Chapter

Persistent Barriers to Implementing Efficacious Mosquito Control Activities in the Continental United States: Insights from Vector Control Experts

Imelda K. Moise, Leo C. Zulu, Douglas O. Fuller and John C. Beier

Abstract

Many barriers undermine vector surveillance and control efforts in the United States. Experts warn that such barriers, including funding, threaten the capacity of public-health surveillance systems to detect emerging mosquito-borne disease and respond appropriately, timely and effectively. This chapter explores the status, barriers, and corrective strategies to effective mosquito surveillance and control in the US based on experiences and insights of the 35 interviewed representatives of diverse mosquito-control programs selected from 18 U.S. states. Although our interest is in mosquito-borne diseases, we focus on the 2016 Zika outbreak. For the most part, this chapter will outline issues relating to mosquito control and surveillance that have persistent among state, county and municipal programs as a result of insufficient and unreliable funding, inadequate trained personnel, poor facilities, and inadequate political support. At the community level, we will discuss issues that hinder mosquito control efforts including apathy and low public awareness, and provide examples of how mosquito control agencies have adapted to "readily" respond to changing vector-borne disease environments, demands and constrained funding.

Keywords: mosquito-borne diseases, Zika, barriers, mosquito control, United States

1. Introduction

The question of how ready United States (U.S.) public health officials are to prevent and control vector-borne disease transmission has received considerable attention since the first West Nile Virus (WNV) outbreak of 1999 in New York renewed by the recent Zika virus (ZIKV) outbreak. The first reported case of local ZIKV transmission through infected mosquitoes in the Continental United States was in Miami, Florida, in late July 2015. Although the global problem of mosquito-borne diseases (MBDs) is "as old as the pyramids" [1], it is a critical time to revisit mosquito control because despite significant gains in reducing the risk and incidence of some MBDs (particularly malaria); the world has seen a rise in the risk and incidence of other MBDs. This is particularly true for viruses transmitted via *Aedes* mosquitoes, such as *Chikungunya*, *Dengue* and ZIKV [2–4]. At the same time, it is nearly impossible to eliminate the local risk of transmission of exotic arbovirus once introduced to an area. Therefore, responding to exotic emerging arbovirus poses new challenges for mosquito control programs [5], as characterized below:

> *"The unpredictable nature and severity of vector-borne disease outbreaks demonstrates the urgent need for careful preparation and the incorporation of vector-control emergency-management activities into overall public health preparedness efforts"* [6].

Experts also worry that although prevention of MBDs is the best way forward and is substantially less costly than mosquito and disease control in response to a disease outbreak [7], MBD surveillance and control continued to be underfunded and to be the subject of budget cuts. In the 2011 U.S. fiscal year, a proposal was made to reduce funding for the Centers for Disease Control and Prevention (CDC)'s MBD program by $26.7 million [8]. The 2016 Congressional resistance and seven-month delay before approving former President Obama's request for emergency funding for ZIKV control [9] further illustrates such challenges. Such moves threaten the capacity of the existing public-health surveillance systems and response activities to deal with MBDs, such as the human WNV disease, Dengue and the ZIKV [10]. A national survey of the 50 state health departments reported a reduction in federal funding for mosquito surveillance of 61% between 2004 and 2012. This reduction resulted in non-tracking of active human cases of WNV in 22% of 56 jurisdictions (mosquito-control districts or territories), discontinued mosquito surveillance in 13%, reduced effort on mosquito trapping and testing in 70%, and reduction in WNV surveillance personnel by 38% [11, 12]. This does not bode well for the recent ZIKV outbreak in Florida and Texas, the serious birth defects it causes in babies, and the current lack limited planning to deal with it [13, 14]. Clinical tests for the ZIKV infection are of limited reliability and there is no vaccine to prevent ZIKV transmission directly from mosquitos or through the sexual transmission pathway. This makes surveillance and control of fundamental importance to prevent further ZIKV transmission and to prepare for dealing with other exotic arboviruses [15].

Maintaining sustainable systems for MBD surveillance can help define the nature and extent of the mosquito problem, provide a basis for evaluating the risk of transmission of MBDs, reduce the cost of responding to emerging vector-borne pathogens and ultimately gauge the efficacy of control activities [8]. While some research has been done on MBD control generically (though Hadler et al., [11, 12] as one exception), little has been done to explore variation in approaches, capacities and the quality of mosquito surveillance and control programs for emerging MBDs across the U.S., let alone from experiences and perceptions of mosquito-control Experts. Few studies have investigated the capacity to effectively surveil, prevent, and control arbovirus infections such as the ZIKV in the US.

In this chapter, inspired by the 2016 ZIKV outbreak in Florida, we use telephone interviews and qualitative research methods in understanding the diversity of current barriers and strategies to implementing efficacious mosquito surveillance and control in the Continental United States, particularly drawing on experiences and perspectives of active vector-control Experts. Insights from Experts can yield a range of locally relevant information that is difficult to obtain from traditional epidemiologic studies. Experts whose perspectives are included in this chapter include those working with state, county, municipal and other local mosquito-control programs or districts. Furthermore, we also provide variation in the

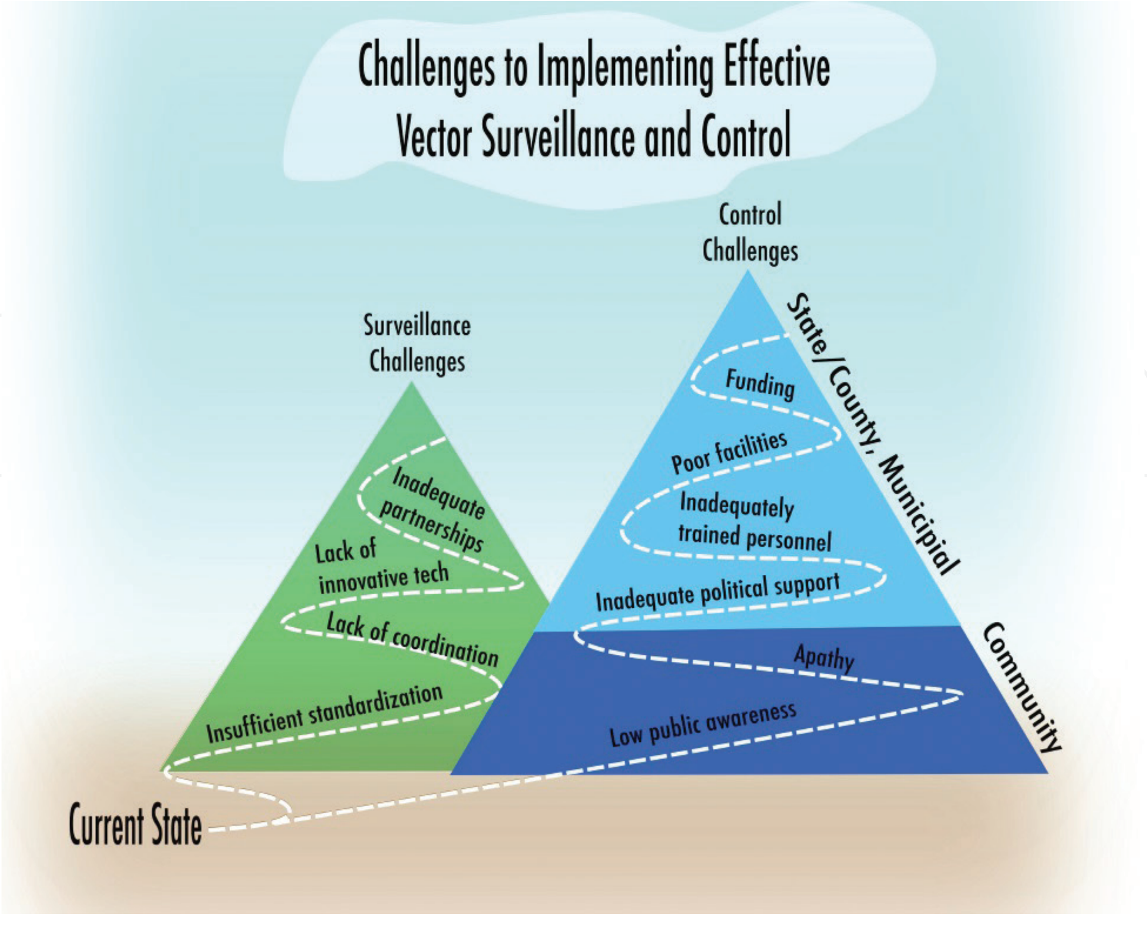

Figure 1.
Challenges that must be addressed before effective vector surveillance and control can be implemented according to the perspectives of 35 interviewed representatives of diverse mosquito-control programs selected from 18 U.S. states.

perceived capacities of state and local mosquito-control programs with different funding structures and state locations across the six US regions, to respond quickly and adequately to emerging MBD threats within the context of Integrated Vector Management (**Figure 1**).

2. Integrated vector management

Integrated vector management involves the optimum use of a mix of methods and resources for the efficient, cost-effective, ecologically sound and sustainable vector management (surveillance and control) in order to control vector-borne diseases. Surveillance of the *Aedes aegypti* and *Aedes albopictus* mosquitos that transmit the Dengue, Chikungunya, and ZIKV viruses generally involves:

1. Determining absence or presence of the vectors in a particular area

2. Identifying the main types of breeding containers for targeted control

3. Detailed mapping of larval sites for the vectors if found in the area

4. Collecting mosquito-population data and identifying density hotspots (high risk)

5. Monitoring impact of control efforts, and

6. Collecting mosquito data on infection rates in ongoing outbreaks and determine thresholds of human infection [14].

Effective mosquito-control programs traditionally include (1) detecting and monitoring mosquito sources; (2) applying larvicides; (3) applying adulticide treatments from the air (aerial spraying) or from the ground using handheld or more mechanized (e.g., from trucks) equipment; and (4) implementing outreach and public education. Further, the CDC recommends source reduction (e.g., container elimination) and larvicide treatments before the beginning of the mosquito season, and adulticide treatments, such as insecticide spraying, after detection of human arbovirus activity [14].

3. Barriers and strategies to implementing sustainable mosquito control and surveillance systems

Statewide mosquito surveys are an essential tool to monitor the presence, diversity, intensity and spatial distribution of mosquito vectors in a state. Responses showed that half (9) of the surveyed states had ever conducted a statewide mosquito-vector survey, and many of the rest had outdated surveys. The oldest conducted in 1940 (Arkansas) while only Arizona and Delaware had conducted one the previous year (2015). Only Delaware reported having conducting annual statewide mosquito surveys. In some rural states (e.g., Arkansas and North Dakota) mosquito control is the sole responsibility of local municipalities while in more urbanized states special mosquito control districts often complement local programs.

Responsibility and capacity for mosquito-vector surveillance and control varied across states. Knowledge about mosquitoes was greatest for mosquito species of concern to public health (e.g., *Aedes aegypti, Aedes albopictus*, and *Culex* species of mosquitoes). These species shaped the surveillance in most local programs. Asked if the ZIKV was an immediate public health concern in their state, respondents in sampled Southern States indicated that ZIKV was an enormous problem. Most respondents in surveyed Northern States indicated that locally transmitted ZIKV was not an immediate problem, mainly because the vectors are rare, absent, or another MBD (e.g., WNV) was more important:

> *ZIKV is not an issue in our state at all, as far as mosquito transmission because we do not have the mosquito Aedes aegypti. It has never been here and we certainly do not expect it to be here. Even the second vector, Aedes albopictus is extremely rare. WNV is much more serious here,* (Mosquito Control Contractor).

Others, while focusing on WNV control, indicated that it was only a matter of time before ZIKV carrying *Aedes aegypti or Aedes albopictus* arrives in their states, as this Mid-western respondent stated:

> *We are going to have a response on it but we are going to continue to work on WNV because WNV kills people in Illinois,* (Independent Mosquito Control Respondent).

3.1 Barriers to mosquito control

3.1.1 Inadequate and inconsistent funding

Mosquito-control efforts and their effectiveness vary greatly among control programs. The biggest factor perceived to determine effective mosquito surveillance and control programs and activities was the funding structure. Almost all the independent mosquito-control district respondents reported having dedicated, well-funded and stable mosquito control programs. The most common sources of funding for these self-funding or autonomous and semi-autonomous districts were local taxes (e.g., a small portion of property taxes and water bills) and revenues for contract work from private companies. On contrast, although respondents in dependent districts reported having a separate stable budget-line item for mosquito-control activities, their funding comes from county budgets and is therefore vulnerable to cuts where and when non-mosquito activities and programs have higher priority.

There was near consensus among Experts from state, county, municipal or other local programs that funding dedicated to mosquito-control activities was insufficient, unstable, and unpredictable. These programs were the most vulnerable to significant budget deficits and inconsistencies because they compete for funding with other departments and programs under tight municipal, county or County Boards of Commissioner budgets. Some interviewees felt that their agencies placed lower priority on mosquito-control activities. This forces them to be more reactive to outbreaks than proactive, an unlearnt lesson of the WNV outbreak with negative implications for program size, content, continuity and effectiveness in the context of the ZIKV outbreak:

> *…You have your director who is running the program but he has very little control over how money is spent. Therefore, when appropriated for mosquito control, but if another department is hurting in the budget arena, they can take some of mosquito control money,* (County Mosquito Control Respondent).

> *We have known even before the days of ZIKV, realizing the importance of mosquito surveillance. Again, sometimes it takes a crisis to make people respond,* (State Mosquito Control Respondent).

3.1.2 Institutional and logistical barriers

Institutional and logistical factors also impeded local vector surveillance and control programs, particularly state, municipal and county programs. Most Experts agreed that facilities and trained staff with requisite skills (e.g., in entomological skills) were insufficient. These shortages undermined essential activities such as effective specimen collection, vector identification, monitoring spatial mosquito distribution, MBD species present, number of cases in the locality, and the continuity of these activities. In a minority of cases, the lack of expertise can be extreme:

> *…A lot of them, they do not have even the expertise where the person who is responsible for the mosquito control is their City Maintenance Worker or their City Water Commissioner. Sometimes it is even the City Auditor. In the small communities, it is sometimes the garbage man* (State Mosquito Control Respondent).

Funding predictability and sustainability emerged as essential requirements to maintain programs and capacity to address emerging MBDs such as the ZIKV infection effectively. Respondents in cash-strapped programs generally attributes funding inconsistences to lack of or vacillating political will. There was consensus on the institutionally disruptive impacts of unreliable funding. These included laying off staff, scaling back surveillance and control activities such limiting mosquito-control activities to larviciding instead of the more targeted and effective adult mosquito-control applications, and suspending such activities altogether in some years. Respondent illustrates such impacts:

> *Once we get money out there and start funding vector control, then all of a sudden, it stops, then people think that we do not care anymore or that it was not the threat that we thought it was originally. …long-term, level, stabilized funding from year to year is the only way to get a good vector control problem in to where we can actually mitigate the potential for disease transmission,* (County Mosquito Control Respondent).

The importance of continuity is such that while most respondents were skeptical that Congress would approve all or part of the federal emergency funding requested for ZIKV control by the Obama Administration in February 2016 in a timely manner, a small number paradoxically worried that some federal funding if provided would be unsustainable. They worried about building a technically and operationally costly surveillance and control program needed for arboviruses on a shaky foundation of federal funding that they considered particularly vulnerable to budget cuts:

> *We go through a few blank years with limited programs in place because we do not have funding to move forward with it. Then ZIKV hits and it becomes a national concern again and my biggest fear is the Federal Government will be nice enough to pass the budget and get money out but that funding isn't sustainable,* (County Mosquito Control Respondent).

> *I am afraid we'll get a good program in place like the one we did with WNV and have surveillance and outreach and really get some abatement going, then all of a sudden the funding dries up and you're stuck again with the need to do something without the capability of doing something,* (State Mosquito Control Respondent).

Ultimately, funding unpredictability undercuts the ability to be proactive, a critical component of MBD control:

> *Once a disease has entered and gotten hold, it's much more difficult to eliminate or control that disease, as opposed to being proactive, monitoring the situation and if a threat is identified, to establish some sort of game plan to be able to control the disease,* (Independent Mosquito Control Respondent).

Some states have sought to balance quality surveillance and cost under tight budgets. Thus, Arkansas traps for the presence/absence of mosquitoes along (both side) of county boundaries. This provides an even geographic spread for vector sampling within a limited area while providing the opportunity to share costs among bordering counties. Many programs focus surveillance on larvae because they know likely breeding sites, such as water containers for *Aedes aegypti,* and bias adult surveillance to areas that have had high *Aedes aegypti* densities in the past.

Another major institutional challenge was inadequate coordination across program service areas. As a mosquito control contractor noted, "there are always mosquitoes flying from outside of your control area," and sometimes beyond their geographic range. Most respondents indicated that this cross-boundary mosquito mobility challenged their response since all surveyed programs (except in Arkansas) limited their activities within their county, township, or other jurisdictional boundaries. Further, differences in resource availability, capacity, methods and priority of vector control across control jurisdictions results in fragmented mosquito surveillance and control and creates gaps in coverage, which undermine the ability of mosquito-control programs to mitigate the risk of MBD transmission across landscapes.

3.1.3 Low public awareness and apathy on mosquito efforts

Most respondents decried apathy (lack of interest or concern), low public awareness of the need and nature of mosquito control, and low political will. This undermined community co-operation in mosquito surveillance and control, including limiting access to private property for trap placement, and participation in mosquito control at the household level (e.g., clearing containers). Further, many respondents cited resistance to chemical use for mosquito abatement among some community members based on environmental concerns, especially adverse non-target impacts, as well as on philosophical opposition to chemicals. They were particularly wary of such worldviews and attitudes because they can erode community trust and co-operation, and undermine control efforts:

> *…we have many people who are philosophically opposed to what we do and they are misinformed, they expose themselves to all sorts of misinformation from various advocacy groups who are anti-pesticides,* (Mosquito Control Contractor).

Many respondents indicated that they had come a long way in balancing public health and environmental concerns. This includes using the most environmentally friendly control chemicals. They also highlighted apathy and lack of knowledge among the public as a major barrier. Nearly all underscored public education as necessary to enhance mosquito control through individual behavior change and to gain community support for programs (including improved budgets and equipment). Many admitted that previous public-education efforts had been inadequate, and often ineffective to effect positive behavioral change. Still, it was clear that Experts considered public education, community engagement, outreach, and media attention important strategies to overcome apathy and mitigate negative perceptions of mosquito control.

Enhanced and more effective public education emerged as an important strategy to address some of the some of the barriers. Respondents recognized the role of federal agencies (e.g., CDC) and states in public education and information dissemination, particularly during disease outbreaks. However, many preferred approaches that involved person-to-person contact, particularly door-to-door visits and school outreach, for their effectiveness in both getting cooperation and participation, and in passing on the message to others in the community. Some respondents indicated that neighborhood residents who actually experience mosquito management efforts were more likely to support vector and pest control programs. Outreach and integration of vector prevention and surveillance in schools is favored as a powerful tool to reach parents through school-going children while also preparing a future generation of informed leaders:

> *We actually have an educational outreach person who works in our biology department and she goes to schools and works with the science teachers …educating kids on mosquitoes and all aspects of their breeding and how to control them,* (State Mosquito Control Respondent).

3.2 Barriers to mosquito surveillance

3.2.1 Lack of standards on sampling and of evaluation of impacts of sub-optimal trap placement on MBD-risk assessment

Interviews revealed wide variation in mosquito-surveillance practices. Beyond virtual consensus that integrated vector management (IVM) is the ideal approach, there were no agreed standards on practices, including accuracy criteria for estimates. There was wide variation in the type, number, sampling protocol, spacing and frequency of mosquito-trap placement across programs. Location of traps was based on diverse and sometimes subjective factors heavily dependent on local contingencies such as resource availability, local Expert knowledge, and convenience. Factors included the practical need to locate traps away from public view to prevent human disturbance and vandalism (deliberate destruction) and accessibility—many practitioners placed traps in public spaces (parks, natural areas) and on properties of willing residents. While laws on access to private property for mosquito abatement varied across states, respondents often negotiated with individual residents for access and permission to place traps thereon. The type of mosquito trap used and the need to avoid vandalism or theft also mattered. Traps that require electricity, such as the New Jersey light traps, commonly used for *Aedes aegypti* and *Aedes albopictus,* are placed close to built-up areas with electricity supply. There was also a bias toward areas already known to have high mosquito densities. The following quotes illustrate some of the locally specific and sometimes-subjective factors that determined sampling particularly trap placements:

> *You want to place it somewhere where you are going to find mosquitos but it comes down to where I can hang it. We have our ideal of where we want to set it, and then it is rather where we can set it,* (Independent Mosquito Control Respondent).

> *You try to cover the area the best you can, but, you know, just depends on what your limitations are. However, for an everyday surveillance, it would not be a good idea just to go to a specific neighborhood and put a bunch of traps out,* (Dependent Mosquito Control Respondent).

> *We sometimes do not' have control over where those traps are placed when there is a volunteer setting traps,* (State Mosquito Control Respondent).

The problems of inadequate and unpredictable funding undermining mosquito control also afflict surveillance. Respondents noted that limited resources (funding, trained staff and others) often promote convenience sampling rather than optimal IVM practice. While some of the resulting inconsistencies are expected to vary due to local and regional variation in vector ecology and MBD transmission dynamics, they undermine cross-jurisdiction coordination and effective surveillance; many respondents noted the need for some standardization.

Reliability of mosquito-surveillance practices is important to guide sound decision-making on control interventions such as source reduction, larvicide treatment and adult reductions (e.g., adulticide). Some respondents admitted that their programs conducted little mosquito testing. A state mosquito-control Expert indicated that some programs conducted testing only when they note unusually high numbers of mosquitoes. While many small communities will use test results to trigger local vector control, "some of them don't even look at the data." Most Experts indicated that they used thresholds (e.g., mosquito larvae, pupal or adult density) derived from mosquito-surveillance data as triggers for fogging or spraying. The thresholds, nevertheless, appeared not standardized and varied greatly by program and species, and some were vague:

> *There is a threshold set that if the mosquito traps show higher than that—or we will send people out and if they report that the landing rate count is at a certain number, we will send planes out,* (Independent Mosquito Control Respondent).

> *In response to Culex, our action thresholds are 50 females or more. As far as Aedes aegypti, and based on work that we did last year, we came up with a numerical threshold of 50 or more females per trap. .... if any of the Aedes aegypti test positive for our arboviruses, then we will go ahead and fog too,* (County Mosquito Control Respondent).

Experts revealed common concerns that the current work environment was reactive rather than proactive and preventive. Many respondents decried the narrow focus on outbreaks of high profile MBDs—the so-called disease *du jour* or disease of the day, e.g., ZIKV, Dengue, and WNV—or on responding to extreme events such as hurricanes or flooding. Both tend to be geographically limited in scope. Many complained that this reactive approach undermined surveillance efforts and their capacity to detect, anticipate and respond to emerging MBDs instead of always playing catch-up:

> *Surveillance is important. Every couple of years, some mosquito disease captures the headlines. Today it is ZIKV; a couple years ago, it was Chikungunya and a couple years before that was West Nile Virus, which means a few years from now, something else will happen,* (Mosquito Control Contractor).

3.2.2 Coordination across mosquito control jurisdictions

Conversations affirmed the general view that at the local scale of operation below the state level the better for surveillance and control because such districts were better able to respond to the high level of variability in vector ecology and social and institutional contexts. With better and stable funding, independent mosquito districts maximized local-scale advantages. Respondents nevertheless highlighted the need for enhanced cross-jurisdiction coordination and some level of standardization of best practices for consistent mosquito surveillance within and across jurisdictions. Some state agencies played this cross-jurisdiction coordination role functionally, administratively or in a regulatory capacity, drawing on broad federal guidelines provided by the CDC and the Environmental Protection Agency. For example, respondents in Florida indicated that the Florida's Department of Agriculture and Consumer Services has Spot Teams that fill surveillance and control gaps by covering areas that have no funding or staff by using contractors or nearby programs, often on a cost-recovery basis in the case of disease control.

Florida also provides a commendable model for statewide coordination among mosquito-control Experts. A non-profit association, the Florida Mosquito Control Association (FMCA) was formed in1922 to promote the interests, exchange information and coordinate the activities members drawn from diverse mosquito-control programs. Coordination includes standardization of practice, information exchange, and professional training and certification. A representative explained FMCA origins and significance:

> *…there was a need for exchange of information and coordination throughout the state. …to help coordinate and get information so that something that is found or discovered is shared with the rest of the State of Florida,* (FMCA Representative).

3.2.3 Partnerships are important

Almost all program respondents reported formal and informal partnerships with other relevant agencies working at different scales—local, county, state, and federal. In addition to drawing overall guidance from the CDC, most respondents cited the Environmental Protection Agency (EPA) as a federal partner. Local partners included the Department of Environmental Quality (DEQ), county health departments, Department of Agriculture and other government and county departments, universities, and other nearby mosquito-control districts, including local communities. Several respondents, particularly from resource-constrained programs, indicated that such partnerships allowed their programs to reduce or externalize some operational costs. Some gained access to external resources through formal contracts, memoranda of understanding (e.g., California), grants, collaboration with other agencies, community volunteers, and local schools. Many programs often used these partnerships to fill skill gaps with external expertise. Some programs extended their available resources though cost savings, use of private contractors, and provision of incentives including grants. The quotes below illustrate such collaboration:

> *They recruit anywhere from eighty to a hundred…We try to have at least one in every county…These are New Jersey traps. The people who are doing this collection, they are volunteering. Every week they will take their… light trap and mail it* (State Mosquito Surveillance Respondent).

> *We have a few contracts with county health departments to do mosquito control, usually surveillance. …. mostly, we work informally,* (Mosquito Control Contractor).

3.3 Future prospects for mosquito surveillance and control

In addition to the barriers identifies to effective mosquito surveillance and control in the context of the ZIKV outbreak, the research also revealed promising measures that can be taken to improve the situation. On funding barriers, findings affirmed the importance of increased funding. Given the nature of mosquito surveillance and control, and the consequent need for long-term investment, however, the predictability and sustenance of funding were even more important. The disruptive adverse impacts of reduced and inconsistent funding also illustrated in other studies, including stoppage of tracking of tracking of human cases of WNV, and reductions in mosquito trapping, testing and surveillance and personnel [10, 11], threaten effective surveillance, and early detection and prevention of MBD transmission, including for the ZIKV. This also includes inconsistent mosquito data from insufficient trap locations that undermine assessment of the risk of human exposure to the vector and MBDs [14, 16]. However, recent increases in funding for interventions and research offer new hope, so long as such funding is sustained particularly at municipal, county and state programs. Such funding includes $1.1 billion in emergency federal funding for ZIKV response (approved in September 2016), CDC funding of the establishment of four MBD s regional Centers of Excellence in the US (approved in December 2016), and state-level (Florida State funding of $25 million for the development of a ZIKV vaccine. Some gains can also be made in creative forms of financing and increases in efficiency in mosquito surveillance and control activities. **Table 1** presents the identified barriers and strategies to implementing sustainable mosquito control and surveillance systems in the US. Emerging ideas included more dependence on local (tax) funding sources as independent control districts, mosquito sampling along county boundaries to share and reduce costs (e.g., Kansas State), cross-jurisdiction collaboration and cost sharing, and the use of citizen science to enhance data collection.

In response to the challenge of lack of inconsistencies in mosquito surveillance techniques, the need for some degree of standardization in sampling protocols while accommodating vector spatial variability has also been noted in other studies.

Barriers	
Inadequate and inconsistent funding (mainly for state, county and municipal programs).	Policies focused on sustaining funding statewide mosquito surveillance and control capabilities.
	Developing partnerships for cost sharing and community training for participation in mosquito trapping, testing and prevention.
Lack of political will and support.	Enhanced public education—raise awareness and concern, influence politicians.
Complex trans-boundary mosquito risks and limited cross-boundary coordination.	Enhanced collaborative arrangements and cooperation across mosquito districts, e.g., skill sharing, contracts, memoranda of understanding, voluntarism.
Limited capacity and specially trained personnel.	Hire skilled personnel and train existing ones on needed skills.
	Use innovative technologies, e.g., smart traps.
	Statewide or regional Experts for mosquito programs and activities.
Philosophical and environmental belief barriers to mosquito control.	IVM—innovative mix of synergistic methods, e.g., environmentally friendly insecticides and application technologies, biological control, habitat reduction.
	More and effective public education and communication with stakeholders.
Legal abatement obstacles to timely response.	Promoting persuasive person-person community outreach to gain voluntary access.
Lack of standardization and inconsistent mosquito data from few trap locations and select locations	Develop standard surveillance methods for particular a subset of conditions, and quality control mechanisms.
	New research on vector biology, control methods and responsiveness to MBDs.
	Adequately funded and consistent surveillance for predicting and reducing human infection.

Table 1.
Barriers and strategies to implementing sustainable mosquito control and surveillance systems.

To be sure, some variability is expected, particularly in *mosquito-control* approaches and practices (e.g., in scope, prioritization, technical methods, etc.) given their need to adapt to geographic variation in vector ecology, MBD transmission dynamics, and socio-institutional conditions. However, for surveillance, Bowman et al., [22] also call for "standardized sampling protocols that adequately consider dengue spatial heterogeneity." Research on mosquito-vector sampling and its impacts on the accuracy of human risk assessment remains relatively limited [17, 18]. Some common mosquito indices are sensitive to sampling differences [18] and others are poorly statistically correlated to the actual risk of disease [17], compounding negative impacts of such inconsistencies. Efforts by the CDC to provide generic guidelines in the USA [13] and the World Health Organization (WHO) to do the same globally [19], and other isolated studies offer a starting point for standardization. One study in Cairns, Australia recommended a sampling intensity of one BG-Sentinel trap for an area of 150 by 150 m (two or three traps for three housing blocks) to monitor *Aedes aegypti,* given the limited spatial dispersal (as little as 78–200 m in some studies) of this container-breeding species [18]. Modern spatially explicit technologies, particularly remote sensing analysis and Geographic Information Systems (GIS), expand the sets of tools for mosquito surveillance at landscape scales. Thus, the Random sampling of trapping locations for *Aedes aegypti* in urban areas based on Geographic Information Systems and satellite imagery has been shown to improve the accuracy of entomological indices compared to those derived through the common biased method of selecting locations or houses that are known to have high vector densities [20].

There are also promising technological advances in mosquito control, including the introduction of biological control and low-cost, eco-friendly pesticides mosquito vectors and safeguard the environment and the public [19]. Recent (November 2016) FDA approval of field trials involving the release of genetically modified (GM) mosquitoes into the wild to control ZIKV and Zengue-carrying mosquitoes for in the Florida Keys, Florida, could increase the number of successful cases of biological control using GMO mosquitoes beyond Brazil and China. Non-GM mosquitoes infected with naturally occurring Wolbachia bacteria also offer early promise as a biological pesticide and have been field-tested in at least three US states against *Aedes albopictus*, and in Clovis city, Fresco County, California (2016) against male *Aedes aegypti* mosquitoes [21]. Gene editing using the CRISPR-Cas9 system facilitates the genetic engineering of mosquitoes to make them infertile or repel pathogens [22]. The use of organic or green-synthesized pesticides is also advancing the quest for inexpensive, nontoxic and eco-friendly methods for killing particular species of mosquitoes or their larvae and pupae. Examples include the use of green-synthesized pesticides, such as silver nanoparticles (AgNP) produced from seaweed (*Hypnea musciformis*) to kill the larvae and pupae of the vector *Aedes aegypti* alone [23] or in combination with mosquito-predator Asian bulldog tadpoles [24]. Other plants have also been tested, such as *Zornia diphylla* leaves against *Anopheles subpictus,* the dengue vector *Aedes albopictus* and the Japanese encephalitis vector Culex tritaeniorhynchus [25] (and the shoofly plant, *Nicandra physalodes, as a botanical* larvicidal *extract to control Anopheles stephensi*, *Aedes aegypti* (dengue vector), and *Culex quinquefasciatus* (filariasis vector) [26]. Although many of these technological advances are still some years before they can be approved for field application [19], more operational or implementation research is needed to further demonstrate their effectiveness in both mosquito control and cost under particularly settings, in order to accelerate their approval and wider use.

Our findings show that the low hanging fruit in improved mosquito-vector surveillance and control lie in improving the institutional capacity of the relevant mosquito-control agencies at local, county, state, and federal scales, and building/strengthening creative partnerships among researchers, mosquito-control Experts and jurisdictions, local communities, schools, and the public at large. Benefits of partnerships fell into four categories: (1) sharing resources and reducing operational costs; (2) reducing apathy and enhancing individual responsibility in household mosquito-control efforts, particularly through person-to-person contact (including citizen science in mosquito trapping and other data collection); (3) strengthening community support to enhance political will and support for more and stable funding; and (4) more effective and sustainable mosquito control across service boundaries. In addition, more effective public education strategies were also crucial, including those involving human contact and the use of volunteers and students in data collection and other mosquito-surveillance tasks under the label of citizen science.

4. Conclusion

While some of the barriers identified in this study are consistent with those identified previously, for instance in regard to WNV outbreaks, their persistence is worrisome. These inadequate surveillance and insufficient, reactive funding that prioritizes responses to the disease *du jour,* and vacillating political will First, funding barriers were acutely import for municipal, county and state mosquito programs. Independent and dependent taxing mosquito districts reported better funding and smoother operations. Second, continuity of funding emerged critical for effective IVM. Disruptions in funding interrupted critical surveillance or control efforts and institutional arrangements and partnerships that take time to build and are hard to replace and restart, threatening the capacity of programs to detect, prevent and control MBD outbreaks.

Another emerging challenge from Experts' perspectives was relatively high variability in *mosquito-surveillance* methods and practices, insufficient standardization and quality control. The lack of standardization can undermine the reliability of entomological indices of mosquito presence or abundance and thresholds derived from the disparate surveillance methods, and assessments of MBD transmission, and ensuing responses. In particular, disparities in practice on mosquito-vector sampling (method, size and representativeness) was a concern because its impacts on common mosquito indices and ultimately on the accuracy of human risk assessment was understudied and often unknown. A degree of standardization is needed to enhance scientific rigor and consistency in mosquito surveillance over space and time. Modern spatially explicit technologies particularly remote sensing analysis and GIS offer promising tools for sampling standardization and surveillance across scales.

Findings also revealed instances of, and further need for, creativity and accommodation among mosquito-control Experts under resource-strained conditions and competing interests that can provide insights for further research and development of best practice for particular settings. Examples include cost-effective and methodologically sound mosquito sampling and MBD risk assessments, adjusting the timing or spatial targeting of insecticide application to meet methodological and special-interest needs (e.g., to minimize harm to bees and maintain good relations with beekeepers); or skipping of particular houses whose owners do not want truck-fogging. Findings further revealed the need to determine the minimum set of surveillance services needed given the tight funding conditions of state, county and municipal programs.

Building effective partnerships among public, private and academic/research institutions, local communities and schools emerged as an important strategy among most mosquito-control Experts. An outstanding challenge was finding effective ways to address opposition to the use of pesticides in mosquito control among local communities. Creative and sustained methods to educate the public on the dangers and benefits of MBD and mosquitos are also needed.

Looking ahead, perspectives of Experts from this exploratory study reveal that increased and reliable funding is a priority to mitigate many of the barriers, ensure effective surveillance and early detection and prevention of MBD transmission at municipal, county or local, and state levels. Recent new funding for responding to the 2016/16 ZIKV outbreak and for research by the US Congress and the CDC at federal level, as well as at state level for at-risk states such as Florida, are promising developments. However, the long-term value lies in their ability to enhance the capacity, cost-effectiveness, and sustainability of programs at multiple scales.

Further introduction into integrated pest management approaches of biological control and low-cost, eco-friendly pesticides hold considerable promise for the mosquitoes and MBD control in the near future while safeguarding the environment and public health broadly. Examples include the release of genetically modified (GM) mosquitoes into the wild to control ZIKV and Dengue-carrying mosquitoes under FDA-approved field-testing in the Florida Keys, Florida, USA. Non-GM mosquitoes infected with naturally occurring *Wolbachia* bacteria also offer early promise as a biological pesticide (in at least three US states) against *Aedes albopictus and Aedes aegypti*. Research is also advancing on organic or green-synthesized pesticides as inexpensive, nontoxic and eco-friendly methods for killing particular species of mosquitoes or their larvae and pupae.

While this study exploratory, qualitative study of is not meant to be statistically representative or generalizable to the entire U.S. of all settings, it offers a wide range of perspectives and insights from mosquito-control Experts on issues including the nature and range of barriers and opportunities for mosquito-vector control in Continental United States. More detailed empirical analysis in selected states, which have had recent outbreaks or are at high risk of ZIKV, such as Florida, Texas and Louisiana, is the next step in terms of research.

Acknowledgements

We thank all the 35 mosquito Experts who participated in the interviews and the research assistants who helped interview them. This publication was supported by Cooperative Agreement Number U01CK000510, funded by the Centers for Disease Control and Prevention. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the Centers for Disease Control and Prevention or the Department of Health and Human Services.

Conflict of interest

The authors declare no conflict of interest.

Abbreviations

AgNP	silver nanoparticles
CDC	Centers for Disease Control
DEQ	Department of Environmental Quality
EPA	Environmental Protection Agency
FDA	Food and Drug Administration
FMCA	Florida Mosquito Control Association
GIS	geographic information system
GM	genetically modified
GMO	genetically modified organism
IVM	integrated vector management
MBD	mosquito-borne diseases
WHO	World Health Organization
WNV	West Nile virus
ZIKV	Zika virus

Author details

Imelda K. Moise[1,3]*, Leo C. Zulu[2], Douglas O. Fuller[1] and John C. Beier[3]

1 Department of Geography and Regional Studies, College of Arts and Sciences, University of Miami, USA

2 Department of Geography, Environment and Spatial Sciences, Michigan State University, USA

3 Department of Public Health Sciences, Miller School of Medicine, University of Miami, USA

*Address all correspondence to: moise@miami.edu

References

[1] Hanem FK. Introductory chapter: Back to the future—Solutions for parasitic problems as old as the pyramids, natural remedies in the fight against parasites. In: Khater DH, editor. Natural Remedies in the Fight Against Parasites. Rijeka, Croatia: InTech; 2017

[2] Slutsker L, Kachur SP. It is time to rethink tactics in the fight against malaria. Malaria Journal. 2013;**12**:140. DOI: 10.1186/1475-2875-12-140

[3] Cauchemez S, Ledrans M, Poletto C, Quenel P, de Valk H, Colizza V, et al. Local and regional spread of chikungunya fever in the Americas. Euro Surveillance. 2014;**19**:20854

[4] Fauci AS, Morens DM. Zika virus in the Americas—Yet another arbovirus threat. New England Journal of Medicine. 2016;**374**:601-604

[5] Hemingway J. The role of vector control in stopping the transmission of malaria: Threats and opportunities. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences. 2014;**369**:20130431

[6] McKenna M. Disorganized mosquito control will make US vulnerable to Zika. Germination. 2016. Available from: http://phenomena.nationalgeographic.com/2016/02/29/zika-mosquito-control/

[7] ASTHO. Public Health Confronts the Mosquito: Developing Sustainable State and Local Mosquito Control Programs. Washington, DC: ASTHO; 2005

[8] Vazquez-Prokopec GM, Chaves LF, Ritchie SA, Davis J, Kitron U. Unforeseen costs of cutting mosquito surveillance budgets. PLoS Neglected Tropical Diseases. 2010;**4**:e858

[9] STAT. Congress Approves $1.1 Billion in Zika Funding. 2016

[10] Couzin-Frankel J. Infectious diseases. Fears of lax surveillance if CDC program cut. Science. 2010;**328**:1088

[11] Hadler JL, Patel D, Nasci RS, Petersen LR, Hughes JM, Bradley K, et al. Assessment of arbovirus surveillance 13 years after introduction of West Nile virus, United States. Emerging Infectious Diseases. 2015;**21**:1159-1166

[12] Hadler JL, Patel D, Bradley K, Hughes JM, Blackmore C, Etkind P, et al. National capacity for surveillance, prevention, and control of West Nile virus and other arbovirus infections—United States, 2004 and 2012. MMWR. Morbidity and Mortality Weekly Report. 2014;**63**:281-284

[13] Shanker D. Zika Is here, and America has no plan to fight it. Bloomberg. 2016

[14] CDC. Surveillance and Control of *Aedes aegypti* and *Aedes albopictus* in the United States. 2016. Available from: http://www.cdc.gov/chikungunya/resources/vector-control.html

[15] Berkelman RL, Bryan RT, Osterholm MT, LeDuc JW, Hughes JM. Infectious disease surveillance: A crumbling foundation. Science. 1994;**264**:368-370

[16] Yoo E, Chen D, Russel C. West Nile Virus Mosquito Abundance Modeling Using Nonstationary Spatiotemporal Geostatistics. In: Chen D, Moulin B, Wu J, editors. Analyzing and Modeling Spatial and Temporal Dynamics of Infectious Diseases. 2015. DOI: 10.1002/9781118630013.ch14

[17] Bowman LR, Donegan S, McCall PJ. Is dengue vector control deficient in effectiveness or evidence? Systematic review and meta-analysis.

PLoS Neglected Tropical Diseases. 2016;**10**:e0004551

[18] Azil AH, Bruce D, Williams CR. Determining the spatial autocorrelation of dengue vector populations: Influences of mosquito sampling method, covariables, and vector control. Journal of Vector Ecology. 2014;**39**:153-163

[19] Fernandes JN, Moise IK, Maranto GL, Beier JC. Revamping mosquito-borne disease control to tackle future threats. Trends in Parasitology. 2018: S1471-4922(18)30008-4 DOI: 10.1016/j.pt.2018.01.005

[20] Troyo A, Fuller DO, Calderón-Arguedas O, Beier JC. A geographical sampling method for surveys of mosquito larvae in an urban area using high-resolution satellite imagery. Journal of Vector Ecology. 2008;**33**:1-7

[21] Zhang S. A California city is fending off Zika by releasing 40,000 mosquitoes every week. Science. 2016

[22] Hammond A, Galizi R, Kyrou K, Simoni A, Siniscalchi C, Katsanos D, et al. A CRISPR-Cas9 gene drive system targeting female reproduction in the malaria mosquito vector *Anopheles gambiae*. Nature Biotechnology. 2015;**34**:78

[23] Roni M, Murugan K, Panneerselvam C, Subramaniam J, Nicoletti M, Madhiyazhagan P, et al. Characterization and biotoxicity of *Hypnea musciformis*-synthesized silver nanoparticles as potential eco-friendly control tool against *Aedes aegypti* and *Plutella xylostella*. Ecotoxicology and Environmental Safety. 2015;**121**:31-38

[24] Murugan K, Priyanka V, Dinesh D, Madhiyazhagan P, Panneerselvam C, Subramaniam J, et al. Predation by Asian bullfrog tadpoles, *Hoplobatrachus tigerinus*, against the dengue vector, *Aedes aegypti*, in an aquatic environment treated with mosquitocidal nanoparticles. Parasitology Research. 2015;**114**(10):3601

[25] Govindarajan M, Rajeswary M, Muthukumaran U, Hoti SL, Khater HF, Benelli G. Single-step biosynthesis and characterization of silver nanoparticles using *Zornia diphylla* leaves: A potent eco-friendly tool against malaria and arbovirus vectors. Journal of Photochemistry and Photobiology B: Biology. 2016;**161**:482-489

[26] Govindarajan M, Khater HF, Panneerselvam C, Benelli G. One-pot fabrication of silver nanocrystals using *Nicandra physalodes*: A novel route for mosquito vector control with moderate toxicity on non-target water bugs. Research in Veterinary Science. 2016;**107**:95-101