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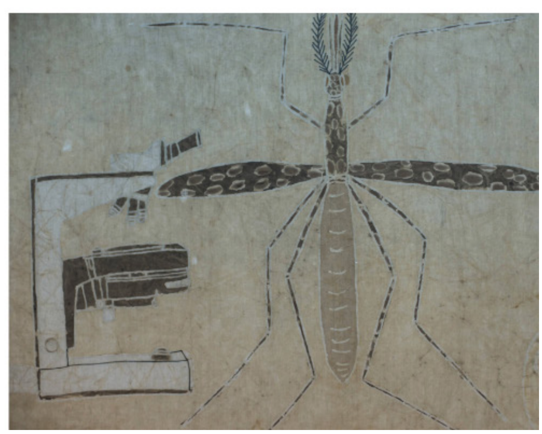

Malaria control lessons from China

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Learning from China's journey to achieve malaria elimination

The country's success is a call to action for other affected areas

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China, burdened with an estimated 30 million malaria cases annually in the 1940s, reached a historic milestone when the World Health Organization certified it malaria-free in 2021. This achievement—in a vast and diverse country of 1.4 billion people—offers crucial lessons for the global malaria fight, especially at a time when 94% of the 263 million cases and 95% of the 597 000 malaria deaths still occur in Africa.[1] Achieving and sustaining control and elimination remain challenging, particularly in the current climate of funding uncertainty, and when considering the sustained effort and investment needed in China over 70 years in the face of both successes and setbacks.

Global and national funding for malaria control has led to major gains in child survival and supported progress towards elimination, with 45 countries and one territory now having achieved this milestone. In countries with ongoing transmission, WHO estimated that 177 million cases and 1million deaths were averted in 2023.[1] Despite the challenges that remain—biological, political, and financial—25 countries reported fewer than 10 cases. However, funding has never approached more than 50% of the levels required for full implementation.

Africa has many countries heavily dependent on external donors. The US has been the largest funder, providing 37% of the $4bn available, and endemic countries provided 33%. If replenishment of the Global Fund (which supports malaria control) and the Global Alliance for Vaccines and Immunisation (funding for malaria vaccines) declines in 2025, malaria cases and deaths are predicted to increase. The hard won gains of the past two decades would be rapidly reversed.

The BMJ Collection on malaria control lessons from China explores the country's path to elimination and how it may inform strategies elsewhere (www.bmj.com/collections/malaria-control-china).[2-6] The collection examines China's national strategy, presents case studies from Hainan and Yunnan provinces and the Huai River Basin, and details the evolving interventions that ultimately led to elimination. It offers important lessons for countries pursuing malaria control and elimination, especially in Africa, where those goals have broad political support.[7]

International lessons

The first lesson is that comprehensive and adaptive strategies are essential. In Hainan Province, elimination was achieved through long term use of overlapping interventions—bed nets, indoor spraying, drug administration, and sustained surveillance. The approach evolved with changing risk levels, showing that persistent but flexible strategies can succeed even in highly endemic areas.

Second, success can breed complacency—and resurgence. In the Huai River Basin, early success in the 1980s led to reduced surveillance and funding, resulting in malaria resurgence in the early 2000s. Control was restored only after reintroducing mass drug administration, robust vector control, and community mobilisation. This highlights the danger of prematurely scaling back efforts and the need for long term vigilance, and echoes experiences in other countries that achieved elimination. At low levels of disease, there is the potential for lagging attention and a clear risk of resurgence.[8]

Third is the importance of cross border and cross sector coordination. Yunnan Province faced challenges from imported cases and multiple vector species along the border with Myanmar and other endemic countries. Success hinged on cross border collaboration, real time data sharing, and joint interventions. Cooperation will be vital in Africa, where national borders are often porous and populations are mobile.[8] Collaborations with agriculture, housing, and water management sectors may also greatly reduce malaria transmission.[9]

Fourth is that larval source management deserves greater attention. China's integration of agricultural innovations—such as rice–fish co-culture and targeted larvicide, substantially reduced mosquito breeding. Though not widely recommended by WHO, such approaches may be valuable in certain African settings. Novel tools such as drones, artificial intelligence, and remote mapping of bodies of water, merit both evaluation and policy attention.[10]

The final lesson is the importance of local data and operational research. China's strategies were informed by surveillance data and local studies. External models are useful but empowering national programmes to generate, interpret, and act on their own data and realities is key. Sustaining surveillance as a national priority is critical and must be extended to the post-certification phase.[11]

Novel approaches to financing are urgently needed. These should be led by national governments and their ministries of finance and include regional banks and innovative partnerships. Moreover, risks from biological challenges such as drug and insecticide resistance point to the parallel need for new tools and local research.

China's malaria-free status is a public health triumph, but it is also a call to action. Elimination requires long term tenacity; not just funds, but data driven foresight. As global malaria efforts face shifting donor priorities and resulting financing gaps, *The BMJ*'s new collection offers timely insights for policy makers, implementers, and funders alike. China and other countries that have achieved elimination have shown us the destination—now the challenge is translation to action for those left behind.

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Stratified sustainable vector control strategies and measures for malaria control and elimination in China: a 70 year journey

Qiyong Liu and colleagues revisit the strategies and measures adopted in China to control and eliminate malaria and discuss what can be learnt from its elimination

Malaria is a mosquito-borne infectious disease that significantly threatens global health. Considerable efforts and investments have led to a steady decline in incidence and mortality over recent decades. However, 249 million cases were reported from 85 countries and areas in 2022, resulting in 608 000 deaths.[1] Notably, approximately 95% of these cases and deaths occurred in the African region. China has had a heavy disease burden of malaria for more than 3000 years, evidenced by the Chinese character for malaria—疟 or nüè—discovered on oracle bone and bronze inscriptions from between 1562 and 1066 BC.[2] Chinese medicine has historically been used to treat people with malaria. However, in the 1940s, before the foundation of the People's Republic of China, the burden of malaria was still immense, with an estimated 30 million annual cases, more than 90% of the population at risk, and a fatality rate of approximately 1%.[3]

KEY MESSAGES

- The ongoing extensive national health campaign launched in China in the 1950s has played a crucial role in China's successful elimination of malaria
- Malaria control in China evolved through six phases: focal investigation and control (1949-59), epidemic containment (1960-79), incidence suppression (1980-99), consolidation of achievements (2000-09), malaria elimination (2010-20), and post-malaria elimination (since 2021)
- Stratified malaria control strategies have been adopted in different regions, with tailored phases based on disease incidence, vector species, and socioeconomic development
- Vector control strategies have evolved over the past seven decades—from eradication of mosquitoes, through integrated mosquito management, to sustainable vector management
- Insecticide treated bed nets, indoor residual spraying, and some agricultural innovations have been shown to be effective in controlling mosquitoes and have contributed to elimination of malaria in China

Amid the grave challenges posed by malaria, China adopted stratified strategies and took various measures to contain the disease. On 14 March 1952 the central government initiated a national health campaign, which called for the public to take action and "eliminate the four pests"—mosquitoes, flies, rats, and sparrows—with mosquito control being one of the core goals. The efforts against mosquitoes' primary habitats and reproductive cycles greatly benefited public hygiene, promoted health knowledge, and played an important role in controlling infectious diseases, including malaria. Meanwhile, a series of malaria related laws and regulations were issued to guide malaria control practices. Following several decades of concerted efforts nationwide, the World Health Organization certified China as malaria-free on 30 June 2021,[4] a remarkable achievement for China and a major milestone of global malaria eradication efforts.

As a mosquito-borne disease, transmission of malaria involves multiple factors, including vectors (*Anopheles* mosquitoes), pathogens (*Plasmodium*), hosts (human and animal hosts), and environmental conditions (for example, temperature, precipitation), which complicates its control. Considerable efforts have been made to target *Plasmodium*, such as rapid diagnosis and treatment (for example, artemisinin)[5] and mass drug administration. However, vector control plays the most important role in blocking malaria transmission, as *Plasmodium* relies on mosquitoes to complete its life cycle and mosquito bites to infect humans. Effective malaria control is heavily dependent on our ability to control mosquito populations.[6]

Although a vast literature is dedicated to elimination of malaria,[7] the significance of vector control is scarcely revisited in China's malaria elimination. Therefore, this article, part of a BMJ collection on malaria control in China, revisits China's seven decade endeavour to control vectors for malaria elimination nationwide. Other articles in this collection explore interventions in specific provinces with distinct conditions over different periods. These include the border province of Yunnan (diverse ecological features, multiple vector species, and underdeveloped economics) since 1980 and the tropical province of Hainan (warm, humid climate year round, with a high volume of tourists and migrant workers) from 1959 to 2011. These national and distinct regional experiences offer valuable insights for countries facing similar challenges. The collection also delves into responses to resurgence of malaria after local elimination and discusses innovative methods for controlling mosquito larvae, aiming to provide a comprehensive view of China's vector control journey for malaria elimination.

Evolving malaria vector control strategies in China

The primary malaria vectors in China are *Anopheles* mosquitoes: *An sinensis*, *An lesteri*, *An minimus*, and *An dirus* (fig 1, panels A-D).[9] Among these, *An sinensis* is the most widespread and dominant species.[10] *An lesteri*, also known as *An anthropophagus*, acts as the main vector for *Plasmodium falciparum* malaria and has a much higher vector competence than *An sinensis*,[10] although its geographical range has shrunk in recent years; it is now mainly found in southwest and northeast China (for example, Liaoning Province).[11] *An minimus* thrives south of the 25°N parallel and

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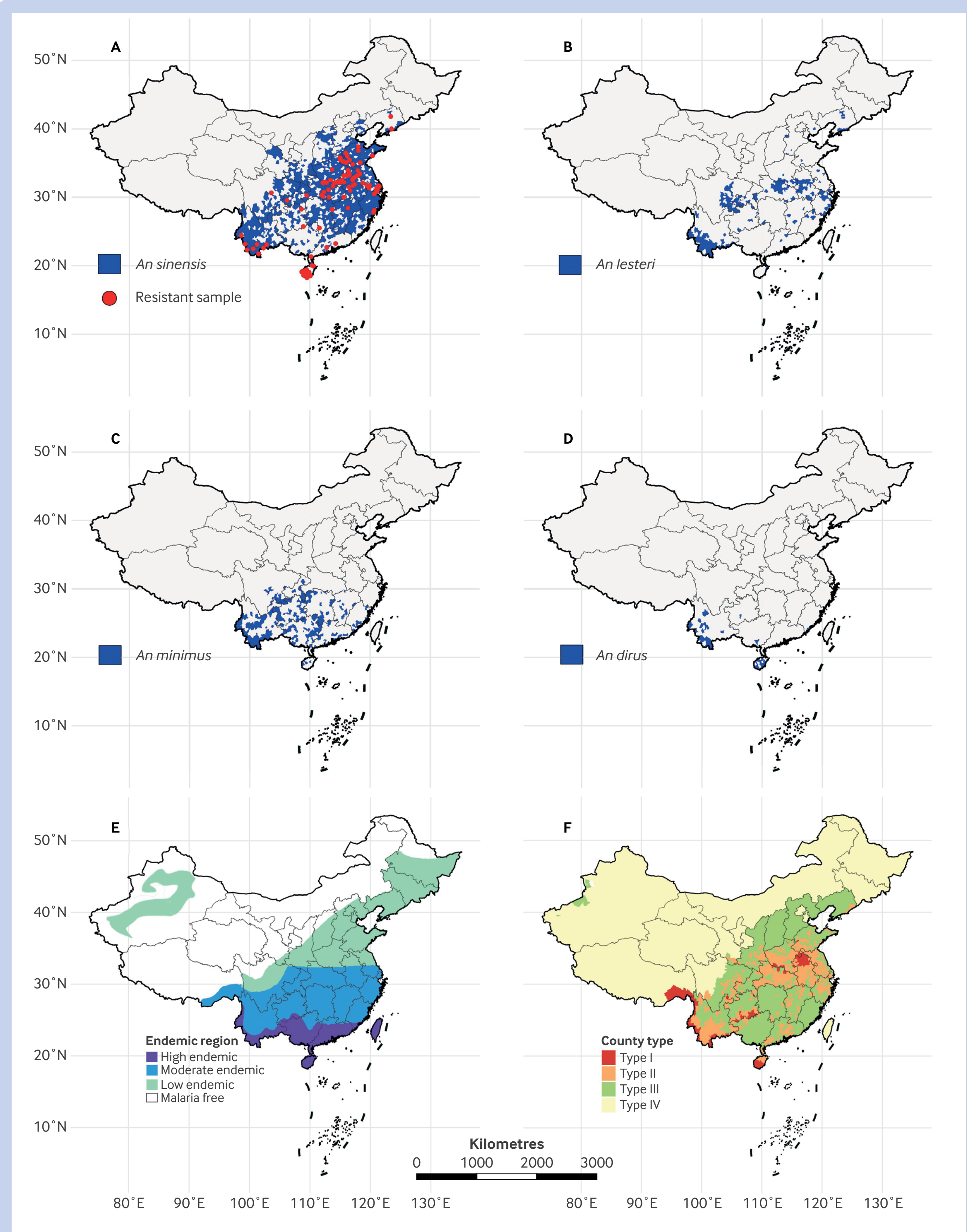

Fig 1 | Geographic distribution of four major malaria *Anopheles* in mainland China between 2000 and 2016: *An sinensis* (A), *An lesteri* (B), *An minimus* (C), and *An dirus* (D).[8] Red dots in map A indicate that insecticide resistance has been reported in *An sinensis* population (data from https://apps.who.int/malaria/maps/threats/). Stratified malaria endemic regions in 1979 (E) and 2010 (F). County type I=annual incidence >10/100 000, with indigenous cases reported in three consecutive years; type II= indigenous cases reported in past three years but annual incidence <10/100 000 in at least one year; type III=no indigenous cases in past three years; type IV=non-malaria endemic regions serves as a primary malaria vector in southern China, whereas *An dirus* can be found in Hainan and Yunnan provinces.

Vector control plays a crucial role in the path towards elimination of malaria, and China has taken various measures to control mosquitoes.[9] Initial efforts were directed towards the elimination of mosquitoes. In 1953 dichlorodiphenyltrichloroethane (DDT) treated bed nets were introduced for *Anopheles* control in Yunnan Province, marking one of the earliest interventions. In 1976 China conducted its first research on pyrethroid insecticide treated bed nets,[9] which proved highly effective in preventing mosquito bites.[12] From 2011 to 2019 more than 2.2 million insecticide treated bed nets/long lasting insecticidal nets were distributed nationwide. Additionally, indoor residual spraying has been widely implemented since 1980 to control malaria vectors in *P falciparum* endemic areas, protecting more than 5.7 million people between 2011 and 2019.[11] To supplement these efforts, agricultural innovations, such as rice-fish co-culture, have also contributed to effective mosquito larval control.

Vector control strategies for malaria in China have evolved over time. In 1978 China introduced integrated mosquito management, which combined environmental, chemical, biological, and physical control methods to target harmful mosquito species. Integrated mosquito management aimed to reduce vector mosquito density below a risk threshold, to eliminate vectors in certain conditions and some areas, and ultimately to wipe out the mosquitoes and diseases carried by them. The implementation of integrated mosquito management from 1986 to 1988 in Shandong and Guangdong provinces resulted in a reduction in mosquito density of more than 90%.[13] Subsequently, integrated vector management was proposed in 1980, following similar principles but encompassing a broader range of vector control techniques.

However, with evolving environmental and social factors in the 1990s and 2000s (for example, climate change, globalisation, urbanisation, changes in land use patterns, and insecticide resistance), malaria remained rampant and resurged in some areas. Amid these challenges, sustainable vector management was introduced in 2004, emphasising the importance of timely vector surveillance to conduct practical risk assessments and formulate control plans for vectors and related diseases on the basis of comprehensive health, economic, and ecological benefits. Sustainable vector management also underscored the benefits of public participation and multi-departmental collaboration to maintain vector populations at a level posing minimal threat of harm. Under the guidance of sustainable vector management, vector surveillance was strengthened and the "epidemic focus response" strategy was practised in a timely and accurate manner, to contain malaria transmission by also targeting mosquito vectors around identified malaria hotspots.

Measures to control malaria in different phases

Since 1949 China has used different strategies and measures to control malaria and its vectors on the basis of epidemic characteristics and socioeconomic development. These practices, including the matter of laws and regulations as well as the stratified malaria control strategy, evolved over six distinct phases, each tackling unique challenges in the fight against malaria (fig 2; box 1).

In phase I (1949-59), the initial malaria control strategy focused on "focal investigation and control" to reduce the incidence and mortality, as well as to curb local outbreaks. To facilitate vector control, the country was stratified into four zones on the basis of *Anopheles* species: zone 1 covered the tropical and subtropical areas (south of 25°N), where *An minimus* served as the main malaria vector in mountainous areas and *An sinensis* in plain areas; zone 2 covered the areas between 25°N and 33°N, where the main vectors were *An lesteri* and *An sinensis*; zone 3 was north of 33°N, where *An sinensis* acted as a dominant vector; zone 4 consisted of malaria-free areas (for example, cold high altitude areas, deserts, and plateaus).[10 14 15]

Malaria was particularly prevalent in phase II (1960-79). In response, four zones were determined according to malaria incidence, from high endemic to malaria-free regions (fig 1, panel E).[14] Control strategies were also locally tailored according to the vector species. In northern China, where *An sinensis* was the main vector, a comprehensive control strategy focused on eliminating infection sources, supplemented by mosquito control. In southern China, where *An minimus* acted as the primary vector, the strategy equally focused on eliminating infection sources and mosquito control.[16] In areas with *An dirus* (for example, Hainan Province), environmental transformation projects were conducted to remove mosquito breeding sites.[15]

As malaria was progressively reduced in phase III (1980-99), the stratified zones were updated on the basis of the changing reports of malaria incidence. Areas with an annual incidence rate above 1% or areas with endemic *P falciparum* malaria were prioritised and control measures were strengthened in these areas. In areas where the incidence rate dropped below 0.05%, the focus shifted to malaria surveillance.

During phase IV (2000-09), in response to the resurgence of malaria and challenges such as insecticide resistance, sustainable vector management was proposed in 2004

Box 1: Summary of temporal changes in malaria prevalence in China

- Malaria was prevalent in China in the 1950s, with a significant mortality rate. In 1950 alone, 2123 malaria related deaths were reported, leading to a mortality rate of 3.85/1 000 000. Various measures were taken in this phase, including a national health campaign to eliminate mosquitoes. By 1959, the incidence had dropped to 234/100 000 and the mortality rate had declined to 0.81/1 000 000.
- The incidence of malaria fluctuated significantly during 1960-79, reaching a record high in 1970, resulting from a combination of food shortages, increased population mobility, and unstable political conditions. By 1979, the incidence had dropped to 255/100 000—a 91% decrease compared with that in 1970. Malaria intensity in China continued to decline significantly in the 1980s and 1990s. By 1999, malaria incidence had declined to 2.4/100 000.
- However, the Huai River Basin in central China experienced an epidemic of *Plasmodium vivax* malaria from 2001 to 2007, leading to a substantial increase in the prevalence of malaria. After strengthening of control measures, malaria incidence dropped back to 1.1/100 000 by 2009. Since the last indigenous malaria case reported in April 2016 in Yunnan Province, China has been malaria-free. However, with thousands of imported cases each year, the challenge remains.

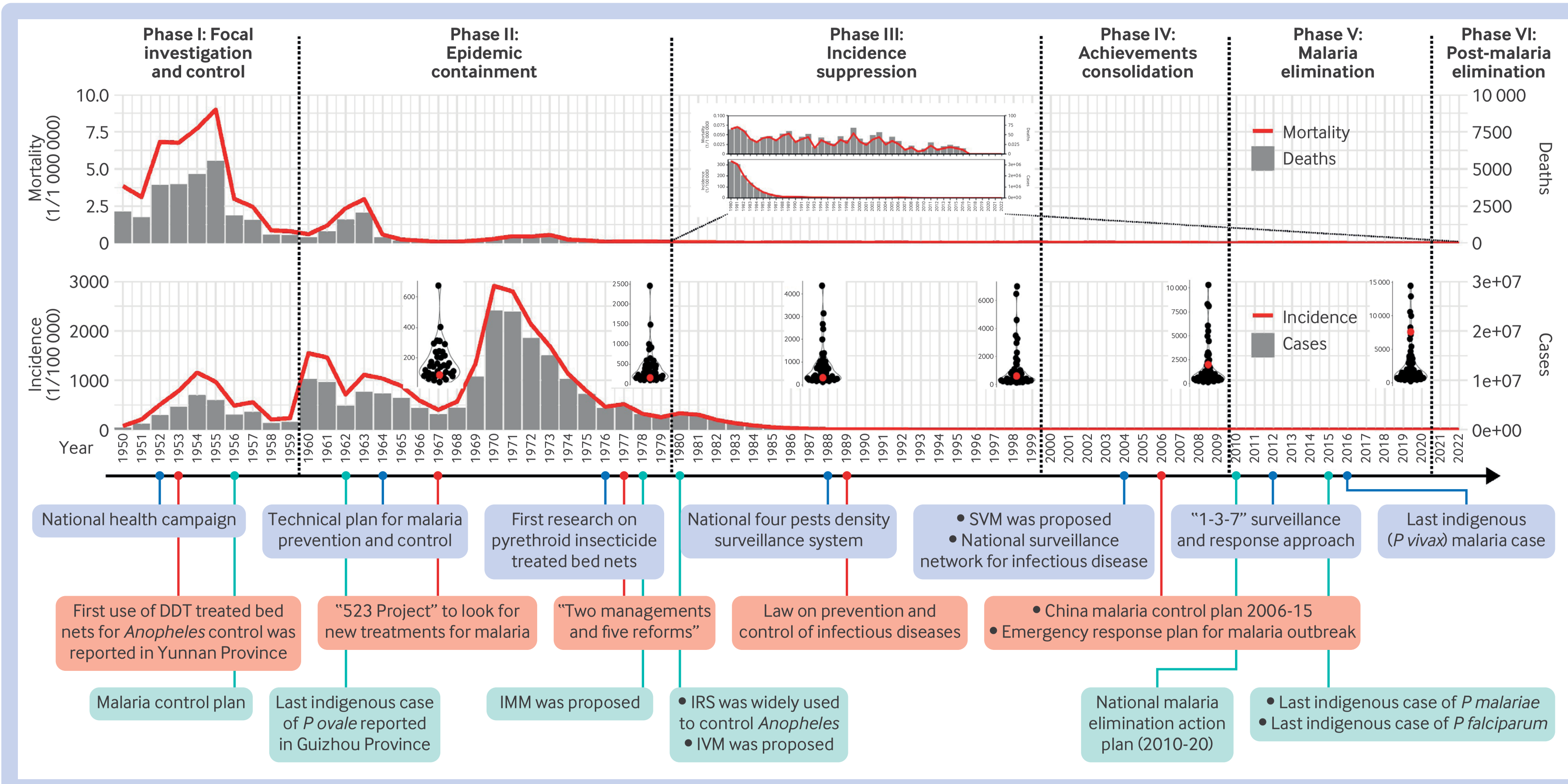

Fig 2 | Mortality rate and incidence of malaria in China since 1950, and corresponding measures taken to eliminate malaria. Mini dot plots represent average gross domestic product per capita (US$) of 54 African countries (black dots) and China (red dot) every 10 years from 1960 to 2019 (data from World Bank: https://data.worldbank.org/indicator/NY.GDP.PCAP.CD). DDT=dichlorodi phenyltrichloroethane; IMM=integrated mosquito management; IRS=indoor residual spraying; IVM=integrated vector management; SVM=sustainable vector management

to guide vector control. For example, in Yongcheng of Henan Province, where an outbreak occurred between 2006 and 2009, *Bacillus sphaericus* was used on *An sinensis* breeding sites to prevent the spread of malaria.[17] In Yunnan Province, housing structures and materials were found to be associated with malaria prevalence. Replacing traditional housing materials (for example, mud and brick, grass-mud mixture, and mud-wood structures) with modern alternatives (for example, concrete and bricks) could significantly reduce mosquito exposure.[18]

In 2010, following the National Malaria Elimination Action Plan (2010-20), the malaria control strategy focused on both individual malaria cases and epidemic spots, aiming to eliminate malaria nationwide in China. Correspondingly, counties were stratified into four types on the basis of malaria incidence (fig 1, panel F),[15] with resources allocated accordingly. Most importantly, the "1-3-7" strategy (case reporting within one day, investigation within three days, and response within seven days) was proposed to enhance case based malaria surveillance and response.[4 19] Meanwhile, a nationwide surveillance network was also established, consisting of well distributed sentinel sites and a laboratory network extending to the county level for diagnosis of malaria since 2010.[20]

Since achieving malaria-free certification in 2021, China has shifted its focus to managing imported cases. Rapid interventions are carried out around the epidemic spot to avoid secondary transmission. For instance, indoor residual spraying is conducted in all houses within a 500 m radius of a confirmed case, and neighbouring residents, particularly those with a fever, have rapid diagnostic tests. Routine pathogen surveillance of mosquito vectors in the field also serves as a crucial proactive measure in preventing the resurgence of malaria in this post-elimination phase.

Key lessons from China's malaria elimination journey

After 70 years of concerted efforts, China finally eliminated a disease that had been prevalent for thousands of years. However, progress towards elimination of malaria was arduous and full of setbacks. During the early stages, mosquito control relied mainly on insecticides, but their frequent application led to fatigue among residents, diminishing public cooperation. The ensuing insecticide resistance and environmental pollution further hindered control of mosquitoes. In addition, famines across China from 1959 to 1961 devastated China's population health and economy, resulting in underinvestment in control of mosquitoes and malaria. Meanwhile, the increased population mobility and the dissolution of some disease prevention facilities exacerbated the malaria situation, leading to a large resurgence of malaria in the 1960s. From the late 1960s to the mid-1970s, political turmoil paralysed the national health system, combined with a large influx of susceptible urban populations to malaria endemic rural regions, triggering two major malaria epidemics in central China. In addition, large dry lands were converted into rice paddy fields to boost rice production, which inadvertently created more larva breeding sites and complicated malaria control efforts.

In the 2000s the prolonged period of low malaria prevalence led to complacency and neglect in malaria control. Funding was significantly reduced, skilled personnel were lost, disease prevention facilities were closed, and public awareness of malaria prevention diminished. In some areas, more than 90% of malaria cases went unreported. This neglect led to the re-establishment of malaria in central China. For example, Yongcheng reported its first malaria outbreak in 2003 after 11 years of being malaria-free, accumulating more than 6500 cases from 2006 to 2010. These setbacks underscore critical lessons in the importance of sustained vigilance and investment in fighting against malaria.

Despite these challenges, China ultimately brought malaria under control and achieved elimination. Some previous studies have discussed different aspects of China's malaria elimination.[7 10 16 21] The factors contributing to the successful elimination are multifaceted, including strong political commitment and leadership,[22 23] public involvement (for example, national health campaign), sufficient financial support (for example, funding from the Global Fund to Fight AIDS, Tuberculosis and Malaria),[20] strengthened surveillance, rapid diagnosis and case management (for example, the "1-3-7" strategy), and timely assessment and supervision. However, vector control is an indispensable component of this success.[6] Owing to a lack of sufficient insecticides, vector control in the early stage primarily relied on environmental management. When a large volume of insecticide was obtainable, vector control shifted to massive application of insecticide, which inevitably led to severe insecticide resistance and environmental pollution. To cope with these problems, integrated mosquito management and sustainable vector management were proposed and practised in China's vector control, underscoring the importance of vector surveillance to maintain low vector populations. Meanwhile, the stratified sustainable vector control also played a key role, which is particularly important for countries with diverse ecological, social, and vector species variations. Control measures were continuously carried out to target vector larvae (for example, the removal of breeding sites, and larviciding) or adults (for example, indoor residual spraying, insecticide treated bed nets/long lasting insecticidal nets). Innovative interventions also contributed, such as rice-fish co-culture to suppress larval breeding and replacing traditional housing materials with modern alternatives to reduce risks of exposure to mosquitoes.

Perspective

Elimination of malaria does not mark the endpoint for control of this disease, but it marks a new beginning for China. Climate change may drive the expansion of mosquito habitat and vector distribution.[24] Such an expansion could increase the risk of spreading malaria, particularly in historically non-endemic regions. Moreover, insecticide resistance is an imminent problem and may undermine the effectiveness of mosquito control (fig 1, panel A).[25] Resistance to antimalarial drugs is another non-negligible challenge in the treatment of malaria.[10]

More importantly, the elimination of malaria in China not only benefits domestic public health but also has a broader significance globally. Considering the evolving economic and social conditions over the past 70 years and the diverse environmental and ecological contexts across China, the strategies and measures adopted in China could provide useful information to other countries and regions still grappling with malaria, particularly for the African region. Although malaria is considered a poverty related disease and associated with inadequate economic development,[26] this does not necessarily mean that malaria could not be controlled or even eliminated in less developed countries. In China's case, the gross domestic product per capita was comparable to those of many African countries before the 1990s but malaria was still brought under control (fig 2). Through initiatives such as the Forum on China-Africa Cooperation (FOCAC), China has launched a series of malaria control projects with African countries since 2000.[27] For instance, launching mass drug administration in Comoros in 2007 led to malaria cases being reduced by 95%.[27] The China-UK-Tanzania Pilot Project conducted between 2015 and 2018 achieved an 81% reduction in malaria prevalence.[28] This project helped to develop the "1,7-malaria reactive community-based testing and response" (1,7-mRCTR), a locally tailored approach adapted from China's "1-3-7" strategy, showing a promising effect on malaria control in Tanzania.[28] Such collaborations offer a platform to share techniques, health products, and intervention strategies in malaria control.[23 29]

China's journey underscores that elimination of malaria is achievable with sustained political commitment, public involvement, adequate financial support, and strengthened stratified sustainable vector control strategies and measures. The lessons and experiences over the past 70 years are invaluable in advancing global health efforts towards the ultimate goal of malaria eradication worldwide.

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Long term monitoring and adaptive strategies: lessons from Hainan's malaria elimination and prevention efforts

Huaiyu Tian and colleagues argue that to improve sustainable malaria control and reduce the risk of disease resurgence, targeted interventions can be optimised for eliminating malaria in areas co-endemic for multiple Plasmodium species

The intensity of malaria transmission is influenced by factors related to the parasite, the human host, and the *Anopheles* mosquito and which of these factors become targets of intervention strategies that aim to treat and prevent infection and disease.[1 2] Although the World Health Organization has certified 40 countries and territories, including China, as malaria free in 2021,[3] evidence to guide elimination planning is lacking in more than half of the cases. WHO defines malaria elimination as the interruption of local transmission of a specified malaria parasite species in a defined geographic area through deliberate activities.[4] Malaria prevalence and interventions have rarely been meticulously documented throughout the long elimination process, leading to a lack of evidence to guide elimination planning.

We aimed to analyse the malaria elimination programme in Hainan, China, between 1959 and 2021 to highlight two topics of relevance to today's global malaria strategy: how to target malaria elimination in high burden areas where the disease remains endemic and how to prevent re-emergence of malaria in areas where it has been eliminated.[5] Selecting the optimal combination of interventions and prioritising these to maximise impact are critical to current elimination efforts.

KEY MESSAGES

- Hainan's success in eliminating malaria lies in the long term effectiveness of a comprehensive approach
- Combining indoor residual spraying with insecticide treated bed nets can ensure maximum coverage to effectively control mosquito vectors
- Sustained case surveillance and continued mosquito control are needed to prevent malaria resurgence
- Effective malaria elimination strategies need to be persistent but adaptable to changing transmission and intervention effectiveness, with supplementary interventions used when necessary

Hainan: among the provinces most severely affected by malaria in China

Hainan, an island province located in southern China, consists of Hainan Island and several smaller surrounding islands. The province has a warm, tropical climate, characterised by substantial precipitation, with annual rainfall ranging from 1000 to 2600 mm and an average annual temperature of 22-27°C. These climatic conditions create an ideal environment for *Anopheles* mosquitoes. Entomological surveys have shown that the abundance of the mosquito population has remained relatively constant over time.[6 7] The baseline infection rates of *Anopheles* mosquitoes in Hainan were significantly higher than in regions with similar malaria transmission environments such as Myanmar.[8] Hainan's climate and environment create favourable conditions for year round malaria transmission, making malaria elimination unlikely to succeed.

From 1959 to 2011, more than 1.3 million cases of clinical malaria were reported in Hainan, with an average annual incidence rate of 5.91 cases per million population (fig 1). Over the past 53 years, the province has reduced the prevalence of malaria from 30% to zero,[4] demonstrating the effectiveness of its tailored strategies. Building on the elimination of indigenous transmission in 2011, strategies have since focused on strengthening the malaria prevention infrastructure, prioritising the mitigation of risks of reintroduction, and maintaining zero transmission. This achievement aligns with WHO's goal of eliminating malaria in at least 30 countries by 2030 and underscores the importance of adapting interventions to specific local conditions.[9] The strategic flexibility in Hainan—continually refining intervention methods as transmission decreased—has been a key factor in its success and offers a model for other highly endemic regions.

Adaptive intervention strategies for malaria elimination in Hainan

Hainan's malaria elimination efforts have been characterised by adaptive strategies tailored to a changing endemic situation (table 1). Central to these efforts has been timely epidemiological investigation of malaria cases and foci conducted by the Centers for Disease Control (CDCs) in various cities and counties. In the early morbidity and infection control stages, when the disease burden is high, mass drug administration and indoor residual spraying were prioritised to rapidly reduce transmission. As the malaria burden declined, interventions shifted during the transmission control stage to more targeted approaches, such as targeted drug administration and the distribution of insecticide treated bed nets. Finally, the CDC implemented the "1-3-7" malaria case management approach in the transmission interruption stage, which mandates case reporting within one day, investigation within three days, and a targeted response within seven days (see other articles in this collection for more information). These adaptive strategies aimed to follow the principles of the WHO Global Technical Strategy for Malaria,[4] combining targeted interventions with innovative tools and implementation methods.

Initially, malaria interventions in Hainan were not rigidly tied to a single stage of the elimination process but were adapted to respond to immediate needs at various points in time. Since 1953 the Hainan Malaria Research Station of the Chinese Academy of Medical Sciences has conducted detailed surveys to map

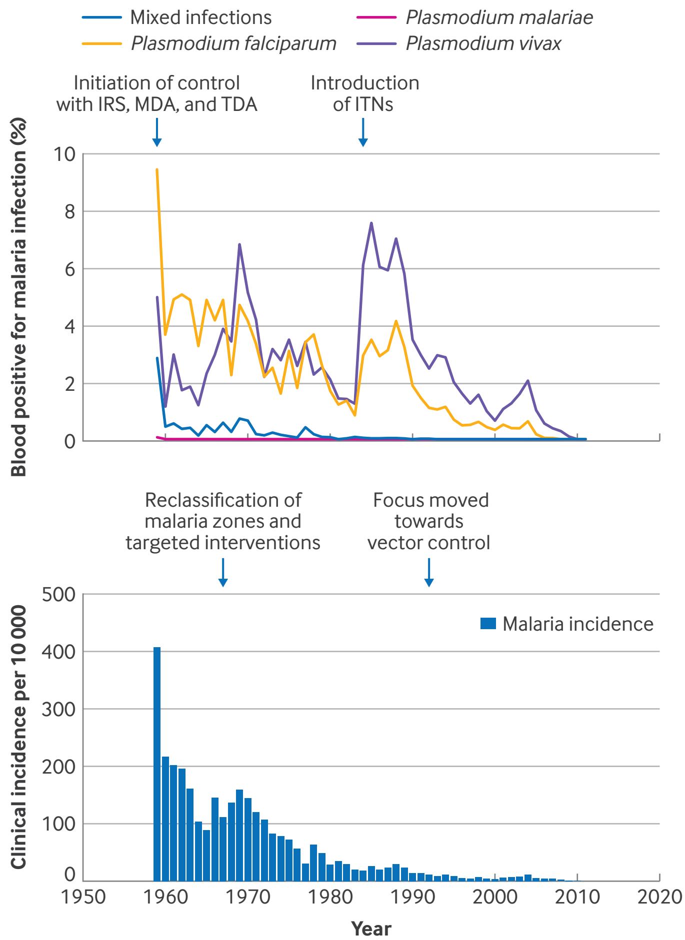

Fig 1 | Malaria epidemics in Hainan between 1959 and elimination of endemic malaria in 2011. Top: lines correspond to changes in positive rates of *Plasmodium vivax*, *P malariae*, *P falciparum*, and mixed infection in sample of general population measured via annual blood examinations. Thick lines show blood positivity for malaria infection. Bottom: bars represent annual malaria incidence. Vertical dashed lines indicate timing of start of four main intervention strategies successfully introduced: indoor residual spraying (IRS), mass drug administration (MDA), targeted drug administration (TDA), and insecticide treated bed nets (ITNs), which were gradually introduced and became widely used in Hainan as malaria control measures

malaria prevalence, informing strategic decisions. In 1958 a comprehensive malaria control campaign was initiated by the Hainan government, with Lingshui and Baoting counties serving as pilot sites. By 1967 Hainan authorities had reclassified malaria zones on the basis of risk of transmission, enabling the implementation of targeted interventions such as indoor residual spraying with DDT (dichlorodiphenyltrichloroethane) and the deployment of piperaquine-primaquine combinations for mass drug administration and targeted drug administration. In 1992 the focus of malaria management moved towards vector control, primarily through the widespread use of deltamethrin treated bed nets. From 2003 to 2011 Hainan further advanced its comprehensive malaria elimination strategy, incorporating seasonal campaigns that targeted high risk groups during peak transmission periods in spring and autumn. After 2011 Hainan authorities focused on maintaining elimination by strengthening surveillance, rapidly responding to imported cases, and maintaining public awareness campaigns.

Key strategies for successful malaria elimination in Hainan

Apply a comprehensive system of vector control and antimalarial drug use

Hainan's success in eliminating malaria can be attributed to the sustained effectiveness of a comprehensive long term approach. Malaria elimination programmes have been regularly carried out in Hainan since 1959, with priority given to indoor residual spraying and mass drug administration. However, the implementation of malaria interventions in Hainan has faced enormous challenges, including inadequate antimalarial resources, insufficient adaptation to climate change, incomplete coverage of preventive measures among the population, and drug resistance. For example, owing to funding adjustments and a shortage of technical personnel, the residual *An minimus* capture rate rebounded to 28.25% in 1978, significantly higher than the 0.91% rate in 1964, leading to ineffective malaria control.[10] In 1994 an early onset of the malaria transmission season owing to the warming climate led to a 19.18% increase in the malaria incidence compared with 1993.[10] Additionally, in 2000 the malaria mortality rate rose to 0.08 per million, driven by the influx of non-immune migrant workers from other provinces into the *P falciparum* endemic regions of central and southern Hainan.[11] Malaria control was subsequently improved through better targeting of elimination strategies supplemented by the joint use of insecticide treated bed nets and targeted drug administration. The case of Comoros, Africa, highlights the importance of surveillance for maintaining suppression of transmission. Although mass drug administration in Comoros initially achieved an impressive 95% reduction in malaria cases, the absence of sustained surveillance and complementary interventions led to a resurgence of cases.[12] By contrast, Hainan's success stems from combining mass drug administration and indoor residual spraying with consistent surveillance and targeted interventions,[13-15] effectively preventing resurgence of transmission.

Establish feasible mosquito vector control programmes

The promotion and widespread use of insecticide treated bed nets have long been a cornerstone of effective vector control, leading to significant reductions in the malaria incidence in regions where they were implemented. Notably, China, including Hainan, was the first country to extensively adopt widespread use of insecticide treated bed nets as a malaria control measure before it was adopted in sub-Saharan Africa.[16] However, recognising the constraints of limited resources, Hainan adapted its approach by shifting to a coverage ratio of one net per three individuals, slightly below the WHO recommended rate (one net per 1.8 individuals).[17] This adjustment proved to be both economically viable and highly effective in the local con-

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Table 1 | Key elimination interventions in Hainan

Intervention strategies	Mechanism of action	Implementation period	Target population/ area	Materials/insecticide used	Coverage/ effectiveness	Supplementary notes
Indoor residual spraying	Kills adult mosquitoes resting on walls before or shortly after blood meal	Spring and autumn	Ultra-high and high malaria areas	6% deltamethrin (240 mg/m²), or 6% lambda-cyhalothrin (240 mg/m²), or 25% DDT (2 g/m)	All dwellings in targeted areas	Local government selects insecticide on basis of vector species and resistance monitoring
Insecticide treated bed nets	Prevents adult mosquitoes from delivering infectious bites as long as person is under net; kills adult mosquitoes, offering individual and community protection	Annual peak malaria season (usually in April)	Malaria endemic areas; residential sites	30 mg permethrin or 15 mg cyfluthrin/m^2 of net	Coverage protection rate: >70% in residential areas; >90% for impregnated/sprayed nets	Supplemented with indoor residual spraying in areas with coverage <70%
Mass drug administration	Reduces parasite population through monthly treatment	April to November	Entire population (>90% coverage)	Two day intermittent treatment with 50 mg piperaquine and 22.5 mg primaquine; short term and intensive therapy that rapidly reduces number of parasites in patient's body	Achieves elimination through pharmacological action with continuous dosing	Combination of antimalarial drugs can be adjusted to piperaquine (150 mg) and primaquine (22.5 mg) on basis of sensitivity monitoring
Targeted drug administration	Prevents transmission among high risk groups; treats existing infections	Spring (by May) and autumn (by September)	Individuals/groups at high risk (eg, recovered malaria cases, people whose occupation puts them at increased risk of malaria infection)	Piperaquine (1-10 tablets) combined with primaquine (24 tablets for four day course and 12 tablets for eight day course)	Drug uptake should be ≥90%	Administered before, during, or after exposure to malaria transmission

DDT=dichlorodiphenyltrichloroethane.

text, particularly in reducing costs while maintaining sufficient protection. By 2011 Hainan's insecticide treated bed net coverage rate was reported to be one net per 1.97 (range 1.05-2.78) individuals. This more flexible approach allowed for broader distribution of insecticide treated bed nets without compromising the core goal of reducing malaria transmission. The success of this model is evidenced by the significant reduction in malaria incidence, with the introduction of deltamethrin treated nets in the 1990s, resulting in a 77.5% decrease in cases within five years.[10]

Furthermore, high coverage of insecticide treated bed nets in malaria endemic areas can provide protection for people who do not use them directly by decreasing mosquito populations.[18-21] Despite huge efforts to deploy insecticide treated bed nets across sub-Saharan Africa, the coverage remains uneven. By 2019 only 36% of households had access to at least one insecticide treated bed net per two individuals.[22] Prompt adjustment, such as modifying the recommended coverage ratio to align with local resource availability, increases the protective benefits of mosquito vector control for users of insecticide treated bed nets and ensures broader distribution within budgetary constraints. The example of Hainan emphasises the importance of local adaptation of global recommendations and shows how, despite resource constraints, significant public health benefits can be made while gradually building up to more ambitious coverage targets.

Engage continuous drug management strategies

Achieving malaria elimination in the context of escalating drug resistance requires continuous and region specific drug administration strategies, as demonstrated in Hainan. Dispersed populations and limited healthcare infrastructure complicate the implementation and monitoring of interventions in malaria-prone areas, such as mountainous and hilly regions. Healthcare facilities at all levels throughout Hainan conduct regular rapid malaria diagnostics in high risk areas, monitor the type of *Plasmodium* infection, and administer drugs to specific populations. The need to comprehensively monitor and tackle safety, efficacy, and resistance concerns associated with new malaria treatments was emphasised by the Mpumalanga Province trial in South Africa.[23] This trial specifically focused on emerging drug resistance patterns and assessed the real world safety and efficacy of antimalarial drugs.

Healthcare facilities at all levels have adopted an approach of using combination or complementary drugs to deal with the problem of drug resistance associated with continuous use of a single drug. This approach involves periodically changing or supplementing drug combinations, with resistance gradually declining after re-testing, before returning to the original regimen. Since the first case of chloroquine resistant *P falciparum* was detected in Sanya, Hainan, in 1974, the prevalence of chloroquine resistant *P falciparum* in Hainan has exceeded 60%. Regular monitoring in Ledong County since 1981 has shown a slow decline in resistance rates following the discontinuation of chloroquine in 1979, with resistance dropping from 97.3% in the early 1980s to 53.7% in the mid-1990s,[11] indicating a gradual recovery of susceptibility. However, resistance to piperaquine has increased owing to its widespread use. Implementing a strict drug regimen and prohibiting the misuse of antimalarials have been effective in slowing the development of resistance. For instance, artemisinin resistant *P falciparum* has been detected at the Cambodia-Thailand

and Thailand-Myanmar borders, although no resistance has been observed at the China-Myanmar border. This may be a result of China's stricter malaria control measures, including enhanced monitoring and drug management policies.[24]

Sustain malaria control with funding from multiple sources

Hainan's success in malaria elimination has been supported by robust and diverse funding and socioeconomic improvements. In 1984 Hainan expanded its malaria control efforts with a five year grant from WHO's Special Programme for Research and Training in Tropical Diseases. Since April 2003 the province has benefitted from the Global Fund Malaria Programme, including participation in the first and fifth rounds of the National Malaria Elimination Strategy Programme. Sustained funding from multiple sources has been crucial to reducing malaria transmission, developing the health workforce, and maintaining these gains over time (see other articles in this collection). Furthermore, reduced poverty, improved living standards, and enhanced healthcare have played a supportive role in sustaining malaria control efforts.

Keys to successful resurgence prevention in Hainan

Maintain a high level of surveillance and emergency response capacity

Despite the successful elimination of malaria in Hainan, the presence of residual malaria vectors and occasional imported cases underscore the continuing risk of malaria resurgence. Having achieved zero clinical malaria infections, the Hainan Health Commission has intensified surveillance of imported cases and rapid emergency responses, focusing on early detection, treatment, prevention, and the rapid deployment of targeted drug administration in the event of a possible concentrated malaria outbreak. By redefining malaria endemic areas and targeting the characteristics of the incidence of malaria in different regions, as well as the current status of malaria prevention, control, and surveillance efforts, the strategy has shifted from "reducing incidence in high risk areas" to "controlling each case and outbreak site to interrupt malaria transmission." This approach is based on the principles of tailoring interventions to local conditions and providing categorised guidance; it builds on a successful pilot project in Tanzania between 2015 and 2018, in which China's 1-3-7 approach was adapted to high transmission areas to establish Tanzania's 1.7 Malaria Reactive Community Testing and Response method.[25]

Strengthen control of *Anopheles* mosquito vector, even after elimination of malaria

An important challenge in sustaining malaria elimination in Hainan lies in the absence of consistently effective insecticides to prevent the disease. As a result, the cornerstone of preventing malaria resurgence has relied heavily on robust vector control measures. These measures have included the widespread use of insecticide treated bed nets, indoor residual spraying, and continuous monitoring of mosquito populations to adapt strategies in response to changes in vector behaviour or resistance patterns. When local or imported malaria cases are detected, the local CDC conducts indoor residual spraying with insecticides such as deltamethrin, malathion, or DDT (government approval is required for emergencies) at transmission hotspots. Mountainous and hilly areas, serving as primary habitats for *An minimus* and *An dirus*—the key malaria vectors in Hainan—pose great challenges. Accordingly, the CDC distributes treated or long lasting insecticidal nets and strengthens mosquito protection for people working in these areas to reduce mosquito populations and stop malaria transmission. Moreover, intermittent irrigation and other measures are implemented in irrigated rice field areas, which are habitats for *An sinensis*, a secondary vector, to reduce potential malaria transmission risks. Insecticidal vector control measures, such as insecticide treated bed nets and indoor residual spraying, were responsible for preventing 78% of clinical malaria cases in sub-Saharan Africa between 2000 and 2015.[26] The reliance on vector control underscores the critical need for sustained investment and innovation in interventions,[27] particularly in the face of potential lapses in drug efficacy and the ongoing threat of climate change and imported cases.

Self-protection awareness in the population to prevent imported re-transmission

Imported cases can influence the proportion of *P falciparum* and heighten the risk of malaria transmission. As a major tourist destination, Hainan experiences a high volume of travel, which inevitably increases the risk of malaria transmission. The persistent presence of malaria vectors on the island, coupled with the frequent importation of malaria cases, heightens the risk of secondary transmission. The potential for re-establishing local transmission from imported cases remains a constant threat. Similarly, in Cape Verde, surveillance from 2010 to 2019 showed that sustained transmission of malaria could be supported only by frequent importation from outside the country. However, frequent international travel has led to a consistent influx of imported cases.[28] These imported cases, when interacting with the local *An arabiensis* mosquito population, have resulted in secondary transmission, thereby increasing the risk of malaria resurgence in a region close to elimination.

Efforts to prevent re-transmission of imported malaria in Hainan focus on two main strategies. Firstly, health education initiatives are actively promoted to raise awareness about self-protection, particularly among people in mountainous areas where mosquito breeding is prevalent, migrant worker mobility is high, and healthcare resources are limited. This helps to encourage timely medical care and reduces the risk of local transmission from imported cases, strengthening overall disease prevention efforts. Secondly, all detected malaria cases are promptly treated within 24 hours, following standardised medication protocols by healthcare facilities at all levels. To tackle the risk of re-transmission, Hainan has participated in China's annual inter-provincial cross examination programme since 1992. This programme aims to enhance the timeliness of diagnosis, ensure adherence to treatment protocols, strengthen collaboration between medical and preventive services, and provide up-to-date information on the risk of drug resistance.[11]

Conclusion

The successful experience of malaria elimination in Hainan illustrates that rigorous evaluation of the effectiveness of malaria control strategies is complex but essential for informing future efforts, thereby substantially reducing the disease burden in malaria co-endemic areas. Additionally, the specific challenges faced in eliminating malaria in Hainan, such as shifts in the dominant *Plasmodium* parasites and the complexity of controlling drug resistant *Plasmodium* infections, are globally relevant, particularly in Africa, where targeting high burden areas and preventing resurgence are priorities. The lessons learnt in Hainan serve as important references for policy makers and public health practitioners in different settings.

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Lessons from failure to success on malaria elimination in the Huai River Basin in China

Qiyong Liu and colleagues consider the experience of basic malaria elimination, resurgence, and re-elimination in the Huai River Basin in central China, as well as lessons learnt to help to inform countries and regions in their approaches to malaria control and elimination

Malaria is still a significant public health threat. After generations of control efforts, China was certified as a malaria-free country by the World Health Organization in June 2021.[1] Not without its challenges, China's experience of eliminating malaria is informative for elimination strategies in other countries and regions.[2-4]

The Huai River Basin (HRB) in central China was the epicentre of two epidemics in the 1960s and 1970s, accounting for 93.1% and 91.2% of total reported cases in China, respectively.[5] A comprehensive control strategy focused on eliminating infection sources, supplemented by integrated mosquito control, was adopted, such that by 1987 most regions in the HRB had achieved "basic malaria elimination"—with incidence rates below 1/10 000.

Unfortunately, malaria resurged in the HRB in 2003 and peaked in 2006. At that time, 62.45% of China's total cases (60 193 cases) were in the HRB.[5] As a result, the government's leadership in malaria control was reenforced through the implementation of comprehensive measures, such as mass drug administration,[5] case management,[6] and sustainable vector management.[7] Consequently, the incidence of malaria in the HRB decreased significantly. No indigenous malaria has occurred in the HRB since the end of 2012 (fig 1).

Given the challenges of global malaria elimination and China's own experience with resurgence then successful elimination, this analysis aims to draw lessons from re-emergence of malaria in the HRB, identify comprehensive measures to combat resurgence, and propose key recommendations to help other countries to prevent malaria rebounds and achieve its ultimate elimination.

KEY MESSAGES

- Resurgence of malaria in the Huai River Basin (HRB) from 2003 to 2006 was primarily a result of the reduction and cessation of malaria and vector surveillance and control efforts after basic elimination in 1988
- The successful re-elimination of malaria in the HRB was achieved through the implementation of comprehensive measures, such as strong leadership, multi-sector collaboration, mass drug administration, case management, sustainable vector management, health education and training, and stable funding
- Continuously sustaining political commitment, effective case management, sustainable vector management, and stable funding are essential for maintaining malaria elimination in the HRB
- China's experience in the HRB offers valuable lessons for countries and regions that are facing the threat of endemic malaria or working to eliminate malaria or curb its resurgence

Malaria in the HRB

The HRB is located between the Yellow River and Yangtze River in central China at 30°55′-38°20′N and 111°55′-120°45′E. With a total area of 191 200 km^2, it stretches for 1000 km from northeast to southwest, with warm temperatures in the north and a subtropical climate in the south.

The HRB's location and climate create optimal conditions for the transmission of malaria—specifically *Plasmodium vivax*, the predominant species in this region.[4] The prevalence of *P vivax* malaria in the HRB makes it crucial to China's overall national strategy against malaria and useful in preventing other epidemics worldwide.

Two sites in the HRB, Yongcheng City of Henan Province and Guoyang County of Anhui Province, are representative areas of endemic *P vivax* malaria that is transmitted by *Anopheles sinensis* Wiedmann (fig 2). Malaria incidence in Yongcheng and Guoyang achieved basic elimination in 1987, followed by a resurgence in 2003 that peaked in 2006. Given their representative nature, understanding respective journeys in malaria control, resurgence, and elimination is a useful and representative exercise.

Contributing factors to malaria's resurgence in the HRB

The resurgence of malaria in the HRB from 2003 was due to the convergence of multiple factors. Key factors contributing to the resurgence have been distilled as follows.

Resource allocation away from malaria control

After the HRB achieved the basic elimination of malaria in 1987, local governments reduced funding for routine malaria control. Between 1992 and 2002, most of the local Centers for Disease Control and Prevention (CDCs) in the HRB either reduced or eliminated funding for malaria control. In Yongcheng CDC, malaria control funding was cut entirely during 1992-2002, compared with an annual average budget of ¥9820 ($2639) during 1987-91, which is equivalent to ¥46 505 ($6400; £4900; €5900) in 2024 after adjustment for annual consumer price index. In Guoyang CDC, the annual average budget of malaria control declined to ¥2736 during 1992-2002, equivalent to ¥8152 in 2024, compared with an average of ¥3080 a year during 1987-91, equivalent to ¥14 586 in 2024 (data from local CDCs, available from the corresponding author). Even though the budget during 1987-91 was already limited, the subsequent reductions had a significant effect on malaria control, particularly in the absence of proactive measures to sustain elimination. Similar trends were observed in other countries,[8] underscoring the risks of resurgence associated with inadequate post-elimination investments in malaria control.

Merger or closure of malaria control facilities

Public health resources are allocated on the basis of disease burdens and public health needs. In the HRB, because of the reduced

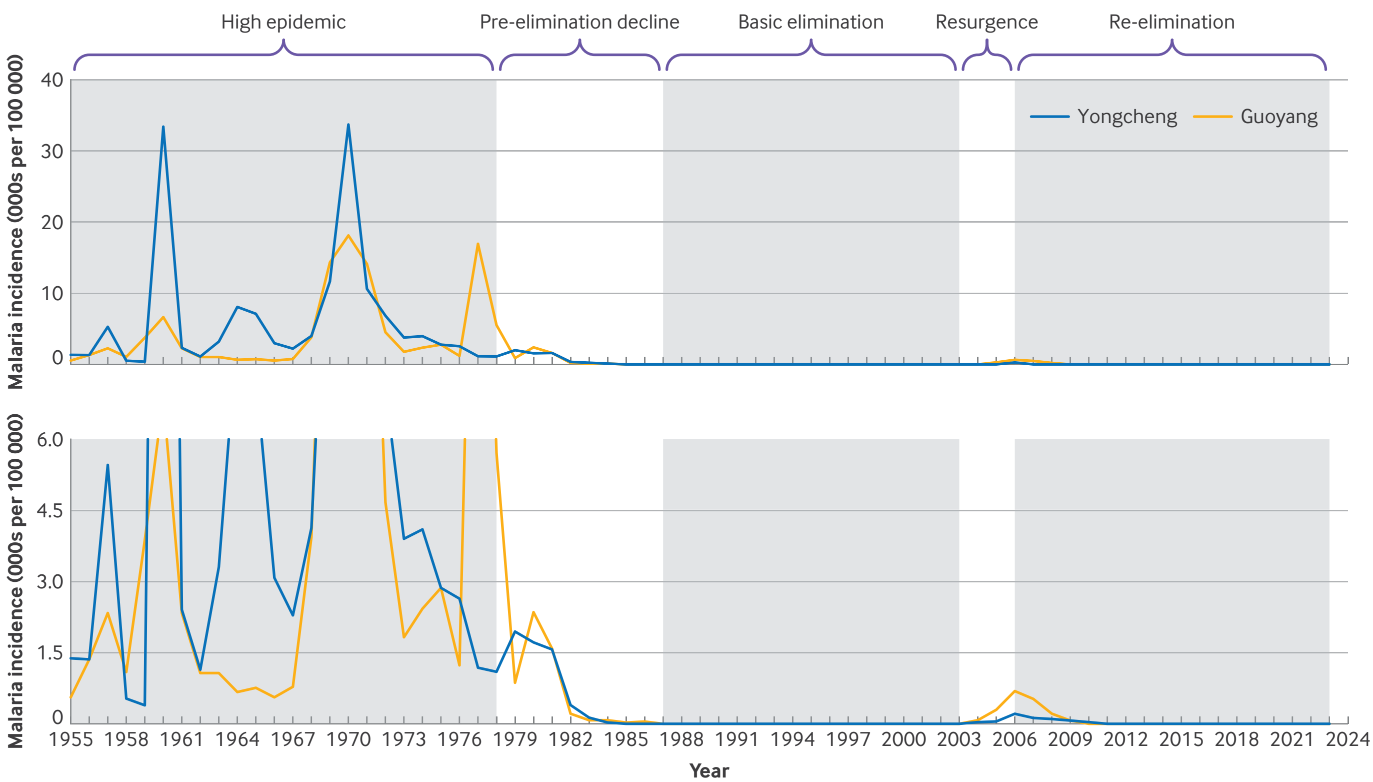

Fig 1 | Dynamics of malaria transmission in Yongcheng City and Guoyang County, Huai River Basin, China (1955-2023). The figure illustrates the phases of high epidemic (1955-77), pre-elimination decline (1978-87), basic elimination (1988-2002), resurgence (2003-06), and re-elimination (2007-23)

funding in rural primary healthcare in connection with tight local finances, township mergers, and a low incidence of malaria for more than 10 consecutive years, some professional sectors of CDCs and public health facilities were merged or closed. This ultimately resulted in a lack of personnel to carry out malaria surveillance and alerts, with delays in the diagnosis and treatment of imported cases.[9]

Loss of medical professionals

In Yongcheng CDC, an average of 31.8 staff members were engaged in malaria control each year from 1987 to 1991 (a total of 159 person years). From 1992 to 2002, most of these people were lost or replaced by new staff. In Guoyang CDC, an average of 6.2 staff were engaged in malaria control annually during 1987 to 1991 (31 person years in total), which dropped to 3.27 staff during 1992 to 2002 (36 person years in total) (data from local CDCs, available from the corresponding author). Massive loss of professionals seriously hampered malaria control in subsequent years.[10 11] Similarly, the reduction of village malaria workers in pre-elimination areas of Indonesia accelerated early malaria resurgence.[12]

Low capacity for detection, diagnosis, prevention, and management of malaria cases

Malaria resurgence in the HRB underscored the consequences of complacency and the dismantling of surveillance systems after basic elimination. The low-to-no malaria cases for more than 10 years hindered both diagnostic awareness among township and village doctors and the ability to diagnose malaria among laboratory personnel. It also led to insufficient supplies of antimalarial drugs and microscopic blood examinations and equipment. For example, in 2005, the average time from onset to diagnosis of 710 malaria cases was 6.27 (standard deviation 5.58) days in Yongcheng,[5] with the longest reaching 66 days.

Underestimating the transmission potential of *An sinensis*

Although the incidence of malaria in the HRB was low and even basically eliminated from 1992 to 2002, the potential for resurgence caused by *An sinensis* should not have been ignored. *An sinensis* was still widely distributed, and key ecological factors suitable for malaria transmission persisted. Even in the basic elimination stage, minimal but sufficient human resources, finances, and material resources are still needed to engage in malaria surveillance and control in order to prevent resurgence.

Comprehensive measures for a successful response after 2006

To curb the resurgence of malaria in the HRB, comprehensive control measures were implemented after 2006. The effectiveness of these measures was evidenced by a drastic decline in local epidemics since their implementation in 2007. The specific measures are as follows.

Government empowerment and responsible leadership structure

Facing the high incidence of malaria, Yongcheng established a response leadership mechanism led by the mayor. This was a four level emergency plan in line with China's statutory reporting of infectious diseases emergency plan, which clarified the malaria control responsibilities of public health infrastructure at all levels through signed target responsibility agreements. Similarly, Guoyang initiated a leadership mechanism headed by the deputy county magistrate in charge, established a malaria control network, and signed a letter of responsibility at all levels.

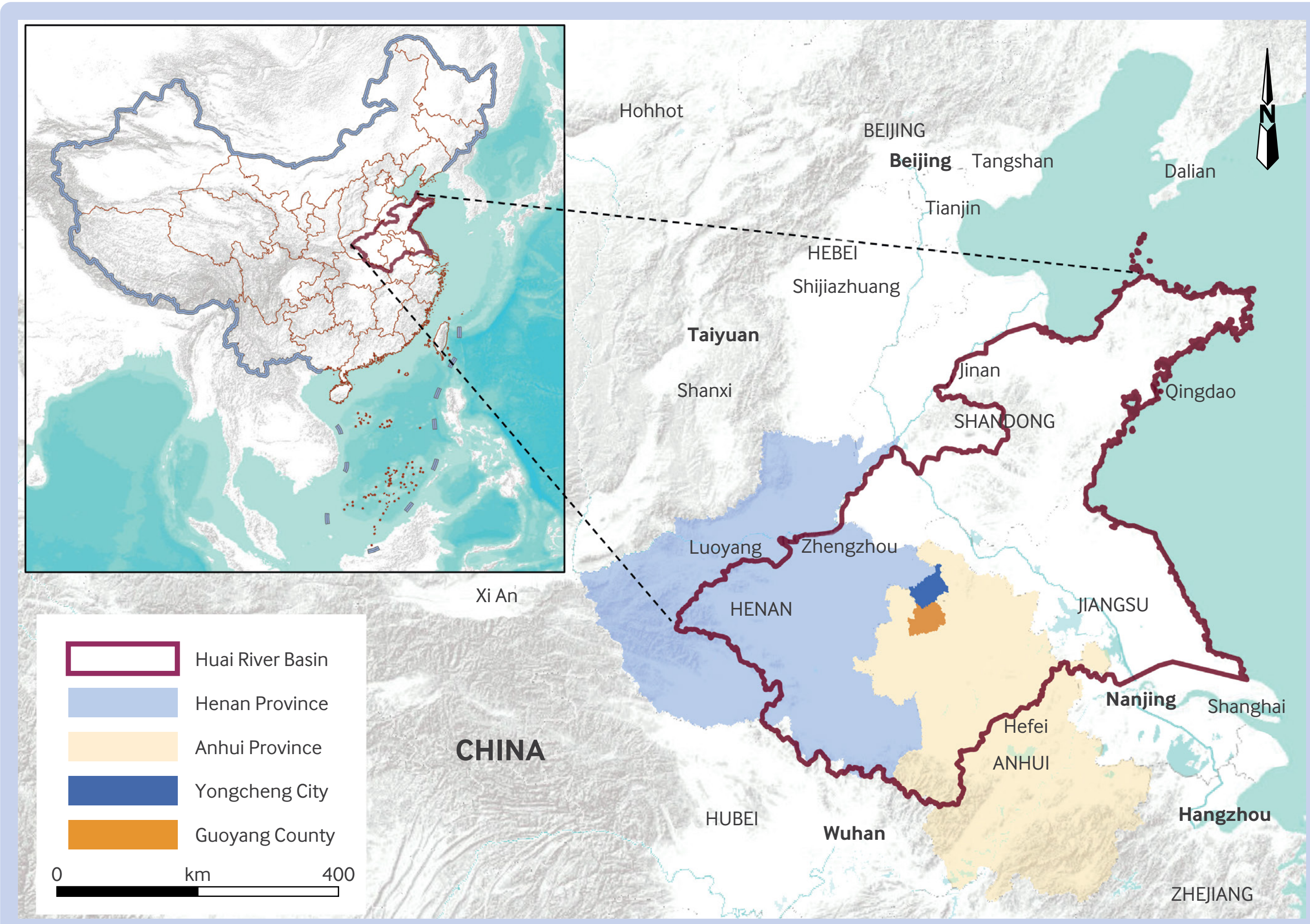

Fig 2 | Study sites in the Huai River Basin of central China

Health administration strengthening mass drug administration

Mass drug administration is considered to be a feasible approach to reduce malaria transmission.[6] In 2006 mass drug administration was implemented in four high incidence townships in Yongcheng, targeting 80 438 residents with chloroquine plus primaquine during spring to prevent relapses. In 2007 malaria incidence was 0.7% in the villages where all people had radical treatment and decreased by 69.6% compared with 2.3% in the previous year.[13] During the transmission season, chemoprophylaxis with piperaquine was administered monthly to residents near water bodies. This action significantly reduced malaria incidence in Guoyang.[6] Similar findings were obtained before the transmission season in the Gambia.[14] In Kenya, mass drug administration significantly reduced the prevalence of *Plasmodium*,[15] and this is regarded as a potent tool for malaria elimination.[16 17]

Hospitals of different levels carrying out blood smear examination for febrile individuals and case management

Blood smear examination for febrile people is an important way to proactively detect malaria cases. Each township health centre carried out blood smear examinations for febrile people during the malaria epidemic season in Yongcheng. Since 2005, all personnel for malaria diagnosis in township health centres have received annual training on microscopic examination techniques. Antimalarial drugs were distributed to village doctors, and then an antimalarial drug use registration system was strictly implemented to avoid misuse.

Government organising proactive malaria vector control

Sustainable vector management was implemented in the HRB.[18] In Yongcheng, biological control using *Bacillus sphaericus* suspension at 8 mL/m^2 with 15 day intervals against *Anopheles* larvae was carried out in 31 administration villages that had malaria outbreaks in 2006.[19] In total, ¥370 000 ($46 000) was used for pesticides and ¥400 000 as labour costs, equivalent to ¥557 291 and ¥602 476 in 2024, respectively. The density reduction rates of *An sinensis* larvae and adults in these villages reached 76-100% and 50-100%, respectively. In Guoyang, a risk area of 100 m around the homes of malaria cases was designated according to the dispersal range of *An sinensis*.[20]

Health administration organising health education and training

A total of 1719 people were trained in Guoyang in 2007, including physicians, microscopists, and healthcare personnel at all levels of healthcare systems. Leveraging a rural three tier healthcare system (county and county level city health departments, township hospitals, and village clinics), residents in epidemic areas received knowledge relevant to malaria through multiple channels, including flyers, manuals, slogans, posters, Henan opera, television

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broadcasts, newspapers, and the annual Malaria Day event on 26 April. From 2007 to 2009, Guoyang distributed 65 000 leaflets, 156 banners, more than 5000 posters, and 1350 manuals.

Co-funded programmes by governments and the Global Fund

Malaria control in the HRB has been jointly supported by governments and five rounds of the Global Fund to Fight AIDS, Tuberculosis and Malaria (GFFATM) since 2003. The local government invested heavily to contain the spread of malaria. For example, from 2007 to 2009, the Yongcheng municipal government allocated ¥800 000 annually, which is equivalent to ¥1 149 783 in 2024, to control malaria epidemics.

Key recommendations for maintaining elimination and preventing reintroduction after certification

Sustain strong political commitment, government leadership, multi-sector cooperation, and whole society participation

After elimination of malaria, maintaining political commitment, empowered leadership structures, and effective multi-sector collaboration remains critical. China has taken several concrete steps to institutionalise these practices. The National Malaria Elimination Action Plan (2010-2020) was jointly issued by 13 ministries in 2010; this was followed by the National Malaria Elimination Work Plan (2016-2020) issued by the National Health and Family Planning Commission in 2016. In 2020, 13 ministries released the Administrative Measures for the Prevention of Re-establishment of Malaria, and China's CDC introduced the Technical Scheme for Prevention of Re-establishment of Malaria after Elimination.

A robust four level emergency response plan is now in place according to China's statutory reporting for infectious diseases and public health emergency. Malaria reporting systems and control institutions in the HRB continue to operate efficiently, ensuring the availability of affordable services for the diagnosis and treatment of malaria.[21] Systematic technical training has been regularly organised for healthcare providers through vocational study, continuing education programmes, and academic annual conferences, ensuring that the capacity of the malaria workforce is maintained. Public engagement is reinforced by enhancing outreach mechanisms and creating broader participation channels to promote awareness and action against malaria.[22 23] These measures have collectively ensured the re-establishment of prevention of malaria. Furthermore, other regions in China that have adopted these strategies have also successfully maintained their malaria-free status, demonstrating the efficacy and scalability of these approaches.[24]

Ensure timely detection and management of imported cases

The risk of reintroduction remains a key concern after elimination of malaria. China has enhanced malaria surveillance in areas at risk and participates actively in regional malaria control initiatives.[21] Continuous surveillance, rapid interventions, and follow-up for imported cases are carried out among migrating populations from high malaria prevalence regions. In-depth public education and promotion campaigns before and during the epidemic season are maintained to enhance residents' awareness of malaria control. To mitigate the threat of reintroduction, strategies such as China's "1-3-7 strategy"[25] or adaptations such as Vietnam's "2-3-7 strategy"[26] can be implemented immediately on detection of an imported case of malaria. The 1-3-7 or 2-3-7 strategy establishes clear timelines for malaria case management: health facilities or practitioners must report a diagnosis within one or two days, health authorities are required to confirm the case and assess the transmission risk by day 3, and by day 7 appropriate measures should be taken to prevent further spread.

Maintain a rigorous vector surveillance and response system

After elimination of malaria, continuous vector surveillance including the monitoring of insecticide resistance has been carried out continuously in the HRB. For imported cases, local CDCs do transmission risk assessments and, where necessary, immediate vector interventions are carried out by professional control agencies under the coordination of the local government. These actions are essential for preventing secondary cases and safeguarding malaria elimination. Biological control methods, such as *Bacillus sphaericus* or *Bacillus thuringiensis* subsp *israelensis* offer additional tools for effective larval source management in many countries.

Ensuring stable funding

One of the major risk factors for malaria resurgence in a country is the reduction of funding for antimalaria programmes after elimination.[27] Sustained, targeted funding was crucial for eliminating malaria in the HRB, China, and other regions. Following elimination, securing stable financial support is necessary to maintain core malaria control capabilities and ensure the long term stability of the malaria control workforce.[8] To prevent the re-establishment of malaria, the Chinese government has ensured the availability of the funds for surveillance and emergency control of imported malaria cases through central transfer payment and other means.

Strengthen international cooperation and share lessons and experience

International collaboration is key to reducing the risk of reintroduction after elimination.[28] Lessons and experience in malaria control and elimination in the HRB and China should be summarised and shared with other countries and regions with similar situations.[29] These experiences detail core elements of successful elimination efforts, such as leadership, proactive case detection, sustainable vector management, and workforce training.[26 30] China's 1-3-7 strategy has been embraced by countries such as Vietnam and Cambodia, accelerating their progress towards malaria elimination.[31 32] On the basis of findings from semi-structured interviews, Malawi anticipates assistance from China in implementing mass drug administration because China possesses extensive experience in executing such programmes.[26] Countries such as El Salvador, which experienced malaria resurgence owing to resistance of vectors to dchlorodiphenyltrichloroethane (DDT) and resistance of parasites to chloroquine,[33] offer lessons for managing similar challenges in the future. Strengthening international cooperation and continuously sharing best practices will be crucial for informing regional and global malaria elimination efforts.

Conclusion

After the basic elimination of malaria in the HRB, the leading reason for the resurgence of malaria in 2003 was the reduction or cessation of public health infrastructure, personnel, and budgets, resulting in low capacity for case management as well as vector surveillance and control. By examining the lessons from the containment, resurgence, and eventual elimination of malaria in China's HRB, other countries and regions still battling malaria, especially those planning to eliminate malaria, can benefit from China's experiences and ultimate success.

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Anopheles larval control deserves a greater priority: lessons in malaria elimination from China

Qiyong Liu and colleagues review China's integrated approaches and proactive practices for controlling Anopheles larvae, offering valuable insights for other countries striving to control or eliminate malaria

Malaria remains a major global public health issue. In 2022, there were 249 million malaria cases worldwide, an increase of five million from 2021.[1] Since 2015, the annual number of cases has risen steadily, with the greatest surge of 11 million cases occurring between 2019 and 2020.[1] As of 2022, malaria remains endemic in 85 countries, including the territory of French Guiana.[1] China, once heavily affected by malaria, achieved a milestone in 2021 when the World Health Organization certified it as malaria-free.[2 3] Sustainable management of vectors, including larval sources, was a key factor contributing to the country's success in eliminating malaria.

Malaria is a life threatening disease caused by *Plasmodium* through bites from infected female *Anopheles* mosquitoes, the main vectors of malaria. Mosquito control is therefore a core component of the malaria elimination strategy.[2] The extensive application of insecticides has played an important part in controlling mosquitoes. In 1955, WHO adopted indoor residual spraying as the core vector control intervention targeting adult mosquitoes under the Global Malaria Eradication Programme.[4 5] However, killing the adult mosquitoes provides only temporary palliation without tackling the main mosquito breeding sources. Larval control, on the other hand, focuses on targeting the immature, aquatic stages of mosquitoes, preventing them from developing into adults. This approach reduces adult mosquito populations and ultimately contributes to effective malaria control.[4]

In China, a number of proactive approaches were implemented to control mosquito larvae. These included the application of larvicides and the removal of mosquito breeding habitats. Additionally, innovative agricultural practices—for example, altering irrigation patterns; rotating rice and upland crops such as cotton, wheat, and vegetables that resist drought and do not require regular irrigation; and co-cultivating rice and fish—were employed to reduce larval populations and suppress adult mosquito reproduction. Nationwide health campaigns and urbanisation further strengthened efforts to eliminate mosquito breeding sites by improving residential environmental hygiene. Together, these integrated approaches disrupted the *Anopheles* mosquito life cycle, reduced the adult population density, and contributed to China's success in malaria elimination.

KEY MESSAGES

- *Anopheles* mosquitoes are main vectors of malaria globally and *Anopheles* larval control is critical in reducing the morbidity and mortality of malaria
- These practices, including agricultural innovations, environmental hygiene improvements, and optimised application of larvicides, provide useful references for other countries facing a heavy burden of malaria and pursing malaria control or elimination.
- Integrating *Anopheles* larval control with the *One Health* principle shows much potential for effective malaria control and elimination

Application of larvicides in malaria epidemic regions

In the comprehensive management of mosquito borne diseases, use of insecticides remains the primary and most direct method of mosquito control, especially during the peak mosquito season.[5] For example, hexachlorocyclohexane and dipterex were widely applied as the main insecticides to reduce larval mosquito density.[6] However, the extensive use of chemical larvicides led to serious environmental concerns such as toxic residues in water and soil. Reports indicated that the organochlorine level in the Han river reached 1075 ng/L, more than double the EU limit of 500 ng/L.[7] Additionally, despite being banned for over 20 years, DDT (dichlorodiphenyltrichloroethane) residues were still detectable in soils across the Yangtze river delta, particularly in paddy fields.[8] Another consequence of extensive pesticide use was the development of resistance. A review found that resistance to DDT among *Anopheles sinensis* was ubiquitous during the 1990s, with 89% of 27 surveillance sites across five Chinese provinces exhibiting significant or emerging resistance.[9]

In contrast to chemical insecticides, biolarvicides such as *Bacillus sphaericus* and *Bacillus thuringiensis israelensis* offer a more environmentally friendly alternative for larval control because of their host specificity and minimal ecological impact.[10] Studies have showed that *B sphaericus* reduced mosquito fecundity and suppressed mosquito population density to a low level.[11] For example, the application of *B sphaericus* and *B thuringiensis israelensis* decreased the larval density of *An sinensis* by 75-100% and 93-99%, respectively.[12 13] Optimal insecticidal effects were achieved by targeting younger larvae with lower concentrations of *B thuringiensis israelensis*, providing a more resource efficient and environmentally friendly approach.[14] Recent adoption of drone technology has further enhanced the larviciding programme.[15] In Zhejiang province, the first round of drone spraying reduced mosquito population density by 27%.[16] Drone spraying has also been used in Africa, where it has shown promising results in controlling malaria.[15]

Innovations in agricultural practices

In addition to larvicidal applications, removing mosquito breeding sites has proved an effective and sustainable intervention for mosquito control. Mosquito larvae develop in stagnant water, and paddy fields are often prime breeding grounds for *Anopheles* mosquitoes. Moreover, the vegetation surrounding paddy fields creates a protected environment for mosquito larvae to hatch and develop. Traditional flooding irrigation methods exacerbate the problem by creating stagnant water in rice fields, offering ideal conditions for mosquito breeding.

Innovative approaches such as intermittent, moistening, and controlled irrigation, along with planting rotations and rice-fish co-culture, have shown considerable success in reducing *Anopheles* breeding sites and larval densities. These methods not only have long term impacts on mosquito control but are also cost effective, enhancing their applicability in low income regions or areas with extensive cultivation that may inadvertently support mosquito populations.

Intermittent irrigation

Intermittent irrigation refers to alternating periods of irrigating a field and then allowing it to dry, either actively or passively, based on the rice plant's growth stage and its sensitivity to water stress. In the early 1930s, intermittent irrigation was successfully implemented in countries such as India and Japan, with experiments showing its effectiveness in controlling mosquitoes breeding in paddy fields.[5] Since 1949, with the initiation of government health campaigns and prioritisation of vector borne disease control in China, research on intermittent irrigation has expanded to evaluate its impact on larval growth and oviposition by female mosquitoes. Hou C et al found that intermittent irrigation significantly altered the ecological environment of paddy fields, resulting in a 74% reduction in the density of *Anopheles* larvae, an increase in rice yields by 338 kg per hectare, and a saving of over 2800 m^3 of irrigation water.[17]

Moistening irrigation

Moistening irrigation is a water saving irrigation method that uses shallow water irrigation to prevent the persistence of standing water in paddy fields. After the rice seedlings establish themselves, shallow irrigation water is provided based on the crop's growth requirements, with subsequent irrigation occurring only after the previous water has dried completely. Unlike traditional pond or flood irrigation, moistening irrigation reduces the volume of standing water and thus decreases mosquito breeding sites. In addition to its role in mosquito control, this method conserves water resources and increases crop yields. An experiment undertaken in the Yellow river irrigation area in Henan province showed that moistening irrigation significantly reduced the density of *An sinensis* in rice fields.[18] Compared with flooded paddy fields, larval density decreased by 84-86%, while rice yields increased by about 10%.[19]

Controlled irrigation

Controlled irrigation maintains a thin layer of water (10-30 mm) over the field after rice seedlings are transplanted. The timing and amount of irrigation are determined by monitoring root-soil moisture, ensuring that water does not persist in the field after irrigation.[20] This method is particularly suited to low lying fields with high groundwater levels prone to waterlogging, as well as cold, waterlogged paddy fields in hilly and mountainous areas, wetlands, and polder fields in river plains.

Initially implemented in countries such as India and Japan, intermittent irrigation was later introduced into China and adapted to local environmental conditions. Adoption of these irrigation techniques followed extensive experimentation, based on the introduction and absorption of irrigation technologies in other countries, incorporating lessons from international practices, while tailoring them to meet local needs. All three methods—intermittent, moistening, and controlled irrigation—showed remarkable effectiveness in managing mosquito larval breeding, conserving water, and increasing crop yields. A significant negative correlation was found between the area of water saving irrigation practices and malaria incidence at the national level in China (fig 1). Selection of the most suitable irrigation method, however, depends on factors such as the local climate, soil conditions, and available irrigation facilities.

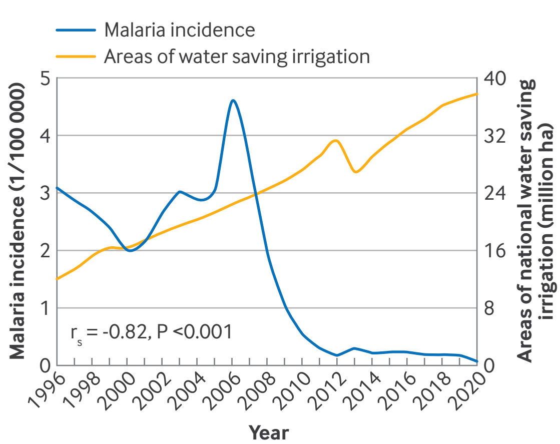

Fig 1 | Relation between malaria incidence and national water saving irrigation area from 1996 to 2020

Paddy-upland rotation

The tillage pattern entails alternating rice cultivation in the summer with dry crops, such as wheat or vegetables, in the winter. Traditionally, paddy fields were left fallow during the cold winter months. By planting dry crops such as wheat, corn, cotton, and vegetables instead, the land—referred to as "upland"—is used more efficiently.[21] This approach reduces considerably the overwintering mosquito larvae in paddy fields. Sichuan province implemented a paddy-upland rotation system that reduced the area of flooded paddy fields by more than half, from 967 000 to 400 000 hectares between 1983 and 1997.[21] The absence of standing water in winter led to a reduction of over 90% in *An sinensis* larval density after the implementation of this rotation system, contributing to a significant decline in malaria incidence.[21] Data from 1994-99 indicated that paddy-upland rotation contributed to a 98% decrease in *An sinensis* density and an 84% decline in the annual incidence of malaria.[22] This analysis also showed a significant negative association between the implementation of paddy-upland rotation and malaria incidence.[22]

Rice-fish co-culture

Rice-fish co-culture is a farming system that integrates rice planting with fish farming. This practice has a long history in China, with records dating back to 220-280 AD. Rice-fish co-culture was initially aimed at enhancing agricultural production.[5] By the 1930s, rice-fish co-culture was proposed as a method for mosquito control. Commonly farmed fish species, such as *Cyprinus carpio* and *Ctenopharyngodon idella*, were widely promoted through various experiments across China.[5] By 2009, roughly 10 million of China's 24.4 million hectares of paddy

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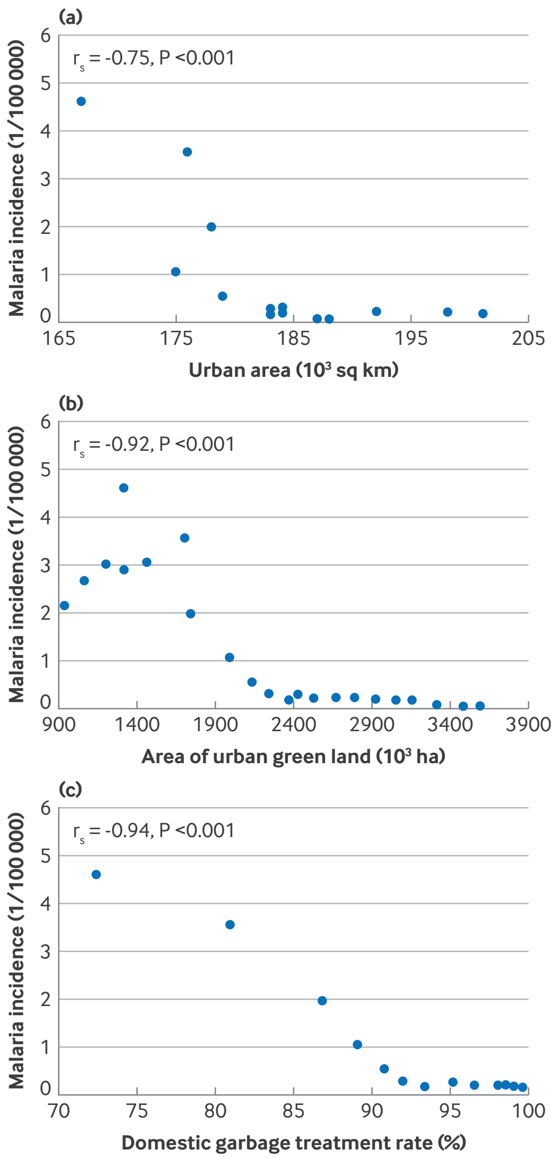

Fig 2 | Relation between malaria incidence and residential environment in China: (a) urban area 2006-21 (b) area of urban green land 2001-22, and (c) domestic garbage treatment rate 2006-22

fields were used for fish farming.[23] Studies showed that rice-fish co-culture reduced the density of *Anopheles* larvae in paddy fields by 80% compared with fields without fish.[24] Additionally, a study in Jiangsu province reported that rice-fish co-culture generated additional income through the sale of fish.[23] Thus, beyond controlling *An sinensis* breeding, rice-fish co-culture also contributed to improved rice production and economic benefits.

Improvement of residential hygiene

Improving residential environments is a critical component of mosquito breeding site management. Since the 1950s, national health campaigns have focused on managing the primary habitats of mosquitoes, such as ditches and ponds, to disrupt their reproductive cycles. These efforts have contributed to improving community hygiene and the control of infectious diseases, including malaria.[3] The removal of mosquito breeding sites and the implementation of mosquito prevention and control measures have been incorporated into a series of hygiene and health promotion programmes, such as the establishment and recognition of hygienic villages, towns, and cities across China.[25] In Zhejiang province, for example, breeding site management practices led to a significant decrease in the presence of larvae, from 23.98% to 2.56% in 2008.[26] Another pilot project in Zhejiang was launched to create “mosquito-free villages” by using environmentally friendly methods to reduce mosquito density.[27] These results were consistent with findings from a study in Anting New Town, Shanghai, where *Anopheles* larval control strategies were integrated into urban planning, including the reconstruction of landscape water bodies to prevent larval breeding by ensuring water flow.[28]

Over the past few decades, China has experienced a massive rural-to-urban migration, leading to the conversion of vast areas of farmland into urban developments.[29] The expansion of urban buildings and infrastructure, including parks, green spaces, and improved waste management systems, has enhanced the residential environment,[29] playing a vital part in reducing the incidence of malaria (fig 2). While urbanisation may not always lead to immediate improvements in residential environments, particularly in terms of eliminating mosquito breeding habitats, it undoubtedly bestows considerable advantages.

Overall, efforts to improve residential environmental hygiene through national health campaigns and urbanisation in China have been effective in removing mosquito breeding sites. These interventions have contributed to a significant reduction in malaria transmission by tackling key factors that support mosquito breeding.

Integrated One Health principle in malaria elimination

It is increasingly recognised that the health of humans, animals, and the environment are interconnected and form an inseparable system.[30] Malaria elimination cannot be achieved by a single discipline or sector alone, underscoring the importance of the One Health principle in controlling and eliminating malaria.

One Health is a globally recognised health strategy based on the premise that human health is closely interconnected with the health of animals and our shared environment.[30] It embraces collaboration among a diverse range of experts working across multiple disciplines and departments to enhance the health of people, animals, and the environment.[30] Here, we summarise China’s experiences with integrating *Anopheles* larval control into the One Health principle—illustrated in figure 3—which could serve as a model for other countries in their efforts to combat malaria.

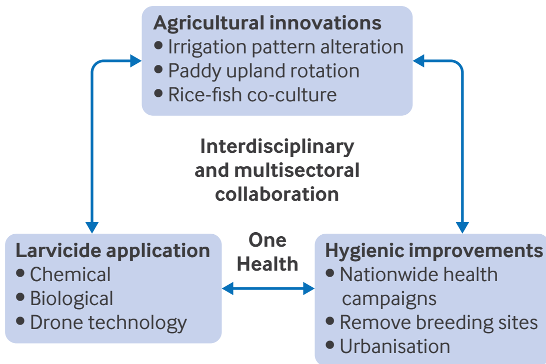

Fig 3 | Integrated One Health principle in *Anopheles* larval control for malaria elimination

Agricultural innovations—Paddy fields provide an ideal environment for *Anopheles* larval breeding, which emphasises the importance of integrated agricultural approaches. Combining agricultural approaches with One Health would not only reduce larval density but also benefit the environment and animals. Different irrigation methods are conducive to maintaining soil fertility in a more balanced way and using water resources efficiently, which could protect the ecological integrity of rice fields. Also, the benefits of these methods by saving water and increasing yield make them particularly applicable to low income countries and regions. Paddy upland rotation and rice-fish co-culture also contribute to building a sustainable and balanced ecosystem and supporting biodiversity in the process.

Environmental improvement—The improvement of residential environments is a crucial component that sustainably balances and optimises the health of humans, animals, and ecosystems. China has initiated a universal health campaign and community level health promotion to remove larval breeding sites and provide better access to health services and improved sanitation. These efforts have contributed to a reduced risk of malaria and improved human health. Additionally, efforts to improve community environmental hygiene can help protect animals from mosquito bites.

Larvicide application—The efficacy of biolarvicides offers an environmentally friendly alternative to chemical larvicides in pursuing malaria control within the One Health framework. To prevent environmental contamination and resistance resulting from the extensive application of chemical insecticides, China has promoted the use of biolarvicides. These biolarvicides effectively reduced larval density while preserving biodiversity and protecting the environment.

Interdisciplinary and multisectoral collaboration—Malaria elimination requires collaboration among a panel of experts working across agriculture, fishery, chemistry, biology, ecology, and medicine. Multiple disciplines are interrelated and coordinated to achieve mosquito control comprehensively and sustainably, promoting the health of humans, animals, and the environment. Efforts made by joint involvement with the government, the community, and the public have contributed appreciably to the successful elimination of malaria.

Conclusion

Malaria remains a considerable threat to public health, with many countries still grappling with endemic cases. In China, control of *Anopheles* larvae has played an essential part in reducing the incidence of malaria as the country progressed from malaria control to elimination. Through constantly exploring innovative approaches, the combined applications of innovative irrigation methods, residential environment improvements, and biolarvicides have proved effective in controlling mosquito larvae. These methods, aligned with the concept of One Health, have made an important contribution to malaria elimination in China. The methods may not always be directly applicable in other countries or regions, and tailored methods are essential to tackle specific local ecological and epidemiological conditions. The lessons learnt from China's experience offer valuable insights for other countries or regions striving to eliminate malaria, accelerating the progress towards a malaria-free world.

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Stratified vector control and proactive cross border collaboration for sustaining malaria elimination in Yunnan, China

Hualiang Lin and colleagues emphasise that achieving and sustaining malaria elimination in border areas requires stratified risk management, targeted vector control, timely epidemiological surveillance and response, environmental improvement, and cross border collaboration for joint prevention and control

Yunnan Province was China's last region to eliminate indigenous malaria transmission owing to its extensive, porous borders with three malaria endemic countries—Myanmar, Laos, and Vietnam.[1] The province faced immense pressure to control imported cases of malaria, particularly during the early years of China's reform and opening-up in the 1980s.[2] Moreover, the complex malaria epidemiology, diverse ecological features, multiple vector species, and underdeveloped economic environment presented significant challenges.

Globally, many countries face similar challenges in controlling cross border malaria transmission. Frequent population movement in border areas, inequalities in healthcare resources between neighbouring countries, and the complexity of cross border collaboration make effectively controlling and eliminating malaria difficult for one single country. For instance, countries in the Greater Mekong Subregion have long struggled with imported malaria cases, as labour migration and trade activities exacerbate cross border malaria transmission.[3 4] Similarly, border regions in Africa, such as those between Kenya and Tanzania, face difficulties in implementing unified and effective interventions owing to differences in malaria control strategies and resource allocation across countries.[5] Tackling cross border malaria transmission is a pressing global priority requiring experiences from countries and regions with successful elimination.

In the 1980s the Chinese government introduced the ambitious goal of elimination of malaria.[6] To achieve this goal, Yunnan province implemented border specific control strategies that incorporated many of the technical measures used throughout China's malaria elimination efforts from 1980 to the present (fig 1). These tailored approaches in Yunnan are particularly noteworthy given Yunnan's unique challenges as a high burden border region characterised by multiple vector species and imported cases, both from travel to malaria endemic areas and cross border mosquito transmission. The successful malaria elimination in Yunnan provides valuable experiences for global malaria control and elimination efforts, especially in bordering areas facing similar cross border challenges.[7] By tackling the complexities of border dynamics and tailoring interventions to local contexts, Yunnan offers insights for how malaria can be eliminated and its reintroduction prevented in areas where the risks are greatest.

KEY MESSAGES

- Eliminating malaria in bordering areas was distinctive and challenging owing to multiple vector species, underdeveloped living environment, and cross border transmissions
- The successful malaria elimination in Yunnan was mainly attributed to stratified risk management, integrated environment management, targeted vector control, and timely epidemiological survey and response.
- Key strategies for sustaining malaria elimination included proactive cross border collaboration, precise surveillance, and timely response
- Besides the strategies and measures to eliminate malaria in China, Yunnan offers some unique insights for effectively managing malaria in bordering areas

Malaria in Yunnan: multiple vectors, living conditions, and cross border transmission

Compared with other regions in China, eliminating malaria in Yunnan was more challenging.[3] Yunnan is home to multiple vector species including *Anopheles sinensis*, *An minimus*, *An dirus*, and *An lesteri*,[8] which have different feeding and resting behaviours and require integrated and sustainable measures for control. In addition, owing to economic constraints and the traditional practice of some ethnic groups, many housing structures were constructed using wood and bamboo,[9] which inadvertently created environments conducive to the breeding and growth of mosquitoes. Importantly, Yunnan also shares a 4060 km land border with three malaria endemic countries—Myanmar, Laos, and Vietnam—within the Greater Mekong Subregion,[10] which is a major risk factor for transmission.

From 1980 to 2023, a total of 472 112 cases of malaria were reported in Yunnan,[11] with a steady declining trend (fig 2).[12] However, most malaria outbreaks in Yunnan were attributed to imported cases or cross border movement of infected *Anopheles* mosquitoes.[13] Between 2011 and 2023, 688 indigenous cases (locally transmitted cases or cases without evidence of importation) were reported, whereas 5394 (88.7%) cases were imported,[11] highlighting cross border transmission as the primary risk factor for malaria's reappearance in Yunnan.

Key strategies for eliminating malaria in Yunnan (1980-2016)

Malaria control strategies over three decades after reform

Since 1980, China's reform and opening-up policies have facilitated economic growth, cross border trade, and labour migration, which contributed to a sharp increase in

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cross border population movement in Yunnan, increasing the importation and spreading of malaria cases. Recognising this challenge, Yunnan's provincial government took direct leadership and implemented a series of malaria control policies to tackle both local and cross border risks. For instance, a malaria control training programme was launched, which trained approximately 35 800 primary health practitioners annually between 1980 and 1998 to enhance local response capacity.[2] Yunnan's provincial health authorities also implemented a mass preventive medication campaign under the support of the Chinese government to curb malaria in cities with severe outbreaks. Yunnan also established a mosquito surveillance system to collect data on *Anopheles* mosquitoes and did research to improve vector control and enhance early detection of malaria cases. These measures reflect a comprehensive approach to managing the unique challenges posed by Yunnan's increasing cross border dynamics.

Stratified risk management and "1-3-7" strategy

Building on the previous three decades of malaria control strategies, the Chinese government further launched the China Malaria Elimination Action Plan (CMEAP) in 2010 to enhance the elimination efforts.[14] According to this plan, districts and counties in Yunnan were classified into three risk levels on the basis of malaria incidence and were required to conduct stratified risk management (fig 3).[15] Counties were classified into category I if indigenous malaria cases occurred every year in 2006-08 and the annual incidence rate was not lower than 0.01%. These counties were required to achieve an epidemic management rate of 50% by 2012 and 100% by 2015. Local Centers for Disease Control and Prevention (CDCs) were responsible for conducting case searches, testing blood samples from individuals with a two week fever history, and implementing vector control measures at outbreak sites. Category II counties were those that had reported indigenous cases during the three years, with an incidence rate lower than 0.01% for at least one year in 2006-08; targets were set to achieve a management rate of 70% by 2012 and 100% by 2015. Category III counties were those without any indigenous cases for the three years and were required to consistently maintain a management rate of 100%.

As part of implementing CMEAP, Yunnan's provincial government implemented a "1-3-7" strategy in 2012. This approach, designed to prevent the spread of imported cases across China,[16] involved a systematic timeline: reporting and treating cases within one day of diagnosis, completing case investigations within three days after reporting, and conducting focal epidemic management within seven days to curb secondary malaria transmission.[16]

Targeted vector control measures and living environment improvement

Although imported cases were the primary concern, local strategies also targeted Yunnan's diverse malaria vectors, including sylvan, domestic, and peridomestic species whose behavioural variability required multifaceted interventions.[17]

An minimus is the primary domestic mosquito species in Yunnan, with approximately 20 times the transmission capacity of *An sinensis*.[17] Since 1980 Yunnan has conducted annual indoor residual spraying once or twice annually. Insecticide treated bed nets and long lasting insecticidal nets treated with pyrethroid insecticides were also widely distributed following CMEAP.[18 19] By 2012 coverage of insecticide treated bed nets and long lasting insecticidal nets had reached 80% in category I and II counties, and this increased to 90% by 2015 (fig 1).[15]

An sinensis, the most common peridomestic malaria vector, feeds around human dwellings and lays eggs in shallow

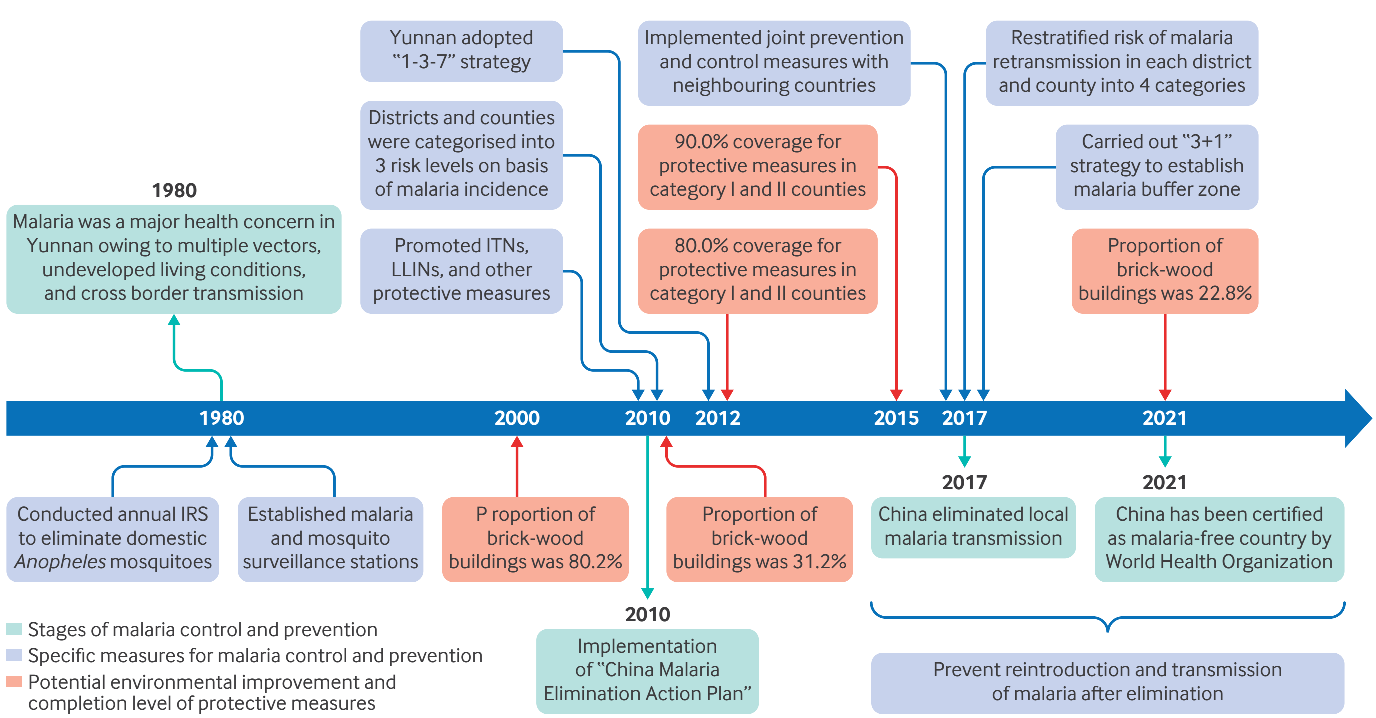

Fig 1 | Timeline of malaria control in Yunnan, China, 1980-2023. IRS= indoor residual spraying; ITN=insecticide treated bed nets; LLIN=long lasting insecticidal nets

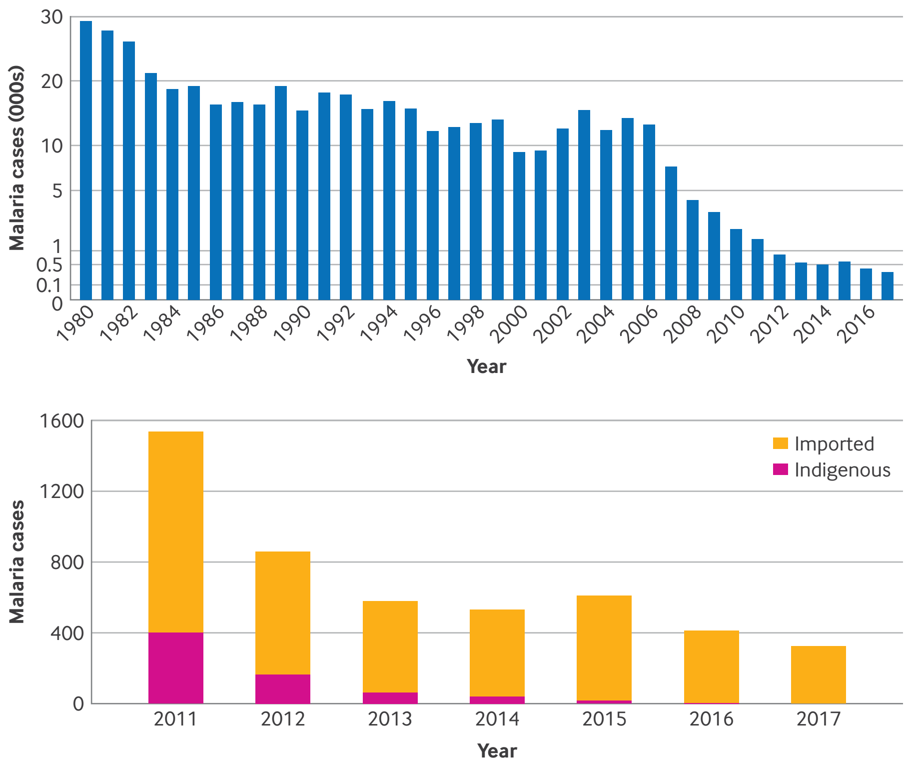

Fig 2 | Time series of malaria cases in Yunnan, 1980-2017. Top plot shows trend of malaria cases, with bottom plot highlighting imported and indigenous cases in Yunnan from 2011 to 2017

waters such as rice fields. Thus, Yunnan adopted the rice-fish farming strategy and had reduced its larval density by up to 80%.[20] Sylvan mosquitoes were controlled with insecticide applications to tropical vegetation around villages and providing outdoor workers with repellents, prophylactic drugs, and long lasting insecticidal nets free of charge.[21 22]

Improving housing structures also played a critical role in reducing human-mosquito contacts. Traditional wooden and bamboo dwellings facilitated mosquito entry owing to the gaps in the eaves and walls and thus increased the risk of malaria transmission.[23] Alongside the economic development, Yunnan's provincial government facilitated the adoption of concrete structures, reducing the proportion of buildings made of these materials in Yunnan from 80.2% in 2000 to 22.8% in 2020.[24] Furthermore, the built-up area increased from 1200.4 km^2 in 2008 to 2012.9 km^2 in 2022 (fig 1), which effectively reduced mosquito breeding grounds.[25 26]

Overcoming challenges of insecticide resistance in malaria elimination

Since 1980, Yunnan has achieved notable success in malaria control. However, long term reliance on single insecticides led to resistance among mosquitoes, presenting ongoing challenges.[27 28] To tackle this problem, Yunnan CDC phased out dichlorodiphenyltrichloroethane (DDT), replacing with organophosphates, then deltamethrin, and eventually the mixture of propoxur (6%) and β-cypermethrin (4%) by 2020. The province also monitors insecticide resistance and prepares alternative insecticides to respond to potential resistance to β-cypermethrin.[24 29]

Insecticide spraying is an affordable and efficient method often favoured by low and middle income countries with severe malaria burdens, especially in Africa and South East Asia.[30 31] The experience and lessons in Yunnan highlight the importance of continuous resistance monitoring, timely insecticide replacement, and use of insecticide mixtures to maintain the efficacy of residual spraying.

Key strategies for preventing cross border retransmission of malaria in Yunnan (2017-23)

Since 2017, malaria cases in Yunnan have been attributed to cross border imported cases (fig 2). Thus, with the guidance of the Chinese government, Yunnan CDC transitioned its focus from tackling both indigenous and imported malaria cases to prioritising the detection and prevention of imported cases, which is one key strategy to sustain malaria elimination.[32]

Re-stratification of malaria retransmission risk

Following the elimination of indigenous cases, Yunnan re-stratified the malaria transmission risk into four categories (I-IV), from high to low, according to the types of imported cases and mosquito vectors (fig 4).[33] Category I counties are those with local vectors in the previous three years and adjacent to malaria endemic regions. In these counties, all township health centres are mandated to test (via rapid diagnostic tests or microscopy) all febrile patients and screen individuals who have been active within 2.5 km of the border. Category II refers to counties with multiple vector species such as *An minimus* and *An lesteri*, capable of transmitting *Plasmodium vivax* and *P falciparum*. In category II counties, all township health centres are required to test febrile patients with a history of travel to malaria endemic areas within the previous two years or previous malaria infection. Category III is defined as counties that have only *An sinensis* and imported *P vivax*, and category IV includes counties without imported cases. In category III-IV counties, only selected township health centres are required to test febrile patients meeting the same criteria as those in category II.

Proactive joint sentinel monitoring along cross border areas

Besides the continuous surveillance for mosquito species and density, and insecticide resistance in Yunnan, proactive joint prevention and control measures were also initiated by establishing cooperative sentinel monitoring sites in neighbouring countries along cross border areas. As of 2023, 20 sentinel sites have been established in Myanmar (13 sites), Laos (four sites), and Vietnam (four sites), corresponding with 19 sentinel sites in Yunnan (fig 4, right side). Each sentinel site in these three countries was paired with a domestic site in Yunnan. All the sites were managed by the corresponding counties within Yunnan.[34] These sites were responsible for simultaneous vector monitoring, technology sharing (such as detection technologies, effective drugs, insecticides, and equipment), and organising regular information exchanges on local epidemic updates and recent prevention experiences.[34]

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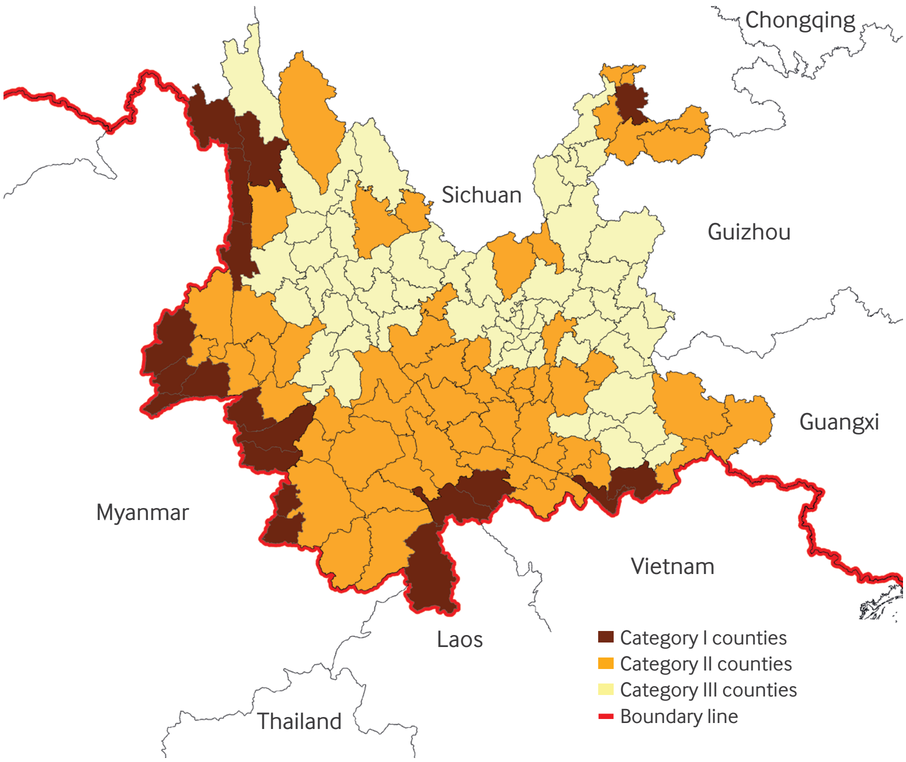

Fig 3 | Spatial distribution of three malaria risk categories

burden, longer shared border, and less developed health infrastructure, with the "3+1" strategy being implemented (fig 4).[35] The "3" refers to three preventive lines, and "1" represents villages, communities, and settlements within 2.5 km of the international border outside the territory of China. In "+1" areas, joint task forces implemented comprehensive malaria control measures. The objective was to strengthen Myanmar's malaria control programmes through financial and technical support, capacity building and training, vector monitoring and control, health education, and treatment guidance.

In regions with the "3+1" strategy, real time monitoring of malaria cases and timely intervention measures were conducted. These included blood examinations, provision of medication, indoor residual spraying coverage, and epidemic investigation and interventions. Sixty six malaria control consultation and service stations were established in 19 counties bordering Myanmar to promptly treat malaria cases, administer health education knowledge, and provide long lasting insecticidal nets for the mobile Chinese population.[36]

Joint "3+1" strategy along China-Myanmar border areas

Since 2017 China has implemented joint prevention and control measures with Vietnam and Laos, focusing mainly on establishing cooperative sentinel sites. Collaboration with Myanmar has been more comprehensive owing to its higher malaria

Lessons on sustaining malaria elimination in the cross border context

On the basis of malaria data (1980-2023) from the Yunnan Institute of Parasitic Dis-

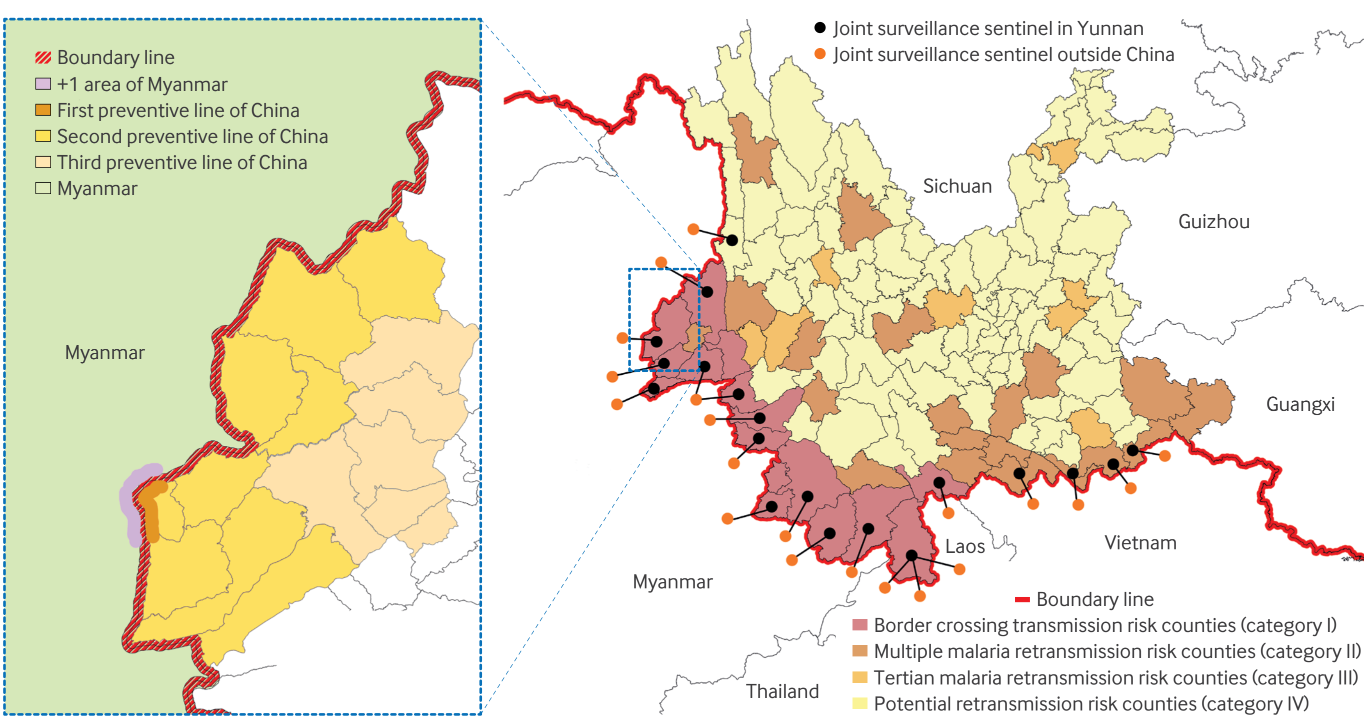

Fig 4 | Re-stratification of malaria retransmission risk in Yunnan and joint "3+1" cross border control strategy. Left side shows distribution of counties within Yunnan's three preventive lines and border areas under "3+1" strategy. Right side shows re-stratification of malaria retransmission risk and distribution of sentinel sites for cross border joint surveillance, prevention, and control within China, as well as in Myanmar, Laos, and Vietnam eases, we did an interrupted time series analysis and found that more than 8400 cases of malaria were successfully prevented following the launch of CMEAP in 2010. Yunnan's approach to malaria elimination possesses several key elements: the leadership of the national and local government emphasising the management of imported cases, and steady cross border collaboration.

However, challenges such as political instability and conflicts in neighbouring countries could threaten the long term sustainability of malaria elimination, particularly by undermining cross border collaboration.[37] Since 2021 the armed conflict in Myanmar has complicated efforts to sustain malaria elimination in Yunnan. Conflict induced economic turmoil in Myanmar disrupted access to antimalarial drugs,[38] creating an insufficient workforce for local malaria control measures. Additionally, the movement of refugees towards the Chinese border heightened the risk of potential retransmission in Yunnan.[39] The conflict has also strained Myanmar's resources, leading to challenges to sustaining joint prevention and control measures. To alleviate the pressure on the joint measures, the Yunnan Institute of Parasitic Diseases dispatched more public health professionals to support joint collaboration in Myanmar.

Yunnan's comprehensive joint prevention measures are currently focused on Myanmar. However, strengthening collaboration with other Lancang-Mekong countries is equally critical, as these countries are also major sources of imported malaria cases in China. The Chinese government will continue implementing the "1-3-7" strategy in Yunnan and provide consistent funding to strengthen joint efforts with Lancang-Mekong countries. This includes fostering stronger cross border collaborations with countries in the Lancang-Mekong River Basin. In 2019 a joint prevention and control platform was established to facilitate the acquisition and sharing of vector and malaria surveillance data, meteorological information, and socio-cultural data.[40] This collaboration also established multiple fever clinic surveillance stations along the China-Laos border and developed a surveillance network covering five northern provinces of Laos.[40]

The successful elimination of malaria in Yunnan, China, despite diverse malaria vector species and cross border transmission, provides valuable experience for achieving and sustaining malaria elimination in other regions, especially the importance of stratified risk management, targeted vector control, timely insecticide replacement, cross border collaboration with stable political conditions, and strong partnerships.

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