

Seasonal time-series forecasting of malaria transmission peaks for optimising antimalarial supply chains: empirical validation with ERA5 and clinical data at Mefou-Assi, Cameroon

Prévision saisonnière des pics de transmission du paludisme par séries temporelles pour l'optimisation des chaînes d'approvisionnement en antipaludiques : validation empirique avec données ERA5 et cliniques à Mefou-Assi, Cameroun

Thematic Track:

- ▶ Track 1 — Renewable Energies, Smart Grids & Energy Intelligence
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1. RÉSUMÉ / ABSTRACT

Résumé (Français)

Le paludisme demeure un défi majeur de santé publique en zone tropicale forestière, où les ruptures de stock de tests de diagnostic rapide (TDR) et de combinaisons thérapeutiques à base d'artémisinine (CTA) lors des recrudescences épidémiques dégradent la prise en charge des cas. Cette étude développe un cadre de prévision par séries temporelles couplant cinq années (2021–2025) de données cliniques consolidées (CS Pyramide et CS CHPSF, Mefou-Assi, Cameroun) et de réanalyse pluviométrique journalière ERA5, afin de tester quatre hypothèses. H1 postule une structure saisonnière bimodale. H2 postule que l'intensité pluviométrique journalière n'explique pas les pics d'incidence : la petite saison des pluies est plus intense (7,42 mm/j) que la grande saison (5,86 mm/j), qui produit pourtant le pic le plus élevé. H3 postule un écart systématique entre l'indice d'amplitude observé et celui attendu de la seule pluviométrie, révélant un résidu non climatique. H4 postule que la seconde chute des mangues mûres, entre mi-février et mai, coïncide avec le pic anormal de mars-avril, agissant comme amplificateur éco-phénologique. Les résultats confirment la bimodalité (pic primaire mars, 91,0 cas ; pic secondaire octobre, 79,0 cas), rejettent l'explication pluviométrique pure, révèlent un excès d'amplitude moyen de +48 % (indice observé 1,17 contre 0,79 attendu) et confirment la concordance phénologique sur cinq années sur cinq. Ce cadre fonde un système d'alerte précoce permettant d'anticiper le repositionnement des stocks de TDR et de CTA de deux à trois semaines, renforçant la résilience climatique des chaînes d'approvisionnement en antipaludiques.

Abstract (English)

Malaria remains a major public-health challenge in tropical forested settings, where antimalarial commodity stock-outs during epidemic surges degrade case management. This study develops a time-series forecasting framework combining five years (2021–2025) of consolidated clinical data (CS Pyramide and CS CHPSF, Mefou-Assi, Cameroon) with daily ERA5 rainfall reanalysis (Open-Meteo) to formalise and empirically test four hypotheses. H1 posits a bimodal seasonal transmission structure synchronised with the two Guineo-equatorial rainy seasons. H2 posits that

the mean daily rainfall-intensity ratio fails to explain incidence-peak intensities, since the minor rainy season shows a higher daily intensity (7.42 mm/day) than the major season (5.86 mm/day) even though the latter produces the higher case peak, rejecting a purely meteorological explanation. H3 posits a systematic gap between the relative transmission-amplitude index and the ratio expected from rainfall intensity alone, revealing a residual, non-climatic amplification signal. H4 posits that the phenology of the second mature-mango fall coincides specifically with the abnormally elevated March–April peak, acting as a major eco-phenological amplifier. Results confirm bimodality (primary peak in March, 91.0 cases; secondary peak in October, 79.0 cases), invalidate the pure rainfall explanation (H2), reveal a mean amplitude excess of +48% (observed index 1.17 versus 0.79 expected; H3), and establish the temporal concordance of the mango-fall calendar with the primary peak (H4). This framework forms the core of an early-warning system enabling a two-to-three-week anticipatory repositioning of RDT and ACT stocks, strengthening the climate resilience of antimalarial supply chains in tropical forested settings.

Keywords: time-series forecasting; ERA5 reanalysis; malaria; H1–H4 hypotheses; supply-chain optimisation; early-warning system; phenology; Cameroon

2. INTRODUCTION

Malaria remains a major endemic disease in sub-Saharan Africa, with an estimated 263 million cases and 597,000 deaths in 2023, nearly 76% of which involve children under five years of age [1]. In humid tropical settings, *Plasmodium* transmission is modulated by complex climatic factors (rainfall, temperature, relative humidity) that structure the developmental cycle of *Anopheles* vectors. Cameroon, a hyperendemic country, records perennial transmission whose seasonal intensity is governed by the bimodal rainfall regime characteristic of the Guineo-equatorial zone [2]. The forested localities of the southern part of the country maintain persistently high transmission despite vector-control interventions, underscoring the need for predictive tools capable of capturing the local ecological determinants of seasonality [3].

Reliable anticipation of transmission peaks is a prerequisite for resilient medical logistics. Stock-outs of rapid diagnostic tests (RDTs) and artemisinin-based combination therapies (ACTs) during epidemic surges degrade the performance of case management and amplify morbidity, while overstocking during low-transmission windows generates waste and opportunity costs. Time-series models coupling high-resolution meteorological reanalysis with local clinical surveillance can thus serve as operational decision-support tools for supply chains at the health-facility and district levels.

In Mefou-Assi (lat. 3°52'N, long. 11°31'E), a recurring empirical observation links the second fall of ripe mangoes (*Mangifera indica*), occurring between mid-February and May, to a marked resurgence in malaria incidence. Fallen fruit and their sugary exudates constitute sources of free sugars that extend the longevity, fecundity, and vectorial capacity of *Anopheles* mosquitoes [4], [5]. Building on consolidated clinical and meteorological observations from 2021 to 2025, this work re-examines and formalises four testable hypotheses:

H1 — Bimodal seasonal profile. The seasonal profile of malaria cases in Mefou-Assi displays a robust bimodal structure, fluctuating in synchrony with the two rainy seasons of the Guineo-equatorial zone.

H2 — Insufficiency of the daily rainfall ratio. The mean daily rainfall-intensity ratio (computed from ERA5 reanalysis) does not explain the intensities of the incidence peaks: the minor rainy season shows a higher daily intensity (mm/day) than the major rainy season, even though the major season produces the higher case peak, which rejects a purely meteorological explanation.

H3 — Residual amplification signal. There is a systematic discrepancy between the relative transmission-amplitude index and the ratio expected from daily rainfall intensity alone, revealing a residual, non-climatic amplification signal.

H4 — Eco-phenological concordance. The suspected phenology (the second fall of ripe mangoes and their sugary exudates) shows a seasonal occurrence that specifically coincides with the

abnormally elevated March–April incidence peak, acting as the major eco-phenological amplifier of transmission.

The contribution of this study is twofold. First, we build and validate a set of operational indicators from five years of consolidated Monthly Activity Reports (MARs) and georeferenced daily ERA5 rainfall data, demonstrating that a purely rainfall-based model is insufficient to predict peak intensity (H1–H2). Second, we show how the residual amplitude signal, explained by the eco-phenological concordance of the mango fall, can be exploited to refine the schedule of preventive stock repositioning (H3–H4), thereby strengthening the climate resilience of local antimalarial supply chains.

Note: the hospital-incidence empirical data used in this study are the subject of a complementary analysis from the perspective of the epistemology of endogenous knowledge, as part of a paper submitted to the journal Théorétiques.

The remainder of this paper is organised as follows: Section 3 reviews relevant work on empirical time-series modelling of malaria, eco-phenological covariates, and health-logistics optimisation; Section 4 details the data sources, indicator construction, and the operational formalisation of H1 to H4; Section 5 presents the results, hypothesis by hypothesis; Section 6 discusses the operational implications for supply-chain resilience; Section 7 concludes.

3. LITERATURE REVIEW / STATE OF THE ART

3.1 Time Series and Climatic Drivers of Malaria Seasonality

Malaria epidemiology in Cameroon is marked by strong heterogeneity, ranging from perennial transmission in the forested and coastal south to seasonal, unstable transmission in the Sudano-Sahelian north [2]. In the forested localities of the southern region, entomological and parasitological surveys repeatedly report persistently high transmission intensities, attributable to a favourable Guineo-equatorial climate and the limited long-term efficacy of insecticide-treated nets [3]. At the regional scale, rainfall and temperature are well-established statistical determinants of malaria seasonality in sub-Saharan Africa, with transmission maintained within a thermal window of approximately 15–40 °C and bounded by rainfall thresholds that vary by climatic zone [6].

Using a mechanistic hydrology–transmission model, Bomblies [7] demonstrated that the temporal distribution of rainfall (rather than its cumulative volume) determines the persistence of larval habitats: sustained daily intensity maintains the hydric saturation and physico-chemical stability of temporary pools. This distinction between volume and intensity underlies the normalised daily rainfall indicator built here to test H2. ERA5 reanalysis products have become a standard meteorological source for epidemiological modelling in regions with low station density, owing to their continuous temporal coverage, homogeneous spatial resolution ($\approx 0.1^\circ$), and validated performance against station observations in Central Africa.

3.2 Eco-Phenological Covariates and Vectorial Capacity

Independently of rainfall, the availability of plant-derived sugar sources is a well-established determinant of *Anopheles* vector fitness: sugar feeding extends adult longevity, increases flight capacity, and enhances fecundity, thereby raising vectorial capacity [8]. Field experiments conducted in Mali demonstrated strong attraction of *Anopheles gambiae* to local fruits and seedpods, a behaviour subsequently exploited in attractive toxic sugar bait (ATSB) strategies [4]. Electrophysiological and behavioural assays confirmed that mango-derived volatile compounds specifically trigger strong olfactory and landing responses in female *An. gambiae* [5], while comparative trials in western Kenya confirmed the competitiveness of fruit-derived attractants relative to synthetic formulations [9]. Beyond survival and fecundity, the composition of the sugar diet also modulates the vector's ability to transmit the parasite itself, a mechanism that reinforces the plausible link between fruit availability and transmission intensity [10]. These findings justify including, in

predictive models of seasonal transmission peaks, a phenological covariate for the time window corresponding to the mango fall, as operationalised here to test H4.

3.3 Predictive Analytics and Health Supply-Chain Resilience

Few studies combine multi-year clinical surveillance, high-resolution climate reanalysis, and local phenological observation to quantify residual transmission asymmetry at the village scale and translate the resulting signal into anticipation lead times usable for medical logistics. Existing early-warning systems generally rely on time-lagged rainfall or temperature thresholds and rarely incorporate fruiting calendars that can shift the peak by several weeks relative to purely climatic expectations. The present work addresses this gap by constructing a relative amplitude index that isolates the non-climatic residual (H3) and by demonstrating its usefulness, combined with eco-phenological concordance (H4), for the preventive repositioning of RDTs and ACTs, an operational contribution to climate-resilient health logistics in tropical forested settings.

4. MATERIALS AND METHODS

4.1 Study Area and Clinical Datasets

Mefou-Assi is a semi-forested village in the Mbankomo commune, located less than 4 km southeast of Yaoundé. The region has a four-season Guineo-equatorial climate: major rainy season (March–June), minor dry season (July–August), minor rainy season (September–November), and major dry season (December–February). Mean annual rainfall over the study period is approximately 1,700 mm (ERA5, 2021–2025). Vegetation is dominated by evergreen forest interspersed with residential mango orchards, whose phenology serves as the covariate for H4.

Epidemiological data were drawn from the consolidated Monthly Activity Reports (MARs) of the CS Pyramide and CS CHPSF health centres. Merging the two registers minimises the under-reporting bias specific to each facility. The MAR records monthly cases confirmed by thick blood smear or RDT. The series covers the period from 1 January 2021 to 31 December 2025 (60 monthly observations per centre, 120 observations in total). Table 1 illustrates the consolidated series for 2021 as an example of the dataset structure.

*Table 1 — Consolidated monthly series of malaria cases, temperature, and rainfall (CS Pyramide + CS CHPSF, 2021).
Source: health-centre MARs and ERA5 reanalysis (Open-Meteo).*

Month	CS Pyramide	CS CHPSF	Total cases	Mean T. (°C)	Rainfall (mm)
January	14	42	56	24.5	17.9
February	37	61	98	25.1	9.1
March	37	46	83	24.1	104.6
April	43	59	102	23.8	202.5
May	18	40	58	23.3	180.4
June	24	20	44	22.8	200.2
July	26	28	54	22.7	109.9
August	15	36	51	22.7	206.8
September	31	45	76	22.5	339.5
October	44	47	91	22.6	326.1
November	30	22	52	22.9	159.6
December	27	31	58	24.0	46.2

4.2 ERA5 Rainfall Data Processing

Daily rainfall values were extracted from the Open-Meteo climatological archive (ERA5 reanalysis, 0.1° spatial resolution) for the site coordinates (3.867°N; 11.517°E) over the period 2021–2025. Daily series were aggregated into monthly totals, then into seasonal sums corresponding to the major rainy season (March–June, 122 days) and the minor rainy season (September–November, 91 days).

4.3 Indicator Construction and Hypothesis Formalisation

H1 is operationalised through the construction of a mean seasonal profile: for each calendar month, the arithmetic mean of consolidated cases over 2021–2025 provides the structural seasonal signature of transmission.

H2 relies on a mean daily rainfall-intensity indicator that normalises seasons of unequal length:

$$P_{\text{daily}} = \frac{P_{\text{season}}}{D_{\text{season}}} \quad (1)$$

where P_{season} is the sum of monthly rainfall for the season and D_{season} its number of calendar days (122 for the major season, 91 for the minor season). H2 is retained if the ratio $P_{\text{daily}}(\text{major}) / P_{\text{daily}}(\text{minor}) < 1$, while the case peak of the major season exceeds that of the minor season, a situation that rejects a purely rainfall-based explanation of peak amplitude.

H3 is operationalised through a relative amplitude index comparing the transmission maxima of the two seasonal windows:

$$I_{\text{amplitude}} = \frac{\text{Peak}(\text{March–April})}{\text{Peak}(\text{Sept–Oct})} \quad (2)$$

If daily rainfall intensity were the sole determinant of peak amplitude, $I_{\text{amplitude}}$ should be close to the daily rainfall-intensity ratio derived from Equation (1). A systematic positive gap between the observed index and this expected ratio constitutes the statistical signature of a non-climatic amplification factor and provides the residual signal exploited by the early-warning rule (H3).

H4 is operationalised through a temporal concordance variable: the documented window of the second ripe-mango fall (mid-February to May) is compared, year by year, with the month of the primary case peak. Concordance is validated when the primary peak (March–April) systematically falls within this documented phenological window, reinforcing the interpretation of the residual isolated by H3 as an eco-phenological amplifier rather than mere statistical noise.

5. RESULTS

5.1 Bimodal Seasonal Structure (Validation of H1)

The consolidated analysis of malaria cases over 2021–2025 reveals a clear bimodal transmission structure (see Figure 1). The mean seasonal profile shows two distinct peaks: a primary peak in March (mean: 91.0 cases) extended by an elevated plateau in April (79.6 cases), and a secondary peak in October (mean: 79.0 cases), preceded by an upturn in September (69.0 cases). Transmission minima correspond to the minor dry season (July–August, mean: 55.5 cases/month) and, to a lesser extent, the major dry season (December–February, mean: 76.1 cases/month). This bimodal alternation, synchronous with the two Guineo-equatorial rainy seasons, validates H1.

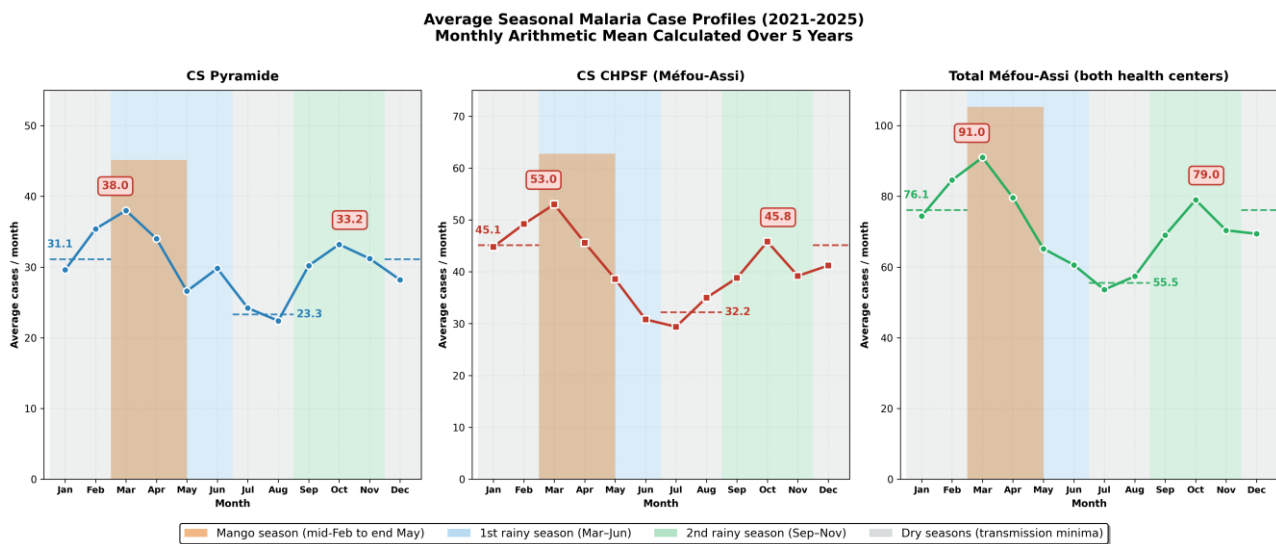


Figure 1 — Mean seasonal malaria case profiles by health centre and combined total, with rainy-season, dry-season and mango-season windows, Mefou-Assi (2021–2025).

5.2 Comparative Rainfall-Intensity Analysis (Rejection of the Pure Rainfall Model — H2)

Table 2 presents the mean daily rainfall per season and per year, calculated using Equation (1). The minor rainy season shows a mean daily intensity of 7.42 mm/day, higher than that of the major season (5.86 mm/day), giving a mean major/minor ratio of 0.79. This pattern, in which the minor season is systematically more intense in daily rainfall, holds for four of the five years observed. Yet it is the major season that produces the higher case peak (see 5.1 and 5.3): daily rainfall intensity is therefore insufficient to explain the relative intensity of the two incidence peaks, which rejects the purely meteorological explanation and validates H2 in its insufficiency formulation.

Table 2 — Mean daily rainfall per season at Mefou-Assi (2021–2025). Source: calculations from Open-Meteo ERA5 data.

Year	Major season (mm/day)	Minor season (mm/day)	Ratio (major/minor)
2021	5.64	9.07	0.62
2022	6.31	6.45	0.98
2023	6.58	7.52	0.87
2024	4.81	6.83	0.70
2025	5.95	7.24	0.82
Mean 2021–2025	5.86	7.42	0.79

5.3 Relative Amplitude Index and Residual Signal (Validation of H3)

Despite lower daily rainfall intensity, the major season systematically generates a higher transmission peak. Table 3 presents the relative amplitude index calculated using Equation (2). The observed mean index of 1.17 is far above the ratio expected on the basis of daily rainfall alone (0.79), corresponding to a mean amplitude excess of +48%. Four of the five years show an index above 1.0, with 2022 (0.78) being the exception least marked by the inter-seasonal rainfall gap. This systematic gap validates H3 and provides the non-climatic residual signal exploited for early warning.

Table 3 — Relative amplitude index of malaria transmission at Mefou-Assi (2021–2025). Value expected from rainfall alone = 0.79.

Year	March–April peak	Sept–Oct peak	Index $I_{\text{amplitude}}$
2021	102	91	1.12
2022	76	98	0.78

Year	March–April peak	Sept–Oct peak	Index I _{amplitude}
2023	92	62	1.48
2024	103	82	1.26
2025	101	82	1.23
Mean 2021–2025	94.8	83.0	1.17

5.4 Eco-Phenological Concordance and Early-Warning Trigger (Validation of H4)

In Mefou-Assi, the mango tree (*Mangifera indica*) flowers in November–December and fruits in February–March. The second fall of ripe mangoes, documented from mid-February and extending to May, releases through rapid decomposition exudates rich in fermentable sugars that selectively attract female *Anopheles* [4]. Table 4 compares, year by year, the month of the primary case peak with this documented phenological window: temporal concordance holds for each of the five study years, with the primary peak systematically occurring in March or April, within the mango-fall window.

Table 4 — Concordance between the month of the primary case peak and the documented phenological window of mango fall, Mefou-Assi (2021–2025).

Year	Month of primary peak	Phenological window (mangoes)	Concordance
2021	April	Mid-February – May	Yes
2022	March	Mid-February – May	Yes
2023	April	Mid-February – May	Yes
2024	March	Mid-February – May	Yes
2025	March	Mid-February – May	Yes

This five-out-of-five-year concordance confirms H4: mango-fall phenology constitutes the most parsimonious eco-phenological amplifier of the residual isolated by H3.

6. DISCUSSION

This study demonstrates that seasonal malaria transmission in Mefou-Assi cannot be explained by rainfall intensity alone (H2), and that the residual amplitude asymmetry (H3), attributable to the eco-phenological concordance of the mango fall (H4), constitutes an exploitable signal for operational forecasting, within a robust bimodal structure (H1).

The validation of H2 is particularly important for model design: although the major season concentrates a higher case peak, the minor season generates a higher daily rainfall intensity (7.42 versus 5.86 mm/day, major/minor ratio of 0.79). This result is consistent with Bomblies' conclusion that temporal distribution (rather than cumulative volume) governs the persistence of larval habitats [7], as well as with regional data showing that rainfall volume and its seasonal distribution jointly determine malaria seasonality [6]. Daily rainfall intensity alone therefore cannot serve as a reliable predictor of the relative magnitude of the two annual peaks.

The mean amplitude index of 1.17, against 0.79 expected from rainfall alone, quantifies a 48% excess that validates H3 and provides a residual directly usable by early-warning algorithms. The systematic concordance (five out of five years) between this residual and the documented mango-fall window (H4, Table 4) offers the most parsimonious explanation for this excess. The relative exception of 2022 (index 0.78), the year with the smallest inter-seasonal rainfall gap (ratio 0.98, Table 2), reinforces the model *a contrario*: when the difference in rainfall intensity between seasons narrows, the relative amplitude of the primary peak approaches the value expected from rainfall alone, suggesting an interaction between the climatic and eco-phenological determinants rather than complete independence of the two factors.

From a logistics standpoint, the four indicators developed here support four concrete decision rules. First, the inter-annual seasonal profile (H1) defines baseline stock levels for each calendar month. Second, the rejection of the pure rainfall model (H2) means that replenishment should not be mechanically indexed to real-time rainfall intensity. Third, the amplitude residual (H3) provides a quantified correction (+48% on average) to be applied to major-season stocks. Fourth, the documented onset of the mango fall (H4) brings forward the pre-positioning window for RDTs and ACTs by two to three weeks ahead of the March–April peak. Joint implementation of these four rules at the health-facility or district level would reduce the likelihood of stock-outs during the primary surge while avoiding overstocking during intermediate dry periods.

Some methodological limitations should be acknowledged. The eco-phenological explanation (H4) remains correlational: the analysis identifies a robust, documented temporal concordance but does not include direct entomological measurements of vector sugar-feeding status, nor quantified phenological monitoring (precise dates, volumes of fallen fruit) beyond field observation. The analysis is based on a single village; its generalisability to other forested localities remains to be tested. In addition, concordance with other local sugar-bearing orchards was not investigated. The spatial resolution of ERA5 (≈ 11 km, i.e. $\approx 0.1^\circ$) retains limitations at the village scale and may smooth out local rainfall variations relevant to larval habitats. Future work combining direct vector assays with multi-site phenological monitoring across diverse phenologies would strengthen both the causal argument for H4 and the operational transferability of the proposed framework.

7. CONCLUSION AND OPERATIONAL SCOPE

This study empirically validates a four-hypothesis conceptual framework for the seasonal dynamics of malaria transmission at Mefou-Assi (Cameroon, 2021–2025), designed for time-series forecasting in support of medical logistics. The bimodal transmission structure is confirmed (H1: primary peak in March, 91.0 cases; secondary peak in October, 79.0 cases). Analysis of ERA5-derived daily rainfall intensity invalidates an exclusively climatic explanation of peak amplitude (H2: the minor season is more intense in daily rainfall (7.42 versus 5.86 mm/day) without producing the higher peak). The relative amplitude index (mean 1.17 versus 0.79 predicted from rainfall alone, i.e. a 48% excess) validates the contribution of a non-climatic amplification residual (H3), whose systematic concordance with the documented mango-fall window in turn validates the eco-phenological hypothesis (H4).

The resulting four indicators (baseline seasonal profile, normalised rainfall intensity, amplitude residual, and phenological trigger) form the core of an operational early-warning system. This system entails four logistical decision rules: (i) size baseline stocks on the mean seasonal profile (H1); (ii) avoid indexing replenishment solely to real-time rainfall (H2); (iii) apply an amplitude correction of about +48% to major-season stocks (H3); and (iv) bring forward the pre-positioning of RDTs and ACTs by two to three weeks from the documented onset of the mango fall (H4). By integrating phenological calendars with high-resolution meteorological reanalysis and local clinical surveillance, health managers can thereby secure the antimalarial supply chain ahead of the primary peak, reducing the risk of stock-outs and strengthening the climate resilience of health logistics in tropical forested settings. Further research combining direct entomological data with multi-site phenological monitoring across variable phenologies would help refine anticipation lead times and support broader deployment of the proposed framework.

8. ACKNOWLEDGEMENTS

We thank the directors of the CS CHPSF and CS Pyramide health centres, as well as their staff, for their hospitality and for granting access to the consolidated Monthly Activity Reports, and the Open-Meteo project for the free provision of ERA5 reanalysis products.

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