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Evaluating the impact of the Malakit intervention on malaria transmission in the Guiana Shield: a mathematical modelling study



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Summary

Background Malaria elimination in mobile and hard-to-reach populations calls for novel, tailored interventions. In French Guiana, the malaria burden is high among the population working in illegal gold mining. Between April 2018 and March 2020, we implemented *Malakit*, a new intervention targeting gold miners, and relying on the distribution of kits for the self-diagnosis and self-treatment of malaria. In this study, we evaluate the impact of *Malakit* on malaria transmission.

Methods We fitted mathematical models of the transmission of *Plasmodium falciparum* (*Pf*) and *Plasmodium vivax* (*Pv*) to surveillance data from Brazil and Suriname and to prevalence data from cross-sectional surveys to estimate the change in treatment coverages and reproduction numbers between the pre-intervention (2014–2018) and intervention (2018–2020) periods. Using counterfactual scenario analysis, we estimated the impact of the intervention on malaria incidence.

Findings Treatment coverage increased in the intervention compared to the pre-intervention period, the effect being stronger for *Pf* malaria (from 20.6% [95% CrI 17.0, 25.7] to 81.7% [95% CrI 67.9, 96.4]) than *Pv* malaria (from 22.3% [95% CrI 19.3, 25.7] to 47.3% [95% CrI 42.6, 52.3]). Concomitantly, the mean reproduction number decreased from 0.96 (95% CrI 0.93, 1.00) to 0.34 (95% CrI 0.22, 0.46), for *Pf*; and from 1.13 (95% CrI 1.10, 1.16) to 0.86 (95% CrI 0.82, 0.90) for *Pv*. We estimated that between 2018 and 2020 *Malakit* helped avert a total of 1231 (95% CrI 589, 1870) and 2406 (95% CrI 1191, 3621) symptomatic infections by *Pf* and *Pv*, respectively, corresponding to a 44.2% reduction of the overall malaria incidence (95% CrI –52.5, –34.5).

Interpretation *Malakit* had a significant impact on malaria transmission by improving the access to treatment for the population working in illegal gold mining in French Guiana. Building on the regional efforts of the past fifteen years, *Malakit* contributed to another step towards malaria elimination in the Guiana Shield.

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Disclaimer: This summary is available in French and Portuguese in the [Supplementary Material](#).

Keywords: Malaria elimination; Hard-to-reach population; Gold mining; French Guiana; Impact evaluation; Mathematical modelling

Research in context

Evidence before this study

Evaluating the outcomes of malaria control interventions is challenging, especially when targeting remote and mobile populations for whom extensive follow-up and data collection are difficult. We searched for previously published evaluations conducted in a similar context. We queried Medline, Embase and Global Health databases for articles and conference communications published between 2012 and 2023 with a title matching the following: (*malaria* or antimalaria* or plasmodium or falciparum or vivax*) and (*eliminat* or fight* or control* or prevent* or prophylaxis or chemoprophylaxis or treat* or test* or diagnos**) and (*"hard to reach" or hard-to-reach or remote or isolated or isolation or mobility or migrant* or (mobile adj2 (population* or worker*)) or distant or itinerant or forest* or mine or mining or miner* or logg**). We found 115 publications relevant to the scope of our research. Eighty studies focused on describing the context of malaria in the population of interest, twenty-eight studies were dedicated to the description or the implementation of a malaria control intervention and seven studies aimed at evaluating the outcome of an intervention, four of which quantified the impact on malaria incidence. Among those four, two studies were controlled randomized trials: one experimented with a mass test and treat approach for forest workers in Lao, and the other evaluated artemether-lumefantrine prophylaxis among forest goers in Cambodia. The remaining two studies relied on routine surveillance data: the first compared the annual incidence before and after a state-wide intervention in rural communities in India, and the second study used interrupted time series analysis to evaluate the expansion of community health workers' services in Myanmar.

Added value of this study

Malakit is a novel strategy based on self-diagnosis and self-treatment targeting the hard-to-reach population of gold miners working illegally in the rainforest of French Guiana. In this study we develop and fit mathematical models to surveillance data and prevalence estimates from cross-sectional surveys in a Bayesian framework, to evaluate the impact of the Malakit intervention. Mathematical models make explicit assumptions about the mechanisms involved in malaria transmission. Fitted to the data, our models quantify the change in treatment coverage and malaria transmission during the implementation of the intervention. Our results strengthen the existing evidence about the effects of the Malakit intervention on treatment practices and the incidence and prevalence of malaria in the targeted population. We demonstrated that Malakit contributed to the progress towards malaria elimination in the Guiana Shield by accelerating the decrease of both *Plasmodium falciparum* and *Plasmodium vivax* transmission.

Implications of all the available evidence

This study provides new evidence to policymakers on the effectiveness of the Malakit intervention on malaria transmission. The results show that in combination with existing malaria control interventions relying on primary care services and community health workers, Malakit could help reduce the malaria burden in other high-risk, hard-to-reach populations. In addition, the modelling approach used in this work may be of interest to other researchers seeking to evaluate the impact of health interventions in contexts where experimental designs are not applicable.

Introduction

Addressing malaria in mobile, migrant, and hard-to-reach populations remains a challenge for countries on the way to malaria elimination, and calls for tailored and innovative strategies to improve access to diagnosis, treatment, and vector protection.^{1–3} In the Amazon, particularly in countries of the Guiana Shield region, the communities involved in gold mining are a typical example of such populations with residual malaria.⁴ In French Guiana (FG), the population working in illegal gold mining has been identified as the main reservoir of malaria in the region. Predominantly infected with *P. falciparum*, they account for the majority of cases exported to the neighbouring countries.^{5,6} Their lack of access to proper diagnosis and treatment translates into self-medication with under-the-counter antimalarials, a major risk for the emergence of resistance.⁷

To address this local and regional challenge, FG, Suriname and Brazil jointly implemented a new intervention named Malakit. This intervention relied on the distribution of kits for the self-diagnosis and self-treatment of malaria, associated with a training session, targeted to gold miners going to work in FG from the borders with Brazil and Suriname.⁸ Between April 2018 and March 2020, health facilitators trained 3733 participants and distributed 4766 kits, reaching about one-third of the targeted population. Cross-sectional surveys conducted before and after the intervention showed an improvement in knowledge and practices of gold miners towards malaria care and a drop in Polymerase Chain Reaction (PCR) prevalence of *Plasmodium* spp.⁹ National malaria surveillance systems recorded a decrease in the incidence of symptomatic cases imported from FG concomitant with Malakit implementation. A preliminary

interrupted time series analysis (ITSA) estimated a 43% reduction of cases notified during the implementation of Malakit.⁹ Still, ITSA does not make explicit assumptions on the mechanisms involved in malaria transmission, precluding the estimation of Malakit coverage and therefore its impact on malaria burden and transmission.

Here we developed two mechanistic mathematical models explicitly accounting for malaria transmission, case detection and Malakit uptake. We employed a Bayesian approach to fit the models to data from surveillance systems and cross-sectional surveys, and estimated changes in treatment coverages and reproduction numbers between the pre-intervention period (2014–2018) and the intervention period (2018–2020). We then quantified the impact of Malakit on malaria incidence and prevalence by comparing models' estimates for the intervention period to counterfactual scenarios without intervention, considering *P. falciparum* (*Pf*), *P. vivax* (*Pv*) and both species combined.

Methods

Population and settings

FG is a French overseas territory located in South America, sharing borders with Brazil in the East, and Suriname in the West. Ninety percent of its land (85,000 km²) is covered by rainforest with a soil rich in gold—a geological characteristic shared with other countries of the Guiana Shield, i.e., Suriname, Guyana, northern Brazil, and southern Venezuela. This gold is the reason for the continuous presence of an estimated population of 10,000 men and women on 500 to 700 illegal gold mining sites.¹⁰ The majority of gold miners are born in Brazil (>95%), 75% are men, with a median age of 38 (IQR: 31, 47), and less than half have a secondary level of education.^{5,9}

Intervention

The Malakit intervention and its implementation have been described previously.^{8,11,12} Coordinated by Cayenne Hospital, Malakit was implemented between April 2018 and March 2020 at five sites mainly located at the borders of FG with Brazil and Suriname (Fig. 1). These sites were selected because of their strategic importance as entry points for gold miners going to FG. The core intervention relied on the distribution of free kits for self-diagnosis and self-treatment of malaria to gold miners by health facilitators. One “malakit”¹ contained three non-species-specific rapid diagnostic tests for malaria (RDT, CareStart™ pLDH), a full course of artemisinin combined therapy (ACT, artemether 20 mg/lumefantrine 120 mg, four pills twice a day, for three days) effective against both *Pf* and *Pv* malaria, and a single dose of primaquine (S-PQ, 15 mg) as a *Pf*

gametocytocidal medication, according to WHO guidelines.¹³ Radical cure against *Pv* hypnozoites was not included in the kit. Before distributing a kit, health facilitators trained the participants to perform an RDT themselves and explained how to take the medication. Long-lasting insecticidal nets (LLINs) were also distributed to the participants during the full course of the intervention at the border between FG and Suriname (as per the pre-existing policy of Suriname) and during the last ten months of the intervention at the border between FG and Brazil.

Malaria prevalence and surveillance data

We conducted cross-sectional surveys before and after the intervention to assess knowledge and self-reported practices about malaria treatment and diagnosis and to estimate the prevalence of *Plasmodium* spp. carriage by PCR in the population.^{5,9} Monthly notification data of malaria cases imported from FG to Brazil and Suriname were obtained from national surveillance systems of the Brazilian and Surinamese malaria programs (freely accessible, refer to *Data Sharing* section). From these surveillance data, we used only cases imported from FG and explicitly recorded as originating from gold mining. We chose not to use surveillance data from FG because they did not consistently allow for the identification of cases specifically originating from mining areas.

Malaria transmission models

We modelled the transmission of *Pf* and *Pv* malaria separately using two deterministic Susceptible-Infectious-Susceptible-like compartmental models. We neglected co-infection and interference between the two *Plasmodium* species, which was justified by the low levels of incidence and prevalence measured in the study population. We used a species-specific human-to-human transmission rate to effectively account for vector dynamics.^{14–16} In our models, the infected population (I) corresponded to individuals with a detectable parasite density in PCR and was distributed into four compartments: asymptomatic (IA), symptomatic but not (or incompletely) treated (IS) and symptomatic treated either by the health system (IT) or by a malakit (IM). Susceptible individuals (S) were free from infection and at risk of infection. In the *Pv* model, infected individuals not receiving a radical cure (i.e., IA, IS and IM) became non-infectious hypnozoites carriers (H) likely to relapse and become newly infected. We assumed that cases notified to the malaria surveillance systems (D) were a fraction of the infected individuals receiving treatment from the health system (IT) (Fig. 2).

Both models relied on the following assumptions: (i) the population size is constant (N), (ii) the mixing of all individuals in illegal gold mining sites in FG is homogeneous, (iii) the force of infection depends on meteorological conditions, with temperature chosen as an

¹Malakit refers to the actual object; whereas Malakit is thereafter used to refer to the intervention.

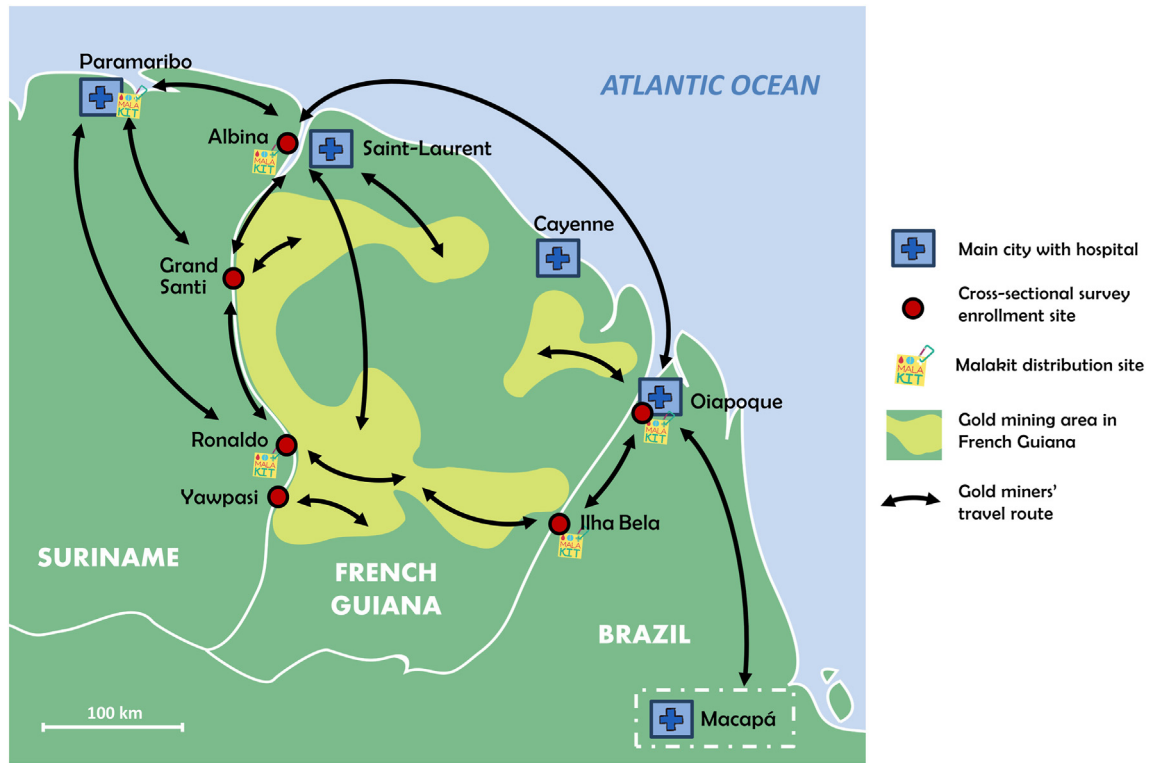


Fig. 1: Map showing the location of Malakit distribution sites and pre/post intervention cross-sectional surveys enrolment sites (red dots) at the borders of French Guiana with Brazil and Suriname.

explanatory variable, assuming a lagged exponential effect; (iv) infected individuals have a constant probability ϵ of being symptomatic; (v) the rate of transmission from asymptomatic individuals is lower than from symptomatic individuals, with a constant ratio $k < 1$; (vi) symptomatic infections are treated (i.e., blood circulating parasites are cleared) with probabilities ϕ_0 and ϕ_1 , prior and during Malakit implementation respectively; (vii) prior to Malakit implementation all symptomatic infections are treated by the health system (ϕ_0), while during the intervention period a proportion m of symptomatic infections are treated with Malakit and a proportion $\phi_1 - m$ are treated by the health system; (viii) the proportion of infections treated by the health system is the same before and during the intervention period ($\phi_0 = \phi_1 - m$); (ix) treatment shortens the infection duration; (x) treatment does not affect the transmission rate; (xi) without treatment, the duration of infection is the same for asymptomatic and symptomatic individuals; (xii) individuals who seek treatment from the health system are notified to malaria surveillance in Brazil and Suriname with a constant reporting fraction ρ ; and (xiii) individuals using a malakit for treatment are not reported to malaria surveillance.

The P_v model relied on the following additional assumptions: (xiv) individuals treated by the health system (IT) receive a radical cure against P_v hypnozoites and do

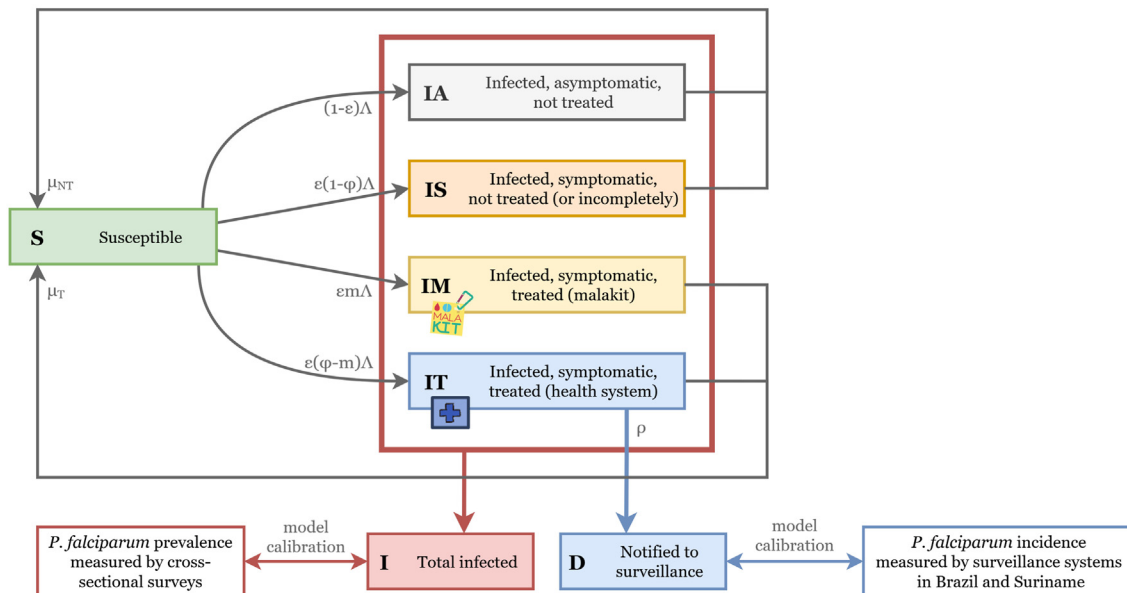
not relapse; (xv) individuals who do not receive treatment from the health system become hypnozoites carriers; (xvi) hypnozoites carriers are exposed to reinfection with the same force of infection as susceptible individuals; (xvii) hypnozoites carriers relapse with a constant rate μ_{HI} ; (xviii) hypnozoites are spontaneously cleared from the carriers' liver with a constant rate μ_{HS} .

Model equations and parameter definitions are presented in the [Supplementary Material](#).

Parameters estimation

We fitted the models separately for P_f and P_v to prevalence and surveillance data. For each species, we estimated the posterior distribution of six parameters: the probability of symptomatic infection (ϵ), the probability of treatment of symptomatic infection, before intervention (ϕ_0) and during intervention (ϕ_1), the transmission rate at average maximum daily temperature (β_0), the temperature-associated amplitude of the transmission rate (α) and the temperature-associated lag of the transmission rate (lag). We fixed the values of the initial number of infected individuals (I_0 , species-specific), the ratio of asymptomatic vs. symptomatic transmission rates (k , species-specific), the duration of infection without treatment (T_{NT} , species-specific), the duration of infection with treatment ($T_T = 7$ days), the reporting

P. falciparum



P. vivax

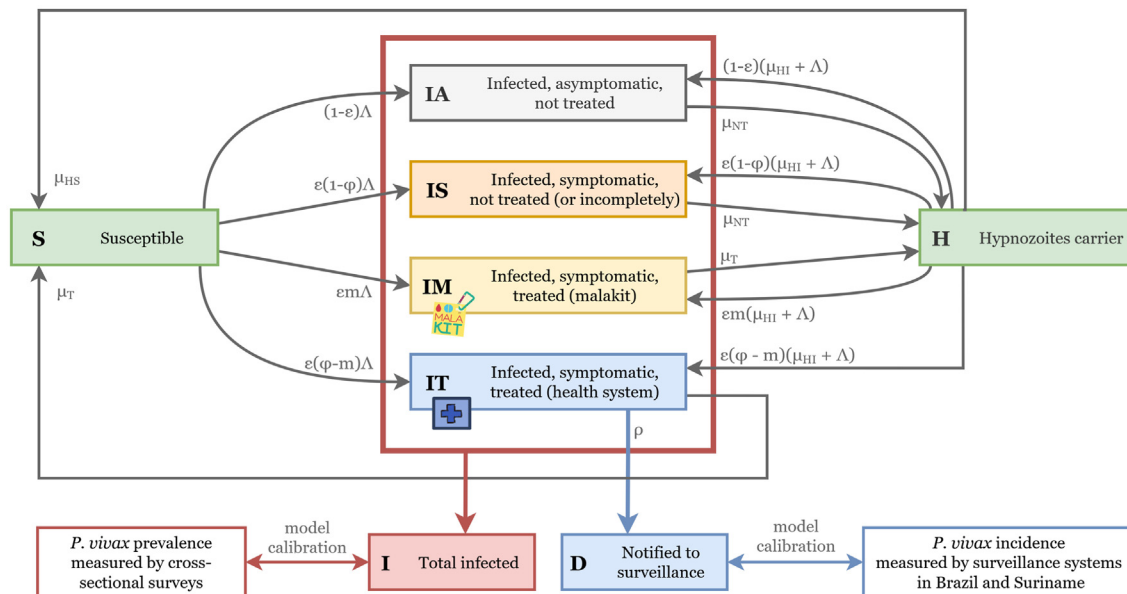


Fig. 2: Compartments used in the malaria transmission models and sources of data used for calibration, for *P. falciparum* (top) and *P. vivax* (bottom). Susceptible individuals (S) may be infected without symptoms (IA), or develop symptoms without appropriate treatment (IS), get treatment from the health system (IT) or from using a malakit (IM, during intervention). Individuals infected with *P. vivax* without radical cure (IA, IS, IM) become hypnozoites carriers (H). A fraction of the cases treated by the health system are notified to malaria surveillance (D). Λ : force of transmission, ϵ : probability of symptomatic infection, ϕ : probability of treatment (treatment coverage), m : probability of using a malakit as treatment ($m = 0$ before intervention), $1/\mu_{NT}$: infection duration without treatment, $1/\mu_T$: infection duration with treatment, ρ : probability of notification to surveillance systems (reporting fraction), μ_{HI} : *P. vivax* relapsing rate, μ_{HS} : *P. vivax* hypnozoite clearance rate. For more details about notations refer to [Supplementary Table S4](#).

fraction ($\rho = 0.69$), *Pv* relapsing rate ($\mu_{HI} = 1/53 \text{ day}^{-1}$) and the rate of hypnozoites clearance ($\mu_{HS} = 1/35 \text{ day}^{-1}$). Justifications for the choice of parameter values are reported in the Supplementary Material (Supplementary Table S4).

The log-likelihood associated to parameters estimates was calculated by fitting monthly simulated notifications to surveillance data assuming Poisson distribution, and simulated prevalence to prevalence studies conducted in 2015, 2018 and 2019 assuming a binomial distribution.

We used R (v4.2.0) and RStudio (v2022.02.3) to run three Markov chains of 100,000 iterations using different seed values, for each model fit. We used the Robust Adaptive Metropolis algorithm developed by Vihola and implemented in R by Helske.^{17,18} We discarded the first 20,000 iterations of the burn-in periods and thinned at a ratio of 1:10 to eliminate autocorrelation and combined the three chains. We checked for convergence to the same stationary distribution both visually and using Gelman statistics from coda R package (Supplementary Table S11).¹⁹

From the posterior distributions of the fitted parameters, we computed the probability of using a malakit m and the reproduction number R , before and during the intervention. We performed a sensitivity analysis by varying the values of I_0 , T_{NT} and μ_{HS} (the latter for *Pv* model only). Finally, we explored the possible effect of the launch of LLIN distribution at the border between Brazil and FG from June 2019 to April 2020 by testing, for each species, a version of the model with stepwise time change in transmission (refer to Supplementary Material section 3.2).

Estimation of the impact of malakit

To assess the impact of the Malakit intervention on malaria incidence and prevalence, we ran simulations parameterized from a sample of 1000 draws from the parameter posterior distributions. For each one of the 1000 draws of parameter values, we compared the model simulation to a matching counterfactual (without intervention) with ϕ_1 set to the pre-intervention value ϕ_0 . We then calculated the difference between the mean prevalence, the mean annual incidence rate and the cumulated incidence estimated by each pair of simulations and derived the mean and 95% Bayesian credible intervals (CrI) from the resulting distributions. Assuming co-infections by both species were negligible, we investigated the overall malaria impact by computing 1) overall estimates of ϕ_0 , ϕ_1 and m using *Pf* and *Pv* estimates (refer to Supplementary Material section 2.1), and 2) overall incidence and prevalence calculated as the sum of *Pf* and *Pv* incidences and prevalences, respectively.

Ethics and regulation

The implementation study of the Malakit intervention was registered on [ClinicalTrials.gov](https://www.clinicaltrials.gov) with the number

NCT03695770. Ethics approvals were obtained from countries where the Malakit study was implemented.⁹ All data from the Malakit project (intervention and cross-sectional surveys) were obtained anonymously after a written consent was collected from participants. The analysis of all data complies with the General Data Protection Regulation (European Union Regulation 2016/679).

Role of the funding source

Cayenne Hospital, as a sponsor, directly managed most of the project funds. Half of the funding was by the European Regional Development Fund via the Interregional Amazon Cooperation Program 2014–2020, supplemented with self-funding from Cayenne Hospital, funds from the French Guiana Health Regional Agency, the European Horizon 2020 Program, and contributions in kind from the Suriname National Malaria Program, as a beneficiary of the Global Fund to Fight AIDS, Tuberculosis and Malaria; the Ministry of Health of Brazil; and the French Development Agency. The funding bodies played no part in the implementation and evaluation of the project.

Results

Pf and *Pv* models' fit to surveillance and prevalence data are shown in Fig. 3. Estimated species-specific parameter values are reported in Table 1. We found that treatment coverage increased during the Malakit intervention period compared with the pre-intervention period. The increase was stronger for *Pf* malaria (from 20.6% [95% CrI 17.0, 25.7] to 81.7% [67.9, 96.4]) than *Pv* malaria (from 22.3% [19.3, 25.7] to 47.3% [42.6, 52.3]). According to our assumptions, this corresponds to a higher probability of using a malakit (m) to treat *Pf* malaria (61.1% [47.9, 74.0]) than *Pv* malaria (25.0% [20.9, 29.2]). According to our model, the improved treatment coverage during the intervention period led to a decline in the transmission of both species, yet with a sharper decrease of the mean reproduction number (R) for *Pf* than *Pv*: 0.96 to 0.34 (−64.2%) vs. 1.13 to 0.86 (−24.2%), respectively. From the estimates provided by the two models, we computed the overall treatment coverage of symptomatic infections caused by either species: we found 21.7% (95% CrI 19.0, 24.3) prior to the implementation of the Malakit intervention and 58.6% (95% CrI 52.6, 64.9) during the intervention. This corresponds to an overall probability of 36.9% (95% CrI 30.4, 43.9) of using a malakit to treat a new symptomatic infection (NSI) by either species.

In the sensitivity analysis conducted for different values of T_{NT} , I_0 and μ_{HS} , the computed estimates of ϕ_0 , ϕ_1 and R consistently had overlapping 95% CrIs for both *Pf* and *Pv* (Supplementary Tables S7 and S8). The launch of LLIN distribution to Malakit participants enrolled at the border between FG and Brazil in June

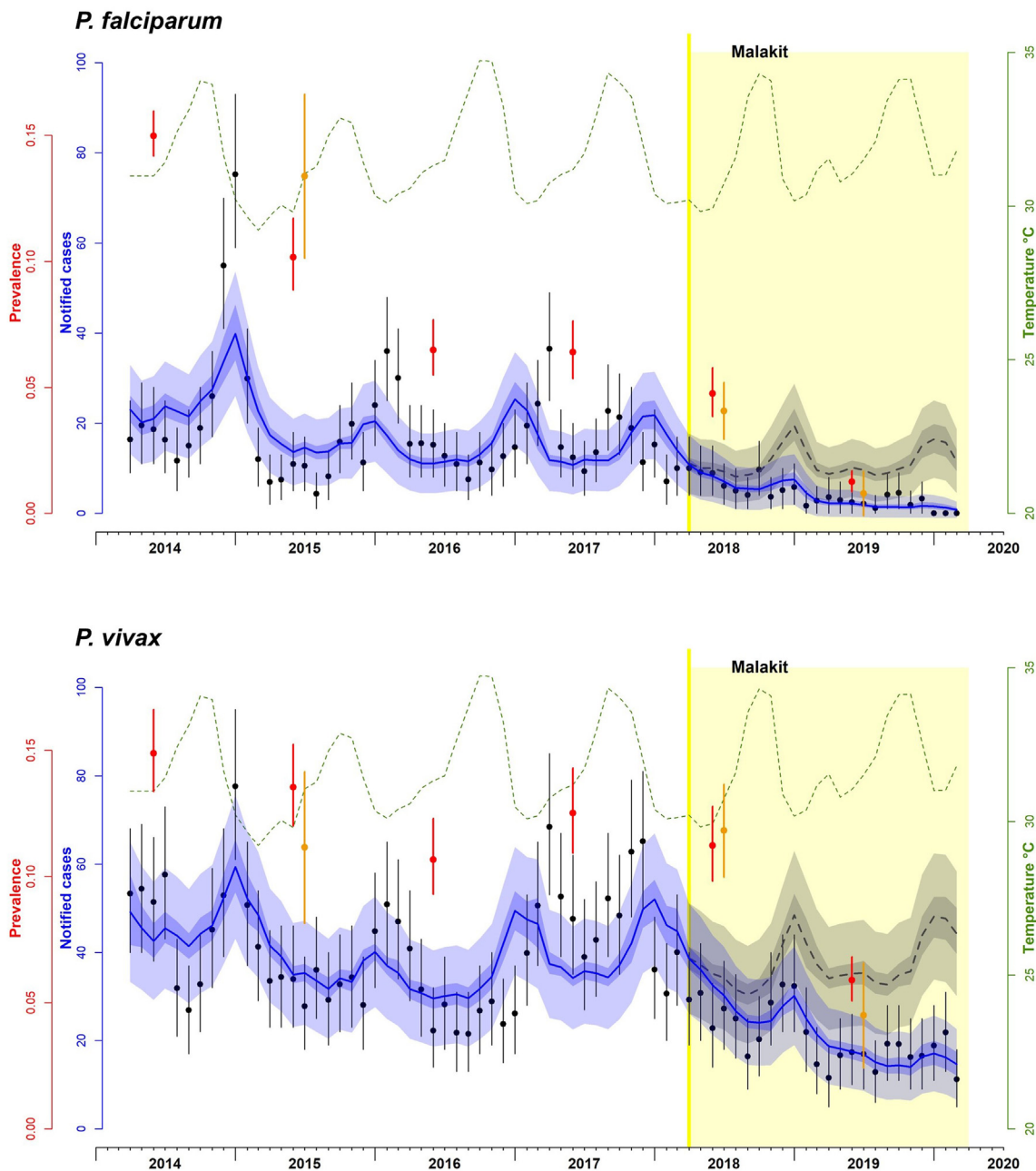


Fig. 3: Monthly incidence of reported cases of malaria (black dots), model-fitted simulations (blue solid line) and counterfactual estimates (dashed grey line) for *P. falciparum* (top) and *P. vivax* (bottom). Annual prevalence measured in PCR surveys (orange dots) and model-fitted estimates of prevalence (red dots). Maximum daily temperature (monthly average) is shown in green dashed line. The period of implementation of Malakit is shown in yellow. Vertical lines represent 95% CrI. For model-fitted and counterfactual incidence (respectively blue and grey), the dark envelopes show the uncertainty (95% CrI) associated with the joint posterior distribution, while the light envelopes account also for the uncertainty resulting from the observed Poisson process.

2019 was not associated with a decrease in the transmission rate (Supplementary Fig. S7).

In the counterfactual analysis, we found that the mean annual incidence rate dropped by almost 75% for

Pf, from 153 NSI/1000/year (95% CrI 116, 191) to 36 (95% CrI 20, 51), and was almost halved for *Pv*, decreasing from 314 NSI/1000/year (95% CrI 260, 368) to 175 (95% CrI 135, 214), prior vs. during the

Parameter	Period	<i>P. falciparum</i>	<i>P. vivax</i>	All species
ϕ: Treatment coverage	Pre-intervention	20.6% (17.0, 25.7)	22.3% (19.3, 25.7)	21.7% (19.0, 24.3)
	Intervention	81.7% (67.9, 96.4)	47.3% (42.6, 52.3)	58.6% (52.6, 64.9)
m: Malakit coverage ^a	Pre-intervention	–	–	–
	Intervention	61.1% (47.9, 74.0)	25.0% (20.9, 29.2)	36.9% (30.4, 43.9)
R: Mean reproduction number (all infections) ^a	Pre-intervention	0.96 (0.93, 1.00)	1.13 (1.10, 1.16)	–
	Intervention	0.34 (0.22, 0.46)	0.86 (0.82, 0.90)	–
ε: Probability of symptoms	Pre-intervention	77.3% (56.1, 97.3)	43.3% (35.8, 51.8)	–
	Intervention	–	–	–
β ₀ : Transmission rate at average temperature (day ⁻¹)	Pre-intervention	0.009 (0.007, 0.010)	0.026 (0.022, 0.030)	–
	Intervention	–	–	–
α: Seasonal amplitude of transmission rate (°C ⁻¹)	Pre-intervention	0.17 (0.14, 0.21)	0.13 (0.10, 0.16)	–
	Intervention	–	–	–
lag: Temperature lag of transmission rate (days)	Pre-intervention	78 (66, 89)	82 (68, 96)	–
	Intervention	–	–	–

^aComputed from other parameters (refer to [Supplementary material](#)).

Table 1: Models results: mean and 95% credible interval of estimated parameters and computed value of Malakit coverage and reproduction number, for *P. falciparum*, *P. vivax* and both species.

intervention ([Supplementary Table S6](#)). Without intervention, the counterfactual scenario predicted that the mean incidence rate would have decreased for both *Pf* and *Pv*, but to a lesser extent: reaching 97 NSI of *Pf* (95% CrI 62, 133) and 295 NSI/1000/year of *Pv* (95% CrI 233, 357). This drop in malaria incidence was also observed for prevalence. The measured total PCR prevalence (symptomatic and asymptomatic infections) of *Pf* decreased on average from 9.0% (95% CrI 8.0, 10.2) to 2.2% (95% CrI 1.7, 2.8), while the prevalence of *Pv* decreased from 12.9% (95% CrI 11.5, 14.5) to 7.3% (95% CrI 6.4, 8.4). Counterfactual simulations without intervention predicted that the total PCR prevalence would have decreased to 5.0% for *Pf* (95% CrI 4.0, 6.2), and to 12.0% for *Pv* (95% CrI 10.5, 13.7).

Computing the overall annual incidence rate of infections caused by either species, we found a drop from 467 (95% CrI 401, 533) before intervention to 211 NSI/1000/year (95% CrI 168, 253) during intervention, vs. 392 NSI/1000/year (95% CrI 321, 464) on average according to the counterfactual scenario without intervention. Therefore, we estimate that Malakit contributed to a 46.2% reduction of the all-species malaria incidence (181/392, [Supplementary Table S6](#)). Similarly, the total PCR prevalence decreased from 21.9% (95% CrI 20.1, 23.8) before intervention to 9.5% (95% CrI 8.5, 10.7) during intervention vs. 17.0% (95% CrI 15.2, 19.2) in the counterfactual scenario, i.e., a 44.1% reduction attributed to Malakit.

When comparing the predictions with and without intervention, we estimate that between 2018 and 2020 Malakit helped avert a total of 1231 NSI of *Pf* (95% CrI 589, 1870) and 2406 NSI of *Pv* (95% CrI 1191, 3621). Indeed, our models estimate that 713 NSI of *Pf* and 3497 NSI of *Pv* occurred during the intervention period and that without intervention this malaria burden would have reached 1944 NSI of *Pf* and 5903 NSI of *Pv*

([Table 2](#)). This corresponds to a total of 1310 infections treated with the use of a malakit: 432 *Pf* infections (95% CrI 311, 554) and 878 *Pv* infections (95% CrI 673, 1082). In line with a stronger increase of treatment coverage for *Pf* than *Pv*, we find a larger decrease in the incidence of symptomatic infections not treated (or incompletely) for *Pf* (–91.3%) than *Pv* (–59.8%).

When considering both species together, we estimate that, without intervention, the burden of malaria would have reached a total of 16,207 new symptomatic and asymptomatic infections between 2018 and 2020 in our study population. With the Malakit intervention, this burden is estimated at 9035 new infections overall. We thus estimate that 7172 infections were averted during the two years of the intervention, of which 3637 would be symptomatic infections.

Discussion

In this work, we used mathematical modelling and Bayesian inference to jointly analyse three independent datasets: surveillance data from Brazil, from Suriname, and prevalence data from repeated cross-sectional surveys. Our results suggest that a significant progression towards malaria elimination was achieved in our study population during the implementation of Malakit, with estimated values of *R* below unity, the theoretical threshold for malaria elimination.²⁰ We find that the elimination process of *Pf* preceded the intervention (*R* = 0.96) and accelerated during its implementation (*R* = 0.34). This is mirrored by the evolution of the incidence rate of *Pf* infection, compatible with a shift from a low transmission intensity (>100 cases/1000/year) to a very low transmission intensity (<100 cases/1000/year).²¹ In contrast, for *Pv*, the shift of *R* below the elimination threshold was concomitant with the intervention.

	Scenario	<i>P. falciparum</i> infections (95% CrI)	<i>P. vivax</i> infections (95% CrI)	All-species infections (95% CrI)
Notified to surveillance (D)	No intervention	272 (220, 323)	903 (819, 986)	1175 (1077, 1272)
	Intervention	100 (76, 125)	535 (476, 593)	635 (572, 698)
	Difference	172 (115, 229)	368 (266, 470)	540 (423, 656)
	% Difference	-63.1% (-73.5, -50.1)	-40.7% (-48.8, -31.7)	-45.9% (-52.6, -38.5)
Symptomatic, treated by the health system (IT)	No intervention	394 (324, 464)	1308 (1197, 1419)	1702 (1572, 1832)
	Intervention	145 (113, 177)	775 (698, 852)	920 (838, 1003)
	Difference	249 (172, 326)	533 (398, 668)	782 (627, 936)
	% Difference	-63.1% (-72.6, -51.4)	-40.7% (-48.1, -32.5)	-45.9% (-52.0, -39.2)
Symptomatic, treated with a malakit (IM)	No intervention	-	-	-
	Intervention	432 (311, 554)	878 (673, 1082)	1310 (1073, 1547)
	Difference	-	-	-
	% Difference	-	-	-
Total symptomatic treated (IT + IM)	No intervention	394 (324, 464)	1308 (1197, 1419)	1702 (1572, 1832)
	Intervention	577 (449, 705)	1653 (1433, 1872)	2230 (1976, 2484)
	Difference	-183 (-329, -38)	-345 (-590, -99)	-528 (-814, -243)
	% Difference	+46.3% (8.7, 93.9)	+26.3% (7.3, 47.3)	+31.0% (13.8, 49.9)
Symptomatic, not treated (IS)	No intervention	1550 (991, 2106)	4595 (3599, 5586)	6145 (5000, 7288)
	Intervention	136 (0, 274)	1844 (1388, 2301)	1980 (1502, 2458)
	Difference	1414 (838, 1987)	2751 (1654, 3842)	4165 (2924, 5405)
	% Difference	-91.3% (-100.1, -79.7)	-59.8% (-71.5, -44.2)	-67.8% (-76.7, -56.5)
Total symptomatic (IT + IM + IS)	No intervention	1944 (1336, 2550)	5903 (4849, 6955)	7847 (6629, 9065)
	Intervention	713 (507, 920)	3497 (2891, 4103)	4210 (3568, 4853)
	Difference	1231 (589, 1870)	2406 (1191, 3621)	3637 (2257, 5015)
	% Difference	-63.1% (-76.3, -42.4)	-40.7% (-53.9, -23.7)	-46.3% (-56.9, -33.1)
Asymptomatic, not treated (IA)	No intervention	578 (11, 1145)	7782 (6005, 9557)	8360 (6498, 10,220)
	Intervention	214 (0, 427)	4611 (3574, 5644)	4825 (3769, 5880)
	Difference	364 (-241, 971)	3171 (1117, 5224)	3535 (1392, 5674)
	% Difference	-63.1% (-119.4, 136.2)	-40.7% (-57.2, -17.8)	-42.2% (-58.0, -20.5)
Total (I)	No intervention	2522 (1968, 3077)	13,685 (11,903, 15,473)	16,207 (14,357, 18,058)
	Intervention	927 (734, 1120)	8108 (7107, 9108)	9035 (8021, 10,051)
	Difference	1595 (1009, 2183)	5577 (3535, 7627)	7172 (5058, 9284)
	% Difference	-63.1% (-72.9, -49.9)	-40.7% (-50.5, -29.0)	-44.2% (-52.5, -34.5)

Table 2: Cumulated malaria incidence of *P. falciparum*, *P. vivax* and all-species infections estimated between April 2018 and March 2020, with intervention (model fitted to data) and without (counterfactual).

We find that the overall coverage of malaria treatment in the study population increased from 21.7% to 58.6% with the implementation of the Malakit intervention, which resulted in a reduction of the estimated reproduction number for both *Pf* and *Pv*. Indeed, access to prompt treatment by ACT accelerates the clearance of circulating gametocytes, and thus decreases the duration of the infection for one episode of *Pf* or *Pv* malaria.^{22,23} When combining the estimates of our two models, we find that after two years of intervention, Malakit contributed to a strong decrease in the overall incidence of malaria infection from 467 to 211 NSI/1000/year. Those estimates align with those from pre-post field surveys: 306 to 142 NSI/1000/year (Supplementary Material). The field surveys found a 2.4-fold increase of the overall treatment coverage (vs. 2.7 with our models), with larger estimates: 27.3% before intervention and 66.2% after intervention (Supplementary Table S3), compared with 21.7% and 58.6% respectively, found in our modelling estimates.

Because Malakit does not offer a radical cure against *Pv* hypnozoites, subsequent *Pv* relapses cannot be prevented. This can explain the lower impact of Malakit estimated on *Pv* transmission, as reported when ACT was implemented in other settings.²⁴ Malakit could also have had an effect on malaria transmission through the increased use of LLINs, by improving access and awareness of this preventive measure among participants.²⁵ However, in our sensitivity analysis, we did not find that the increase in LLIN distribution was associated with a decrease of the transmission rate. Given one-fifth of gold miners report working at night and the diurnal biting behaviour of *An. darlingi* observed in the Guianese rain-forest, there is, in fact, little evidence about the effectiveness of LLINs for malaria prevention in the context of our study population.^{26,27}

Strengths and limitations

Several alternative explanations must be considered before drawing conclusions on the causal relationship

linking the decrease of malaria transmission to the implementation of Malakit. To our knowledge, Malakit was the only intervention implemented at large scale between 2018 and 2020 targeting the gold mining population in FG, and no significant changes occurred in the management of the health systems of FG, Suriname and Brazil during that period for this population. Our models account for seasonal and long-term climate variations with a force of transmission dependent on temperature, and weather records show that temperature and rainfall were quite stable between 2014 and 2020 in FG. Police operations implemented since 2008 by the French authorities aim to destroy logistical equipment and mining networks, but their impact on reducing the size of the population of gold miners is uncertain. Indeed, gold mining activity appears to have remained stable over this period and, with the exception of the period between March–April 2017, a stable number of police operations were conducted between 2015 and 2019.²⁸

The two models presented in this work rely on several simplifying assumptions. At the individual level, the dichotomy between symptomatic and asymptomatic infected individuals assimilates two related yet distinct phenomena: clinical expression and infectiousness. In our models, symptomatic individuals carry higher levels of parasitaemia compared to asymptomatic individuals and remain so during the full course of infection. At the population level, we modelled malaria transmission on a single patch with the assumption of homogeneous transmission in all mining sites. Our results thus reflect an average picture of a more complex and heterogeneous reality. Although we consider these assumptions acceptable in the context of this study, the progressive reduction of regional malaria incidence will translate to an increased spatial and temporal heterogeneity, making it even more challenging to evaluate future interventions. In this case, agent-based models could become a powerful tool to account for this greater complexity, both at the individual and population scales.²⁹

Generating robust evidence about the effectiveness and impact of public health interventions is challenging, especially when working with mobile and hard-to-reach populations. Clustered randomized trials, commonly held as the gold standard design for outcome evaluation, are impractical to implement in this context.³⁰ We identified only two published trials which evaluated a malaria control intervention amongst a hard-to-reach population in the past ten years.^{31,32} The models proposed here optimally combine different sources of data, each providing partial information, and their findings are in line with those estimated independently from pre-post intervention field surveys. Although the data available may differ, this model-based triangulation approach could be useful in other settings with especially challenging environments to better inform decision-making towards malaria elimination.

Perspectives

Malakit is a risk-reduction intervention. It was primarily designed as a pragmatic response to the threats to malaria control resulting from long-existing practices of self-medication in a mobile and hard-to-reach population. Malakit is a complex intervention, with two core components: the kit and the training provided by facilitators. These two components act synergistically and cannot be separated. Although the diffusion of the kit alone could provide an alternative to uncontrolled self-medication, the actual improvement of practices with regards to malaria self-diagnosis and self-treatment and, eventually, the prevention of resistance emergence, can only result from a timely health education action. In turn, this improvement is effectively made possible with the availability of the kit.

In this work we complement the body of evidence already published on the outcome evaluation of Malakit by estimating its impact on malaria transmission.⁹ These positive results led to the integration of Malakit into the policy of the malaria programmes of Suriname in 2021, and French Guiana in 2024.³³ One remaining question is whether these results could be replicated in a different context. Gender-specific mechanisms, not investigated in this work, may yet influence the success of the Malakit intervention, including uptake, adherence, biological response to treatment and adverse effects. Indeed, previously published data on Malakit suggest distinct uptake and effectiveness outcomes in our study population: women represented 33.6% of the participants in the intervention, while pooled data from cross-sectional surveys indicate that women account for 25.1% of the gold mining population in French Guiana. The same data show weak evidence of better practices of malaria diagnosis and treatment among women than men.⁹ Further refinements of this modelling study could help investigate gender-specific patterns of the impact of Malakit, and inform its transfer to populations with a different gender structure.

In another publication, we describe a process to guide the transfer of Malakit.³⁴ We identify several key factors that determine the success of the implementation of Malakit: the economic and political context, the allocation of sufficient funding and the availability of competent and committed human resources.³⁵ Adaptations of Malakit in a new context require a careful consideration of the risks and long-term consequences associated with poor implementation of the intervention, such as: inadequate storage of the kit, use beyond the expiration date, errors of RDT interpretation leading to improper or delayed treatment, poor adherence to ACT stimulating the development of drug resistance, and interruption of kits distribution. These factors and risks need to be assessed, and monitored, during the early phase of the transfer process; in the later phase, once implemented in a different context, the methodology developed in this work may be adapted to evaluate

the impact and effectiveness of the intervention and eventually form the basis of a cost-effectiveness analysis.

Conclusion

Through a modelling approach, we assess the effectiveness of Malakit as a malaria control intervention in the specific context of the mobile and hard-to-reach population involved in illegal gold mining in French Guiana. Our findings show that Malakit had a significant impact on both *P. falciparum* and *P. vivax* transmission, through improved access to prompt treatment by ACT and S-PQ for the treatment of symptomatic malaria infections. Building on the efforts of the healthcare community during the past fifteen years, Malakit constitutes an additional step towards elimination of malaria in the Guiana Shield. This new intervention—training individuals to self-diagnose and self-treat using a free kit—could be integrated into global strategies aiming at eliminating malaria in populations beyond the reach of the health systems.

Contributors

MD, MG, YL, MSM, SV, HH, PM and AS conceived the Malakit study and wrote the protocol.

YL, AS, MD, LM, YL (IPG), HH and PM accessed and verified the data.

LM and YL (IPG) conducted PCR analyses.

YL, CP, RM developed the model.

YL coded and calibrated the model, analysed the data and results.

YL, MD, RM and CP wrote the draft of the manuscript.

All authors reviewed the manuscript.

Data sharing statement

All datasets, R scripts and MCMC traces used in this work are available online from the following GitHub repository: https://github.com/ymlambert/malakit_mcmc. For more information, please contact the corresponding author (YL).

Editor's note

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Declaration of interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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OML is a staff member of the Pan American Health Organization/World Health Organization (PAHO/WHO). The author alone is responsible for the views expressed in this publication and does not necessarily represent the decisions, policy or views of the PAHO/WHO.

Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.lana.2025.101123>.

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