Malaria Journal

RESEARCH

Open Access

Spatiotemporal dynamics of malaria and climate influence on its incidence in Condorcanqui Province, 2005–2022

Milagros Saavedra-Samillán[1], Fátima Burgos[1], Flor García Huamán[1,2], Hugo O. Valdivia[3], Dionicia Gamboa[4,5] and Stella M. Chenet[1,6*]

Abstract

Background Amazonas is a region in northern Peru with the second-highest incidence of malaria. Approximately 95% of the cases are reported in the Condorcanqui province, where native communities living along the banks of Santiago River lack access to potable water, sewage, and electricity. This study aimed to analyse malaria's spatial, temporal, and climatic characteristics in Condorcanqui to guide future studies and prevention strategies.

Methods A database provided by DIRESA-Amazonas was evaluated. Database included cases from 44 health facilities serving 112 native communities. According to the malaria control programs implemented in Peru, the study was divided into three periods: 2005–2010, 2011–2016, and 2017–2022. A Spearman correlation analysis was also conducted to assess the relationship between malaria incidence and climate variables.

Results During the study periods, 10,632 cases were reported, including *Plasmodium vivax* (84.87%), *Plasmodium falciparum* (14.91%) and *Plasmodium malariae* (0.23%) infections. Annual incidence rates (AIRs) significantly varied across the study periods ($p < 0.001$). A significant reduction in malaria incidence occurred during the first period, largely attributed to PAMAFRO programme interventions. Subsequent periods, showed a gradual increase in cases, with a peak of *P. vivax* in 2019 and the reintroduction of *P. falciparum*. Males and individuals aged 0–11 years presented the greatest number of cases. Significant correlations were found between malaria incidence and the Oceanic Niño Index (ONI) at lag0 ($\rho = 0.14$, $p = 0.037$), corrected precipitation at lag1 ($\rho = 0.16$, $p = 0.020$), and minimum wind speed at lag1 ($\rho = 0.15$, $p = 0.024$).

Conclusions Malaria incidence in Condorcanqui has increased over the last 5 years, driven by climatic influences such as the ONI, precipitation, and low wind speeds. Without immediate preventive efforts, cases are expected to continue rising. Effective control strategies must tackle the social, economic, and political issues that heighten vulnerability, such as poverty and limited healthcare access. Maintaining control initiatives and tailoring them to local needs will be essential for achieving long-term reductions of malaria in Peru.

Keywords Spatiotemporal, Climate, Malaria, Condorcanqui, Amazonas

*Correspondence:
Stella M. Chenet
stella.chenet@untrm.edu.pe
Full list of author information is available at the end of the article

Background

Malaria is a life-threatening parasitic disease transmitted to people through bites of infected female *Anopheles* mosquitoes. In humans, five parasite species can cause malaria, but two of them represent a significant threat: *Plasmodium falciparum* and *Plasmodium vivax*, with *P. vivax* being the most common species responsible for 75% of all malaria cases in the Americas [1]. In Peru, endemic malaria areas are primarily located in the Amazon basin. The Peruvian Amazon covers approximately 78,282,060 hectares, accounting for 60.9% of the national territory. This area includes regions such as Loreto, Amazonas, Ucayali, and Madre de Dios, all of which are significantly impacted by malaria [2].

Between 1954 and 1967, the disease was kept under control, with 1500 cases registered in 1965 due to significant malaria elimination efforts [3]. This level of malaria was maintained until 1970 when a gradual increase in the number of cases was detected. By the 1990s, malaria significantly reemerged, with nearly 250,000 cases reported in 1998, with Loreto, Tumbes, Junín and Piura regions being the epicentres of the epidemic [4, 5]. During that time, the increase in malaria incidence was associated with the reintroduction and spread of the *Anopheles darlingi* vector and the emergence of drug resistance to chloroquine and sulfadoxine-pyrimethamine [6]. As a result, in 2001, Peru introduced artemisinin-based combination therapy to control uncomplicated malaria caused by *P. falciparum* [7]. In 2000, the incidence of malaria decreased to 68,323 cases; however, it resurged again in 2005, reaching 110,119 cases [8, 9].

Control and elimination programmes were established over time to reduce the number of malaria cases in Amazonas and across the country. For instance, the Malaria Control Project in the Border Areas of the Andean Region (PAMAFRO) was implemented between October 2005 and September 2010. This programme enforced strategies to control the spread of the disease and strengthened diagnostic efforts [10, 11]. Likewise, in 2017, the Zero Malaria Programme (PMC) was implemented for 5 years; nevertheless, this programme prioritized Loreto due to its high endemicity [12].

Loreto accounts for 94% of the cases in the country, followed by Amazonas, Junín, Cusco, San Martín, Ucayali, Ayacucho and Madre de Dios [13]. Amazonas is the region with the second highest malaria incidence, with Condorcanqui being the province with the highest number of cases. This province is one of the most deprived areas of Peru; its native communities face a critical absence of essential services, such as potable water, sewage systems and electricity. Among the three districts of Condorcanqui (Nieva, Rio Santiago and Cenepa), Rio Santiago accounts for 95% of the malaria cases. Until 2018, *P. vivax* was the predominant species; however, in 2019 *P. falciparum* was reintroduced, and the total number of cases increased up to 2.6 fold compared to the previous year [14].

Amazonas and other malaria-affected regions have recently been included in Peru's Malaria Elimination Plan (2022–2030), structured in three phases. Phase I focus on applying known strategies in areas with high and very high disease prevalence, with interventions tailored to the level of risk and micro-stratification at the community level. Phase II prioritizes the reduction of asymptomatic malaria by implementing new diagnostic strategies and methods in areas with moderate and low prevalence. Finally, phase III is oriented towards eliminating residual malaria, complementing actions such as outbreak interventions and active case detection (ACD) programmes [8].

For effective malaria control, including ACD is crucial because it allows an accurate assessment of the burden of the disease. ACD may include testing a defined population, including those who do not seek medical attention, to identify individuals who may be asymptomatic, particularly in low-transmission settings. In contrast, passive case detection (PCD) relies on individuals self-reporting symptoms or seeking medical attention, underestimating infections and residual parasite carriers [15].

In this context, comprehensive malaria surveillance covering all endemic areas is essential. Condorcanqui's proximity and population mobility to malaria-endemic areas such as Loreto and Ecuador suggest sustained transmission of the disease. Therefore, this study aimed to analyse the spatiotemporal dynamics of malaria transmission in Condorcanqui, focusing on identifying areas and features that may be optimal targets for disease control. Additionally, the impact of climatic variables on malaria spread was evaluated.

Methods

Study site

Condorcanqui Province is in the northeastern region of Amazonas, bordering Ecuador to the northwest and Loreto to the east. Its capital is Santa Maria de Nieva, which comprises three districts (Nieva, Rio Santiago, and Cenepa) and three watersheds (Marañon, Cenepa, and Santiago) [14], with an area of 17,984.29 km^2 (45.35% of Amazonas). This province has an estimated population of 52,275 inhabitants [16], and most of them (95%) belong to the Awajun and Wampis ethnicities [17]. It is characterized by a humid tropical climate, with temperatures reaching 35 °C, average annual rainfall of approximately 4800 mm, and relative humidity exceeding 90% [14] (Fig. 1).

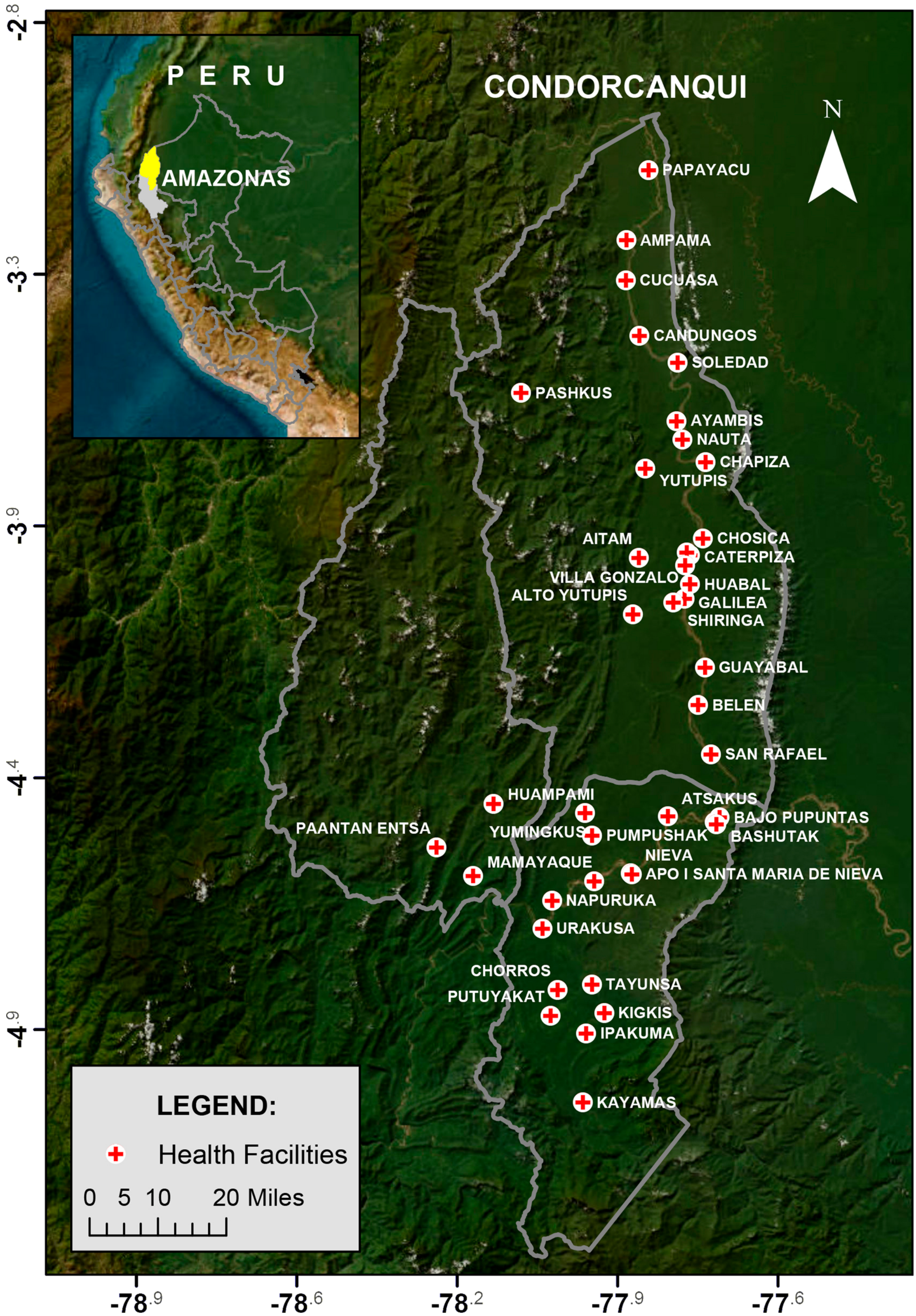

Fig. 1 Distribution of health facilities affected by malaria in Condorcanqui Province (2005–2022). The map shows the distribution of 42 health facilities where malaria cases were reported during the study period

Database

Malaria data was obtained from the Regional Health Directorate of Amazonas (DIRESA-Amazonas) and cross-checked with a secondary open source, the Peruvian Center for Disease Control and Prevention (CDC Peru). The final database included malaria cases reported from 2005 to 2022 in 44 health facilities (including health posts, health centres, and hospitals) located in the districts of Río Santiago (23), Nieva (18), and Cenepa (3).

Trend and distribution of malaria cases

To assess the distribution of malaria cases, the data was categorized into three six-year periods according to the control programmes implemented in Peru: 2005–2010 (PAMAFRO), 2011–2016 (Post-PAMAFRO), and 2017–2022 (PMC and Peru's Malaria Elimination Plan). Location maps of health facilities and the geographical distribution of malaria cases were created using ArcMap v.10.8. Two out of the 44 health facilities could not be mapped due to the lack of coordinates for those health posts.

Analysis of demographic and climate data

The National Institute of Statistics and Informatics (INEI) obtained population information at the district level to calculate the annual incidence. Cases were analysed according to *Plasmodium* species, gender, and age, determining frequencies and percentages per period. Age groups were categorized into children (0–11 years), adolescents (12–17 years), young people (18–29 years), adults (30–59 years) and older adults (over 60 years).

El Niño-Southern Oscillation (ENSO) data retrieved from the National Oceanic and Atmospheric Administration website (https://www.psl.noaa.gov/) were utilized for analysis, with the Oceanic Niño Index (ONI) serving as the metric to assess the ENSO phenomenon. This index captures both warm periods ($> +0.5$ °C), which are indicative of El Niño events, and cold periods (< -0.5 °C), which indicate La Niña events [18].

For meteorological variables, a grid of points with an equidistant distance of 0.1 degrees was established for the affected districts using QGIS v.7 software. Meteorological data were obtained from NASA's Goddard Earth Science Data and Information Services Center (GES DISC). The meteorological variables included the corrected precipitation (mm), specific humidity (%), maximum and minimum temperatures (°C), and maximum and minimum wind speeds (m/s).

Statistical analysis

Data was processed and analysed using RStudio software v. 4.3.1. Analysis was conducted using the number of reported malaria cases as an independent variable to identify possible changes in the disease incidence over time. The annual incidence rate (AIR) per 1,000 inhabitants, the incidence rate ratio (IRR), and the 95% confidence intervals were determined over the eighteen-year period (2005–2022). The IRR is defined as the ratio of the AIR for each year to the AIR from 2006, which is used as the reference in the denominator. The 95% confidence intervals were estimated using the standard error derived from these rates. Moreover, chi-square tests were used to determine variations in the average AIRs across the three categorized periods and to identify significant variations in malaria cases across these periods for each demographic variable.

Spearman correlation was conducted to assess the associations between climatic variables and malaria incidence. A lag period spanning from zero to 2 months was considered given the malaria intrinsic incubation of 4–14 days, extrinsic incubation of 8–14 days and *Anopheles* life cycle of 10–14 days [19, 20]. The lag2 variable denoted the predictive variable 2 months before the assessed malaria incidence, lag1 represented 1 month prior, and lag0 referred to the current month of malaria incidence.

Results

Temporal analysis of malaria cases

Three periods (2005–2010, 2011–2016 and 2017–2022) with significantly different AIRs were identified ($p < 0.001$). Between 2005 and 2022, a total of 10,632 cases of malaria were recorded across 44 health facilities in Condorcanqui. An increase in malaria incidence occurred in 2006, especially among patients infected with *P. vivax*. Nevertheless, between 2006 and 2010, the AIR experienced a consistent decline of 99%, from 35.5 to 0.14 (Table 1; Fig. 2). This substantial reduction resulted in a corresponding decrease in IRRs, from 1.0 to 0.0. In August 2014, a resurgence of *P. vivax* cases was registered, reaching an AIR of 21.62 in 2015, and by mid-2017, four cases of *P. falciparum* were reported in Nieva. In 2019, a high AIR of 52.28 was recorded due to increased *P. vivax* cases and the confirmed reintroduction of *P. falciparum* (807). During 2020, the total number of cases remained constant but dropped by half in 2021. Finally, in 2022, the cases increased again, leading to an AIR of 44.01.

Geographic distribution of malaria cases

In the initial period, 34 health facilities reported a total of 2,180 cases, with the highest number in Yutupis (466), San Rafael (425) and Guayabal (344). During the second period, cases significantly decreased, with 25 health facilities reporting only *P. vivax* cases; Nauta (271) reported the highest number of cases, followed by

Table 1 Annual incidence rates (AIR) of malaria by species in Condorcanqui (2005–2022)

	Total			***P. falciparum***			***P. vivax***		
Years	**AIR**	**IRR***	**95% CI**	**AIR**	**IRR***	**95% CI**	**AIR**	**IRR***	**95% CI**
2005	0.25	0.01	0.00–0.36	0.09	0.01	0.00–7.46	0.31	0.01	0.00–0.36
2006	35.52	1.00	0.63–1.59	8.58	1.00	0.39–2.58	29.52	1.00	0.60–1.67
2007	15.84	0.45	0.25–0.81	7.70	0.90	0.34–2.37	11.62	0.39	0.20–0.78
2008	5.15	0.14	0.06–0.37	0.20	0.02	0.00–1.96	4.89	0.17	0.06–0.43
2009	3.04	0.09	0.03–0.28	0.28	0.03	0.00–1.41	2.90	0.10	0.03–0.33
2010	0.14	0.00	0.00–0.75	0.00	0.00	0.00–0.00	0.14	0.00	0.00–0.90
2011	0.07	0.00	0.00–3.27	0.00	0.00	0.00–0.00	0.07	0.00	0.00–3.95
2013	0.06	0.00	0.00–5.08	0.00	0.00	0.00–0.00	0.06	0.00	0.00–6.12
2014	7.31	0.21	0.09–0.46	0.00	0.00	0.00–0.00	7.31	0.25	0.11–0.56
2015	21.62	0.61	0.36–1.04	0.00	0.00	0.00–0.00	21.62	0.73	0.42–1.28
2016	6.98	0.20	0.09–0.44	0.00	0.00	0.00–0.00	6.98	0.24	0.10–0.54
2017	30.17	0.85	0.52–1.38	0.21	0.02	0.00–1.86	30.06	1.02	0.61–1.69
2018	20.53	0.58	0.34–1.00	0.00	0.00	0.00–0.00	20.53	0.70	0.40–1.22
2019	52.28	1.47	0.96–2.25	46.00	5.36	2.59–11.11	29.28	0.99	0.59–1.65
2020	42.95	1.21	0.78–1.89	5.00	0.58	0.19–1.76	37.95	1.29	0.79–2.08
2021	17.90	0.50	0.29–0.89	2.72	0.32	0.08–1.24	16.54	0.56	0.31–1.02
2022	44.01	1.24	0.80–1.93	10.80	1.26	0.51–3.08	38.61	1.31	0.81–2.11

AIR Annual incidence rates (/1000 population), *IRR* incidence rate ratio

*Reference = IRR from 2006

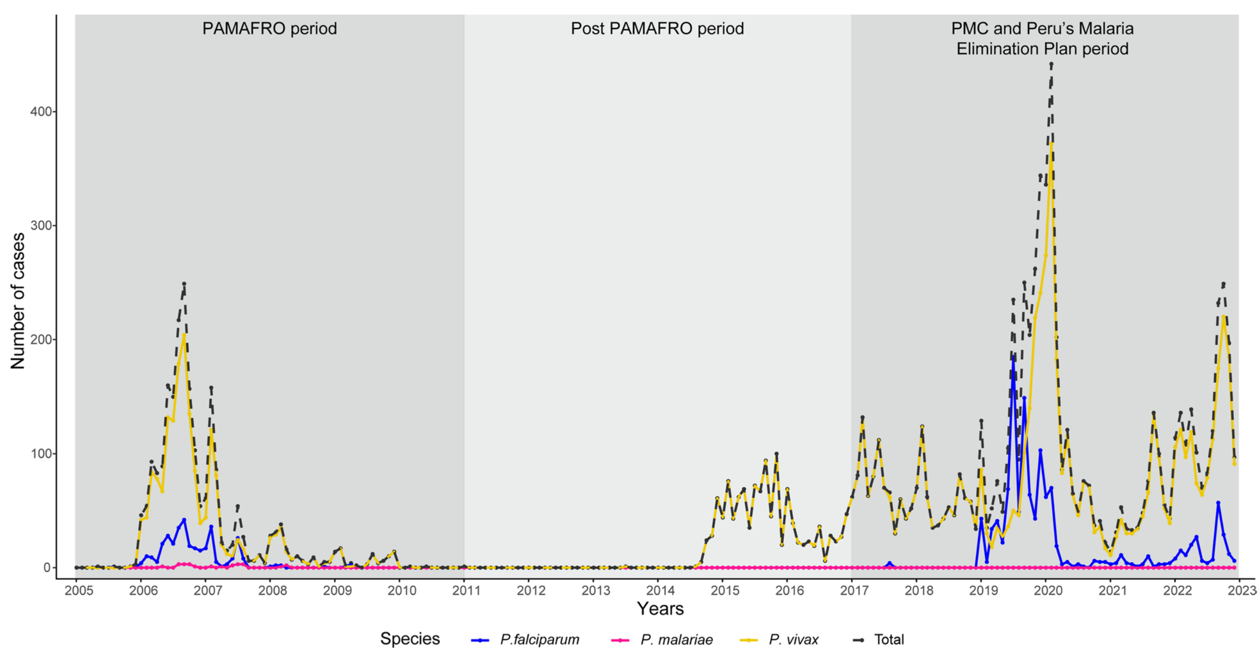

Fig. 2 Monthly and annual timeline of the number of malaria cases in Condorcanqui (2005–2022). Cases were categorized by to *P. falciparum*, *P. malariae* and *P. vivax* infections. The timeline spans three periods corresponding to malaria control programs in Peru: PAMAFRO period (2005–2010), Post-PAMAFRO period (2011–2016), and PMC and Peru's Malaria Elimination Plan period (2017–2022)

Yutupis (204) and Soledad (187). Subsequently, in the last period, 38 health facilities reported cases, with Chapiza (1,497), Nauta (810) and Yutupis (799) in middle Rio Santiago showing the largest numbers. Malaria expansion occurred in upper and lower Rio Santiago, where Pashkus and Shiringa health posts reported cases for the first time. Similarly, an increase in cases was observed in Nieva, with most occurrences reported at the Atsakus health post (Fig. 3).

Demographic characteristics of patients with malaria

Based on sociodemographic characteristics, *P. vivax, P. falciparum,* and *Plasmodium malariae* accounted for 84.87, 14.91, and 0.23% of the infections, respectively. In terms of gender, men accounted for 52.16% of the total diagnosed cases. Among the age groups, ages 0–11 presented the greatest number of cases (45.34%), followed by 18–29 years (18.62%) and 30–59 years (17.40%), while the > 60 group presented consistently lower percentages across all evaluated periods (Table 2).

Climatic variables and malaria incidence

Between 2005 and 2023, Peru experienced the following El Niño events: weak intensity in 2005, 2012, 2017, 2019 and 2020; moderate intensity in 2006 and 2018; and vigorous intensity in 2009, 2015–2016 (Fig. 4). Spearman's correlation analysis revealed significant correlations between malaria incidence and ONI at lag0 ($\rho = 0.14$, *p-value* = 0.037) and lag1 ($\rho = 0.15$, *p-value* = 0.029), corrected precipitation at lag1 ($\rho = 0.16$, *p-value* = 0.020) and lag2 ($\rho = 0.14$, *p-value* = 0.041), and minimum wind speed at lag1 ($\rho = 0.15$, *p-value* = 0.024) in Condorcanqui (see Table 3).

Discussion

This study highlights a significant increase and expansion of malaria cases in recent years and demonstrates the impact of climatic factors on the occurrence of malaria in Condorcanqui. During the first study period, there was a remarkable 99% reduction in malaria cases, as indicated by low AIR values, and a shift from reporting infections caused by *P. falciparum, P. malariae,* and *P. vivax* to exclusively reporting cases of *P. vivax*. Concurrently, the implemented PAMAFRO control programme encompassed a range of extensive activities aimed at mitigating malaria transmission. The programme significantly reduced cases, achieving a 63% decrease between 2000 and 2011 [21]. This success was attributed to comprehensive strategies, such as enhancing microscopic diagnosis, ensuring treatment availability, distributing insecticide-treated mosquito nets, training local health personnel, and promoting community participation in environmental management [11].

Nevertheless, during the second period, the abrupt cessation of PAMAFRO initiatives, coupled with favorable climatic conditions, contributed to a resurgence of malaria in the Amazon rainforest by 2014 [22]. In that year, Condorcanqui reported an increase in cases attributed to the absence of a sustainability plan following the conclusion of PAMAFRO. This province reported *P. vivax* infections exclusively, alongside a prevalent occurrence of asymptomatic and submicroscopic cases [23, 24], facilitating local transmission and endemicity [25]. The persistence of infections by this species can also be attributed to the presence of hypnozoites, which can lead to relapses in patients who do not complete the treatment or lack adequate follow-up [26, 27].

In the last study period, the continued resurgence of *P. vivax* and reintroduction of *P. falciparum* led to increase in the number of cases, resulting in AIRs of up to 52.28. In contrast, neighboring endemic regions like Ecuador and Loreto experienced relatively stable malaria cases number throughout this period**.** In Ecuador, *P. vivax* cases progressively increased from 2018 to 2022, peaking in 2021, while *P. falciparum* cases rose in 2019 before declining [28]. Conversely, in Loreto, malaria cases sharply decreased from 2017 to 2020, likely due to effective control measures. However, there was a resurgence in cases in 2021 and 2022, which reached 22,346 [29]. This increase may be attributed to heightened population movement and favourable conditions for vector proliferation.

In 2022, Rio Santiago emerged as one of the most malaria-affected districts in Peru, with 1640 cases reported. This is the sixth district with the highest incidence nationwide, behind the Andoas, Yaravi, Trompeteros, Urarinas, and Pastaza Districts, located in Loreto [30]. Within Rio Santiago, malaria predominantly affects the middle and upper areas. Among them, the native community Alianza Progreso, known for its diverse social, commercial, and economic activities, attracts individuals from other communities who stay overnight, creating an important malaria transmission hub [14]. Additionally, medical attention for the inhabitants of Alianza Progreso and three other communities is centralized at the Chapiza health post, thus explaining why this facility documented the most significant number of cases. Additionally, increased human movement for educational, occupational, and commercial purposes from the middle and upper areas of Santiago to lower Santiago and Nieva intensifies the interaction between the population and malaria vectors, including *Anopheles benarrochi* B, which has been previously reported in Condorcanqui [31, 32]. This phenomenon has contributed to a surge in cases in less affected areas, such as Shiringa and Atsakus.

On the other hand, climate plays a crucial role on malaria epidemics. During El Niño events, characterized by warmer temperatures and increased rainfall, ideal conditions are created for malaria vectors [22]. This intensifies vector activity, resulting in more frequent feeding and faster blood digestion [33]. Intense El Niño events, such as those in 1982–1983 and 1999 in Ecuador

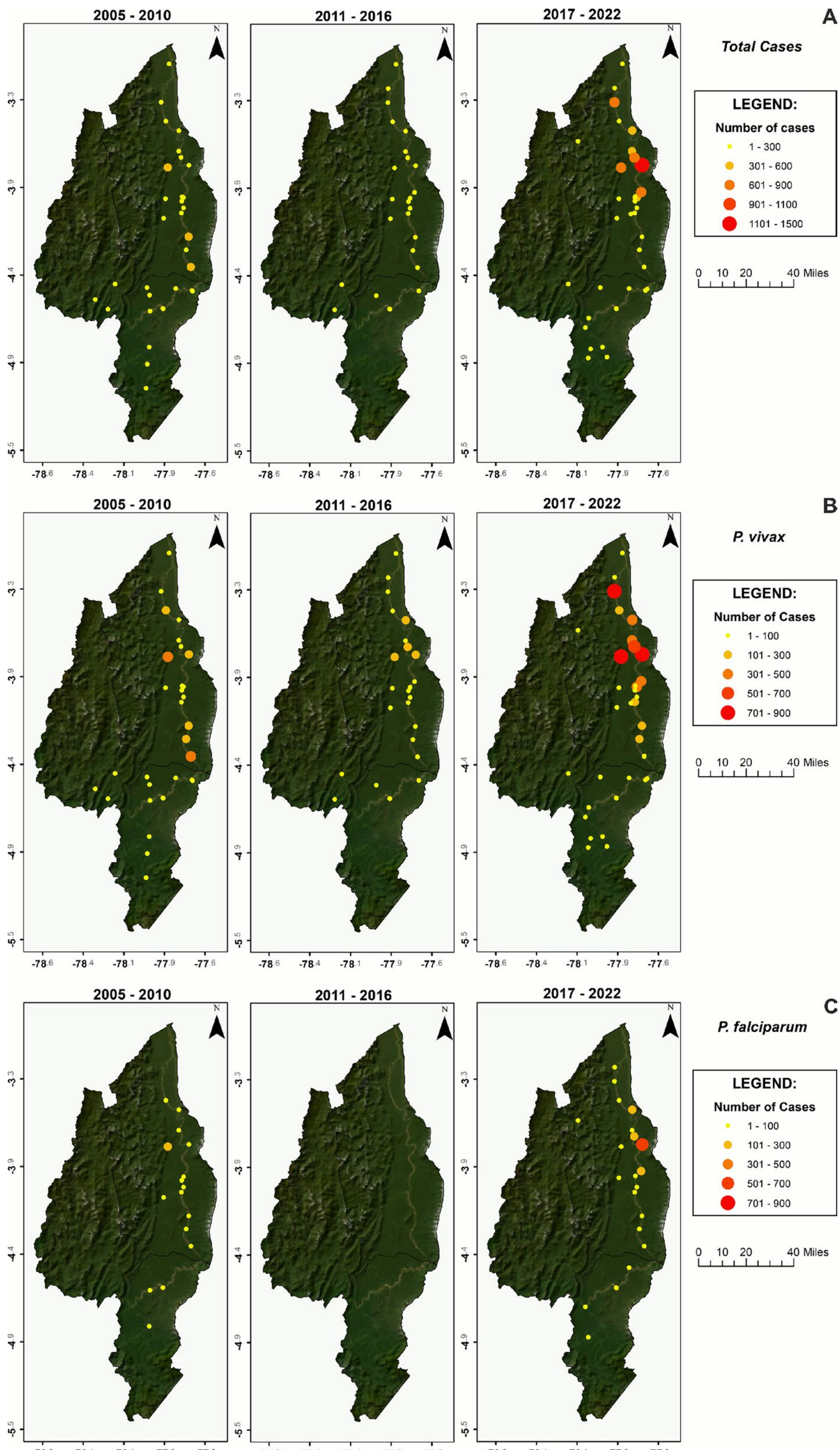

Fig. 3 Geographical distribution of malaria cases by health facilities in Condorcanqui (2005–2022). The maps are shown in intervals of six years, indicating: (**A**) Total cases, (**B**) *P. vivax* cases, and (**C**) *P. falciparum* cases

Table 2 Frequency of malaria cases in Condorcanqui (2005–2022) categorized by species, gender, and age

Characteristic		2005–2010		2011–2016		2017–2022		Total		*p-value*
		N	%	N	%	N	%	N	%	
Species	*P. falciparum*	342	15.69	0	0.00	1243	17.16	1585	14.91	0.001*
	P. malariae	24	1.10	0	0.00	0	0.00	24	0.23	0.33
	P. vivax	1814	83.21	1207	100.00	6002	82.84	9023	84.87	0.34
Gender	F	1023	46.93	551	45.65	3512	48.47	5086	47.84	0.96
	M	1157	53.07	656	54.35	3733	51.53	5546	52.16	0.96
Age group	0–11	1125	51.61	648	53.69	3048	42.07	4821	45.34	0.46
	12–17	351	16.10	173	14.33	1248	17.23	1772	16.67	0.87
	18–29	403	18.49	196	16.24	1381	19.06	1980	18.62	0.88
	30–59	268	12.29	172	14.25	1410	19.46	1850	17.40	0.41
	> 60	33	1.51	18	1.49	158	2.18	209	1.97	0.91
Total		2180		1207		7245		10632		100.00

* *p-value < 0.05 was considered significant*

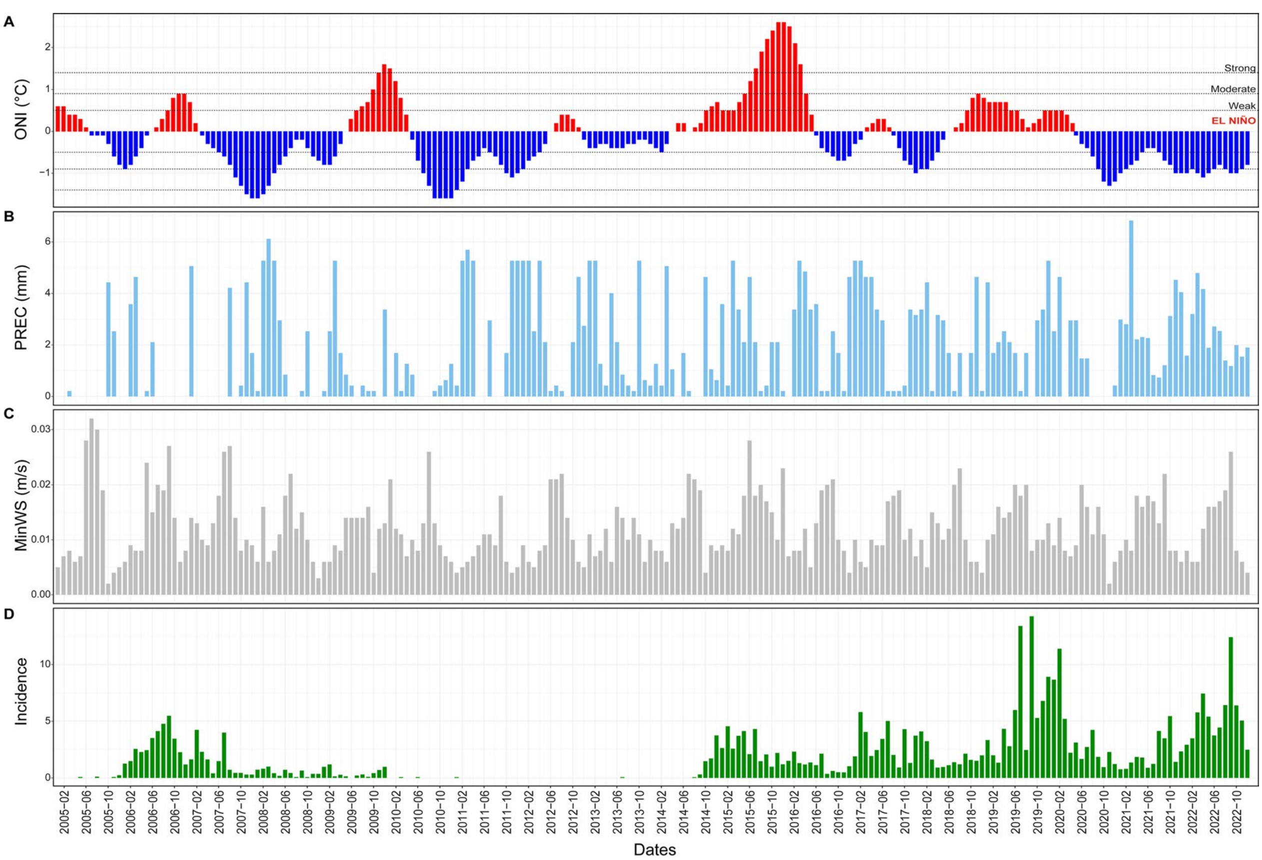

Fig. 4 Monthly series of malaria incidence and significant climatic variables in Condorcanqui (2005–2022). It illustrates: (**A**) Oceanic Niño index (°C), (**B**) corrected precipitation (mm), (**C**) minimum wind speed (m/s) and (**D**) malaria incidence

and 1998 in Tumbes, resulted in malaria transmission peaks. In contrast, La Niña events, known for colder and drier conditions, may have contributed to a decline in cases from 1998 to 2001 [34]. The findings revealed a weak positive correlation between the ONI and malaria incidence. A significant La Niña event in 2010, with an

Table 3 Spearman correlation between malaria incidence and climatic variables in Condorcanqui (2005–2022)

Variable	Lag	rho	*p-value*
Oceanic Niño Index (ONI)	Lag0	0.14	0.037*
	Lag1	0.15	0.029*
	Lag2	0.15	0.025*
Corrected Precipitation	Lag0	0.12	0.090
	Lag1	0.16	0.020*
	Lag2	0.14	0.041*
Relative humidity	Lag0	0.05	0.463
	Lag1	0.06	0.383
	Lag2	0.05	0.439
Maximum temperature	Lag0	− 0.03	0.698
	Lag1	− 0.04	0.578
	Lag2	− 0.02	0.734
Minimum temperature	Lag0	0.01	0.933
	Lag1	− 0.02	0.766
	Lag2	0.01	0.876
Maximum wind speed	Lag0	− 0.04	0.557
	Lag1	− 0.03	0.636
	Lag2	− 0.04	0.568
Minimum wind speed	Lag0	0.12	0.073
	Lag1	0.15	0.024*
	Lag2	0.12	0.086

[*] p-value < 0.05 was considered significant

ONI value of − 1.6 °C, led to unfavourable conditions and, coupled with malaria control efforts of the PAMAFRO project, suppressed transmission below a critical threshold. Conversely, intense El Niño events from 2015 to 2016 reached an ONI value of 2.6 °C. They resulted in a resurgence of malaria and endemic transmission, like what was observed in Ecuador during the 1982–1983 event [34].

Other climatic variables, such as precipitation and minimum wind speed, have shown correlations with malaria incidence. In Condorcanqui, precipitation contributes to the formation of water reservoirs, especially in areas lacking sanitation and maintenance, and people residing near these water bodies face greater exposure to malaria [35]. Studies have also revealed that larval density increases in the area as the average wind speed decreases [36]. Conversely, higher wind speeds improve air circulation, reducing the concentration of CO_2 and thereby limiting the *Anopheles* population [37]. Despite the results demonstrating a relationship between climate variables and incidence, sustained support for interventions, such as those provided by PAMAFRO, can mitigate the effects of climate change [22].

Demographic analysis revealed that the number of reported malaria cases was higher among men (52.16%) and individuals aged 0–11 years (45.34%). Malaria progresses rapidly in children under 5 years of age due to their limited immunity, rendering them particularly vulnerable to the disease [38, 39]. Studies have also demonstrated an association between malaria and malnutrition in children [38]. Therefore, the anaemia prevalence among the Awajún and Wampis populations increases their susceptibility to the disease. On the other hand, the surge in cases among young individuals, especially males, is linked to their occupational activities in indigenous communities, such as fishing, hunting, and gathering, which constantly expose them to the vector [41]. It is worth noting that studies conducted in Piura and Loreto have shown significantly lower numbers of positive malaria cases among age groups under 5 years old and between 0 and 20 years old, respectively [42, 43]. These disparities underscore the necessity of understanding malaria dynamics in a localized context, given the varied transmission conditions across different regions.

In the Rio Santiago District, timely diagnosis and treatment are challenged by difficult access to the area, compounded by geographical isolation, long distances, and, limited transportation options, which affect the ability of the health system to efficiently manage malaria outbreaks [40]. Malaria surveillance in Condorcanqui is conducted by trained staff at local health post, who collect blood samples from suspected cases and prepare the blood smear slides. Since most health posts lack laboratory facilities, these slides are typically sent to nearby health centers for microscopic diagnosis. This process, while functional, can lead to delays in both diagnosis and treatment due to transportation and communication constraints.

Once diagnosed, patients receive treatment tailored to the specific parasite species. Although severe malaria cases are rare in Condorcanqui are rare, patients requiring hospitalization or advanced care are transferred to the main hospital in Nieva district, which is equipped to provide complex medical treatment.

Finally, it is vital to acknowledge the limitations of the study. Data collection relied on records from DIRESA-Amazonas, which primarily uses PCD based on microscopic and rapid diagnostic test (RDTs). Microscopy, while widely accessible, detects parasitaemia only above 10 parasites/μL, often missing asymptomatic carriers with low parasite densities that molecular techniques—10–100 times more sensitive—can identify [44]. The use of RDTs introduces further limitations, as some fail to detect certain genetic deletions, leading to false negatives. Lastly, the lack of recorded geographic coordinates for all health posts hindered accurate mapping of four locations, limiting the ability to visualize the dispersion of cases in those areas.

Conclusions

Malaria incidence in Condorcanqui has risen alarmingly over the past five years, linked to climatic factors such as Oceanic Niño Index (ONI), precipitation, and minimum wind speed. Without timely preventive measures, the region faces a high risk of further increase in cases.

Effective control, however, requires more than biomedical interventions; it demands a focus on the social, economic, and political factors that exacerbate vulnerability. Issues such as poverty, limited healthcare access, and inadequate health education significantly heighten community susceptibility, underscoring the need for socioeconomic development initiatives to mitigate these risks.

A multi-sectoral approach is essential, engaging community organizations, healthcare providers, educational institutions, and government agencies in a cohesive effort to build a comprehensive response. Ensuring the continuity of control programmes and policies and adapting efforts to changing regional needs is also critical to sustain long-term progress. Only through this coordinated and inclusive strategy can we effectively reduce the malaria burden in the region and other affected areas of Peru.

Abbreviations

PAMAFRO	The Malaria Control Project in the Border Areas of the Andean Region
PMC	Zero Malaria Program
ACD	Active case detection
PCD	Passive case detection
DIRESA–Amazonas	Regional directorate of health-amazonas
AIR	Annual incidence rate
IRR	Incidence rate ratio
ENSO	El Niño-Southern Oscillation
ONI	Oceanic Niño index

Acknowledgements

The authors would like to thank all the health personnel from DIRESA-Amazonas who collected the data and care for the population with malaria in the endemic areas of Amazonas.

Disclaimer

The views expressed in this article are those of the author and do not necessarily reflect the official policy or position of the Department of the Navy, Department of Defense, or the U.S. Government.

Author contributions

Conceptualization of the study: MSS, HOV, DG, SMC. Data curation: MSS, FB, FGH. Methodology and formal analysis: MSS, FB, HOV, SMC. Investigation: MSS, FGH, DG. Supervision: HOV, DG, SMC. Writing-Original Draft Preparation: MSS, FB. Writing-Review and Editing: FGH, HOV, DG, SMC. Funding acquisition: HOV, SMC.

Funding

The study was carried out with the support of the project with Contract No. PE501078584-2022-PROCIENCIA "Vigilancia genómica de *Plasmodium* y su impacto en el control de la malaria en comunidades nativas de la región Condorcanqui, Amazonas"—MALARIA. This work was also supported by the US DoD Armed Forces Health Surveillance Division, Global Emerging Infections Surveillance Branch (AFHSD/GEIS), PROMIS ID P0091_24_N6.

Availability of data and materials

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

The study is part of the project with Contract No. PE501078584-2022-PROCIENCIA "Vigilancia genómica de *Plasmodium* y su impacto en el control de la malaria en comunidades nativas de la región Condorcanqui, Amazonas" – MALARIA, with ethical approval from Universidad Nacional Toribio Rodriguez de Mendoza de Amazonas.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Author details

[1]Instituto de Investigación de Enfermedades Tropicales (IET), Universidad Nacional Toribio Rodríguez de Mendoza de Amazonas (UNTRM), Chachapoyas, Peru. [2]Facultad de Ingeniería y Ciencias Agrarias, Universidad Nacional Toribio Rodríguez de Mendoza de Amazonas (UNTRM), Chachapoyas, Perú. [3]Department of Parasitology, U.S. Naval Medical Research Unit SOUTH (NAMRU SOUTH), Lima, Peru. [4]Departamento de Ciencias Celulares y Moleculares, Facultad de Ciencias e Ingeniería, Universidad Peruana Cayetano Heredia, Lima, Peru. [5]Instituto de Medicina Tropical Alexander von Humboldt, Universidad Peruana Cayetano Heredia, Lima, Peru. [6]Facultad de Medicina, Universidad Nacional Toribio Rodríguez de Mendoza de Amazonas (UNTRM), Chachapoyas, Peru.

Received: 21 July 2024 Accepted: 22 November 2024
Published online: 18 December 2024

References

1. WHO. World malaria report 2023. Geneva: World Health Organization; 2023.
2. Benavides M. Amazonía Peruana. Instituto del Bien Común. 2009. https://www2.congreso.gob.pe/sicr/cendocbib/con2_uibd.nsf/F8440238F27FDE78052575D600683BBE/$FILE/Amazonia_Peruana.pdf
3. Rosas-Aguirre A, Llanos-Cuentas A, Speybroeck N, Cook J, Contreras-Mancilla J, Soto V, et al. Assessing malaria transmission in a low endemicity area of north-western Peru. Malar J. 2013;12:339.
4. Chowell G, Munayco CV, Escalante AA, McKenzie FE. The spatial and temporal patterns of falciparum and vivax malaria in Perú: 1994–2006. Malar J. 2009;8:142.
5. Ministerio de Salud. Impacto económico de la malaria en el Perú. Lima, Perú; 1999 p. 124. https://bvs.minsa.gob.pe/local/minsa/1763.pdf
6. Cabezas C, Neyra D, Ruebush TK. El proceso de adecuación y cambio en la política del tratamiento de la malaria por *Plasmodium falciparum* en el Perú. 1999–2001. Rev Peru Med Exp Salud Pública. 2003;20:162–71.
7. Ruebush TK, Neyra D, Cabezas C. Modifying national malaria treatment policies in Peru. J Public Health Policy. 2004;25:328–45.
8. Ministerio de Salud. Plan hacia la eliminación de la Malaria en el Perú 2022–2030. 2022. https://bvs.minsa.gob.pe/local/fi-admin/RM-034-2022%20MINSA.pdf
9. Rosas-Aguirre A, Gamboa D, Manrique P, Conn JE, Moreno M, Lescano AG, et al. Epidemiology of *Plasmodium vivax* malaria in Peru. Am J Trop Med Hyg. 2016;95:133–44.

10. Organismo Andino de Salud. "Compartiendo lecciones aprendidas". Proyecto Control de la Malaria en las Zonas Fronterizas de la Región Andina: Un Enfoque Comunitario - PAMAFRO. 2009. https://www.orasconhu.org/documentos/01%20-%20LIBRO%20LECCIONES%20APRENDIDAS%20FINAL%202009%20-3.pdf
11. Soto-Calle V, Rosas-Aguirre A, Llanos-Cuentas A, Abatih E, DeDeken R, Rodriguez H, et al. Spatio-temporal analysis of malaria incidence in the Peruvian Amazon Region between 2002 and 2013. Sci Rep. 2017;7:40350.
12. Torres K, Ferreira MU, Castro MC, Escalante AA, Conn JE, Villasis E, et al. Malaria resilience in South America: epidemiology, vector biology, and immunology insights from the Amazonian International Center of Excellence in Malaria Research Network in Peru and Brazil. Am J Trop Med Hyg. 2022;107:168–81.
13. Ministerio de Salud. Número de casos de malaria, Perú, 2020–2024*. Centro Nacional de Epidemiología, Prevención y Control de Enfermedades.; 2024 p. 15. https://www.dge.gob.pe/portal/docs/vigilancia/sala/2024/SE18/malaria.pdf
14. Montenegro CC, Bustamante-Chauca TP, Pajuelo Reyes C, Bernal M, Gonzales L, Tapia-Limonchi R, et al. *Plasmodium falciparum* outbreak in native communities of Condorcanqui, Amazonas. Perú Malar J. 2021;20:88.
15. WHO. A framework for malaria elimination. Geneva: World Health Organization; 2017.
16. Instituto Nacional de Estadística e Informática. Población proyectada. Sistema de Información Regional para la Toma de Decisiones. Lima, Perú; 2023. https://www.inei.gob.pe/estadisticas-indice-tematico/
17. Municipalidad Distrital de Río Santiago. Plan de desarrollo concertado del distrito de Río Santiago al 2021. 2021 p. 68. https://muniriosantiago.gob.pe/demuna.html
18. Instituto del Mar del Perú. Índice Niño Oceánico (ONI). 2024. https://www.imarpe.gob.pe/imarpe/index2.php?id_seccion=I0178090500000000000000
19. Duque C, Lubinda M, Matoba J, Sing'anga C, Stevenson J, Shields T, et al. Impact of aerial humidity on seasonal malaria: an ecological study in Zambia. Malar J. 2022;21:325.
20. Zhang Y, Liu S, Bai Z. A periodic malaria model with two delays. Physica A. 2020;541:123327.
21. Pan American Health Organization. Informe de la situación de la malaria en las Américas 2014—Perú, 2016. Washington, D.C.; 2017 p. 116. https://iris.paho.org/handle/10665.2/33881
22. Janko MM, Recalde-Coronel GC, Damasceno CP, Salmón-Mulanovich G, Barbieri AF, Lescano AG, et al. The impact of sustained malaria control in the Loreto region of Peru: a retrospective, observational, spatially-varying interrupted time series analysis of the PAMAFRO program. Lancet Reg Health Am. 2023;20:100477.
23. Pajuelo-Reyes C, Valencia HJ, Montenegro CC, Quezada E, Gonzales L, Cruz N, et al. Epidemiological analysis of COVID-19 cases in native Amazonian communities from Peru. Epidemiologia. 2021;2:490–501.
24. Rojas LM. Factores asociados a la prevalencia de malaria en tres comunidades nativas del distrito de Río Santiago, Condorcanqui. San Martín De Porres: Universidad Peruana Cayetano Heredia; 2024.
25. Martin TCS, Vinetz JM. Asymptomatic *Plasmodium vivax* parasitaemia in the low-transmission setting: the role for a population-based transmission-blocking vaccine for malaria elimination. Malar J. 2018;17:89.
26. Delgado-Ratto C, Soto-Calle VE, Van den Eede P, Gamboa D, Rosas A, Abatih EN, et al. Population structure and spatio-temporal transmission dynamics of *Plasmodium vivax* after radical cure treatment in a rural village of the Peruvian Amazon. Malar J. 2014;13:8.
27. Rovira-Vallbona E, Contreras-Mancilla JJ, Ramirez R, Guzmán-Guzmán M, Carrasco-Escobar G, Llanos-Cuentas A, et al. Predominance of asymptomatic and sub-microscopic infections characterizes the *Plasmodium* gametocyte reservoir in the Peruvian Amazon. PLoS Negl Trop Dis. 2017;11:e0005674.
28. Cabas D, Caluña W, Herrera F, Herrera J. Epidemiología de la Malaria en Ecuador de 2018–2022. RECIAMUC. 2023. https://doi.org/10.2682/reciamuc/7.(1).enero.2023.151-162.
29. Ministerio de Salud. Número de casos de malaria, Perú 2019–2022. Centro Nacional de Epidemiología, Prevención y Control de Enfermedades. 2022. https://www.dge.gob.pe/portal/docs/vigilancia/sala/2022/SE52/malaria.pdf
30. Ministerio de Salud. Número de casos de malaria, Perú, 2020–2023*. Centro Nacional de Epidemiología, Prevención y Control de Enfermedades.; 2023 p. 12. https://www.dge.gob.pe/portal/docs/vigilancia/sala/2023/SE52/malaria.pdf
31. Villegas-Pingo M, Zumaeta J, Rojas LM, Gonzales L, Tapia-Limochi R, Moreno M, et al. Natural *Plasmodium* infection of *Anopheles benarrochi* B (Diptera: Culicidae) in native communities of the Province of Condorcanqui, Amazonas-Peru. Research Square. 2023 https://www.researchsquare.com/article/rs-3409121/v1
32. Ramírez IJ, Lee J, Grady SC. Mapping multi-disease risk during El Niño: an ecosyndemic approach. Int J Environ Res Public Health. 2018;15:2639.
33. Jones AE, Wort UU, Morse AP, Hastings IM, Gagnon AS. Climate prediction of El Niño malaria epidemics in north-west Tanzania. Malar J. 2007;6:162.
34. Krisher LK, Krisher J, Ambuludi M, Arichabala A, Beltrán-Ayala E, Navarrete P, et al. Successful malaria elimination in the Ecuador-Peru border region: epidemiology and lessons learned. Malar J. 2016;15:573.
35. Stresman GH. Beyond temperature and precipitation: ecological risk factors that modify malaria transmission. Acta Trop. 2010;116:167–72.
36. Fimia Duarte R, Osés Rodríguez R, Castillo Cuencas JC, Iannacone J, Alarcón-Elbal PM, Paul M, et al. Influencia de algunas variables meteorológicas en la modelación de la dinámica poblacional de mosquitos (Diptera: Culicidae) con importancia entomoepidemiológica en la provincia Villa Clara, Cuba. Neotrop Helminthol. 2018;12:47–62.
37. Endo N, Eltahir EAB. Modelling and observing the role of wind in anopheles population dynamics around a reservoir. Malar J. 2018;17:48.
38. Roberts D, Matthews G. Risk factors of malaria in children under the age of five years old in Uganda. Malar J. 2016;15:246.
39. Rosado J, Carrasco-Escobar G, Nolasco O, Garro K, Rodriguez-Ferruci H, Guzman-Guzman M, et al. Malaria transmission structure in the Peruvian Amazon through antibody signatures to *Plasmodium vivax*. PLoS Negl Trop Dis. 2022;16:e0010415.
40. Protopopoff N, Bortel WV, Speybroeck N, Geertruyden JPV, Baza D, D'Alessandro U, et al. Ranking malaria risk factors to guide malaria control efforts in African Highlands. PLoS ONE. 2009;4(11):e8022.
41. Vittor AY, Pan W, Gilman RH, Tielsch J, Glass G, Shields T, et al. Linking deforestation to malaria in the Amazon: characterization of the breeding habitat of the principal malaria vector, *Anopheles darlingi*. Am J Trop Med Hyg. 2009;81:5–12.
42. Fernandez-Camacho B, Peña-Calero B, Guillermo-Roman M, Ruiz-Cabrejos J, Barboza JL, Bartolini-Arana L, et al. Malaria seroepidemiology in very low transmission settings in the Peruvian Amazon. Sci Rep. 2024;14:2806.
43. Guthmann JP, Llanos-Cuentas A, Palacios A, Hall AJ. Environmental factors as determinants of malaria risk. A descriptive study on the northern coast of Peru. Trop Med Int Health. 2002;7:518–25.
44. Lazrek Y, Florimond C, Volney B, Discours M, Mosnier E, Houzé S, et al. Molecular detection of human *Plasmodium* species using a multiplex real time PCR. Sci Rep. 2023;13:11388.

Publisher's Note