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New Cost-Benefit of Brazilian Technology for Vector Surveillance Using Trapping System

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Abstract

The recent introduction of chikungunya and Zika virus and their subsequent dispersion in the Americas have encouraged the use of novel technologies for adult *Aedes* surveillance to improve vector control. In Brazil, two platforms for surveillance of eggs and gravid *Aedes aegypti* have been developed. First, it consists of using data of sampling of eggs in ovitraps associated with GIS technologies to monitor *Aedes* spp. populations. Although effective, it is not realistic to use in a large-scale epidemic scenario as it requires a large amount of human resources for field and laboratory activities. Second, it consists of trapping female *Ae. aegypti* citywide at fine spatial and temporal scales for vector surveillance (MI-*Aedes*) to detect high *Aedes* infestation areas using a GIS environment and the identification of arbovirus-infected trapped mosquitoes by RT-PCR (MI-Virus platforms). Such integration of continuous vector surveillance and targeting vector control in hotspot areas is cost-effective (less than US\$ 1.00/person/year), and it has been shown to reduce mosquito population and prevent dengue transmission. The main advantage of the MI-*Aedes* platform over traditional mosquito surveillance is the integration of continuous vector monitoring coupled with an information technology platform for near real-time data collection, analysis, and decision-making. The technologies also provide data to model the role of climate on the vector population dynamics.

Keywords: surveillance, vector control, novel technologies, adult trap, MI-*Aedes*, MI-Virus

1. Introduction

The public health impact of arthropod-borne viruses (arboviruses) has increased dramatically over the last 50 years with diseases such dengue and chikungunya spreading to new geographic locations and increasing in incidence [1]. Most of the known arboviruses were initially isolated in tropical areas such as Africa, South America, and some Asian countries [2]. In fact, many of the diseases transmitted by arthropods encountered today not only existed but were widespread in their distribution before written records began and are among the major causes of illness and death in many countries. In recent years, and despite efforts to control vectors, the prevalence of viral infections transmitted by arthropods worldwide has increased. However, changes in viral genetics, host, and vector population as well

as the global climate facilitated, among other factors, the expansion and spread of arboviruses in the world. The expansion of global human population, migratory movements of people and animals, and rapid disordered urbanization led to a closer contact between man and animal reservoirs, thereby increasing exposure to infection with arboviruses [2].

Various arboviruses including the important public health concern dengue virus (DENV) [3], yellow fever virus [4], chikungunya virus (CHIKV) [5], and Zika virus (ZIKV) [6] have *Aedes aegypti* (**Figure 1**) and *Aedes albopictus* as vectors. The most prevalent human arboviral infection is caused by DENV that accounts for approximately 100 million annual infections worldwide with almost half of the world's population at risk of infection [7, 8]. Since CHIKV was firstly detected in the Americas in December 2013, it has caused more than 1.7 million of confirmed or suspected cases. At least 48 countries and territories of the Americas confirmed the autochthonous circulation of ZIKV [9].

Historically, surveillance of vectors that transmit arboviruses was focused on immature stages (eggs, larvae, and pupae) with little emphasis given to the adult mosquito. The oviposition trap (ovitrap) developed in the 1960s [10] is still being used to detect *Aedes* spp., especially when vector population is low (**Figure 2a**). However, surveillance of adult female population is necessary to evaluate the impact of vector control interventions, to detect arboviruses, and to look for insecticide resistance alleles. Interventions that also require surveillance of adult mosquito population include evaluations on the efficacy of insecticide-treated materials, the release of sterile or genetically modified insects, and the dispersion of spatial repellents.

In light of the requirements listed above, various traps have been developed to monitor the populations of *Aedes* spp. and other arthropods by sampling eggs and host-seeking or gravid females. Traps devised to catch adult *Ae. aegypti* are divided into two major classes: active and passive. Passive traps are low cost and capture gravid *Ae. aegypti* without electricity using funnels, sticky cards, or insecticides. In these traps, water or an infusion of hay is used to attract the insects. Examples of sticky traps for adult vectors are MosquiTRAP, Gravid *Aedes* Trap (GAT), and Autocidal Gravid Ovitrap (CDC-AGO) (**Figure 2b–d**) [11]. The catch rates of passive traps depend on factors such as size, color, and type of attractant, among others. In contrast, active traps use an electrical device—for instance, a battery-operated fan that sucks the insects into the trap. BG-Sentinel (**Figure 2e**) is an example of active trap used to capture adult mosquitoes.

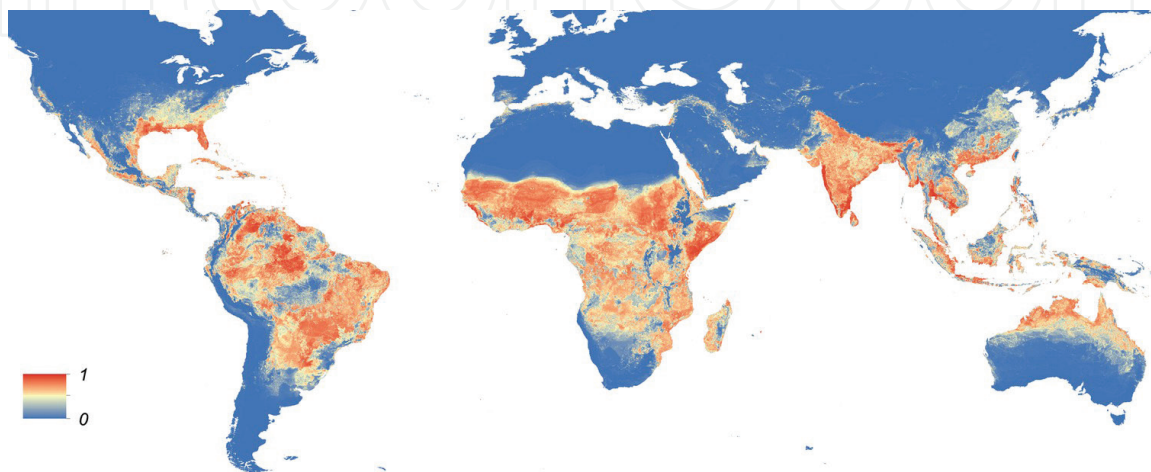


Figure 1. Global map of forecasted probability of occurrence of *Aedes aegypti* at a spatial resolution of 5×5 km (Kraemer et al. [1], <https://doi.org/10.7554/eLife.08347.004>).



Figure 2.
 Passive mosquito traps used for surveillance: (a) ovitrap, (b) MosquiTRAP, (c) *Aedes Gravid Traps* (GAT), (d) *Autocidal Gravid Ovitrap* (CDC-AGO), and (e) the active trap BG-Sentinel.

Health authorities are increasingly employing new technologies in order to achieve integrated *Aedes* management. In this context, predictive mathematical modeling has the potential to help authorities to act preemptively by rapidly preparing vector alerts and mobilizing the resources needed for an integrated vector management whenever an imminent surge of mosquitoes and, therefore, a higher risk of infection with arboviruses are likely to take place. Also, by assessing the data collected by surveillance traps for adult mosquitoes using spatial statistics, it is possible to present data correlating the infestation index with other variables such as the vector control method used, epidemiological data, virus-infected mosquito data, and climatic data, among others [12]. The automated presentation of the results obtained directly from the field allows the integrated analysis of entomological data with geographic information system (GIS), thereby enabling the deliverance of immediate vector control responses to the precise localities presenting the highest levels of mosquito infestation.

Climate is an important factor in the geographic and temporal distribution of arthropods. It is also relevant for the patterns of dispersion and efficiency in the transmission of arboviruses by arthropods to their hosts [13]. Considering the perspectives regarding global climate changes, it is likely that arboviruses will continue to colonize new regions of the planet. Thus, research regarding the role of climate in the population dynamics of vectors and predictions of future scenarios depend on the ability of climate-based models to describe associations with arboviruses. Monitoring the effect of climatic variations on vector surveillance and control can be achieved by technological platforms with adequate space-time resolution.

This chapter presents two study cases of vector surveillance by sampling egg and adult *Aedes* spp. mosquitoes in Brazilian municipalities. It also provides a comprehensive description of innovative web platforms that process, in near real time, data regarding adult vector abundance and arbovirus identification from mosquitoes caught in sticky traps strategically positioned in urban areas. The information gathered can be used to rapidly activate vector control actions making these platforms successful and cost-effective tools to deal with arboviral disease threats by public health authorities.

2. Gravid mosquito traps

The ovitrap has been used for many decades as a sensitive, inexpensive, passive surveillance tool for detecting the presence of gravid mosquitoes [10, 14]. The addition of a larvicide or autocidal mechanism allows long-term use of ovitraps with minimal risk of the device becoming a productive source of adult mosquitoes [15]. In spite of these positive attributes, ovitraps only provide information on the number of collected eggs and cannot produce accurate information about the

number of gravid *Aedes* mosquitoes. This is because a single female can lay different numbers of eggs in a single ovitrap [16], and therefore, information on the presence of eggs alone does not produce enough information about the levels of infestation of a particular area. Another shortcoming of the ovitrap is that it requires laboratory logistics for egg counting, hatching, and identification of the larvae. Consequently, information about the vector population is delayed by at least 1 or 2 weeks [17].

Ovitrap can be modified to collect gravid females by incorporating an adhesive capture surface (sticky ovitraps). Adult female mosquitoes collected in sticky ovitraps provide a direct measure of adult abundance, and those can also be morphologically identified in the field and processed to detect arboviruses [18, 19]. Sampling with sticky ovitraps is a more sensitive method to detect and estimate adult mosquitoes in comparison with sampling of immatures [20–22].

A major advantage of using sticky traps is that the captured mosquitoes can be readily identified in the field at the time of trap inspection. This avoids the need for additional specialized human labor and the delay imposed when samples have to be delivered to laboratories to identify the mosquito [20]. The abundance of adult mosquitoes was successfully estimated in three areas of Rio de Janeiro, Brazil, by using sticky traps [23]. Obviously, these kinds of field-ready results are only possible if field agents are well-trained to identify the mosquito species of *Ae. aegypti*. Indeed, well-trained agents have been shown to accurately (95–100%) identify *Ae. aegypti* captured using the sticky trap MosquiTRAP [24]. However, a later study found that mosquito identification in the laboratory was superior to that performed in locus by trained field agents [25]; divergent results presented by these studies may be due to differences in the way the field agents were trained and qualified.

Several sticky trap models have been developed to capture gravid *Ae. aegypti* in Brazil [20, 26], Australia [18], Italy [27], Porto Rico [28], and Malaysia [29]. All rely on a combination of visual and olfactory stimuli for the oviposition behavior of gravid *Aedes* spp. Typically, a sticky trap consists of a black matte plastic container of any size, an entrance port, water, an oviposition attractant, and a sticky card using an odorless entomological glue to retain the gravid mosquito. Once stuck, the mosquito remains in resting position. Those that escape usually lose one or more legs remain adhered to the sticky card. Identification of collected mosquitoes is still possible with their thoraces since they usually remain somewhat visible [18, 20]. Sticky traps do not require electricity or batteries and are, therefore, low-cost devices.

The oviposition attractants include infusions of organic materials such as hay [15], grass infusions [30], or synthetic lures [31]. The chemical composition of synthetic oviposition attractants was derived from research that identified volatiles of grass infusions that were behaviorally active in laboratory, semi-field, and field studies. The synthetic oviposition attractant Atr*Aedes*TM used in the MosquiTRAP consists of a mixture of nonanal, decanal, and 3-methylphenol, which is released from a sealed-tube reservoir system for approximately 45 days at a constant rate to continually attract the target species [31]. The main advantage of using synthetic attractants is that the synthetic lure has a constant attractiveness over time and has a pleasant smell, whereas grass infusions need to be transported and rest for 5–7 days to be active and are smelly.

The place where the sticky trap is positioned in the investigated premises is important to increase the mosquito catch rate. Studies in Brazil revealed that when the sticky trap MosquiTRAP was placed outdoor, it captured five times more females than indoor traps [26]. This is probably because host-seeking *Ae. aegypti* feed on human blood indoors but lay eggs outdoors after a few days of digesting

the blood meal. Moreover, outdoor traps allow vector control workers to sample the mosquitoes without inconveniencing homeowners and are notably well-accepted by local communities [17, 18, 27, 32].

The potential of the MosquiTRAP for trapping gravid *Ae. aegypti* has been compared with the Nasci aspirator [33] and backpack aspirator [34]. Sticky traps collected a higher number of mosquitoes and are more cost-effective and operationally easier, besides being less inconvenient to householders than active traps. MosquiTRAP has been also compared with BG-Sentinel trap and Adultrap and ovitrap with favorable results [35].

Altogether, sticky traps are perhaps the most appropriate tools for *Ae. aegypti* surveillance and the development of new entomological indices for the detection of epidemic outbreaks in urban areas. Interestingly, a study comparing the ability to detect *Ae. aegypti* by the different surveillance methods (larval survey, ovitrap, and the sticky trap MosquiTRAP) showed that ovitrap and the sticky trap predicted dengue occurrence better than larval survey, both spatially and temporally. However, ovitrap clusters showed less accuracy in pinpointing the dengue risk areas, and the sticky trap presented better results for signaling dengue transmission risk both geographically and temporally (Figure 3) [36].

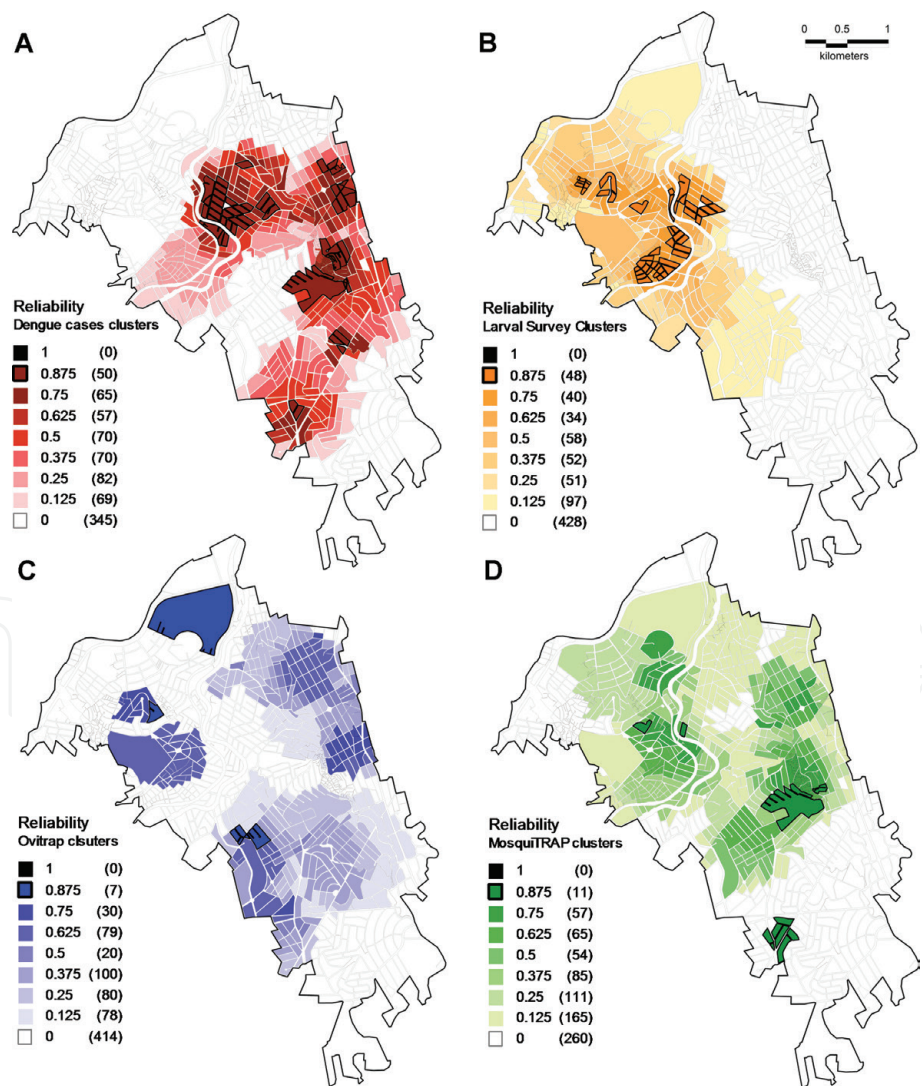


Figure 3. Cluster reliability maps of (A) dengue cases, (B) larval survey, (C) ovitrap, and (D) MosquiTRAP catches in Belo Horizonte (Minas Gerais, Brazil) from January 2007 to June 2008. Darker colors represent higher reliability values (Belo Horizonte city, Minas Gerais State, Brazil, Adapted from De Melo et al. [36]).

3. Use of geographic information system (GIS) for vector surveillance

GIS is a powerful automated system for the capture, storage, retrieval, analysis, and display of spatial data that offer expanding opportunities for epidemiology because it allows a spatial perspective on a disease. The integration of vector surveillance with the mosquito traps and georeferencing technologies has emerged as an important tool for fighting *Ae. aegypti* and transmission of arboviruses [31, 37, 38].

By georeferencing the ovitrap and sticky traps, the egg collection and adult catching data obtained during *Ae. aegypti* surveillance was used to generate maps that show the areas of high and low infestation [31, 39–42]. This information provides real-time data and allows spatial analyses to determine vector control actions and to evaluate their impact on mosquito populations and infection with arboviruses [31, 39, 43]. The continuous surveillance of *Aedes* population allied with mathematical modeling strategies (described below) allows reliable predictions of infestation, as shown in Brazil [12].

4. Brazilian case studies

Two types of traps associated with georeferencing systems were developed and evaluated continuously in Brazil: (1) ovitraps associated with the surveillance platform MSCP-*Aedes* (Monitoring System and Population Control for urban *Aedes*) and (2) sticky traps for gravid *Aedes* mosquitoes associated with a real-time, large-scale surveillance system known as MI-*Aedes* platform (from Portuguese “Monitoramento Integrado do *Aedes*”). Both systems will be described below, with emphasis on the adult trapping technology—MI-*Aedes*—since it has been used in the last 13 years in hundreds of Brazilian cities.

4.1 Monitoring system and population control for urban *Aedes* (MSCP-*Aedes*)

The MSCP-*Aedes* platform was developed by the National Institute for Space Research (INPE) and Research Center Aggeu Magalhães (CPqAM), Oswaldo Cruz Foundation (Fiocruz), located in Recife city, Pernambuco State, Brazil. The potential of ovitraps in reducing the population of *Aedes* spp. was evaluated for 1 year (April 2014–April 2015), during all seasons of the year (summer, autumn, winter, and spring), by the deployment of 464 georeferenced traps in five areas of Recife, the capital city of the state of Pernambuco, located in northeastern Brazil. Thirteen egg collection cycles were performed with 98.5% of the ovitraps being positive for *Aedes* eggs. At the end of the study, more than 4 million eggs were collected from the environment, and the *Ae. aegypti* population in one of the five localities evaluated was significantly reduced. The platform provided information on the spatial-temporal distribution of *Aedes* spp. eggs. Using this data, maps generated within a GIS environment helped the health authorities to prioritize the city areas in most need of vector control actions [40] (**Figure 4**).

Another pilot trial of the MSCP-*Aedes* system was carried out from March 2008 to October 2011 in two other cities of Pernambuco State, Brazil: Ipojuca and Santa Cruz [37]. After the first 2 years of evaluation, a significant decrease in the density of eggs was observed in both cities showing the potential of the MSCP-*Aedes* platform associated with the vector control actions conducted by the health authorities to reduce mosquito abundance (**Figure 5**). However, the MSCP-*Aedes* platform required a great number of people to accomplish the field and laboratory activities, which is not realistic to use in a large-scale scenario.

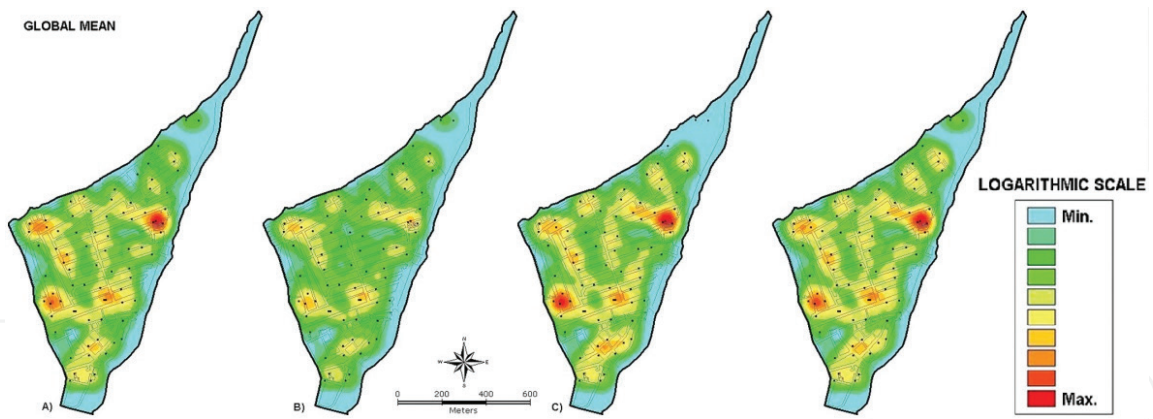


Figure 4. Spatial distribution of *Aedes* spp. eggs in Brasília Teimosa (Recife, Pernambuco State, Brazil), in June–July 2004 (A), December 2004 (B), and March 2005 (C). Green, low infestation; yellow, intermediate infestation; red, high infestation. The map at the right shows the mean number of eggs for the whole period (April 2004 to April 2005). Adapted from Regis et al. [40].

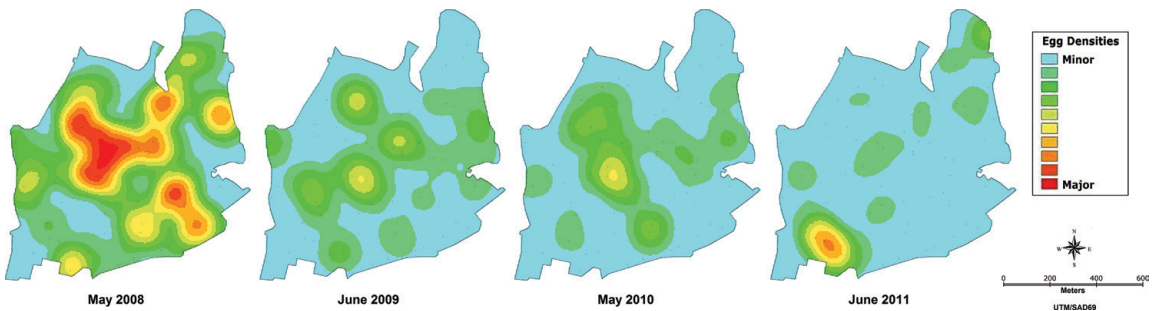


Figure 5. Spatial distribution of *Aedes* eggs at the high-density period (May–June) in Ipojuca (Recife, Brazil), Pernambuco State, 2008–2011. The mass suppression of eggs using 2700 control ovitraps started in October 2009 (Adapted from Regis et al. [37]).

4.2 Integrated *Aedes* surveillance system (MI-*Aedes*)

The innovative MI-*Aedes* platform was developed in Brazil by a university-company partnership between the Federal University of Minas Gerais and the university’s “spin-off” Ecovec, in Belo Horizonte, Minas Gerais State. University-Company partnerships have been stimulated by the Brazilian Innovation Law, which aims to foster the generation of innovations and dissemination of new technologies aiming to solve national (and international) problems [44, 45]. The World Health Organization has praised this new technology for the surveillance and generation of entomological indices [46]. More details about the platform are given below.

The MI-*Aedes* platform consists of (a) the sticky trap MosquiTRAP (baited with a *AtrAedes* to generate mosquito abundance indices), which is placed within blocks of urban areas 250 m equidistant from each other and inspected weekly, (b) the recording of entomological data on electronic spreadsheets or by cell phone during trap inspection, and (c) an Internet site that integrates real-time adult mosquito surveillance data and GIS technology to provide entomological indices [12, 31, 36, 38, 41, 47, 48] (Figure 6).

The information used for vector control relies on (1) weekly surveillance of gravid *Ae. aegypti* infestation of the municipality street blocks, (2) re-infestation surveillance of the monitored blocks, (3) identification of hotspot areas, and (4) production of entomological indices.

The MI-*Aedes* Web-data system consists of three integrated software developed to simplify information gathering and processing: (a) the “geo-mosquito

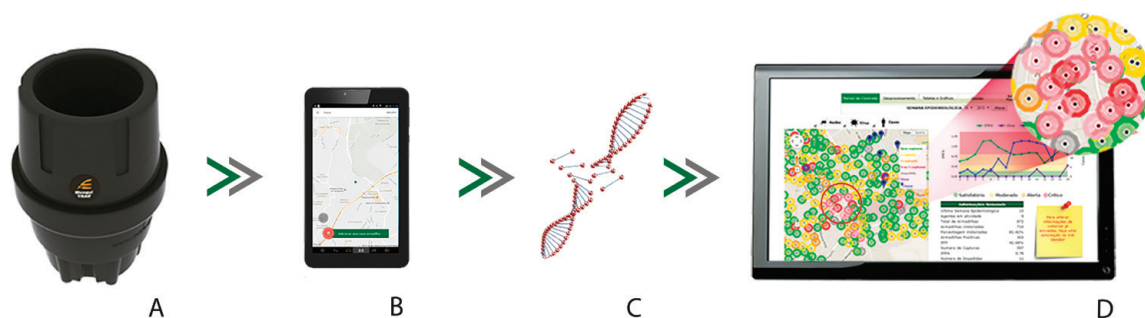


Figure 6.

The MI-Aedes platform consists of (A) sticky trap (MosquiTRAP), (B) cell phone for sampling GIS mosquito data, (C) MI-Virus (optional—see text for detail), and (D) Internet georeferenced maps at real time that produces automatic data for entomological indices.

collection,” which is installed in portable devices (e.g., cell phones) to record household information, placement of the trap within the residence, and *Ae. aegypti* field capture data; (b) the “monitoring,” which processes the field data to produce tables with entomological indices and graphs showing trends; and (c) the “geo-Aedes,” which produces georeferenced maps of mosquitoes captured with the sticky MosquiTRAP and makes them available to users on the Internet on a weekly basis.

There are several advantages of using electronic spreadsheets or mobile phone over conventional data acquisition systems. The field data can be accessed immediately (premises visited and scheduled for visits, trap locations, residents’ names, and so on), and the entomological indices can be produced automatically. Also, there is no delay between the data that is reported to the database and the database that is available for web mapping and public health access.

The MI-Aedes platform was evaluated in hundreds of Brazilian cities for more than 10 years and showed to greatly reduce arbovirus transmission [41]. The georeferenced maps presented weekly on the Internet by the MI-Aedes platform allowed health managers to identify the infestation status of city blocks by the colors green, yellow, orange, and red, according to the number of adult *Ae. aegypti* females captured (**Figure 7**). The weekly data evaluating vector infestation levels became an important information for dengue control programs because it helped public health managers to optimize *Ae. aegypti* control activities with improved precision of the target activities to the infested blocks. Indeed, a study analyzing three Brazilian municipalities revealed that following implementation of the MI-Aedes platform, the weekly vector control indicator established by the entomological “mean female *Aedes* index” (MFAI) was reduced (**Figure 7**) and so was the number of dengue cases [31]. Further research showed how the health authorities used the platform to evaluate the performance of the control measures employed by them within the area covered by the MI-Aedes [12, 41].

4.2.1 Virus detection of trapped gravid *Aedes* spp. collected by the sticky trap MosquiTRAP

The detection of gravid mosquitoes infected with arboviruses such as DENV, CHIKV, and ZIKV is an important information for public health managers looking to control *Ae. aegypti* infestation and the spread of arboviral diseases in hotspot areas. The inclusion of a strategy to identify the arbovirus present in infected mosquitoes trapped in the MosquiTRAP into the MI-Aedes platform was intended to provide additional information regarding the spread of arboviruses and serve as an early warning system for epidemics since viral detection in mosquitoes can precede detection in humans. Accordingly, a rapid and well-established method for arbovirus identification [49] was associated with the MI-Aedes platform to create an

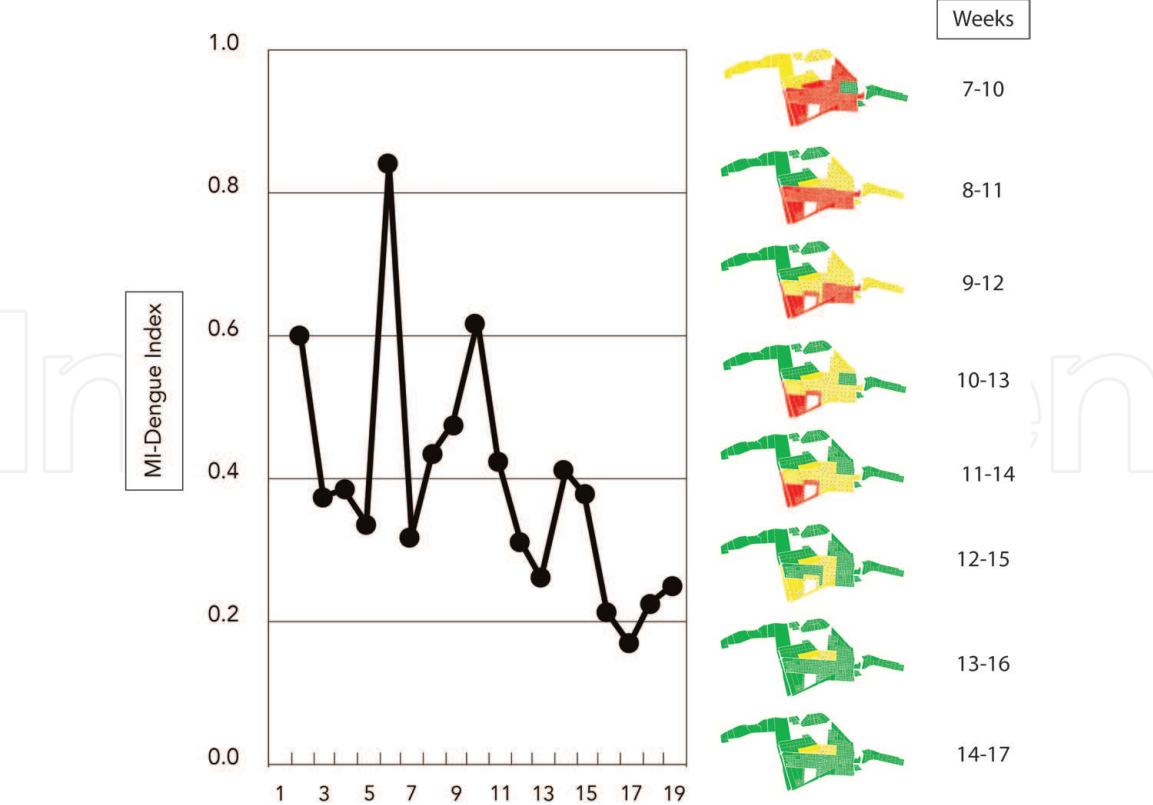


Figure 7. Temporal and spatial analysis of neighborhoods in the municipality of Presidente Epitácio (São Paulo State, Brazil) (2008). Colored maps are classified according to the entomological indices from epidemiological week 7–16 (February–April, summer). In epidemiological weeks 7–10, there were 44 and 55% of neighborhoods classified as “dengue alert” and “critical,” respectively. Weeks 14–17 were 88.9 and 11.1% of the municipality’s territory as “risk-free” and “dengue alert,” respectively, indicating a strong seasonal variation in the *Aedes aegypti* population density that was probably influenced by the climate conditions or targeted control measures. Adapted from Eiras and Resende [31].



Figure 8. Logistic of the Integrated Monitoring Virus (MI-Virus). Weekly, caught female *Aedes aegypti* by MosquiTRAP are place in barcoded Eppendorf tube and send by post to laboratory for RT-PCR analysis. Bar code provides GIS trap position. Source: Ecovec Company, Belo Horizonte, Minas Gerais State, Brazil.

Integrated Monitoring Virus (MI-Virus) platform. The trapped *Ae. aegypti* and *Ae. albopictus* are placed in Eppendorf tubes with guanidine and sent by mail for virus detection and identification by reverse transcriptase RT-PCR (**Figure 8**).

In Brazil, the MI-Virus platform was tested in hundreds of municipalities to detect and map not only *Ae. aegypti* abundance but also the presence of mosquito populations infected with different arboviruses such as DENV, CHIKV, and ZIKV. The use of MosquiTRAP to detect DENV-infected gravid *Ae. aegypti* trapped by was performed in Brazil [41, 50] and Colombia [51]. In In 2017, the MI-*Aedes* and MI-Virus platforms were used during an outbreak of chikungunya in Governador Valadares city, located in the southeastern state of Minas Gerais, Brazil (data not published). The real-time data obtained by the MI-*Aedes* platform and the confirmation of CHIKV by the MI-Virus (**Figure 9**) led the health authorities to act quickly and employ additional vector control activities to target areas with the

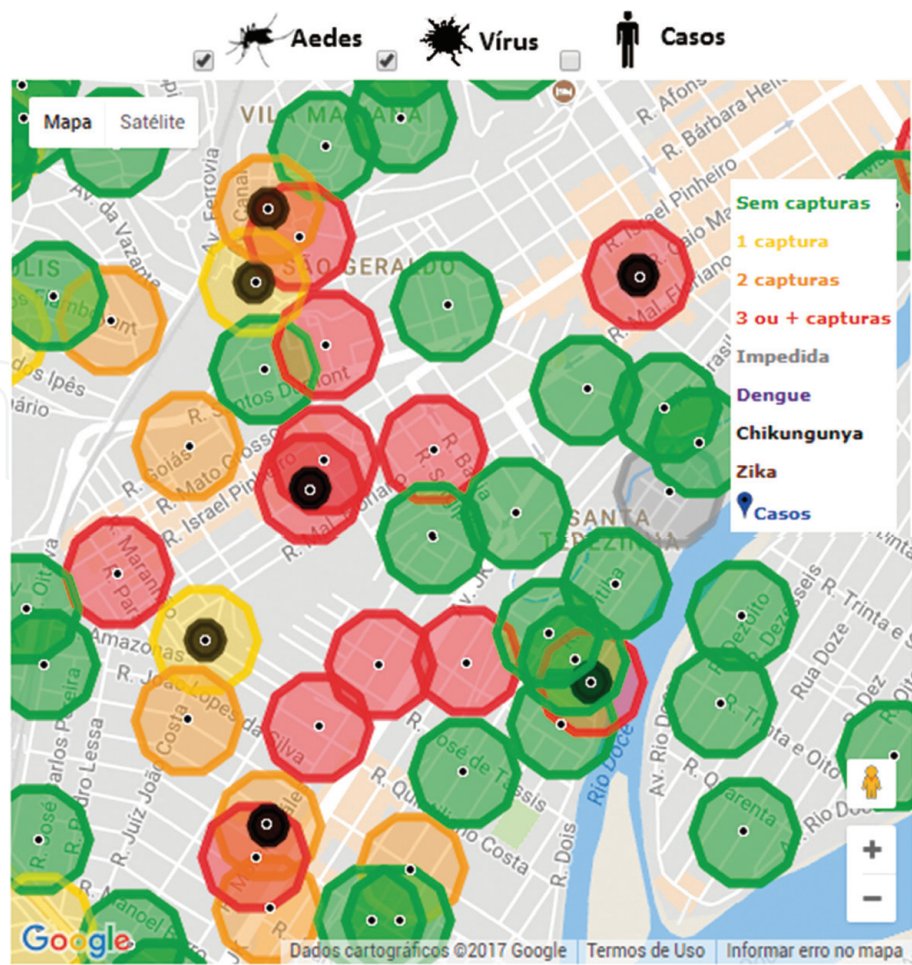


Figure 9. Data obtained by the MI-Aedes platform and MI-Virus deployed in Governador Valadares city, Minas Gerais State, Brazil (epidemiological week 11, March 05–11, 2017). Dark dots at colored circles mean MosquiTRAP (GIS) position. Colored circles mean infestation status of mosquito abundance (see text for further detail). Black circles mean infected *Aedes aegypti* by chikungunya virus captured by MosquiTRAP (data not published). Source: Ecovec company, Belo Horizonte, Minas Gerais State, Brazil.

highest mosquito densities. As a result, abundance of *Ae. aegypti* and chikungunya cases reduced significantly (data not published). Futures studies should be conducted of arbovirus detections in other areas.

4.2.2 Modeling the population dynamics of *Aedes aegypti* using MI-Aedes

Once vector surveillance and control are established as the recommended approach to manage vector-borne diseases, the ecological problem of the population dynamics of mosquitoes arises as a fundamental question [52]. In such context, mathematical modeling has a twofold role: to assist the validation of these novel technologies by providing methods to predict the population dynamics of adult mosquitoes and to offer ways to improve the surveillance indices. As an ecological problem, the infestation by mosquitoes is influenced by many anthropic (everything that results from human action such as sanitation and mosquito breeding container) and non-anthropic variables (temperature and rainfall) [53]. It has been well established that the population dynamics of different stages of *Ae. aegypti* and viral transmission are influenced by environmental variables, especially those of climate: temperature, humidity, and precipitation [54–58]. The vector-virus-human system can generate multiple sources of complexity for modeling. The vector management approach of considering the female population as a risk of infection indicator helps to simplify the modeling efforts, which can decouple the complex

ecological vector-virus-human system and focus on the mosquito population. In addition, the surveillance platform MI-*Aedes* generates a huge amount of sampling data from many localities [12, 59, 60]. These huge data banks provided basis for many modeling studies such as a novel stochastic point process pattern algorithm that identify the spatial and temporal association between DENV-infected mosquitoes and human cases. This process showed a strong and significant association between high DENV incidence in mosquitoes and the onset of symptoms in humans at specific spatial and temporal windows [61]. Also the model goodness-of-fit studies based on the number of sticky traps and suggests a minimum of 16 traps for the MI-*Aedes* at the neighborhood level for mosquito surveillance [62].

Decades of studies regarding the effects of temperature, precipitation, and humidity on vector population and the occurrence of infectious disease cases generated controversial conclusions, suggesting that the phenomenon depends on local specificities, as extensively demonstrated for dengue [54, 63]. Nevertheless, it is well established that temperature affects the physiology of the mosquito and virus and, consequently, is associated with the vector population size and dengue cases [13, 58, 64–66]. Humidity greatly affects the development of vector stages and the number of dengue infections [67, 68]. Although precipitation is strongly correlated with humidity, due to its complex pattern and unpredictable influence in the environment, it figures as the most complex meteorological variable [69]. Notwithstanding, precipitation is a good explanatory variable for dengue cases and mosquito population size [70]. Hence, the construction of models to explain the effects of climatological variables cannot disregard the complete set of these influential variables.

The problem of describing or even predicting a response time series such as disease cases or infestation can be approached with descriptive models, which provide a model time series solution by fitting coefficients and/or functions in accordance with past lagged time series of a set of explanatory variables. Belonging to that class are the regressive models, which have been used for predicting or describing the number of dengue cases or the degree of adult *Ae. aegypti* infestation [12, 56, 59, 71]. Through a descriptive model, time series of temperature, precipitation, wind velocity, and humidity were analyzed as explanatory variables for the adult mosquito abundance index MFAI in the subhumid tropical climate of the city of Governador Valadares, Brazil [59]. In the study, generalized linear models (GLM) with time lags and interaction terms between explanatory variables were used to identify the following significant associations: interaction between lagged temperature and humidity with the mosquito abundance data obtained on the previous week. Transient associations were mapped in a periodogram using wavelets and revealed significant effects for precipitation and wind velocity. Interestingly, the wavelet technique identified non-stationary effects on the relationship between meteorological variables and infestation.

Another study using descriptive models was conducted in the city of Porto Alegre, located in a humid subtropical region of southern Brazil. It used data derived from monitoring the *Ae. aegypti* adult female population in the course of MI-Dengue (nowadays, MI-*Aedes*) surveillance platform [12]. As described above, the platform employs sticky traps to capture adult *Ae. aegypti* females to provide a weekly infestation index. To predict mosquito abundance in subsequent weeks, time series data from previous weeks regarding the maximum, minimum, and mean temperature, precipitation, humidity, and mosquito abundance were fitted in a set of proposed models using generalized additive models (GAM). The best power of prediction was achieved when previous values of minimum temperatures and adult females were included in the set of explanatory variables (**Figure 10**). Precipitation was not a significant explanatory variable for the humid temperate climate of Porto

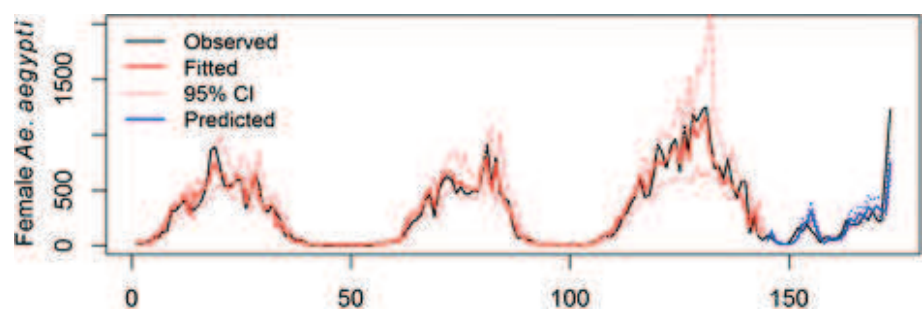


Figure 10. Observed adult infestation index MFAI and predicted generalized additive models (GAM) with meteorological and infestation data as explanatory variables for the city of Porto Alegre, Rio Grande do Sul, Brazil. From September 2012 to January 2016 (Figure extracted from da Cruz Ferreira et al. [12]).

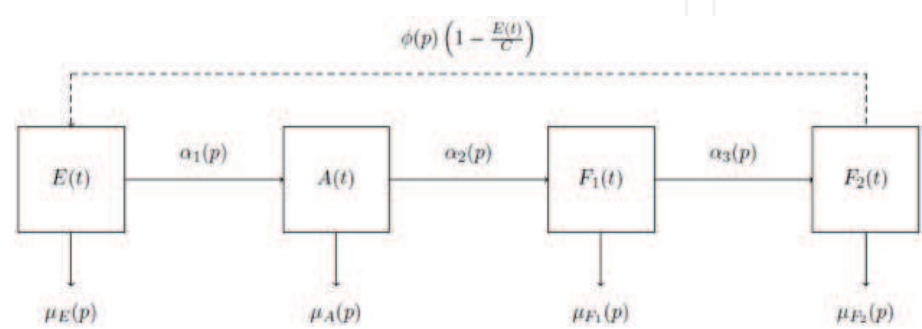


Figure 11. Mechanistic model comprising the populations of the stages of development of *Aedes aegypti*: $E(t)$, $A(t)$, $F_1(t)$, and $F_2(t)$, which are the populations of eggs, aquatic forms, and females pre and post blood meal, respectively. The rates of development of the model are set to depend on precipitation p . The curves are generated after solving a system of nonlinear differential equations, the preferred framework to represent that class of models (data not published).

Alegre, presumably because precipitation is less seasonal in this region. The association between mosquito infestation and the number of dengue cases was positive, indicating that the infestation index MFAI is a good indicator for the risk of arboviral transmission [12].

Mechanistic models have the same goal of describing or even predicting a time response series as the descriptive models but differ from the latter because they are structured with realism based on the natural phenomena, for example, the population model comprises the biological cycle of *Ae. aegypti*. Hence, through these models, from deviations and corrections for adjustment to the data, it is possible to reveal the cause-effect relations of the underlying phenomena.

Mechanistic models have been used to study and predict vector infestation and the number of dengue cases [60, 72–78]. One such model was developed to account for the effect of precipitation on the stages of development of *Ae. aegypti* by setting the model parameters as dependent on the precipitation index (in millimeters) (Figure 11) [60]. Figure 12 illustrates the model result considering the infestation index MFAI and the precipitation from June 2009 to December 2010 for the city of Sete Lagoas, Minas Gerais, Brazil.

4.2.3 Cost-benefit of the MI-Aedes platform

Dengue epidemics pose a heavy burden on health services and the economy of any country. Recently, studies in eight countries in the Americas and Asia have shown that the cost of epidemics in these countries reached approximately US\$ 1.8 billion per year [79, 80]. This number only refers to the money spent on outpatient and hospital expenses and did not consider costs such as those related to

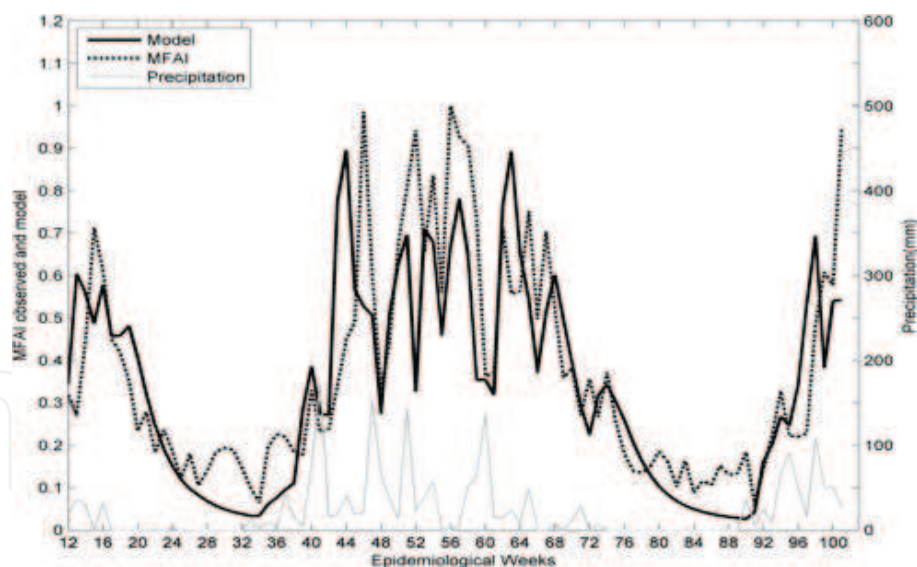


Figure 12.

Comparison of 83 epidemiological weeks covering the time series data of *Aedes aegypti* females captured divided by the number of traps (MFAI), the model result, and the precipitation index in the municipality of Sete Lagoas, Minas Gerais, Brazil. From June 2009 to December 2010 (J.L. Acebal—data not published).

surveillance and vector control activities. The economic losses imposed by arboviral diseases involve the patient's withdrawal from productive activities, drug expenses, hospitalization, medical consultations, treatment of sequelae, and death [81].

The time needed to treat and recover from arboviruses varies. On average, dengue removes the affected patient for 10–12 days from their work activities. The ZIKV may lead to birth defects including microcephaly and other severe brain malformations, which impose lifetime incapacity. Recovery from chikungunya varies from months to years [82].

Following the guidelines of the National Program for Dengue Control (PNCD), the MI-*Aedes* and MI-Virus technologies were adopted by the health authorities of the state of Minas Gerais (Brazil) and implemented in 21 cities with a high incidence of dengue in the period 2009–2011. The total cost of the program for all 21 cities for 2 years of work was less than US\$ 1.5 million, making an average of US\$ 71,428 per city. It included 4700 sticky traps, 115,000 sticky cards, synthetic oviposition attractants, RT-PCR on all mosquitoes caught in the traps, Web software licensing, cell phones, and technical support, among other items. The number of people benefited by the program was approximately 2 million, making the cost per habitant per year around US\$ 0.70. The cost-effectiveness was calculated as the cost of running the MI-*Aedes* and MI-Virus platforms divided by the number of cases of prevented arboviral diseases compared with cities that did not use the MI-*Aedes* platform and relied only in the PNCD guidelines. The MI-*Aedes* and MI-Virus platforms prevented a total of 27,191 cases at a total cost of US\$ 7.5 million, thus saving approximately US\$ 0.4 million in direct costs (health care and vector control) and US\$ 7.1 million in lost wages (societal impact) annually [41]. The cost-effectiveness of the platforms MI-*Aedes* and MI-Virus in cities with high mosquito infestation levels emphasizes the power of using these new technologies in vector control practices.

Currently, the MI-*Aedes* platform is running simultaneously in 154 Brazilian cities targeting approximately 7.5 million people, using about 12,000 sticky traps, and performing 625,000 trap inspections and around 8200 RT-PCR analysis per month on pooled mosquitoes (source: Ecovec. Ltd).

Investing more effort into integrating MI-*Aedes* strategies and costs with vector control operations, and standardizing the MI-*Aedes*-based control system across

cities, should help to increase the platform cost-effectiveness. Future studies should be conducted for developing new predictive model of serotype dynamics across cities for accurate arboviruses transmission.

5. Conclusions

In Brazil, two platforms for surveillance of eggs and gravid *Aedes aegypti* have been developed. First, the use of gravid traps associated with GIS technologies was used in Brazil in the last years to monitor *Aedes* spp. populations. The MSCP-*Aedes* platform is based on data collected upon sampling of eggs in ovitrap works. Although effective, the platform requires a large amount of human resources for field and laboratory activities that is not realistic to use in a large-scale epidemic scenario.

Second, the MI-*Aedes* and MI-Virus platforms described herein have been used in hundreds of cities and in a variety of scales besides of being a cost-effective (less than US\$ 1.00/person/year) approach to reduce mosquito population and prevent the transmission of arbovirolosis such as dengue, chikungunya, and Zika [13, 41]. The main advantage of the MI-*Aedes* platform over traditional mosquito surveillance is the integration of continuous vector monitoring at fine spatial and temporal scales coupled to an information technology platform for near real-time data collection, analysis, and decision-making.

The surveillance data generated with the MI-*Aedes* platform is used to calculate weekly vector indices and detect hotspots to help health authorities to strategically manage vector control resources. The platform is suitable to be implemented at worldwide scale because it does not require extensive infrastructure or expertise. For example, one field surveillance agent can visit 70–100 traps per week, conduct mosquito identification, and feed the database using a cell phone. More importantly, the MI-*Aedes* platform is the only large-scale mosquito surveillance system with a good track record on the prevention of cases of dengue [41]. Used to their optimum level, as tools for analysis and decision-making, the MI-*Aedes* and MI-Virus platforms are information management vehicles with high public health potential. Indeed, it is worth mentioning that this platform not only provides a wide range of GIS tools for *Ae. aegypti* surveillance, but the data collection and processing modules can be adapted to monitor other diseases, such as AIDS, tuberculosis, malaria, and leishmaniosis, among others.

6. Future studies

Studies with MI-*Aedes* platform should be continuously conducted to improve the accuracy and threshold of arbovirus outbreaks. The sensitivity of trap device of the MI-*Aedes* platform will be enhanced by replacing the MosquiTRAP by the GAT as it has been shown to be more effective [11]. Currently, studies using MI-*Aedes* and MI-Virus technologies for monitoring vector and virus circulation (DENV, CHIKV, and ZIKV) together with new mathematical models are very important tools to address targeted areas for vector control address. Future studies using MI-*Aedes* platform in association with integrated mosquito control alternatives, such as *Wolbachia* and transgenic mosquitoes, should be also conducted. Those combinations of interventions will be best applied in sustained, proactive implementation and will likely be suitable for rapid control of a developing epidemic. In addition to such proactive strategies, arbovirus prevention will benefit from greater capacity for outbreak response, before outbreaks have peaked and begun to decline on their own.

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Conflict of interest

The authors claim no conflict of interest.

List of abbreviations

AGO	Autocidal Gravid Ovitrap
AIDS	acquired immunodeficiency syndrome
CDC	Centers for Disease Control and Prevention
CHIKV	chikungunya virus
CPqAM	Research Center Aggeu Magalhães
DENV	dengue virus
Fiocruz	Oswaldo Cruz Foundation
GAM	generalized additive models
GAT	Gravid <i>Aedes</i> Trap
GIS	geographic information system
GLM	generalized linear models
INPE	National Institute for Space Research
MFAI	mean female <i>Aedes</i> index
MI- <i>Aedes</i>	from Portuguese “Monitoramento Integrado do <i>Aedes</i> ”
MI-Dengue	from Portuguese “Monitoramento Inteligente da Dengue”
MI-Virus	integrated monitoring of virus
MSCP- <i>Aedes</i>	monitoring system and population control for urban <i>Aedes</i>
PNCD	National Program for Dengue Control
RT-PCR	reverse transcription polymerase chain reaction
ZIKV	Zika virus

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