Spatiotemporal Distribution of Vector Mosquito Species in Maricopa County, Arizona: The highest West Nile virus disease incidence area in the United States in 2021

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Abstract

Mosquito-borne diseases are a major global public health concern and mosquito surveillance systems are essential for the implementation of effective mosquito control strategies. The objective of our study is to determine the spatiotemporal distribution of vector mosquito species in Maricopa County from 2011 to 2021. The Maricopa County Mosquito Control surveillance system utilizes BG-Sentinel and EVS-CDC traps throughout the entire urban and suburban areas of the county. We estimated specific mosquito species relative abundance per unit area using the Kernel density estimator in ArcGIS 10.2. Our results show that vector mosquito species are widely distributed and abundant in the urban areas of Maricopa County. A total of 691,170 *Culex quinquefasciatus*, 542,733 *Culex tarsalis*, and 292,305 *Aedes aegypti* were collected from 2011 to 2022. The relative abundance of *Ae. aegypti* was highly seasonal peaking in the third and fourth quarters of the year. *Culex quinquefasciatus*, on the other hand, was abundant throughout the year with several regions consistently yielding high numbers of mosquitoes. *Culex tarsalis* was abundant but it only reached high numbers in well-defined areas bordering natural and rural areas. The well-defined species-specific spatiotemporal patterns found in this study can be used to develop and/or refine vector control strategies.

Keywords: *Aedes aegypti*, *Culex quinquefasciatus*, *Culex tarsalis*, Arbovirus

Introduction

Mosquito-borne diseases are a major global public health concern [1–4]. The incidence of dengue has increased substantially in the last decades, from 500,000 reported cases in 2000 to 2.4 million in 2010 and 5.2 million in 2019 [5]. The current estimate is 390 million dengue virus (DENV) infections worldwide every year [6]. Between 2015 and 2018, there were more than 1 million confirmed cases of Zika in the Americas followed by a significant increase in fetus malformation as a direct consequence of Zika virus (ZIKV) infection during pregnancy [3,4].

Albeit on a smaller scale, arboviral infections have also increased in the United States. The ZIKV was introduced multiple times in the United States in 2016 leading to 224 locally transmitted human cases in Florida and Texas [9–11]. Local transmission of the DENV has also been reported in Florida. In 2020, Monroe County experienced a major dengue outbreak with 65 confirmed locally transmitted cases. In the same year, 6 locally transmitted cases of dengue were reported in Miami-Dade County [12–14].

While local outbreaks of dengue and Zika were reported in the United States, the West Nile virus (WNV) has become endemic and the most widespread mosquito-borne arbovirus in North America [15]. WNV has been detected in more than 60 mosquito species in the continental United States (CONUS) [16], however, selected species in the genus *Culex* such as *Culex quinquefasciatus*, *Culex pipiens*, *Culex tarsalis*, and *Culex nigripalpus* are responsible for driving most of the epizootic and epidemic WNV transmission. Birds are the natural reservoir hosts of WNV as they are able to develop viremia high enough to infect mosquito vectors. Humans, horses, and other mammals

are not able to amplify the virus to viremic levels high enough to infect mosquitoes and are therefore considered dead-end hosts [16,17].

Since it was first detected in New York in 1999 [18], the WNV has progressively become endemic in all states in the contiguous United States and has been sporadically detected in Alaska, Hawaii, and Puerto Rico [19]. From 1999 to 2020 a total of 52,532 human cases were reported in the United States leading to 2,456 deaths [20].

Maricopa County, Arizona is located in the Sonoran Desert ecoregion spreading through 23,890 km^2. It has a hot desert climate with long hot summers and short winters [21]. According to the 2020 census [22], Maricopa County has a population of 4,420,568 people, being the most densely populated county in Arizona as well as in the Sonoran Desert ecoregion. There are three major cities in Maricopa County, Phoenix (the Arizona state capital, and the fifth-most populous city in the United States), Mesa, and Chandler. It has historically been one of the counties most affected by West Nile virus disease in the United States with an average of 70 cases reported every year in the last decade. However, 1,427 cases of West Nile were reported in this county in 2021, the highest ever reported in a single county in the United States [12].

Controlling mosquito populations is widely considered the most effective way of preventing the spread of mosquito-borne diseases [23]. However, the development and implementation of effective mosquito control strategies in urban areas is complex and difficult to put into action [24]. They rely on a framework consisting of multiple successive actions that need to be implemented for a successful intervention. The first step in the implementation of effective strategies is the development of an extensive and reliable mosquito surveillance system [25]. Such a system is key to assessing the

mosquito community composition, identifying factors influencing the population dynamics of mosquito species, estimating the relative abundance of populations of different vector mosquito species, and providing evidence for ascertaining and anticipating patterns in mosquito movement and demographics that are essential for the development of mosquito control strategies. The aim of this study is to determine the spatiotemporal distribution of vector mosquito species in Maricopa County, Arizona, by analyzing mosquito surveillance data collected from 2011 to 2021.

Results

The Maricopa County Environmental Services Department Vector Control Division Surveillance System was comprised of 478 traps in 2011 and new traps were gradually included over the years as the surveillance system expanded (Figure 2). From 2016 to 2021 the number of traps remained similar with 781 and 833 traps, respectively. A total of 691,170 *Cx. quinquefasciatus*, 542,733 *Cx. tarsalis*, and 292,305 *Aedes aegypti* were collected from 2011 to 2022 by the traps in the Surveillance System (Figure 1, Supplementary Table 1).

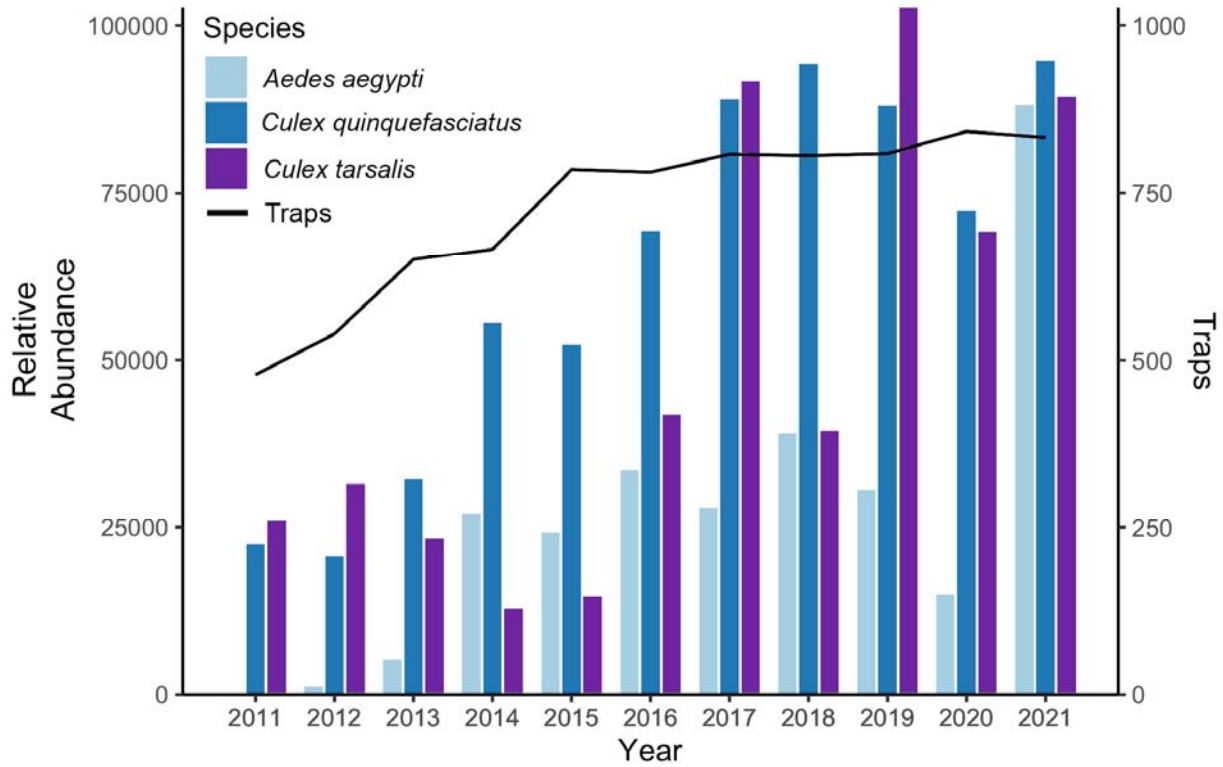

Figure 1. Number of active traps in the Maricopa County Environmental Services Department Vector Control Division Surveillance System (black line) and the number of mosquitoes collected by year from 2011 to 2021.

Over the study period, *Ae. aegypti* gradually expanded its range and relative abundance in the urban areas of Maricopa County. In particular, a substantial increase in the range of *Ae. aegypti* was observed in 2021 in relation to 2020, when a total of 88,187 specimens were collected by the traps in the surveillance system (Figure 2A). In contrast to *Ae. aegypti*, *Cx. quinquefasciatus* was already commonly found in the urban areas in Maricopa County in 2011. However, since 2011, *Cx. quinquefasciatus* became

more confined to specific areas of the county and is particularly abundant in those areas. Since 2016, *Cx. quinquefasciatus* started to increase in abundance, especially in the southeastern region of Maricopa County (Figure 2B). Although *Cx. tarsalis* could be detected in urban areas, this species was mainly confined to specific areas of Maricopa County, primarily to areas inside or bordering natural or rural areas. By 2021, *Cx. tarsalis* had gradually expanded its range, but it remained highly abundant in this ecological niche (Figure 2C, Supplementary Tables 2 and 3).

Figure 2. Kernel density-based heat map of the relative abundance of vector mosquito species collected by the Maricopa County Environmental Services Department Vector Control Division Surveillance System from 2012 to 2021. The color gradient represents the sum of mosquitoes collected by each trap in a 12-month period; (A) *Aedes aegypti*; (B) *Culex quinquefasciatus*; and (C) *Culex tarsalis*. The figure was produced using ArcGIS 10.2 (Esri, Redlands, CA), using layers available at

the Maricopa County GIS Mapping Applications available at: https://www.maricopa.gov/3942/GIS-Mapping-Applications.

Our results show great seasonal variations in the mean numbers of mosquitoes collected in Maricopa County. Rainfall is one of the most important drivers for the proliferation of mosquitoes in the region, and the peaks in abundance of *Cx. quinquefasciatus* and *Cx. tarsalis* overlap with the peak of the rainy season in the Spring and later in early Fall. Furthermore, rainfall is potentially an important driver for the increase in the abundance of *Ae. aegypti* over the year until the beginning of the dry season, when the abundance of *Ae. aegypti* populations is drastically reduced. Each of the three vector mosquito species, *Ae. aegypti*, *Cx. tarsalis*, and *Cx. quinquefasciatus*, displayed different population dynamic patterns peaking in abundance at different times of the year indicating that even though rainfall is an important driver for their proliferation, each species responded differently to the rainfall (Figure 3).

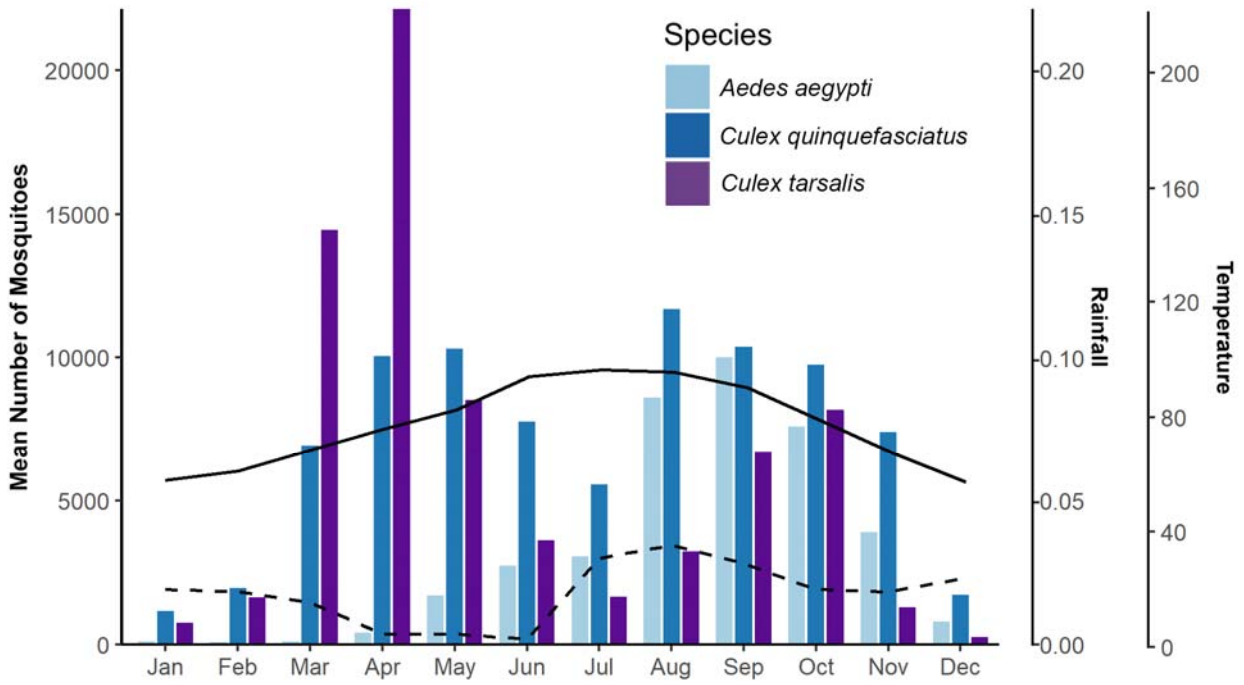

Figure 3. Mean number of *Aedes aegypti*, *Culex quinquefasciatus*, and *Culex tarsalis* collected by the Maricopa County Environmental Services Department Vector Control Division Surveillance System from 2016 to 2021. Solid line represents the monthly mean average temperature (Fahrenheit) between 2016 and 2021; Dashed line represents the monthly mean average rainfall (inches) between 2016 and 2021.

The mean number of collected *Ae. aegypti* varied greatly within each year. It was virtually absent during the first quarter of the year yielding a low number of mosquitoes collected by the traps in the surveillance system. It then gradually increased in abundance and range during the second quarter, showing the highest abundance in the southeastern part of the county. This species peaked in abundance during the third

quarter of the year covering most of the urban areas of Maricopa County and reaching high abundance in several geographical areas. The mean number of *Ae. aegypti* collected in the fourth quarter of the year was smaller than in the third quarter albeit areas with high abundance were still present (Figure 4A).

Culex quinquefasciatus was abundantly found in Maricopa County year-round. The mean number of *Cx. quinquefasciatus* was the highest during the second and third quarters of the year with many areas of the county yielding an average higher than 10 mosquitoes per trap per day. One region bordering rural and leisure areas in the southeastern part of the county yielded more than 10 mosquitoes per trap per day on average, the whole year round (Figure 4B). *Culex tarsalis* was moderately affected by seasonality. The mean number of *Cx. tarsalis* remained constant during the second, third, and fourth quarters of the year with specific areas yielding high numbers of mosquitoes. During the first quarter collections of *Cx. tarsalis* were not as abundant as in the other quarters of the year, but for one region bordering rural and leisure areas in the southeastern part of the county. Furthermore, *Cx. tarsalis* yielded the highest average number of mosquitoes collected in a selected group of traps bordering natural and rural areas. Even though the mean number of *Cx. tarsalis* reached high levels in those specific areas, it was not abundantly found in urban areas. (Figure 4C).

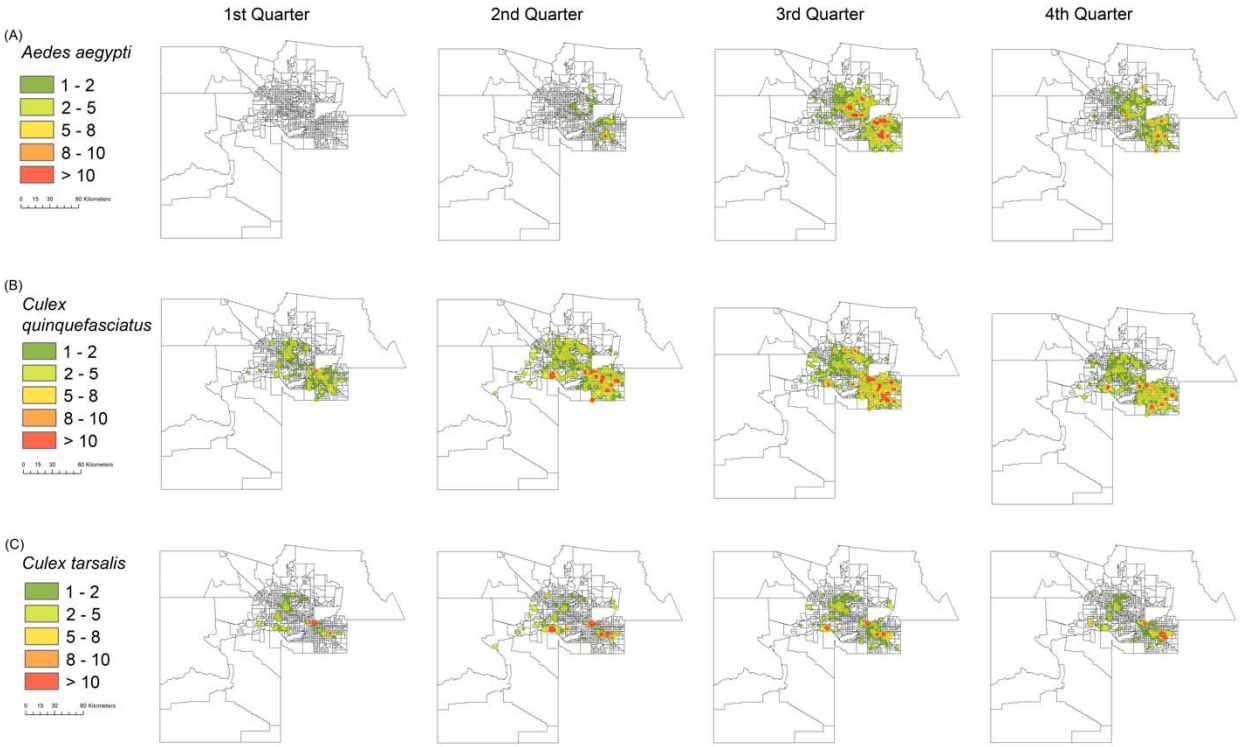

Figure 4. Kernel density-based heat map of the mean number of *Aedes aegypti*, *Culex quinquefasciatus*, and *Culex tarsalis* collected by the Maricopa County Environmental Services Department Vector Control Division Surveillance System from 2016 to 2021. The color gradient represents the mean number of mosquitoes collected by each trap in a 3-month period. The figure was produced using ArcGIS 10.2 (Esri, Redlands, CA), using layers available at the Maricopa County GIS Mapping Applications available at: https://www.maricopa.gov/3942/GIS-Mapping-Applications.

Discussion

Anthropogenic changes in the environment create favorable conditions for the development of vector mosquito species that can exploit the resources available in

urban areas [26]. The decreased biodiversity in those urban areas increases the contact rate between mosquito vector species and human hosts, increasing the risk of arbovirus transmission to humans [14,27,28]. Our results show that vector mosquito species are widely distributed and abundantly found in the urban areas of Maricopa County, Arizona. *Aedes aegypti* gradually become more abundant and expanded its range since only one specimen was collected in 2011. In 2012, 1,189 *Ae. aegypti* were collected; by 2014 that number increased to 27,208, and by 2021 a total of 88,187 specimens were collected indicating a substantial increase in its relative abundance over the years. A similar phenomenon could be observed for *Cx. tarsalis* and *Cx. quinquefasciatus*, and although they were already present in great numbers since 2011, with more than 20,000 specimens from each species collected that year, reaching 89,401 collected specimens *of Cx. tarsalis* and 94,774 of *Cx. quinquefasciatus* in 2021.

The high abundance of vector mosquitoes in Maricopa County represents a potentially dangerous scenario. *Aedes aegypti* is the primary vector of dengue, chikungunya, yellow fever, Zika viruses, and *Cx. quinquefasciatus* and *Cx. tarsalis* are vectors of the WNV, Saint Louis Encephalitis, Eastern Equine encephalitis, and Japanese Encephalitis viruses [29]. The close proximity of these mosquito vector species to human populations increases the risk of arbovirus transmission as observed in the WNV disease outbreak in Maricopa County resulting in approximately 1,500 cases of WNV disease in 2021 [12].

The relative abundance of *Ae. aegypti* was highly seasonal with fewer mosquitoes collected in the first 3 months of the year followed by a moderate increase in numbers in the second quarter indicating that the environmental conditions were not

conducive to the proliferation of *Ae. aegypti* during the first quarter of the year. However, as the year progressed a substantial increase in the abundance of *Ae. aegypti* was observed in the third and fourth quarters. The observed seasonal variation in the abundance of *Ae. aegypti* can potentially be an important driver for arbovirus transmission in Maricopa County as its abundance and range increased as the year progressed, therefore, potentially increasing the contact rate between *Ae. aegypti* and human hosts.

Culex quinquefasciatus, on the other hand, was abundantly found during all seasons of the year. It was not as abundant in the first quarter as it was during the remaining of the year, but it could be found throughout the urban areas during that time of the year. Several regions consistently yielded high numbers of *Cx. quinquefasciatus* mosquitoes indicating that those areas were hot spots and were able to support high numbers of *Cx. quinquefasciatus* the whole year-round. *Culex tarsalis* was also abundantly found in Maricopa County but in contrast to *Ae. aegypti* and *Cx. quinquefasciatus*, it only reached high numbers in well-defined areas bordering natural and rural areas. However, this is not surprising because *Cx. tarsalis* larval habitats include irrigation agricultural runoff, wetlands, sewage effluent, oil field run-off, and lake beds [30], all these habitat types are rarely associated with urban areas. Human cases of WNV disease have been consistently reported in Arizona, being one of the most affected states in the United States. The high abundance of *Culex* vector species, especially the year-round presence of *Cx. quinquefasciatus*, has major implications for the likelihood of WNV transmission in Maricopa County as was the case observed in

2021, when approximately 1,500 human WNV disease cases were reported in the county [12].

Our results showed well-defined spatiotemporal patterns for each of the species included in this study. However, the main drivers for the variations in the population dynamics of each mosquito vector species are still not well understood and determining how these species are driven by the availability of resources at the microgeographic scale is essential to improving the effectiveness of mosquito control operations [31]. This is especially important for the development of control strategies targeted to reduce the abundance of *Cx. tarsalis*, and to a lesser extent *Cx. quinquefasciatus*, since the analysis of their population dynamics revealed a high abundance of both species in well-defined areas. Furthermore, there is a need to assess and validate the effectiveness of different control methods and strategies aimed to reduce mosquito populations in urban areas focusing on how the proliferation of vector mosquito species can be locally reduced by source reduction, community engagement, and by modifying specific features of the urban built environment that facilitate the proliferation of vector mosquito species [31–34]. Developing and implementing effective mosquito control strategies is a difficult task with many factors that can potentially hinder the effectiveness of mosquito control interventions, such as levels of insecticide resistance, diel activity of target mosquito species, and outdated and ineffective mosquito control tools [35–37].

This study is not without limitations. Mosquitoes were collected using BG-Sentinel and CDC traps. Even though these traps are the gold standard for collecting mosquitoes in urban areas, they may have underestimated the presence of less

anthropophilic mosquito species. Furthermore, new traps were gradually added during the period of this study increasing the sampling effort over time, and even though we were able to show an increase in the relative abundance of mosquitoes it is a limitation in our study.

Effective mosquito control operations rely on multiple factors, with the most important being consistent and reliable mosquito surveillance systems, community engagement, and targeted source reduction. Now, more than ever, effective mosquito control strategies are needed to curb the increase of mosquito-borne disease outbreaks. Effective mosquito surveillance systems are key for guiding and implementing mosquito control strategies and should be considered a priority for local, state, and federal public health professionals.

Methods

The Maricopa County Environmental Services Department Vector Control Division surveillance grid covers the entire urban and peri-urban areas of the county with approximately one trap per square mile. The surveillance system is comprised of BG-Sentinel traps baited with BG-Lure (Biogents AG, Regensburg, Germany) (ranging from 13 traps in 2016 to 8 traps in 2021) and EVS-CDC traps baited with CO_2 (ranging from 478 traps in 2011 to 825 traps in 2021). Each trap is deployed once a week for 24 hours for 50 weeks a year (Figure 5). All collected mosquitoes are transported to the Maricopa County Environmental Services Department Vector Control Division Laboratory and morphologically identified to species using taxonomic keys [38]. BG-

Sentinel traps baited with BG-Lure and EVS-CDC traps baited with CO_2 attract female mosquitoes seeking hosts for blood-feeding [39]. Even though male mosquitoes were sometimes collected, male data was not included in the proposed analyses.

We used the geodesic method for densities in square kilometers to calculate the magnitude-per-unit area (number of inputs per point - i.e., mosquito relative abundance) using the Kernel density estimator in ArcGIS 10.2 (Esri, Redlands, CA). Figures were created with layers available at the Maricopa County GIS Mapping Applications available at: https://www.maricopa.gov/3942/GIS-Mapping-Applications.

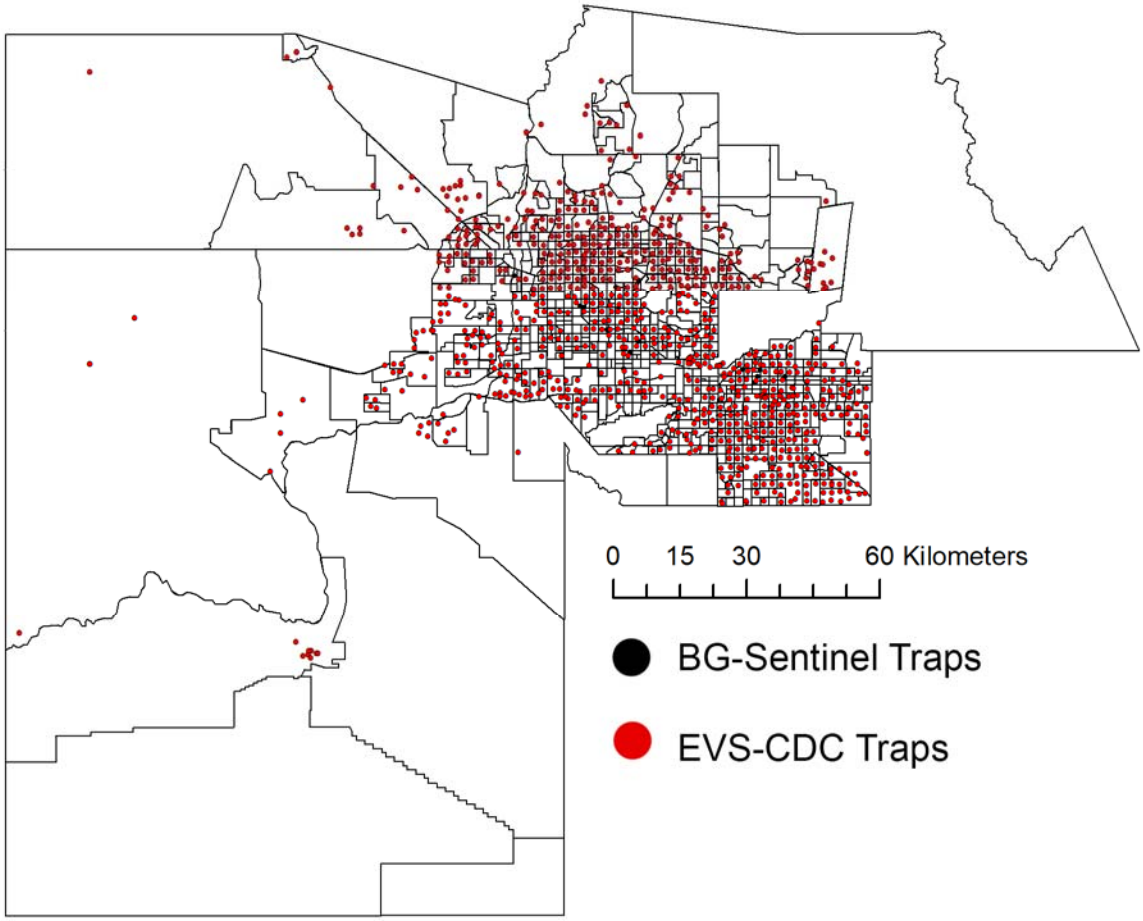

Figure 5. Map of Maricopa Mosquito Control Surveillance System. BG-Sentinel traps are shown in black; EVS-CDC traps are shown in red.

Supplementary Table 1. Number of traps and mosquitoes collected by the Maricopa County Environmental Services Department Vector Control Division Surveillance System from 2011 to 2021.

Supplementary Table 2. Number of mosquitoes (*Aedes aegypti*, *Culex quinquefasciatus*, and *Culex tarsalis*) collected per trap.

Supplementary Table 3. Number of mosquitoes (*Aedes aegypti*, *Culex quinquefasciatus*, and *Culex tarsalis*) collected by the 478 traps in use since 2016.

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