Strategy to eliminate invasive *Anopheles stephensi* from Africa

Contents

Foreward

To be added

Acknowledgements

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Abbreviations

ATSB - Attractive Targeted Sugar Baits
CDC – Centers for Disease Control and Prevention
eDNA - Environmental DNA
EDRR - Early Detection and Rapid Response
GIS – Geographic Information System
IVM – Integrated Vector Management
ITN – Insecticide Treated Net
IRS – Indoor Residual Spray
LSM – Larval Source Management
NGO – Non-Governmental Organization
OECD - Organisation for Economic Co-operation and Development
PCR – polymerase chain reaction
SIT – sterile insect technique
STS – Slowing the spread
WHO – World Health Organization

1. *Anopheles stephensi* in Africa

1.1 Introduction

Anopheles stephensi is a malaria vector mosquito native to South Asia, distinguished by its capacity to exploit artificial water containers as larval habitats, a trait that underpins its success in urban environments. Historically, the western limit of its distribution extended only to the eastern coast of the Arabian Peninsula; however, during the 2000s the species was detected along the western coast of the Peninsula (Alahmed *et al.* 2009), and in 2012 it was first reported in Africa, in Djibouti (Faulde *et al*. 2014).

The WHO African Region bears the overwhelming majority of the global malaria burden, accounting for approximately 94% of cases and 95% of deaths (WHO World Malaria Report 2024). Malaria transmission in Africa is currently driven by several highly efficient vectors, including *An. gambiae*, *An. coluzzii*, *An. arabiensis*, and *An. funestus*. The introduction and spread of an additional competent vector capable of sustaining transmission in urban settings is therefore of serious concern, particularly in the context of rapid urbanization across the continent.

1.2 Current spread and knowledge on its implication in transmission

In September 2012, adult *An. stephensi* were collected at a quarantine station located between Djibouti City and Loyada in Djibouti, and in February 2013 *Anopheles stephensi* was subsequently detected within Djibouti City itself. Although these findings were published in mid-2014 (Faulde *et al*. 2014), they did not initially attract widespread concern. Attention increased only after *An. stephensi* was detected in Ethiopia and Sudan in 2016 (Carter *et al*. 2018; Ahmed *et al*. 2021), prompting the initiation of large-scale surveillance programmes in Ethiopia (Balkew *et al*. 2021) and Sudan (Abubakr *et al*. 2022). The species was later reported from Somalia (2019) and Eritrea (2021/2022), followed by detections further west in Nigeria (2020), Ghana (2022), and Niger (2024), indicating substantial westward spread into West Africa. Recent detection in Kenya (2022) suggests southward expansion as well. Importantly, the order in which *An. stephensi* has been detected does not necessarily reflect the true sequence of its spread, as surveillance efforts have been uneven across countries and time. Ongoing population genetic analyses are expected to provide greater insight into invasion pathways and dispersal dynamics (Dennis *et al*. 2025).

Assessing the role of *An. stephensi* in malaria transmission has been challenging, as many of the locations where it has been detected experience relatively low malaria incidence. Nonetheless, a marked increase in malaria cases was observed in Djibouti following the establishment and spread of *An. stephensi* (Seyfarth *et al*. 2019). In Ethiopia, a case–control study conducted in Dire Dawa identified a strong association between proximity of households to *An. stephensi* breeding sites and malaria incidence (Emiru *et al*. 2023). Further research is required to clarify the epidemiological significance of *An. stephensi* across Africa, including its apparent zoophilic tendencies, interactions with *Aedes aegypti* and other vector species, and the influence of seasonality on transmission dynamics.

1.3 WHO initiative on *An. stephensi*

In 2022, the WHO launched an initiative against the spread of *An. stephensi* in Africa. This initiative had five key aims: 1) increasing collaboration; 2) strengthening surveillance; 3) improving information exchange; 4) developing guidance; and 5) prioritizing research.

The initiative also noted that there were three key strategies that could be adapted for the control of invasive vectors, namely control, containment, and elimination. These options are discussed in greater detail below.

2. Defining elimination from Africa as the end goal

The spread of *An. stephensi* into Africa's urban areas poses a significant challenge for national malaria programs. With rapid urbanization underway—and an estimated two-thirds of Africans projected to live in cities by 2050 (OECD 2025)—preventing malaria from establishing a foothold in urban environments is critical (WHO 2022). Even low-density *An. stephensi* populations could support persistent, low-level transmission across large urban centers.

Vector control in densely populated cities is inherently difficult, and ongoing urban transmission could also seed infections into nearby rural areas. As a result, once *An. stephensi* becomes entrenched, it could severely undermine long-term malaria elimination efforts. This threat underscores the importance of slowing its spread and ultimately eliminating the species from the African continent.

Although *An. stephensi* has already spread into several countries in Africa, it remains essential to clearly define the overarching objective and determine how best to achieve it. The sections that follow outline recommended actions for WHO Member States to consider in pursuing the goal of elimination.

3. Adopting an Invasive Species Framework

Invasive species are typically defined as non-native organisms that cause harm and whose spread is aided by human activities (Iannone *et al*. 2020). *Anopheles stephensi* fits this definition in Africa, as well as in other regions such as Sri Lanka and Yemen. Consequently, principles from invasion science should play a central role in shaping the response. The key concepts are represented in the invasion curve shown in Figure 1.

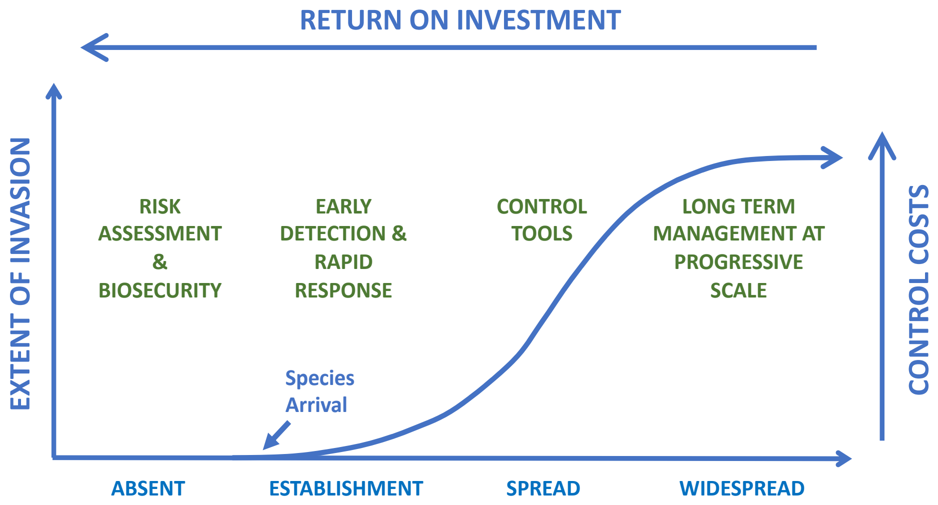

Figure 1. The invasion curve showing progressive steps in the invasion process and the priority actions associated with each step. Arrows indicate how costs tend to increase as the extent of the invasion increases and that the earlier the response, the greater the return on investment.

The invasion curve illustrates how an invasion progresses—from initial arrival, to establishment, and eventually to widespread dispersal—and outlines the key strategies suited to each stage. It also underscores the critical value of **Early Detection and Rapid Response (EDRR)**: the sooner an invasive species is identified and contained, including preventing its arrival altogether, the lower the cost of control and the higher the return on investment.

4. Building a strategy

The invasion curve is often applied to a single location, with a species' progression along the curve reflecting changes over time. In the case of the *An. stephensi* invasion in Africa, however, the concept can also be viewed spatially, with different countries positioned at various stages of the curve. This spatial perspective offers a useful framework for defining country-specific priorities and guiding appropriate actions.

For countries where *An. stephensi* is not yet detected, the main focus should be on prevention. This includes identifying possible introduction pathways, screening goods arriving from affected regions, and establishing surveillance systems capable of detecting incursions and ensuring they are promptly reported and addressed.

In countries experiencing recent incursions, the priority is to determine the extent of the invasion and concentrate on eradication efforts to prevent the species from becoming established and spreading further. A rapid, intensive response is essential—both to eliminate local populations and to maintain pressure even after detections cease. Although long-distance dispersal routes are not fully understood, current evidence does not indicate that reinvasion is inevitable once local elimination has been achieved.

Countries with established *An. stephensi* populations will need to sustain these efforts across broader areas and longer periods, beginning with containment and slowing the spread, and ultimately working toward population reduction and eradication. These measures will take place in addition to, and not in place of, existing control work.

Where *An. stephensi* is already widespread, the focus shifts toward long-term management and mitigation. This will require sustained effort and likely an area-wide approach aimed at reducing population densities and pushing back the invasion front over time.

5. Turning strategy into action

The following sections outline recommended actions for WHO Member States as they work toward the overarching objective of *An. stephensi* elimination. Many of these recommendations build on interventions already used to control *An. stephensi* in endemic settings (see WHO 2024 for additional context). Although future research and the development of new tools and strategies could strengthen these efforts (examples are provided in Section 8), the emphasis here is on measures that can be implemented immediately across the different stages of intervention. A core principle of EDRR is timely action, and substantial progress can be made using currently available—though sometimes imperfect—tools, as demonstrated by the case studies presented in the Boxes below.

5.1 Species absent – prevention and detection

Successful invasion of a species involves sequential steps of dispersal from a source population, arrival in a new location, survival and establishment in that new location, and then population build up and spread leading to impact. If a species is currently absent from a location, the priority biosecurity actions are to reduce the chances of it arriving and then to detect it promptly if this fails.

5.1.1 Arrival

Because long-distance dispersal is somewhat unpredictable and large areas remain at risk—meaning incursions could occur virtually anywhere and at any time—preventing *An. stephensi* from arriving is difficult. Nevertheless, several measures can help reduce the likelihood of introduction:

- **Reducing source populations.** The invading mosquitoes must originate from established populations, so lowering the number and size of these source populations will in turn reduce propagule pressure[1]. Possible strategies for controlling and suppressing these populations are explored in the following sections. For an Africa-wide, coordinated response, it is crucial to recognize that efforts to reduce the density and spread of *An. stephensi* within already invaded areas will benefit not only the regions currently affected, but also those where the species has yet to become established.
- **Restricting dispersal pathways to reduce spread.** *An. stephensi* may spread through several pathways, including overland transport—especially in vehicles carrying water containers or livestock—as well as by sea or air. Many recorded detections of *An. stephensi* have occurred along major transport corridors, suggesting that land and maritime movement are likely drivers of its regional dispersal. Consequently, ports (particularly those with shipping connections to Asia), dry ports, and border-control or customs checkpoints should be closely monitored in line with International Health Regulations (WHO 2016b). These locations may also warrant

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[1] Propagule pressure is a measure of the total number of individuals of a species and the frequency at which they are introduced into a non-native environment.

enhanced vector-control interventions, such as larviciding, spatial emanators, space spraying, or other targeted measures

5.1.2 Surveillance

Currently, surveillance methods used to detect the presence or absence of *An. stephensi* are largely the same as those employed in standard entomological monitoring for other mosquito species. Adult sampling commonly relies on CDC light traps, human landing catches, pyrethrum spray catches, gravid traps, and various types of resting collections, while larval surveillance typically involves dipping in aquatic habitats. However, *An. stephensi* exhibits variable biting and resting behavior and may not be efficiently captured in the same places where major African malaria vectors are usually sampled. For this reason, it is advisable to also include cattle or goat shelters in adult sampling when they are available. Likewise, the larval habitats of *An. stephensi*—particularly in urban environments—can differ from those of other species. Surveying a broader range of water sources, such as wells, water storage containers, and construction pits, will help ensure a more complete understanding of its presence and distribution.

What may be even more critical than the specific surveillance method is *where* and *when* surveillance is carried out, and *how* the resulting information is applied:

- **Systematic surveillance throughout the potential invasive range.** So far, *An. stephensi* has been detected in only a few African countries. However, it is uncertain whether this apparently limited distribution truly reflects the insect's current range or whether the species is actually more widespread but remains undetected—either because surveillance has not been conducted in certain areas or because existing surveys failed to detect it. To design and assess an effective continent-wide control strategy, a comprehensive understanding of *An. stephensi*'s distribution is essential. Knowing the places where the mosquito is absent is just as important as knowing where it has already been found.

- **Monitoring in areas where *An. stephensi* is most likely to occur**, including the leading edge of its invasion within a country and in neighbouring countries. Several countries bordering affected regions appear to have little or no surveillance in place despite the imminent risk of spread. Modelling and remote sensing can also guide surveillance efforts. Identification of likely larval sites (eg. Water storage, construction sites) can also help facilitate surveillance.

- **Intensive surveillance in areas where *An. stephensi* has been found but has been eliminated or appears to have disappeared naturally**. In regions where *An. stephensi* has been detected and control efforts appear to have successfully eliminated it, continued monitoring is essential. Overlooking small, residual populations could enable the mosquito to rapidly re-establish itself in areas thought to be cleared. Sustained, careful surveillance is therefore critical to preventing reinvasion.

- **Reacting to unexpected changes in malaria.** Increases in malaria cases (or general fever cases) in urban (or rural) settings, particularly in patients who have not recently left the area, may be an indicator of the presence of *An. stephensi* and should be confirmed through targeted sampling to enable appropriate vector control actions.

- **Leveraging other mosquito sampling activities.** Mosquitoes are collected for a range of purposes, including insecticide-resistance monitoring, arbovirus vector surveillance, ecological research, vector incrimination, and field evaluations of control tools. These routine activities offer valuable opportunities to detect *An. stephensi*, complementing any targeted surveillance efforts. To make the most of this, it is crucial that entomological samples are carefully examined and that any unfamiliar mosquito species are fully characterized.

- **Identification of mosquitoes**. All the surveillance activities rely on the development and maintenance of strong entomological capacity to accurately identify *An. stephensi*. Countries that encounter unfamiliar mosquito species should immediately investigate to determine what has been collected. Whenever possible, morphological identification should be validated through molecular methods.
- **Timely reporting.** A notable feature of the short history of *An. stephensi* surveillance in Africa is the frequent delay—sometimes lasting years—between detection and reporting. In some instances, these delays stemmed from difficulties in morphological or molecular identification; in others, researchers postponed reporting until they could publish their findings, or encountered reluctance from National Malaria Control Programmes to release the data. To help prevent further spread, any new detection of *An. stephensi* should be communicated as quickly as possible, whether through the Malaria Threats Map (https://apps.who.int/malaria/maps/threats/), direct email notification to neighboring countries, or scientific channels such as presentations, posters, or journal publications.

5.1.3 Resistance to invasion

Given the unpredictable nature of dispersal and the challenge of preventing all incursions, a key biosecurity strategy is to reduce the probability of successful establishment should the species arrive. Building a system resistant to invasion by *An. stephensi* requires combining resilient urban infrastructure with integrated vector management (IVM). Urban planning and water infrastructure should minimize standing water through reliable piped water supplies, covered storage containers, well sealing, and effective drainage. Construction standards should reduce unintended breeding sites in buildings and public spaces. These physical measures should be complemented by IVM approaches that integrate routine larval source management, targeted use of larvicides, and surveillance embedded within existing health and municipal systems. Cross-sector coordination, sustained community engagement, and rapid response capacity together create a preventive system that reduces probability of establishment.

Box 1. Illustrative case studies on surveillance and detection.

Initial detection of An. stephensi in southern Niger

Mosquitoes were collected as part of an ecological survey assessing mosquito biodiversity in Gayi, a rural village in southern Niger (Moustapha *et al*. 2025). On a single early morning, 220 adult mosquitoes were sampled indoors from 19 houses using battery-powered aspirators. Of these, 184 were morphologically identified as belonging to the *Anopheles* genus. Subsequent morphological and molecular analyses confirmed that eight specimens were *An. stephensi*. This species was found resting indoors alongside other mosquitoes, including *An. coluzzii*, *An. gambiae* s.s., and *An. arabiensis*.

No *An. stephensi* larvae were detected in domestic water storage containers, pots, earthenware vessels, or outdoor breeding sites such as mud-block formation areas or a pond. These larval results should be interpreted cautiously, as sampling effort was limited and larval densities may have been very low. Nonetheless, they underscore the importance of conducting both adult and larval surveys when possible and demonstrate that *An. stephensi* is not necessarily restricted to urban environments.

The study was initially designed to document mosquito biodiversity in a seasonal transmission setting. The unexpected detection of *An. stephensi* highlights the value of detailed characterization of entomological samples. Targeted investigations are now needed to determine whether *An. stephensi* is truly established and, if so, to assess the extent of its spread. These studies should be paired with intensified control measures to enable the elimination of these emerging founder populations.

Scaling up surveillance following initial detection of An. stephensi in Kenya

The study of Samake *et al*. 2025 documents the spatial distribution and population genetic structure of *An. stephensi* in Kenya, following initial detection in 2022. Surveillance activities were scaled-up across multiple Kenyan counties over 2 years, confirming that *An. stephensi* is now widely established, with detections concentrated in urban and peri-urban areas and occasional presence in rural settings. The species is exploiting human-made larval habitats, such as water storage containers, that are not consistently targeted by conventional malaria control interventions in Kenya. These findings highlight the importance of adapting surveillance systems to include habitats and settings relevant to the invasion ecology.

Population genetic analyses reveal low to moderate genetic differentiation among populations, consistent with recent introduction followed by rapid expansion and ongoing gene flow. The genetic patterns suggest a limited number of introduction events, after which spread has been facilitated largely through human-mediated movement. This underscores the need for early detection at points of entry, transport corridors, and urban centers, where rapid response measures could have the greatest impact in limiting establishment and spread.

From an EDRR perspective, the study demonstrates that opportunities for prevention and early containment may already have been missed in parts of Kenya, but also emphasizes that further spread can still be slowed through timely action. The evidence supports prioritizing intensified surveillance, particularly at the invasion front and in high-risk urban settings, coupled with rapid, targeted larval source management.

Overall, the study reinforces core EDRR principles: early detection lowers long-term control costs, rapid response can prevent widespread establishment, and delays in action allow invasive populations to expand.

Although extensive surveillance efforts may seem difficult to justify, it is important to recognize that early detection substantially reduces the cost of eradication (see Figure 2). Surveillance cannot guarantee that every new incursion will be found, but without it, all incursions will inevitably go undetected. The key message is that taking some action is always better than taking none. Imperfect tools or tactics should not be used as a reason to delay or avoid action.

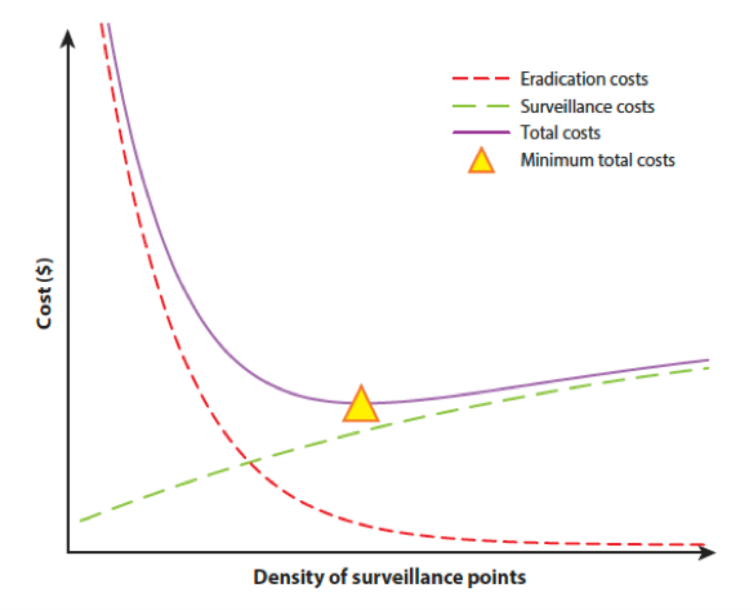

Figure 2. Theoretical composite and total costs of invasion as a function of surveillance effort (taken from (Liebhold *et al.* (2016)). Total costs are the sum of eradication costs and surveillance costs. Eradication costs decrease with surveillance effort because invasions are discovered earlier. Optimal surveillance occurs where total costs are lowest.

5.2 Species establishment – rapid response

The first detection of *An. stephensi* in a previously unaffected location represents a critical intervention point with greatest potential for successful containment and elimination. A clear, coordinated strategy is required to ensure that detection is rapidly verified, the extent of the incursion is defined, and appropriate control measures are implemented without delay (i.e., it is important that the efforts related to *An. stephensi* not stall at surveillance and that the emphasis shifts from determination of its spread to control). This response should be guided by the principles of EDRR.

5.2.1 Management Framework

- **Confirmation and Notification**. Immediate confirmation of species identity is essential. Morphological identification should be conducted by trained entomologists and, where possible, confirmed using molecular methods. Once confirmed, findings should be promptly reported through national malaria programmes, regional coordination mechanisms, and international platforms such as the Malaria Threats Map. Rapid information sharing with neighbouring countries is critical to enable heightened vigilance and preparedness.
- **Delimiting the Incursion**. Following confirmation, targeted surveillance should be rapidly scaled up to determine the spatial extent of the incursion. This should include both adult and larval surveys, prioritizing urban and peri-urban areas, transport corridors, water storage sites,

and other high-risk habitats. Surveillance intensity should be sufficient to distinguish between a localized introduction and a more widespread, established population.

- **Immediate Vector Control Response**. Where populations appear localized, the primary objective should be elimination. Control efforts should focus on larval source management, including removal or modification of breeding sites, covering or sealing water storage containers, and application of WHO-prequalified larvicides where necessary. There is also potential to use larvivorous fish, an approach with a long history of application in Asia and one of the main tools utilized in the ongoing incursion in Sri Lanka (see Box 3). However, additional research is needed to support its use in Africa, including practical considerations—such as suitable fish species, distribution methods, stocking densities, and appropriate water bodies—as well as environmental concerns, particularly the risk of non-target effects.

  Adult control measures, such as spatial emanators or targeted indoor residual spraying, may also be considered to rapidly reduce adult populations in affected areas. Control activities should be implemented quickly and sustained beyond the point at which the species is no longer detected. Absence of the species should be confirmed for several years after the last positive detection, and routine monitoring (as outlined in Section 5.1.2 above) should be maintained long term.

- **Community Engagement and Risk Communication**. Early engagement with communities is essential to ensure access to breeding sites and acceptance of interventions. Clear communication (including radio advertisements, text messages, social media, etc) should emphasize the preventive nature of the response and the benefits of early action, particularly in urban settings where the risk of sustained transmission is highest.
- **Integration and Coordination**. Response activities should be integrated with existing vector control and surveillance programmes, including those targeting other urban vectors such as *Aedes* spp. Coordination across sectors (e.g. health, water, urban planning, transport, communication) can substantially enhance effectiveness and sustainability.
- **Review and Adaptation**. Ongoing monitoring should be used to assess the effectiveness of interventions and adapt strategies as needed. Documentation of actions and outcomes will contribute to regional and global learning and strengthen preparedness for future incursions.

It is important to acknowledge that malaria transmission linked to *An. stephensi* may be minimal at this early stage of invasion. However, targeting these highly localized populations is unlikely to incur substantial costs and therefore may not pose a significant trade-off with existing National Malaria Control Programme priorities, even those with limited budgets.

Box 2. Illustrative case study from Ghana on response to initial incursion.

In response to the WHO 2022 call to strengthen surveillance for *An. stephensi* in Africa, routine entomological monitoring in Accra was expanded to include both morphological and molecular identification methods (Afrane *et al*. 2024). Larval sampling was conducted across eight urban sites during dry and rainy seasons in 2022, with larvae reared to adulthood for species identification using PCR and sequencing. Among 1,169 mosquitoes identified, four specimens (0.34%) were confirmed as *An. stephensi*.

Notably, *An. stephensi* larvae were found in dugout wells associated with irrigated vegetable farms and roadside ditches, environments that differ from the container-based habitats typically reported in Asia and parts of East Africa. Larvae were detected alongside *An. gambiae s.s.* and *An. coluzzii*, suggesting ecological overlap with dominant local malaria vectors. The mosquitoes were detected far from major ports of entry, implying either earlier undetected introduction or secondary spread within the country.

Detection of *An. stephensi* initiated the development of a national action plan combining immediate containment measures with medium- and long-term strategies to limit spread, reduce transmission risk, and strengthen national preparedness. To date there have been no further detections of *An. stephensi*.

Immediate actions focused on rapid communication, coordination, and awareness. The presence of *An. stephensi* was promptly reported to WHO, national authorities, partners, the media, and the public. Public communication initiatives were launched to inform communities about the mosquito and appropriate preventive actions. A national task force was established to provide strategic oversight and technical guidance, ensuring a coordinated and multisectoral response. These early steps—designed to build awareness, mobilize stakeholders, and create institutional mechanisms for rapid action—were underpinned by a targeted program of control aimed at eradication of the isolated populations, primarily based on larval source management, including: systematic mapping and characterization of breeding sites; removal or modification of breeding sites to prevent mosquito access; targeted application of appropriate larvicides.

Medium- to long-term actions prioritize strengthening surveillance, vector control, capacity building, and community engagement. Enhanced entomological surveillance has been integrated into routine activities to improve understanding of the bionomics, distribution, and seasonal dynamics of *An. stephensi*. This includes screening archived mosquito samples and conducting ongoing collections at national sentinel sites to detect possible historical presence and current spread. Training programs for national, district, and community-level personnel have been implemented to improve identification skills and knowledge of key larval and resting habitats, ensuring early detection and targeted control.

5.3 Increase in distribution and abundance – containment and slowing the spread

5.3.1 Scale up and spatial stratification

In settings where *An. stephensi* is established and continuing to spread, a logical response is to expand the interventions described in the preceding section (e.g. see Box 3). However, experience from the management of other invasive species highlights the added benefits of implementing a coordinated, area-wide strategy that applies spatially stratified approaches tailored to different stages of invasion. One such example, which provides many potentially valuable lessons for *An. stephensi*, is the area-wide management of the invasive European gypsy moth *(Lymantria dispar)*, now called the spongy moth, in the United States (the details below are summarized from the more detailed account of Liebhold *et al.* 2021).

Background

The spongy moth is one of the most damaging invasive forest pests in the United States, capable of causing widespread defoliation, ecological degradation, and economic losses. Introduced in the late 1800s, the species has continued to expand its range, yet it occupies only a fraction of its climatically suitable habitat. This constrained spread reflects the long-term success of coordinated, area-wide management programmes implemented across federal and state agencies.

Management Framework

The U.S. spongy moth programme is built around three complementary, spatially explicit components:

- **Early Detection and Eradication.** Extensive pheromone-trap networks are deployed in uninfested areas, particularly along transport corridors and other high-risk pathways. When isolated populations are detected, rapid response actions—most commonly aerial applications of biological pesticides—are used to eliminate populations before establishment. This approach has successfully eradicated hundreds of incipient infestations.
- **Slowing the Spread (STS).** The STS programme targets low-density populations along the invasion front between infested and uninfested regions. Using GIS-based decision-support tools, surveillance data guide targeted interventions that suppress reproduction and population growth ahead of the advancing front. Techniques include mating disruption using pheromones and selective insecticide treatments. This proactive strategy has substantially reduced the rate of range expansion.
- **Suppression in Infested Areas.** In regions where spongy moths are already well established, management focuses on reducing outbreak severity and mitigating ecological and economic impacts. Integrated tactics include insecticide applications, forest management practices, and protection of high-value resources rather than complete eradication.

Key Policy Lessons

- **Early action is cost-effective:** Investments in surveillance and rapid response substantially reduce long-term management costs.
- **Area-wide coordination matters:** Success depends on sustained collaboration across jurisdictions and agencies.
- **Data-driven decision-making improves outcomes:** Standardized surveillance and analytical tools enable efficient targeting of interventions.
- **Long-term commitment is essential:** Managing invasive species is a multi-decade effort requiring stable funding and institutional capacity.

5.3.2 Lessons for *Anopheles stephensi*

The U.S. spongy moth programme demonstrates that invasive species spread can be significantly slowed—and local populations eliminated—through integrated, area-wide strategies aligned with early detection and rapid response principles. This model provides valuable lessons for addressing the spread of *An. stephensi* in Africa. Although the species differ biologically, both invasions share key characteristics: human-mediated dispersal, delayed detection, and the potential for rapid expansion across large geographic areas. The U.S. experience demonstrates that coordinated, long-term strategies grounded in EDRR can substantially limit spread and impact—an approach directly applicable to *An. stephensi*.

Early Detection and Surveillance

Spongy moth control relies on dense, standardized surveillance networks focused on high-risk pathways such as transport corridors and ports of entry. Similarly, *An. stephensi* surveillance in

Africa should prioritize urban centers, transport hubs, dry ports, and border crossings, where introductions are most likely. Routine entomological surveillance—augmented by molecular identification—can function as an early warning system, just as pheromone trapping does for spongy moths.

Rapid Response and Local Elimination

A cornerstone of spongy moth management is the rapid eradication of newly detected, localized populations before establishment. Evidence from Sri Lanka, Ghana, and Nigeria suggests that *An. stephensi* populations may also be eliminated when detected early and targeted with intensive larval control. As with spongy moths, delays allow populations to expand beyond readily achievable eradication scales.

Slowing the Spread at the Invasion Front

The U.S. *Slow the Spread* programme focuses on suppressing low-density populations ahead of the invasion front to reduce expansion rates. For *An. stephensi*, a comparable strategy would involve intensified surveillance and proactive larval source management at the leading edge of invasion, including in countries not yet reporting the species but adjacent to invaded areas.

Area-Wide, Coordinated Management

Spongy moth control succeeds because it is coordinated across states and agencies using shared data and decision-support tools. *An. stephensi* similarly requires regional coordination across African countries.

Policy Implications

The spongy moth experience demonstrates that **intervening earlier on the invasion curve preserves management options and reduces long-term costs**. Applying this structured, area-wide approach to *An. stephensi* offers a realistic framework for slowing spread, preventing urban malaria transmission, and protecting malaria elimination goals across Africa.

Box 3. Illustrative case study on containment of *An. stephensi* in Sri Lanka.

Anopheles stephensi was first detected in Sri Lanka in December 2016 during larval sampling in Mannar District, an area with strong transport links to southern India. Investigations revealed widespread breeding in cemented wells and presence in domestic water storage containers, as well as adult populations detected through multiple survey methods. In response, the Anti Malaria Campaign (AMC) launched an initiative to eliminate the species from invaded areas. Entomological surveillance was intensified nationwide, with particular focus on urban areas, transport hubs, and points of entry. Between 2017 and 2018, *An. stephensi* was detected in four additional districts in the Northern and Eastern provinces. Vector control measures were simultaneously scaled up, primarily through chemical larviciding and the introduction of larvivorous fish into wells. By 2022–2023, detections were limited to only two districts, suggesting a substantial contraction in the species' known distribution.

Several key lessons emerged from this experience. First, routine entomological surveillance proved critical for detecting the invasive species. Although Sri Lanka had maintained a long-standing surveillance system, *An. stephensi* was not included in national identification keys until after its detection in 2016, despite earlier predictions of its spread from India. This highlights the need for surveillance systems and identification tools to anticipate high-risk invasive species, even in malaria elimination settings.

Second, maintaining an experienced entomological workforce enabled a rapid and targeted response. Expanded surveillance—including larval surveys and adult sampling—facilitated early detection in new districts and informed focused interventions. Existing staffing, infrastructure, and flexible funding allowed AMC to respond quickly, contributing to the apparent containment of *An. stephensi* before it became widely established.

Third, larval source management, particularly well closure and the use of larvivorous fish (*Poecilia reticulata*), showed promise but raised questions about sustainability and cost-effectiveness. Filling abandoned wells proved effective in Mannar but was difficult to replicate elsewhere due to limited local government support. While the presence of larvivorous fish was associated with the absence of *An. stephensi* larvae, fish survival varied widely, and community practices—such as excessive chlorination of wells—may limit effectiveness. Local ecological conditions and community acceptance emerged as critical determinants of success.

Finally, integrating *An. stephensi* surveillance and control with broader vector-borne disease programmes improved efficiency. In Sri Lanka, malaria prevention activities were combined with dengue, leishmaniasis, and filariasis programmes under an integrated vector management framework.

Overall, Sri Lanka's experience demonstrates the value of early detection, sustained entomological capacity, targeted larval control, and integrated programming in responding to invasive *An. stephensi*.

5.4 Species widespread – management and suppression

5.4.1 Further scale up

Where *An. stephensi* populations are already widespread, efforts must inevitably move toward sustained population suppression integrated into routine vector control programmes, with recognition of the increased costs and reduced feasibility of complete elimination. Nevertheless, the examples presented in Box 4 illustrate that elimination may still be achievable and should not be discounted as an objective.

5.4.2 Optimisation of strategies

Given the challenge of sustained control over potentially large areas, there is increasing need to optimize control strategies to maximize cost-effectiveness. For example, a recent study conducted in Kebri Dehar, Ethiopia, demonstrated that breeding of *An. stephensi* was extremely uneven between water containers, with only a small fraction producing the vast majority of mosquito larvae (Yared *et al*. 2025). These "superproductive" sites were mostly large, permanent water reservoirs, such as ground-level cisterns used for construction or residential water storage. Small containers, such as tires, or ephemeral water-holding items contributed little, especially during the dry season. Model simulations indicated that targeting these stable water reservoirs with larvicide during the dry season could dramatically reduce adult mosquito populations. For example, with high coverage (≥ 60% of stable habitats treated), elimination was theoretically possible, whereas treating both stable and ephemeral habitats did not meaningfully increase impact beyond focusing on stable ones alone. Overall, the study suggests that malaria control programs can be more effective and efficient by focusing on the large, consistently water-filled containers that produce most *An. stephensi* larvae, especially during the dry season when these sites are most important. These findings offer a blueprint for larval source management in seasonal environments, shifting away from a broad “treat everything” strategy toward more targeted, high-yield intervention. These theoretical predictions are ripe for empirical testing and implementation.

As an example for adult control, a study by Waite *et al.* (2017) investigated how control tactics might need to be modified when malaria vectors exhibit strong zoophilic behaviour that reduces exposure to conventional indoor interventions like insecticide-treated bed nets (ITNs) and indoor residual spraying (IRS). The study suggested that existing control tools targeted at human dwellings are likely insufficient to prevent transmission but that increasing mosquito mortality associated with non-human feeding cycles—such as through vector control measures targeting livestock or zoophilic habitats—can shift transmission towards elimination**.** Practical strategies might include extending control measures beyond human dwellings to include insecticide treatment of cattle shelters or use of systemic insecticides on livestock, approaches that increase mosquito mortality during zoophilic feeding. With respect to *An. stephensi* in Africa, this study underscores a broader principle: **vector behaviour and ecology critically shape control effectiveness**. *An. stephensi*’s unique breeding and feeding habits potentially reduce effectiveness of classic indoor control tools. Effective control of *An. stephensi* requires response frameworks that recognise behavioural and ecological realities. Integrating targeted larval control, behaviour-informed interventions, and rapid response mechanisms is critical.

5.4.3 Integration into national vector control strategies

If the species is fully established then at some point this requires a shift from dealing with an acute problem to dealing with a chronic problem, which in turn, requires adaptation of national vector control strategies. Key approaches to extending existing national control program strategies include:

- **Continued surveillance of the spread in countries where it is widespread**. This is important for determining the rate and extent of spread, as well as potentially describing density or patterns of seasonal variation.
- **Expand intervention targets beyond households**. Control strategies should systematically address larval habitats**,** outdoor resting sites, and non-domestic water sources, especially in urban and peri-urban areas where *An. stephensi* thrives.
- **Prioritise larval source management (LSM)**. Environmental management, container modification, and the use of WHO-recommended larvicides or biological control tools should form the backbone of *An. stephensi* response, particularly during early invasion stages.
- **Adopt behaviour-informed control strategies**. Interventions should be tailored to local *An. stephensi* ecology, including consideration of outdoor biting, flexible host-feeding, and container-based breeding. Novel tools (e.g. attractive toxic sugar baits or systemic insecticide approaches) could be effective in this behavioural context and warrant investigation.
- **Embed response within Early Detection and Rapid Response (EDRR)**. Rapid identification, targeted intervention, and sustained follow-up are essential to prevent (re) establishment. Entomological surveillance systems must be capable of detecting low-density populations and triggering immediate control action.

- **Integrate with urban health and vector-borne disease programmes**. Alignment with dengue, cholera, and water and sanitation/waste management programmes can improve efficiency and sustainability, particularly in rapidly urbanizing settings.

Box 4. Illustrative case studies on widespread control and elimination.

There are currently no clear examples of programmes that have eliminated *An. stephensi* from areas where its populations have become widespread. Nonetheless, case studies involving other vector species demonstrate that elimination is possible even when populations span vast regions and cross national borders. For example, *An. gambiae s.l.* was accidentally introduced into northeastern Brazil in the mid-1930s, establishing across an area of 54 000 km^2. In response, the Brazilian government launched a large-scale eradication campaign in 1939. The strategy focused on intensive use of larvicides, elimination of breeding sites, meticulous surveillance, and rapid response teams treating every breeding site detected. By 1940, *An. gambiae* populations had collapsed, and in 1942 Brazil was officially declared free of the species. This campaign provides a landmark example of the potential for coordinated vector elimination over an extensive scale using conventional control tools.

Similarly, New Zealand successfully eradicated the invasive Australian saltmarsh mosquito, *Aedes camptorhynchus*, following its accidental introduction in 1998 from Australia. The strategy involved a comprehensive, multi-pronged approach integrating larvicides, habitat management (clearing drains, filling ponds, and vegetation removal), intense surveillance, legislation to enforce control, and public engagement. After a 10-year effort, it was declared eradicated from New Zealand, representing a major achievement in biosecurity.

Another landmark example, although not a mosquito, is the New World Screwworm in North America (Valdez-Espinoza *et al.* 2025). In the earlier part of the 20th century the screwworm ranged from the Southern U.S. (extending further north during the warmer months), through Central America and into Latin America. This livestock pest was eradicated from the United States and Mexico through a large-scale program using sterile-fly releases. The U.S. began the effort in Florida between 1957 and 1960, releasing millions of sterile flies weekly and eliminating the pest. The program later expanded nationwide and in 1972, extended to Mexico. By 1987, most of Mexico was free of the pest, and from 1988 to 1991 the campaign extended through Central America, reaching Panama, which declared eradication in 2006. Eradication in the U.S. and Mexico (1960–1991) cost US$955 million (figure adjusted for inflation). The benefits of eradication are far greater: $1.35 billion annually in the U.S., $495 million in Mexico, and $132 million in Central America. Areas where the pest remains endemic continue to face major economic losses.

6. Cross-cutting considerations to support implementation

6.1 Existing control activities for other vectors

A variety of interventions already used to control *An. stephensi* in endemic regions are available, several of which are described in WHO (2024). Insecticide-treated nets and indoor residual spraying have both shown effectiveness against numerous *Anopheles* species, and when these tools are used to target existing disease vectors, they may also provide incidental benefits by suppressing *An. stephensi*. Likewise, larval control measures aimed at vectors that share similar breeding habitats are likely to affect *An. stephensi* as well. These co-benefits may be especially strong in programs designed to control other urban vectors, such as *Aedes* species.

6.2 Bylaws

Bylaws are effective tools for local governments to ensure the creation of larval sites is avoided. Some of these bylaws could include mosquito-proofing of water storage containers and construction requirements that allow inspectors to access water storage containers (e.g. Bombay Act No. III of 1888).

6.3 Urban planning

Urban planning can play a critical role in preventing the establishment of *An. stephensi* by shaping environments that limit the availability of suitable breeding and resting sites. Planned urban development with reliable piped water, effective drainage, and waste management reduces reliance on household water storage, a key habitat for this species. Building designs that avoid water accumulation in tanks, wells, and construction sites further constrain larval development. Integrating vector risk considerations into housing, transport, and infrastructure projects, particularly in rapidly expanding peri-urban areas, can substantially lower invasion risk. When aligned with public health objectives, urban planning becomes a long-term preventive measure against *An. stephensi* establishment.

6.4 Community engagement

Community engagement is imperative for effective and sustainable vector control. In particular, communities can play an important role in larval source management to remove or cover containers in and around the home that can act as larval habitats. Community actions may also be useful in the areas of waste management and environmental management.

6.5 Multisectoral response

It is important that the response to the spread of *An. stephensi* should have a multisectoral approach (WHO 2020). This approach should engage multiple actors, as noted below.

6.5.1 Governmental

The primary actors for funding and eliminating *An. stephensi* from Africa are the governments of countries where An. stephensi has been found. Further monitoring should also be done in neighboring countries. These governments can conduct vector control measures, monitoring, and collaborate with non-governmental actors. Specific actors within the government that may play a role are the Ministries of Health, municipalities and city governments, border control, and the military.

Ministries of Health

Ministries of Health have experience in conducting large-scale public health interventions, such as implementation of indoor residual spraying or insecticide treated net campaigns. Additionally, these ministries are adept at the use of entomological and epidemiological monitoring.

Border control and customs

Border control and customs authorities provide an important possibility for preventing the movement of *An. stephensi* throughout Africa. Population and cargo mobility data is often used by border control officials to monitor and limit cross-border and internal movement of communicable diseases. As of yet, there is no analogous approach to *An. stephensi*.

Military

The military may play an important role in the implementation of vector control. The organization of the military lends itself to operations requiring a focus on detail, tight deadlines, and high levels of rigor. Additionally, some of the areas where *An. stephensi* have been found are in areas with security concerns (e.g., Somali province, Ethiopia).

6.5.2 Non-governmental

Non-governmental organizations (NGOs) may play an important role in facilitating training of health workers, implementation of vector control, and community sensitization. These actions should be coordinated with governmental activities.

Funding agencies

Funding agencies can play an important role in funding the work that needs to be done to eliminate *An. stephensi* from the region. Some of these have already started funding monitoring and control work in these countries, but additional support will be needed including scope for regional coordination, recognizing that actions in one country reduce invasion pressure on others. Investment in shared surveillance platforms, reporting mechanisms, and harmonized response protocols is critical. Regional coordination was a key element in the success of the Southern Cone Initiative to Control/Eliminate Chagas (Schofield 1997).

Private sector

The private sector may have important contributions to the efforts to eliminate *An. stephensi*. These are particularly valuable in relation to larval sites. Waste management companies can ensure that containers (tarpaulins, tires) are removed and stored in a way that do not hold standing water. Tires in particular might be destroyed through pyrolysis. Water companies might work to ensure a minimum of stockage in households, or that any water be stocked in ways to prevent oviposition by *An. stephensi*. Other options for private sector participation include: private purchasing of LLINs, private health centers providing health data into government systems, or increased control of mosquitoes at port facilities.

Academic and research institutions

Academic research should be conducted to increase our understanding of the genetics, biology, distribution, and control measures possible against *An. stephensi*.

7. Pilot projects to strengthen the case for elimination

The apparent disappearance of *An. stephensi* from Accra, Ghana—following control activities primarily involving larviciding—and from parts of Nigeria, even with limited vector control, suggests that early, targeted action may make elimination possible. *An. stephensi* has also been eliminated from several districts in Sri Lanka (WHO 2024). However, it remains unclear how much climatic conditions or other local factors in Ghana, Nigeria, and Sri Lanka contributed to these outcomes.

Pilot elimination projects would be highly valuable for determining how *An. stephensi* could be successfully eliminated in Africa. Such projects could test various vector-control approaches (as outlined above) across different ecological and operational contexts, providing insights that can inform both this strategy and national action plans. Potential pilot projects might include:

- Local elimination of *An. stephensi* from isolated villages in Somali Province, Ethiopia.
- Elimination of *An. stephensi* from city locations in Ethiopia, such as Adama or Kebri Dehar, through targeted larval control and other behaviour-informed interventions.
- Use of larvivorous fish in selected locations in Africa. Further evaluation of larviciding would be of use, but there is a particular knowledge gap for larvivorous fish for which there is not an existing recommendation. Community perceptions related to acceptability should be evaluated.
- Evaluation of community acceptability and engagement for any new vector control approach.

8. The role for novel control and prevention tools, and the need for continued innovation

Although sustained and well-optimized deployment of existing control tools can substantially slow spread and, in some contexts, achieve elimination even at large spatial scales, implementation remains challenging, particularly in the face of resource constraints. In this context, novel tools offer the potential to reshape control strategies and further advance progress toward elimination. The illustrative approaches described below are at different stages of development and operational readiness, but collectively they highlight a growing and increasingly diverse toolbox to support prevention, containment, and long-term population suppression.

- **Attractive Targeted Sugar Baits (ATSBs)** exploit the sugar-feeding behaviour of mosquitoes by offering attractive sugar sources laced with oral toxins. ATSBs have demonstrated mixed results but a recent study in temporary settlements in Nigeria showed particular promise (Allen *et al.* 2025). For *An. stephensi*, ATSBs could be deployed in peri-domestic and peri-urban settings as a complementary adult control measure.
- **Spatial emanators** release volatile chemicals that reduce mosquito entry, biting, or resting in treated spaces without necessarily killing mosquitoes. A recent large scale randomized controlled trial in Kenya demonstrated significant reduction in malaria transmission using transfluthrin-treated emanators (Ochomo *et al.* 2025). Given *An. stephensi*'s adaptability to urban environments and variable indoor–outdoor behaviour, spatial repellents could help reduce human–vector contact in settings where indoor residual spraying or nets are less effective.
- **Sterile Insect Technique (SIT)** involves mass-rearing male mosquitoes and sterilizing them—typically via irradiation—so that when released, they compete with wild males and produce no viable offspring, leading to population decline over successive generations. For *Anopheles* vectors, SIT has been explored conceptually and experimentally, although operational releases in the field remain limited due to challenges in mass rearing, sex separation, and maintaining sterile male competitiveness under natural conditions. In the specific case of *An. stephensi*, a

dedicated SIT development effort is underway, coordinated by researchers at Sun Yat-sen University in China in collaboration with partners such as the FAO/IAEA Insect Pest Control Laboratory, with the aim of producing an SIT technical package, laying the groundwork for future field trials in African settings (Global Grand Challenges 2022).

- **Genetic control tools** offer longer-term, area-wide suppression or elimination potential. These include genetic sterile insect technique, gene drive systems, and other population modification strategies (e.g. see James *et al.* 2020; WHO 2020; Apte *et al*. 2024). While most work has focused on African malaria vectors such as *An. gambiae*, gene-drive constructs have been developed in *An. stephensi* that achieve high levels of population modification in laboratory settings within a few generations, suggesting the feasibility of future suppression strategies (Adolfi *et al.* 2020). Other approaches such as self-limiting mosquitoes, which involves releasing genetically modified males whose offspring fail to survive, represents a more advanced genetic suppression approach already used operationally against *Aedes aegypti* (e.g. Carvalho *et al.* 2015; Spinner *et al.* 2022). Adaptation of this platform for *An. stephensi* is underway, including importation into contained facilities and preparation for pilot releases in Djibouti. Important to note is that substantial regulatory, ethical, and ecological considerations remain, and field deployment in Africa will require extensive preparatory work.
- **Enhanced molecular surveillance**, including high-throughput PCR and genomic tools, can improve early detection, track invasion pathways, and monitor insecticide resistance (Favia *et al*. 2019). Molecular diagnostics, including species-specific PCR and real-time PCR assays, vastly improve detection sensitivity—allowing identification of *An. stephensi* even when present at low abundance in mixed species samples (Singh *et al.* 2023). Early detection through improved molecular tools would enable rapid response and containment.
- **Environmental DNA (eDNA)** surveillance offers a promising, non-invasive method to detect mosquito presence from water samples without the need to collect larvae or adults (Kristan *et al*. 2023). eDNA could be particularly useful for early detection of *An. stephensi* in large urban areas where conventional surveillance is logistically challenging.
- **Smartphone apps** are increasingly being used in mosquito surveillance and identification research, enabling rapid, low-cost data collection and supporting both citizen science and professional entomology. For example, an app with a pictorial morphological key was shown to accurately distinguish between multiple *Anopheles* species, including *An. stephensi*, using a few simple inputs, which can improve field identification when expert taxonomists are unavailable (Gupta *et al.* 2021). More advanced approaches combine computer vision and machine learning with smartphone imaging, such as the VectorCam app paired with a macro lens, which uses on-device algorithms to classify mosquitoes into genera and key malaria vector groups instantly without internet access (Dasari *et al.* 2024). These smartphone-based tools are still under development but demonstrate how portable, accessible technologies could extend surveillance reach, enhance early detection of *An. stephensi*, and support rapid response efforts by linking field observations to central databases for analysis and mapping.

Together, these emerging tools highlight opportunities to strengthen *An. stephensi* detection and control through innovation. While none are standalone solutions, strategic integration with established vector control and surveillance systems could substantially enhance Africa's capacity to reduce the long-term public health impact of this invasive vector.

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