection [7, 8].

At the cornerstone of malaria control are national vector control programmes, including the distribution of long-lasting insecticide nets (LLINs), indoor residual spraying (IRS), and larviciding. Another important prevention tool is chemoprophylaxis, which involves intermittent preventive treatment for pregnant women (IPTp), seasonal and perennial malaria chemoprevention (SMC and PMC) for children, and mass drug administrations under specific epidemiological circumstances [9]. In addition to national programmes, individuals at risk can privately adopt measures, such as using mosquito repellents, modifying houses to prevent mosquito entry, practising waste management, and acquiring bednets from the private market.

Beyond the pandemic, considerable evidence shows that the disruption of malaria control is associated with a resurgence in malaria cases, defined as an increase in cases to levels observed before the implementation of the respective interventions [10]. Indeed, the limited accessibility and availability of vector control have been identified as the main barriers to reducing the risk of malaria infection during the pandemic [11]. Interruptions are particularly critical for children with low immunity due to previous protection, possibly resulting in reduced human capital formation in the long term [12].

Further, a resurgence in malaria cases may have been delayed for several months due to the disruption of control measures. After administration, LLINs and IRS retain their (bio-)efficacy for up to 24 and 10 months, respectively [13, 14]. Consequently, individuals who received LLINs and IRS before March 2020 may have had functioning nets and indoor protection in the months following the onset of the pandemic, but little or no protection by 2022 if no new vector control tools were administered.

Despite the significant burden of malaria, comprehensive national vector control programmes targeting the general population have yet to be structurally implemented in Gabon, the focus of our study, and LLINs are primarily distributed on World Malaria Day (25 April). As a result, coverage rates for key vector control initiatives remain low, with LLIN usage in Lambaréné's province declining from ~30% in 2012 to 15% in 2019–21 [15]. However, with the start of the pandemic, the overall provision and access to malaria control measures were further reduced due to the prioritisation of COVID-19 prevention, disruptions in the supply chains of malaria control tools, [16] and restricted mobility from countrywide curfews. Most importantly, the community-based LLIN distributions on World Malaria Day did not occur in 2020 and 2021, coinciding with a decline in LLIN use among paediatric patients in Gabon's capital from 2019 to 2021 [8].

This study is motivated by the research question of whether a malaria resurgence occurred post pandemic and whether this resurgence can be associated with pandemic-related disruptions in malaria control. Our objective was to assess this question by using observational data from two tertiary hospitals in Lambaréné, Gabon.

The strengths of this case study are the use of several sensitivity and robustness analyses to account for limitations typical of observational data, particularly from resource-limited settings, and consideration of the specific study context and climatic factors. Climatic factors, in particular, can have counteracting or compensating effects that might not be captured in national-level estimates. By focusing on the local context, we provide a more nuanced understanding that complements broader epidemiological data. Further, we applied autoregressive integrated moving average (ARIMA) models within the interrupted time-series (ITS) framework [17, 18] due to their ability to account for past values and error terms while offering flexible predictive capabilities [19–21]. This relatively novel combined approach has not yet been widely applied in epidemiology [22] but is particularly well suited for analysing time-series data with the characteristics observed in this study.

This study was conducted within ORCHESTRA, a H2020-funded project (grant agreement no. 101016167).

Methodology

Study area

Gabon is a Central African country with equatorial climate, experiencing two main annual rainy and two short dry periods. As of 2019, malaria accounted for 7.25% of the nation's disability-adjusted life years [23]. Despite the high burden, funding for malaria control has been scarce in recent years, relying primarily on domestic sources. In 2005, Gabon initiated the free administration of LLINs and IPTp for pregnant women during the second and third trimesters of pregnancy, resulting in a reduction in malaria among this targeted group [24]. However, IPTp coverage remains low and has declined in recent years, while bednets are rarely available.

This study draws on observational data from two tertiary referral hospitals in Lambaréné, Gabon, which constitutes the main catchment area regarding malaria, with some referrals from the province. As of a 2013 census, the town had a population of 39 000 [25] Malaria transmission in Lambaréné is perennial and predominantly caused by the *Plasmodium falciparum* species [26]. The first COVID-19 case in Gabon was reported in March 2020, followed by countrywide lockdowns and curfews throughout 2020 and

2021. Vaccinations began in March 2021 (details in Supplementary Materials I).

Outcome variables

The primary outcome is the malaria diagnosis rate from 2018 to early 2023, calculated as the monthly number of malaria diagnoses by 1000 all-cause diagnoses across all wards in both hospitals, including malaria and excluding COVID-19 diagnoses. This accounts for interruptions in hospital activity, population growth, and shifts in healthcare-seeking behaviour, along with other unobserved factors. Malaria diagnoses include both inpatient and outpatient cases, and were based on clinical evaluations or rapid diagnostic tests (RDTs). Data collection was disrupted between June and December 2021 and, from January 2022 onwards, data were available from only one hospital.

In a sub-analysis, we examined maternal malaria. Reduced access to antenatal clinics (ANCs) and the absence of community healthcare worker-delivered care due to the pandemic may have reduced IPTp coverage, increasing the exposure to infection among pregnant women. However, unlike those for the general population, malaria programmes targeting pregnant women are typically more structured. Interruptions might therefore lead to a faster and more pronounced resurgence due to the required frequent administration of IPTp [9] and the vulnerability of this group [27]. Malaria incidence in pregnancy was calculated by adjusting the monthly number of malaria diagnoses in pregnant patients by the number of end-of-pregnancies (births, medically necessary abortions, and stillbirths), multiplied by 1000.

To test the plausibility of a decrease in malaria control activities as the explanation for the resurgence in malaria cases, we examined the occurrence of skin diseases over the same period, namely those that are infectious or caused by poor hygiene. Their occurrence might have been affected by the pandemic, e.g. through altered healthcare-seeking behaviour, social distancing, and improved hygiene practices. However, we would not expect a gradual resurgence as in malaria due to the absence of national programmatic control efforts, making this group of diseases suitable for a placebo test. [28] The dermatosis diagnosis rate consists of monthly skin disease diagnoses per 1000 overall non-COVID-19 diagnoses (see Supplementary Table S1).

Covariates

We retrieved the total monthly precipitation (Precip) in Lambaréné from Meteoblue [29], as the malaria diagnosis rate is strongly correlated with prior-month precipitation (details in Supplementary Materials I) [30]. For the sub-analysis, we additionally considered the rate of IPTp administered to pregnant women, calculated as the number of doses delivered per number of end-of-pregnancies. Further, we included a binary variable indicating months of 'borderline marked seasonality' (BorderMarkedSeason), defined as the 7 months contributing >75% of annual cases [30]. This variable captures characteristics specific to the pregnant population, including (i) higher numbers of births around April and May, leading to more ANC visits and thus malaria diagnoses in the preceding trimester; and (ii) seeking ANC after spending the summer months outside of Lambaréné (details in Supplementary Materials II). Lastly, three ITS variables capture the overall trend (Trend), linear and quadratic changes in the trend (CovTrend, $CovTrend^2$), and level changes (CovLevel).

Statistical analysis

For each outcome, we applied ARIMA models within an ITS framework [19] by using two model specifications: (i) truncated data up to the beginning of the gap and (ii) the full series, including missing data. In the sub-analysis, two additional models include the rate of IPTp doses per pregnancy as a covariate. With the interruption set to March 2020, the models account for an autoregressive term, 4 months of precipitation lags, and ITS covariates (details in Supplementary Materials II).

Furthermore, we constructed counterfactuals had the COVID-19 pandemic not occurred, which allowed confirmation and visual comparison of the ITS model results. Counterfactuals were not only trained on the dynamics of pre-pandemic disease rates, but also accounted for precipitation throughout the entire study period, as rainfall is exogenous to the pandemic and explains a large share of the variation in malaria occurrence. As a sensitivity analysis, we moved the month of the interruption date to test whether the primary effect coincides with the first identification of SARS-CoV-2 in the country.

Findings

Descriptive statistics

Supplementary Figure S4 illustrates the number of malaria diagnoses at the two hospitals, including the data gap in 2021. Peaks in the malaria diagnosis rate tend to be preceded by peaks in precipitation (Supplementary Figure S2). Overall, 54% of malaria cases were among female patients and 76% of diagnoses were based on RDTs, leaving 24% that were made on clinical grounds. Among maternal malaria diagnoses, 93% were RDT-based. Both malaria incidence in pregnancy and the rate of IPTp per pregnancy exhibit high monthly variation, with pregnant women receiving an average of 1.07 doses of IPTp during pregnancy (Supplementary Figure S7).

Main analysis: results

Model Ia reveals a drop of 41.15 ($P = 0.025$) malaria cases per 1000 all-cause diagnoses with the onset of the pandemic (CovLevel, Table 1), followed by a positive change in trend compared with the pre-pandemic period (CovTrend) of 3.86 ($P = 0.009$) malaria diagnoses per 1000 all-cause diagnoses. In contrast, Model IIa suggests that the overall change in trend is determined by both CovTrend and $CovTrend^2$, indicating an increasing but concave malaria diagnosis rate peaking at 193 malaria diagnoses per 1000 all-cause diagnoses in January 2022. Specifically, the coefficient for CovTrend is 7.32 ($P = 0.001$) and –0.19 ($P = 0.001$) for $CovTrend^2$. In this model, prior-month precipitation (Precip) is strongly positively associated with the malaria diagnosis rate.

These findings are reflected in the counterfactual, as the observed initial drop and subsequent peaks in 2022 visibly lie outside the counterfactual and its confidence interval (CI) (Supplementary Figure S15). Reversely, a within-sample prediction of Model IIa captures the first increasing and then decreasing trend in the malaria diagnosis rate (Supplementary Figure S16).

Sub-analysis: results

All models estimate a drop in maternal malaria diagnoses per 1000 pregnant women with the onset of the pandemic (CovLevel), followed by a positive change in the trend (CovTrend, Table 2). However, all associated P values are >0.05. In all models except Model Ib°, months of borderline

Table 1. Malaria diagnosis rate: ARIMA–ITS model results (coefficients).

	Model Ia	Model Ib
Precip (lag 1)	0.08*	0.13***
	(–0.01, 0.17)	(0.03, 0.22)
Precip (lag 2)	–0.01	0.05
	(–0.14, 0.12)	(–0.07, 0.17)
Precip (lag 3)	0.05	0.04
	(–0.05, 0.15)	(–0.06, 0.13)
Precip (lag 4)	–0.06*	–0.05
	(–0.13, 0.01)	(–0.13, 0.04)
Trend	–0.05	–0.38
	(–1.96, 1.86)	(–2.72, 1.96)
CovLevel	–41.15**	–47.32**
	(–77.22, –5.07)	(–90.28, –4.36)
CovTrend	3.86***	7.32***
	(0.96, 6.75)	(2.85, 11.79)
$CovTrend^2$		–0.19***
		(–0.30, –0.08)
Constant	147.00***	131.99***
	(107.94, 186.05)	(90.57, 173.41)
AR (lag 1)	–0.14	–0.08
	(–0.47, 0.20)	(–0.38, 0.21)
Sigma	21.83***	26.61***
	(12.77, 30.89)	(18.13, 35.09)
N	36	50

Confidence intervals in brackets. ARIMA: autoregressive integrated moving average; ITS: interrupted time series; Precip: precipitation; CovLevel: Covid-19 level change; CovTrend: Covid-19 trend change; $CovTrend^2$: Covid-19 squared trend change; AR: autoregressive coefficient.
Model Ia uses data truncated to May 2021, marking the start of a data gap from June to December 2021. Model IIa uses the full-time series, including the period of missing data, and adds a non-linear change in trend through a quadratic term. A lag of *n* refers to using the value of a given variable from *n* months before the month of the outcome variable.
*$P < .10$, **$P < .05$, ***$P < .01$.

marked seasonality (BorderMarkedSeason) are strongly linked to increased maternal malaria incidence. Instead, in Model Ib°, the prior-month rate of IPTp doses per pregnant woman is one of the main predictors for maternal malaria (67.00, $P = 0.019$). In contrast to the general population, prior-month precipitation is not strongly associated with maternal malaria. Notably, three distinct peaks occurred after the onset of the pandemic, clearly exceeding pre-pandemic levels and lying outside of the counterfactual and its CI (Supplementary Figure S21). Furthermore, a within-sample prediction of Model IIb visualises that the model estimates a slight increase after the onset of the pandemic; however, one observed peak remains above the CI of the prediction (Supplementary Figure S22).

Placebo test and sensitivity analysis: results

In the case of dermatoses, neither model results nor counterfactuals identify meaningful changes with the onset of the pandemic (details in Supplementary Materials III, Supplementary Table S9, and Supplementary Figure S26). The sensitivity analysis suggests that the key event occurred in March 2020 (Supplementary Table S10).

Discussion

This study identifies a malaria resurgence in two tertiary hospitals in Lambaréné following the onset of the SARS-CoV-2 pandemic. Specifically, we estimated an initial drop in the malaria diagnosis rate, possibly due to stronger risk-averse behaviours among malaria patients, who may have been more likely to self-medicate [8, 31] and avoid healthcare facilities compared with all hospital patients. This was followed by a progressive increase to a peak above pre-pandemic levels, likely due to a gradual decrease in the efficacy of vector control tools that were administered before the pandemic. A subsequent decrease might signal that the disruption in malaria control lasted for ∼2 years before coverage recovered.

So far, several studies have aimed to link increases in malaria cases to the pandemic. Research from western [8] and south-eastern Gabon [32], Zambia [33], and The Gambia [7, 34] reported an increase in cases. However, other unaccounted factors might have also contributed to the rise. Indeed, the authors of the latter two studies suggest that their findings might be partially explained by a decrease in malaria testing during 2021 and an unusually heavy rainy period in 2022. Additionally, a study from Ghana observed a decrease in admissions for complicated malaria cases in 2020, which the authors attributed to risk-averse behaviours, as mortality rates rose significantly that year [35]. In contrast, a Benin study documents ambiguous changes in healthcare-seeking behaviour, with some individuals visiting healthcare centres less frequently and others more often [36].

We can partially rule out some factors mentioned above. First, our model accounts for periods of increased precipitation affecting malaria transmission, such as the unusually strong rainy season at the end of 2022. Additionally, the malaria diagnosis rate is adjusted for overall changes in healthcare-seeking behaviour, as it is measured relative to the total number of diagnoses made at the hospitals. This adjustment helps to account for reduced access to care, which would impact all diagnoses, not just malaria. Furthermore, the total number of diagnoses remained stable before and after the pandemic, suggesting that healthcare access was not drastically impeded (Supplementary Figure S6).

These findings are not reproduced in the analysis of malaria in pregnancy. This could be due to malaria control measures targeted at pregnant women being prioritised both by healthcare systems and within households. Indeed, the annual rate of IPTp per pregnancy did not substantially decrease after the onset of the pandemic (Supplementary Figure S9), suggesting that healthcare services for pregnant women continued. Yet, the observed peaks in maternal malaria that exceed pre-pandemic peaks (Supplementary Figure S21) are alarming due to the adverse health effects of malaria infections on both mother and child. A study in Uganda similarly found no change in maternal malaria admissions [37], while research from Ghana showed an increase in outpatient maternal malaria cases, likely due to decreased ANC visits and disrupted LLIN distribution [38].

Importantly, the positive association between maternal malaria and the rate of IPTp doses per pregnant woman administered in the month prior does not imply that IPTp is ineffective at preventing or even contributes to an increase in maternal malaria. Rather, it reflects the limitations of aggregate data, which precludes exploring individual-level variations. Those who received IPTp are not necessarily the same individuals who later contracted malaria. More likely, the positive coefficient arises from increased IPTp distribution anticipating annual malaria peaks or coinciding with months of higher ANC attendance.

Table 2. Malaria incidence in pregnancy: ARIMA–ITS model results (coefficients).

	Model Ib	Model Ib°	Model IIb	Model IIb°
Precip (lag 1)	–0.01	–0.12	0.06	0.04
	(–0.26, 0.23)	(–0.33, 0.09)	(–0.16, 0.27)	(–0.18, 0.26)
Precip (lag 2)	0.17	0.07	0.23**	0.22**
	(–0.09, 0.44)	(–0.19, 0.33)	(0.03, 0.42)	(0.03, 0.42)
Precip (lag 3)	–0.00	0.11	–0.03	–0.02
	(–0.21, 0.21)	(–0.13, 0.34)	(–0.23, 0.17)	(–0.23, 0.19)
Precip (lag 4)	–0.09	–0.23**	–0.03	–0.04
	(–0.28, 0.09)	(–0.45, –0.00)	(–0.21, 0.16)	(–0.24, 0.15)
BorderMarkedSeason	91.01***	45.81	100.43***	96.96***
	(44.02, 137.99)	(–9.61, 101.23)	(58.23, 142.62)	(50.27, 143.66)
IPTp (lag 1)		67.00**		7.91
		(10.84, 123.15)		(–33.39, 49.21)
Trend	–2.02	–2.76*	–2.44	–2.59
	(–5.75, 1.71)	(–5.86, 0.34)	(–6.27, 1.40)	(–6.54, 1.37)
CovLevel	–4.29	–9.23	–21.10	–19.62
	(–82.18, 73.60)	(–69.65, 51.19)	(–110.53, 68.34)	(–109.22, 69.98)
CovTrend	3.95	5.29*	8.34	8.38
	(–4.10, 12.01)	(–0.92, 11.50)	(–2.58, 19.26)	(–2.82, 19.58)
$CovTrend^2$			–0.11	–0.10
			(–0.40, 0.19)	(–0.40, 0.19)
Constant	73.19*	87.17**	41.70	42.43
	(–5.22, 151.59)	(13.58, 160.75)	(–35.79, 119.19)	(–34.64, 119.50)
AR (lag 1)	–0.13	–0.18	0.00	0.01
	(–0.63, 0.36)	(–0.69, 0.33)	(–0.44, 0.45)	(–0.45, 0.46)
sigma				
	45.98***	42.56***	49.06***	48.99***
	(31.90, 60.07)	(24.39, 60.72)	(37.52, 60.59)	(37.29, 60.70)
N	36	36	48	48

Confidence intervals in brackets. ARIMA: autoregressive integrated moving average; ITS: interrupted time series; Precip: precipitation; BorderMarkedSeason: borderline marked seasonality; IPTp: intermittent preventive treatment for pregnant women; CovLevel: Covid-19 level change; CovTrend: Covid-19 trend change; $CovTrend^2$: Covid-19 squared trend change; AR: autoregressive coefficient.
Models Ib and Ib° use data truncated to May 2021, marking the start of a data gap from June to December 2021. Models IIb and IIb° use the full-time series, including the period of missing data, and add a non-linear change in trend through a quadratic term. The circle index (°) indicates that the model additionally includes the rate of IPTp per pregnant woman with a lag of 1. A lag of *n* refers to using the value of a given variable from *n* months before the month of the outcome variable.
*$P < .10$, **$P < .05$, ***$P < .01$.

The data used in this study provide a meaningful representation of malaria cases in Lambaréné before and during the pandemic for several reasons. The two tertiary hospitals serve a relatively small population, making them the likely point of care for most patients, including referrals from local dispensaries. Accessibility to these hospitals is high, as many Gabonese residents are covered by the national health insurance scheme. The reliability of the data is further ensured, as they are derived from insurance reimbursement reports. Finally, by analysing the diagnosis rate, we account for population changes and healthcare service disruptions, suggesting that the observed rise in malaria cases is likely due to reduced access to malaria control tools rather than other factors.

While we cannot claim causality, we demonstrate a robust association between the increase in the malaria diagnosis rate and the pandemic-related decline in malaria control, further supported by the placebo test and sensitivity analysis. Data constraints precluded the application of quasi-experimental methods; for instance, a suitable control unit for difference-in-difference models would need to exhibit a similar pre-pandemic temporal pattern to malaria while not being affected by the pandemic.

The study's limitations include its low generalisability to other regions, the gap in data in 2021, and a short pre-pandemic data window, which restrict the training of the model. Data were only available in monthly aggregates, while weekly data would have captured short-term outbreaks better and improved the estimation of the relationship between the malaria diagnosis rate and meteorological factors.

Conclusion

We identified and quantified a gradual resurgence in the malaria diagnosis rate after the onset of the COVID-19 pandemic in Lambaréné, Gabon. The most plausible explanation is that the pandemic decreased malaria control, while existing tools remained efficacious for some months, thereby delaying the observed effect. This conclusion is supported by the unchanged dermatosis diagnosis rate, reflecting diseases that are not targeted by specific control measures. These results highlight the importance of maintaining malaria control efforts during emergencies. For maternal malaria, no meaningful increase was estimated, suggesting that targeted control efforts for this vulnerable group were maintained. However, the observed peaks in maternal malaria post pandemic raise concerns due to the serious risks posed to pregnant women and their children. Further research using more granular clinical, climate, and behavioural data is needed to better understand the impact of the pandemic on malaria in the general, and particularly the maternal, population.

Ethics approval

This study was conducted by using aggregated, anonymised data of monthly malaria cases obtained from the Rawiri District Hospital and the Albert Schweitzer Hospital. As the research involved no individual patient data and all data were provided in a de-identified and aggregated format,

formal ethics approval was not required. Written permission to use these data was obtained from the directors of both participating hospitals.

Acknowledgements

This work would not have been possible without the Centre de Recherches Médicales de Lambaréné (CERMEL) as well as Mouélé Modeste and Evrard Moutembi, who gathered the data. Over several meetings, our collaborators from the ORCHESTRA consortium, in particular Lulla Opatowski, Jan Hasenauer, and Jérémie Guedj, provided us with valuable feedback. Lastly, we thank the participants of the Severo Ochoa-funded workshop 'The Contribution of Health Economics to Vector-Borne Disease Control and Elimination: Current Status and Improving the Policy Impact of Health Economics Research' held in Barcelona in December 2023, as well as Caterina Guinovart and Raquel González for their unwavering support.

Author contributions

F.R. analysed the data and wrote the manuscript. S.A. gathered the data. Y.J.H. contributed to the initial idea of the study. S.A. and Y.J.H. helped to contextualise the results and provided information on the study area. M.H. helped to revise the analysis. A.A.A. and B.L. assisted with data acquisition. I.L.R. and E.S. were jointly responsible for conceptualising and supervising the study, and contributed to the writing of the manuscript. All authors read, revised, and approved the final manuscript.

Supplementary data

Supplementary data is available at *IJE* online.

Conflict of interest

None declared.

Funding

This study was conducted within ORCHESTRA (Connecting European Cohorts to Increase Common and Effective Response to SARS-CoV-2 Pandemic), a project funded by the European Union's Horizon 2020 research and innovation programme [grant agreement no. 101016167]. We acknowledge support from MCIN/AEI/10.13039/501100011033 [grant number CEX2023-0001290-S] and the Generalitat de Catalunya through the CERCA Program. CISM is supported by the Government of Mozambique and the Spanish Agency for International Development (AECID). Funders had no role in the study design, data collection, analysis, or interpretation of the results.

Data availability

Data are available on request. The data underlying this article will be shared on reasonable request to Scherif Adegnika (scherif.adegnika@cermel.org).

Use of artificial intelligence (AI) tools

Grammarly and ChatGPT were selectively used to improve English grammar and readability. No AI tools were used for data analysis, interpretation of results, or writing of original scientific content. The authors take full responsibility for the content of the study.

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International Journal of Epidemiology, 2025, 54, 1–7
https://doi.org/10.1093/ije/dyaf140
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