

Effect of Trapping Methods, Weather, and Landscape on Estimates of the *Culex* Vector Mosquito Abundance



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ABSTRACT: The local abundance of *Culex* mosquitoes is a central factor adding to the risk of West Nile virus transmission, and vector abundance data influence public health decisions. This study evaluated differences in abundance estimates from mosquitoes trapped using two common methods: CO₂-baited CDC light traps and infusion-baited gravid traps in suburban, Chicago, Illinois. On a weekly basis, the two methods were modestly correlated ($r = 0.219$) across 71 weeks over 4 years. Lagged weather conditions of up to four weeks were associated with the number of mosquitoes collected in light and gravid traps. Collections in light traps were higher with higher temperature in the same week, higher precipitation one, two, and four weeks before the week of trapping, and lower maximum average wind speed. Collections in gravid traps were higher with higher temperature in the same week and one week earlier, lower temperature four weeks earlier, and with higher precipitation two and four weeks earlier. *Culex* abundance estimates from light traps were significantly higher in semi-natural areas compared to residential areas, but abundance estimates from gravid traps did not vary by the landscape type. These results highlight the importance of the surveillance methods used in the assessment of local *Culex* abundance estimates. Measures of risk of exposure to West Nile virus should assess carefully how mosquito abundance has been estimated and integrated into assessments of transmission risk.

KEYWORDS: abundance, *Culex*, gravid traps, landscape, light traps, weather, West Nile virus, arbovirus

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Introduction

The World Health Organization has estimated that vector-borne diseases account for nearly 17% of the global burden of all infectious diseases.¹ Mosquitoes are one of the most important disease vectors and can transmit many pathogens including those that cause malaria, dengue, West Nile fever and encephalitis, St. Louis encephalitis, yellow fever, Japanese encephalitis, Zika, and chikungunya.² The risk of exposure to mosquito-borne pathogens is often estimated using indices that include estimates of vector abundance. Vectorial capacity, for example, takes into account the vector, host, and vector–host interaction, and is a commonly used risk index for assessing the prevalence of malaria and dengue.^{3–5} Similarly, dengue transmission risk is often measured using the house index, which is the percentage of houses infested with the larvae or pupae of *Aedes* mosquitoes.⁶

Estimates of interactions between vectors and hosts are also commonly used to estimate the risk of West Nile virus (WNV) transmission.⁷ Due to the multi-host transmission cycle of WNV, Kilpatrick et al developed an index combining vector abundance, the fraction of blood meals taken from mammals, WNV infection prevalence, and a vector competence index for alternative vector species to assess WNV transmission risk.⁸ A simpler vector index, measured as the product of mosquito abundance and the WNV infection rate in mosquitoes, has also been used for WNV transmission risk estimation.^{9–11} The advantage of the later method is that it is simple to calculate, and data are more readily collected; however, it does not consider vector competence. Because mosquitoes of different species transmit different pathogens, vector–pathogen–host interactions differ across systems, so system-specific abundance and infection risk estimates



must be tailored for particular mosquito-borne diseases and particular areas.¹²

In the United States, mosquitoes of the genus *Culex* are the vectors for WNV transmission, with nearly 96% of the WNV positive pools obtained from just a few *Culex* species.¹³ The proportional distribution of these species varied by region, with *Culex tarsalis*, *Culex quinquefasciatus*, and *Culex pipiens pipiens* and *Culex restuans* being dominant in the western, southern, and north central regions, respectively.¹³ In the Chicago, Illinois, region, which is the focus of this study, *Culex pipiens* complex and *C. restuans* have played the most important role in the enzootic as well as the epidemic cycle of WNV transmission.¹⁴ The *C. pipiens* form *molestus* has been detected in this region as well, but data are limited.¹⁵ The life history of *Culex* mosquitoes includes aquatic stages (eggs, larvae, and pupae) and the adult terrestrial stage. Females lay rafts of eggs on the surface of standing water, with a preference for water rich in organic content. Depending upon weather and food availability, adults emerge in about 10–14 days.¹⁶ Adult gravid female *C. pipiens* enter diapause in the fall to overwinter.^{16,17}

Temperature and precipitation play an important role in the life history and population dynamics of mosquitoes. In temperate climates, warmer weather in the spring accelerates mosquito activity, and higher temperatures generally shorten the time between blood meal acquisition and oviposition.^{12,18} The lifespan of adult *Culex* spp. varies considerably depending on the temperature.^{19,20} Adult female mosquitoes raised over a range of constant temperatures had an average longevity ranging from 11 days to over 92 days.²⁰ The shortest observed life span for both sexes was less than two weeks at 30 °C, while they survived more than 90 days at 15 °C.²⁰ This suggests that mosquito survival is higher when the temperature is between 15 °C and 30 °C, and lower when it exceeds 30 °C. In natural systems, weather conditions in the weeks prior to mosquito capture (lagged weather) can predict the number of mosquitoes captured.^{21–23} Even off-season meteorological conditions can affect mosquito abundance due to diapause conditions²⁴ and because prior year drought conditions may reduce the number of predators, resulting in increased mosquito populations.²⁵

Many other factors can affect the local abundance of mosquitoes. For example, the availability and distribution of larval habitats depend on both weather and local landscape features. Suitable larval habitats, such as natural water bodies, catch basins, and containers, are required to maintain the mosquito population in an area²⁶ and rainfall plays a key role in maintaining these habitats. *Culex* mosquitoes need wet conditions to reproduce, but heavy rainfall can reduce the survival rate of *Culex* vectors both at the adult stage and during larval development.^{27,28} Local vegetation influences mosquito abundance by providing resting sites and sugars to mosquitoes, and different species of vegetation can promote or reduce the emergence rates of adult *Culex* mosquitoes.^{29,30} In urban areas of Connecticut, significantly higher numbers of *C. pipiens* and *C. restuans* were found in areas with moderate vegetation as

measured from imagery using a vegetation index.³¹ In other studies, orchard habitat,³² forested areas³³ and medium height trees were associated with higher *Culex* abundance.³⁴ In a study conducted in Amherst, Erie County, NY, *Culex* abundance increased with more mixed urban land use, grass and agriculture land cover, and industrial and recreational areas.³⁵

The abundance of *Culex* spp. mosquitoes in an area is estimated by counting the number of *Culex* spp. mosquitoes collected per trap and then adjusting that for the number of nights in which traps were actually set. The most commonly used traps to collect *Culex* mosquitoes are CO₂-baited CDC light traps and infusion-baited gravid traps. Light traps baited with CO₂ attract nocturnal phototactic mosquitoes and rely on chemotaxis by host-seeking females, whereas gravid traps attract ovipositing mosquitoes by providing breeding habitat.³⁶ Light traps attract host-seeking female mosquitoes that may be parous, but are more often unfed and nulliparous³⁶ and are useful to capture a diversity of mosquito species³⁷, whereas gravid traps primarily collect ovipositing female *Culex* mosquitoes.³⁸ Mosquitoes collected in gravid traps are especially suitable for WNV surveillance if detection of infection status is included in the surveillance plan because gravid mosquitoes have had at least one gonotrophic cycle and are thus more likely to be infected.^{39,40} Underlying weather conditions and trap locations might affect the number of *Culex* being captured in light and gravid traps; however, the differences in these relationships are not well documented.

The main objective of this study was to compare abundance measures and factors associated with differences between two common methods for trapping *Culex* vectors in Illinois: CDC light traps baited with dry ice and gravid traps containing a liquid oviposition attractant. We evaluated the effects of the trapping method on estimates of *Culex* abundance, taking into account weekly weather conditions and landscape features. We conducted the study between 2009 and 2012 in a suburban Chicago, Illinois, a region with significant WNV activity. Secondarily, we evaluated the relationship between *Culex* abundance and WNV mosquito infection rate during the same period.

Methods

Study area and data sources. The study area was in south Cook County, Illinois, located in the near suburbs of the city of Chicago (Fig. 1). The study area is approximately 17 km² with a population of around 20,000 people in several municipalities. This study was part of a broader investigation of WNV transmission ecology.^{41,42}

Mosquitoes were collected for 18 weeks from late May to early October each year (weeks 22–39) from 2009 to 2011 and for 17 weeks (weeks 23–39) in 2012, using both CDC miniature light traps and infusion-baited gravid traps. Light traps were hung from a tree or any other structure at a height of about 1.5 m above the ground with a cooler containing dry ice attached each night. Gravid trap oviposition attractant was made by



Figure 1. Light and gravid trap sampling locations in suburban Chicago. Stars represent CDC light trap locations, triangles represent gravid traps. A circle around the shape indicates multiyear locations. Green indicates semi-natural areas, and the gray color indicates urban residential or commercial areas. The inset shows the state of Illinois, USA with the black dot indicating the neighborhoods where mosquito collections occurred (Alsip, Evergreen Park, Oak Lawn) between 2009 and 2012.

placing a half cup of alfalfa pellets in five gallons of water in a carboy that was placed in the sun for about seven days prior to use (to allow fermentation of organic matter) and changed every two to four weeks. A portion of both types of traps was set up in the evening and collected the following morning each collection day during each week of collection. Traps were distributed throughout the study area in different representative landscapes, including semi-natural sites (cemeteries, parks, and rights of way), and residential areas. The basis for the specific site selections has been described elsewhere.^{14,41–43} Over the four-year study period, the number of light trap locations ranged from 29 to 76 per year, with 119 unique locations; and the number of gravid trap locations ranged from 11 to 31 per year, with 48 unique locations. Any trap locations with coordinates recorded less than 20 m apart were treated as a single location. Within a single year, data from these traps were combined. Nearly 99% of the traps were located 50 m away from each other in the same year, with a few exceptions when separated by physical barriers such as a road or thick vegetation. Some, but not all, of the trap locations were used in all four years. Among the light traps, 55, 42, 16, and 6 trap locations were used for one, two, three, or four years, respectively. Among the gravid traps, 24, 11, 10, and 3 trap locations were used for one, two, three, or four years, respectively.

After collection, trained personnel determined the mosquito species and sex, and then pools of up to 50 female

Culex spp. (*C. pipiens* complex and *C. restuans*) were tested for WNV using quantitative rt-PCR.⁴⁴ Given the difficulties in morphologically differentiating *C. pipiens* complex and *C. restuans*, these two species were pooled together and hereafter are referred to as *Culex* spp.⁴⁵ *Culex* spp. are considered the primary enzootic and bridge vectors of WNV in this area.^{13,45} The average number of *Culex* spp. per trap night was calculated for each trap location and for the 71 collection weeks across 2009–2012. The minimum infection rate (MIR) of WNV in mosquitoes was estimated using the maximum likelihood method implemented in the program PooledInfrRate version 4.0.⁴⁶ In addition to calculating the MIR for the local study-related mosquito collections, we obtained and calculated the MIR of *Culex* spp. from WNV testing reported to the Illinois Department of Public Health for the broader region (Cook County) during the same time period.

Daily weather records from January 2009 to December 2012 were obtained from the nearest NOAA weather station at the Midway International Airport, Chicago, Illinois, nine miles north of the study area. Weather records included daily minimum and maximum temperature, precipitation, average humidity, and average and maximum wind speed. Average weekly temperature (°C) was calculated as the mean of the daily minimum and the maximum temperatures for each week. Weekly averages of daily humidity, average wind speed, and maximum wind speed were calculated as the mean of



their respective seven readings from that week, and weekly precipitation was calculated as the sum of the precipitation during that week.

Statistical Analysis

The weekly abundance estimates from light trap collections were compared with the abundance measured from gravid traps. Then, temporal and spatial analyses were performed separately for light and gravid traps. The response variable for all analyses was the average number of *Culex* per trap night. Data from traps, where a trap failed on a given night, were removed from analyses to avoid the artifact of pseudo-negative catches. Predictor variables for temporal analyses included weekly average temperature, total precipitation, average humidity, average wind speed, and average maximum wind speed of the same week. In addition, we assessed each of these predictor variables at one to four week lags. In total, there were 25 weather variables: five each for temperature, precipitation, average humidity, average wind speed, and average maximum wind speed (Table 1).

Descriptive statistics were calculated using the command PROC UNIVARIATE in SAS 9.4 (SAS Institute Inc.). The Shapiro–Wilk W statistic (>0.9) was used to test the normality of outcome variables. In the original dataset, the *Culex* spp. per trap night in both light and gravid traps was not normally distributed ($W < 0.9$). We subsequently identified as outliers the *Culex* spp. per trap night data above the 95th percentile, and captures higher than that value were assigned the value of the 95th percentile, after which data were normally distributed

($W > 0.9$). Pearson's product-moment correlation coefficient was used to measure the association between weekly average *Culex* spp. per trap night by trap type. Bivariate correlation analyses of individual predictor variables were conducted, and variables with $P < 0.2$ were selected for inclusion in a multivariable regression model. Multiple linear regression analysis was performed to explore the relationship between the response variable and the selected predictor variables using the command PROC GLM in SAS. The variance inflation criterion ($VIF < 10$) was used to evaluate multicollinearity among explanatory variables. The Akaike Information Criterion (AIC) was used to evaluate candidate models. The model with the lowest AIC value was selected as the model that best fit the data.⁴⁷ The variable selection criterion for the final multivariate regression was $P < 0.05$.

For spatial analysis, light and gravid trap locations from 2009 to 2012 were classified as being either in residential areas or in semi-natural areas. Analysis of variance (ANOVA) tests were performed to evaluate whether *Culex* spp. abundance in light and gravid traps differed by the land cover type. The dependent variable was the average number of *Culex* spp. per trap night in gravid traps and light traps. The independent variable was the landscape type (whether the traps were located in residential or semi-natural areas).

Results

Light traps captured 18,978 *Culex* spp. mosquitoes from 3,444 trap nights with 14–76 light traps set per week during 71 weeks from 2009 to 2012. Across all light trap collections, abundance

Table 1. List of explanatory variables used in the temporal analysis to show their relationship with weekly *Culex* abundance in light and gravid traps.

| S.N. | VARIABLES | ABBREVIATION |
|----------|--|--|
| A | Temperature (Degrees celsius) | |
| 1 | Average temperature of the same week | Temp_samewk |
| 2 | Average temperature one to four weeks before | Templagwk1, Templagwk2, Templagwk3, Templagwk4, |
| B | Precipitation (Centimeters) | |
| 1 | Average precipitation of the same week | Preci_samewk |
| 2 | Average precipitation one to four weeks before | Precilagwk1, Precilagwk2, Precilagwk3, Precilagwk4 |
| C | Humidity (Percentage) | |
| 1 | Average humidity of the same week | Avghumidity_samewk |
| 2 | Average humidity one to four weeks before | Humiditylagwk1, Humiditylagwk2, Humiditylagwk3, Humiditylagwk4 |
| D | Average wind speed (Kilometer per hour) | |
| 1 | Average wind speed of the same week | Avgwind_samewk |
| 2 | Average wind speed one to four weeks before | Avgwindlagwk1, Avgwindlagwk2, Avgwindlagwk3, Avgwindlagwk4 |
| E | Average maximum wind speed (Kilometer per hour) | |
| 1 | Average maximum wind speed of the same week | Avgmaxwind_samewk |
| 2 | Average maximum wind speed one to four weeks before | Avgmaxwindlagwk1, Avgmaxwindlagwk2, Avgmaxwindlagwk3, Avgmaxwindlagwk4 |



estimates ranged from 0 to 266 *Culex* spp. per trap night, with an overall mean of 5.5 (± 12.9 SD). Over the 71 weeks, the weekly light trap collections with all locations combined averaged between 0.4 and 24.3 *Culex* spp. per trap night, with a mean of 5.1 (± 3.9 SD). Annually, for light traps, 2010 had the highest overall average *Culex* spp. per trap night measure, with a value of 7.2 (± 5.5 SD). The next highest average abundance estimate per trap night was 4.5 (± 3.1 SD) in 2009, followed by 4.4 (± 3.4 SD) in 2012, and 4.1 (± 2.8 SD) in 2011.

Gravid traps captured a total of 22,345 *Culex* spp. from 1,561 trap nights with 6–31 gravid traps set per week during 71 weeks from 2009 to 2012. Across all gravid trap collections, abundance estimates ranged from 0 to 533 *Culex* spp. per trap night with a mean of 14.3 (± 33.2 SD). Over the 71 weeks, the weekly gravid trap collections with all locations combined averaged from 0.1 to 192.6 *Culex* spp. per trap night with a mean of 16.1 (± 24.6 SD). For gravid traps, the highest overall average *Culex* per trap night was in 2009, with a value of 26.2 (± 44.5 SD). The next highest average abundance estimate per trap night was 18.6 (± 13.1 SD) in 2010, followed by 10.1 (± 9.1 SD) in 2012, and 8.4 (± 7.0 SD) in 2011. The highest annual MIR for the small study area alone was 15.7 in 2009, followed by 11.8 in 2010, 9.2 in 2012, and 0.6 in 2011. County-level MIR was 1.0 in 2009, 5.3 in 2010, 9.8 in 2012, and 3.5 in 2011.

Gravid traps usually captured more *Culex* spp. each week than light traps (Fig. 2). The exception was during the weeks 35–39 in 2011 and weeks 36–38 in 2012, when the light

traps had higher capture rates. This happened when weather conditions during those weeks were within the average range for those weeks. Additional weeks of data would be needed to better explain these patterns. The weekly *Culex* spp. abundance estimates (Fig. 3) averaged across the four years demonstrated that there was greater variance in *Culex* spp. abundance collected in gravid traps compared to light traps, and there was a slight peak in gravid trap collections around weeks 26–29 and again at weeks 32–34. In light traps, a bimodal distribution was observed with a first peak at week 26 and a second peak at weeks 32–34 (Fig. 3). After week 33 (about mid-August), abundance was generally low and decreasing in both trap types, and most of the anomalous *Culex* spp. collections occurred earlier in the season. Of the more than 5,000 collections, 95 data points (individual collections) were removed from the analysis in four years from light traps and gravid traps due to trap failures.

With 71 weeks of data without truncating for outliers, there was no measurable correlation between average abundance in light traps and the average abundance in gravid traps ($r = 0.03$). However, after truncating the outliers, the correlation was stronger, although still marginal ($r = 0.219$; $P = 0.06$; $N = 71$) (Fig. 4).

Temporal Analysis

Using AIC, light trap data were best fit with a model that included five weather variables (AIC = 319.6), which explained

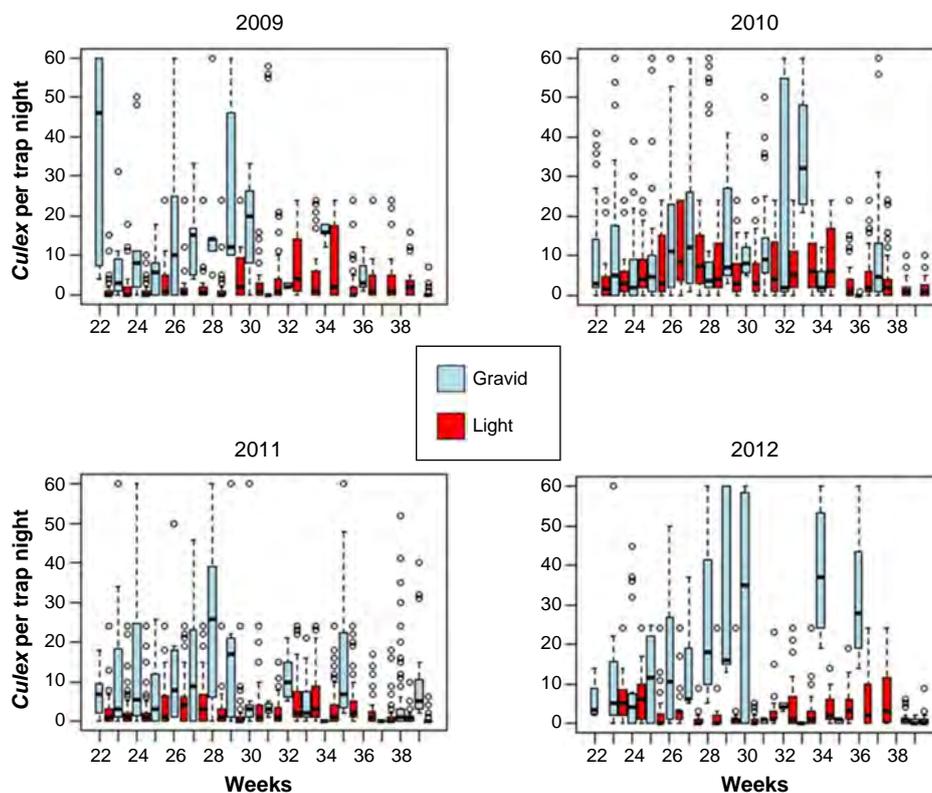


Figure 2. Box plots of the weekly average *Culex* abundance in light and gravid traps from 2009 to 2012.

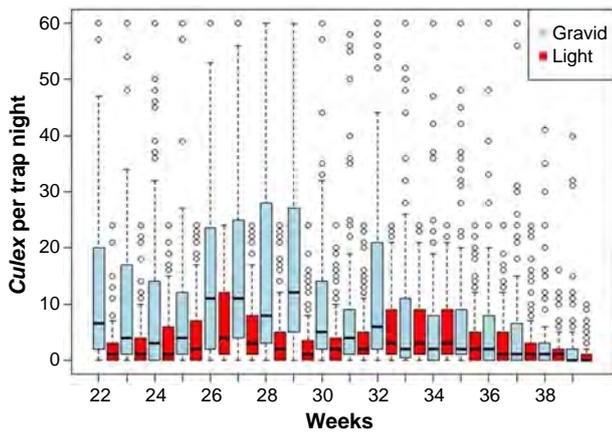


Figure 3. Box plot of overall weekly *Culex* abundance in light and gravid traps with weeks combined for the years from 2009 to 2012.

28% of the variation in *Culex* spp. abundance (adjusted $R^2 = 0.276$) (Table 2). For gravid traps, data were best fit with an analogous model including five weather variables (AIC = 484.2), which explained about 30% of the variability of abundance (adjusted $R^2 = 0.303$) (Table 3). In light traps, the *Culex* spp. abundance was higher with higher temperature in the same week, higher precipitation one, two, and four weeks before, and a lower maximum average wind speed in the same week (Table 4). In gravid traps, the *Culex* spp. abundance was higher with higher temperature in the same week and one week before, higher precipitation two and four weeks before, and lower temperature four weeks before (Table 5).

Spatial Analysis

Of the 119 light trap locations, 53 were in semi-natural areas and 66 were in residential areas. From the light traps, the

average number of *Culex* spp. captured in natural areas was 5.3 (± 5.0 SD) and was 2.7 (± 3.1 SD) in residential areas. Of the 48 gravid trap locations, 29 were in semi-natural areas and 19 were in residential areas. From gravid traps, the average number of *Culex* spp. captured in natural areas was 12.4 (± 8.5 SD), whereas for residential areas it was 11.8 (± 7.5 SD). While both light and gravid trap collections resulted in higher numbers of *Culex* spp. when traps were located in the semi-natural areas (Fig. 5), the difference was statistically significant only for light traps ($P = 0.0002$).

Discussion

Our results demonstrated that *Culex* abundance estimates across urban landscapes vary with the trapping method, and that spatial, temporal, and weather-related factors influence these estimates. In particular, strong winds reduced abundance in light traps but did not noticeably affect gravid trap collections. Abundance estimates were generally higher in semi-natural areas from both trap types, but this difference was stronger for light traps. Both gravid and light traps had higher abundance when set during weeks with warmer temperatures and when conditions were wetter during the previous several weeks. Higher abundance in gravid traps also followed warmer temperatures during the prior week, but this effect was not seen in light traps. Cooler temperatures four weeks prior also increased gravid trap abundance. Gravid traps collected more *Culex* spp. mosquitoes compared to light traps. The differences observed in the collections from light and gravid traps may be related to their tendency to collect mosquitoes from different life stages. It is also possible that gravid traps attract *Culex* spp. mosquitoes more than light traps do, and pull in mosquitoes from larger areas.

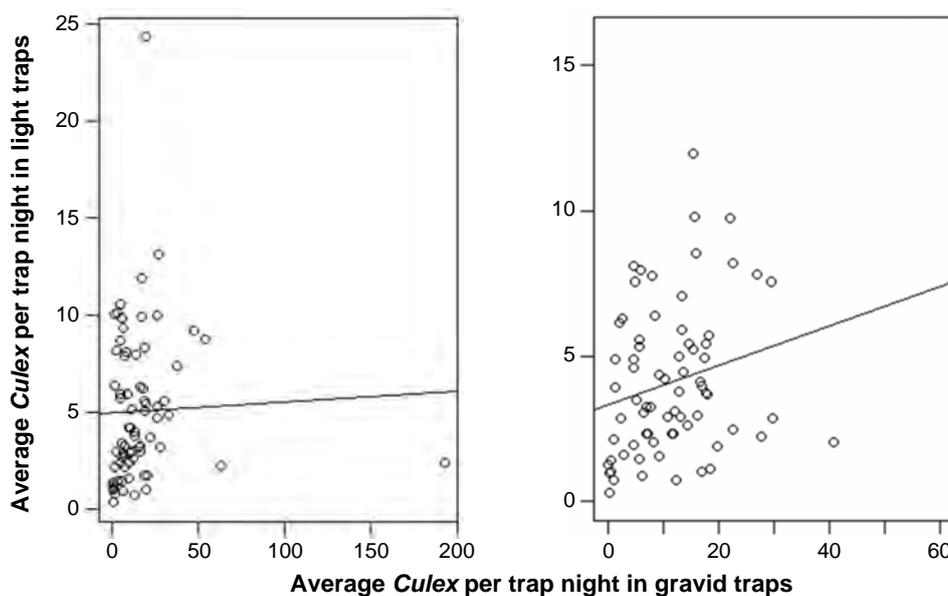


Figure 4. Scatter plots between weekly average *Culex* per trap night in light and gravid collections with all original numbers (left) and after truncating of outliers (right).

**Table 2.** Candidate models for predicting the abundance of *Culex* spp. in light traps.

| MODEL | VARIABLES INCLUDED | K | -2 LOG LIKELIHOOD | AIC | ΔAIC |
|-------|---|----|-------------------|-------|------|
| 1 | Avgtemp_samewk, Precilagwk1–2 and 4, Avgmaxwind_samewk | 6 | 305.6 | 319.6 | 0 |
| 2 | Avgtemp_samewk, Templagwk1, Precilagwk1–2 and 4, Avgmaxwind_samewk | 7 | 304.2 | 320.2 | 0.6 |
| 3 | Avgtemp_samewk, Precilagwk1 and 4, Avgmaxwind_samewk | 5 | 309 | 321.0 | 1.4 |
| 4 | Avgtemp_samewk, Templagwk1, Precilagwk1–4, Avgmaxwind_samewk | 8 | 303.4 | 321.4 | 1.8 |
| 5 | Avgtemp_samewk, Templagwk1, Precilagwk1–4, Avgwindlagwk3, Avgmaxwind_samewk | 9 | 302.5 | 322.5 | 2.9 |
| 6 | Avgtemp_samewk, Templagwk1, Precilagwk1–4, Humiditylagwk2, Avgwindlagwk3, Avgmaxwind_samewk | 10 | 302.2 | 324.2 | 4.6 |
| 7 | Avgtemp_samewk, Templagwk1–2, Precilagwk1–4, Humiditylagwk2, Avgwindlagwk3, Avgmaxwind_samewk | 11 | 302.2 | 326.2 | 6.6 |
| 8 | Null model | 1 | 333.8 | 337.8 | 18.2 |
| 9 | Global (all explanatory variables included) | 26 | 285.1 | 339.1 | 19.5 |

Table 3. Candidate models for predicting the abundance of *Culex* spp. in gravid traps.

| MODEL | VARIABLES INCLUDED | K | -2 LOG LIKELIHOOD | AIC | ΔAIC |
|-------|--|----|-------------------|-------|------|
| 1 | Avgtemp_samewk, Templagwk1 and 4, Precilagwk2 and 4 | 6 | 470.2 | 484.2 | 0 |
| 2 | Avgtemp_samewk, Templagwk1 and 4, Precilagwk4 | 5 | 472.5 | 484.5 | 0.3 |
| 3 | Avgtemp_samewk, Templagwk1 and 4, Precilagwk2 and 4, Avgwindlagwk4 | 7 | 470.2 | 486.2 | 2.0 |
| 4 | Global (all explanatory variables included) | 26 | 448.9 | 502.9 | 18.7 |
| 5 | Null | 1 | 501.2 | 505.2 | 21.0 |

Table 4. Model parameters for the top-ranked model using weather variables to predict the abundance of *Culex* spp. in light traps.

| VARIABLE | PARAMETER ESTIMATE | F-VALUE | P-VALUE | STANDARDIZED PARAMETER ESTIMATE |
|---|--------------------|---------|---------|---------------------------------|
| Average temperature of the same week | 0.219 | 3.04 | 0.003 | 0.332 |
| Precipitation one week before | 0.212 | 2.13 | 0.036 | 0.229 |
| Precipitation two weeks before | 0.183 | 1.80 | 0.076 | 0.199 |
| Precipitation four weeks before | 0.216 | 2.22 | 0.029 | 0.232 |
| Maximum average wind speed of the same week | -0.117 | -1.92 | 0.058 | -0.217 |

Table 5. Model parameters for the top-ranked model using weather variables to predict the abundance of *Culex* spp. in gravid traps.

| VARIABLE | PARAMETER ESTIMATE | F-VALUE | P-VALUE | STANDARDIZED PARAMETER ESTIMATE |
|--------------------------------------|--------------------|---------|---------|---------------------------------|
| Average temperature of the same week | 0.515 | 1.79 | 0.077 | 0.240 |
| Temperature one week before | 0.746 | 2.25 | 0.028 | 0.313 |
| Temperature four weeks before | -0.721 | -3.59 | 0.0006 | -0.387 |
| Precipitation two weeks before | 0.437 | 1.44 | 0.153 | 0.146 |
| Precipitation four weeks before | 0.665 | 2.21 | 0.031 | 0.221 |

Temperature is an important factor in mosquito abundance because it affects the life history traits of mosquitoes. The positive association between prior temperature and *Culex* abundance has been observed in several other studies.^{21,48–52} Mechanistically, high temperatures may support faster growth of mosquito larvae⁵³ and adult emergence and increase the number captured. However, following emergence, the

ambient temperature may either increase or decrease adult mosquito longevity. Lebl et al found that higher temperatures two weeks prior to capture increased *Culex* abundance in light traps²¹, while accumulated temperature one to four weeks before capture was negatively correlated with *C. pipiens* abundance.⁵⁴ These equivocal findings suggest that there may be a temperature threshold, above or below which mosquito

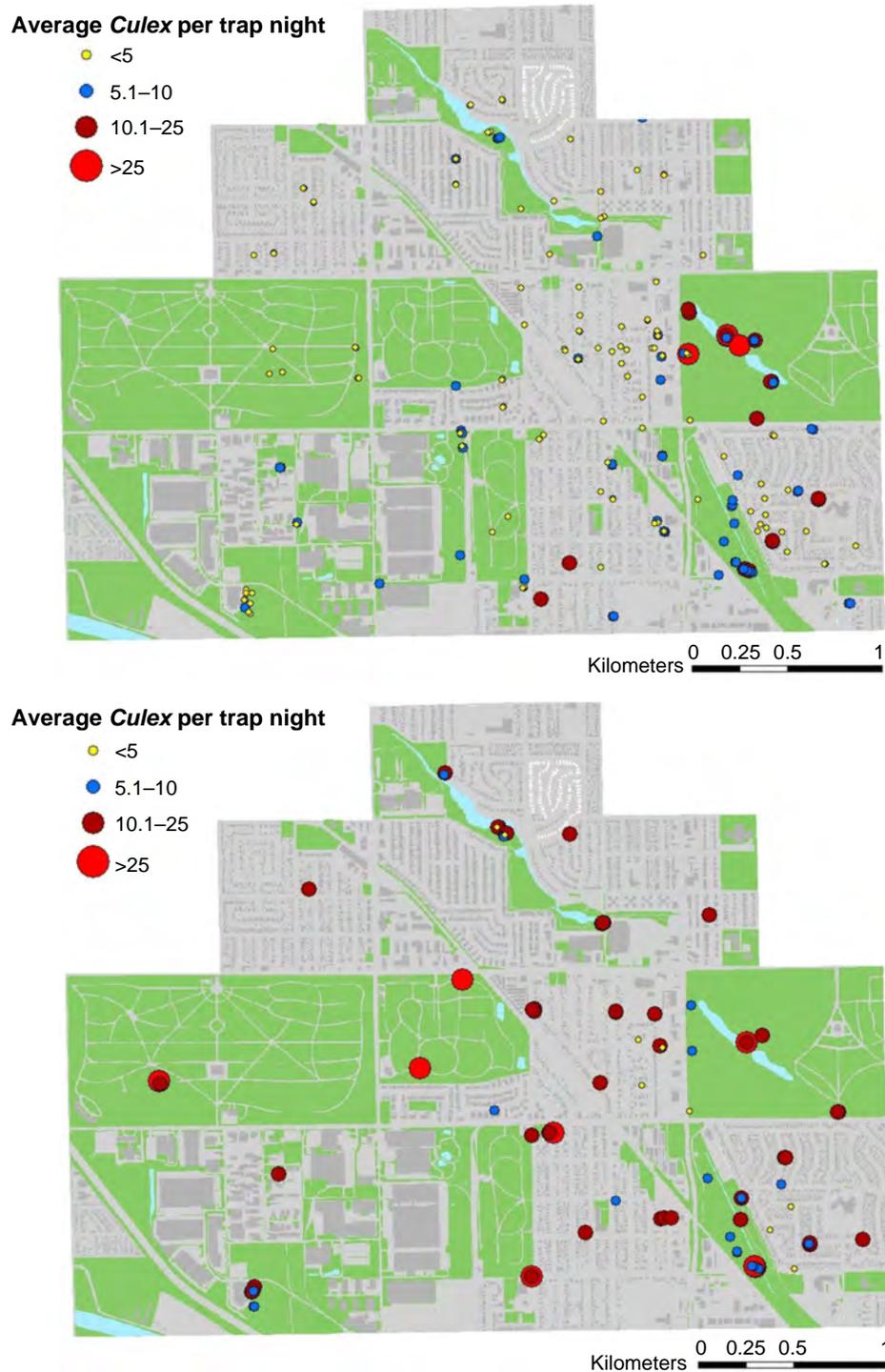


Figure 5. Map showing the spatial distribution of *Culex* per trap night in light (top) and gravid collections (bottom).

survival and activity markedly decrease. Higher abundance of mosquitoes in gravid traps after cooler temperatures four weeks before suggests that mosquito longevity may increase in cooler temperatures, making a larger pool of adults ready to oviposit with higher temperatures.⁵⁵

Precipitation also appears to drive *Culex* abundance. The positive relationship between precipitation at one to four weeks prior and *Culex* abundance has also been observed in other studies.^{21,42,45,47} However, the relationship between precipitation

and *Culex* abundance is not necessarily linear. Pecoraro et al found no association between weekly precipitation and *Culex* abundance,⁵¹ but at more protracted temporal scales, correlations were positive in some years and negative in others.⁴⁸ Lebl et al found that precipitation had a weaker association with abundance than other weather variables, with higher precipitation over 10 weeks associated with higher abundance. In the same Chicago study system, Gardner et al documented that *Culex* larval abundance was associated with low rainfall,



and suggested that precipitation greater than 3.5 cm during a single week may *flush* immature *Culex* out of larval habitats.²⁸ Our data with adult mosquitoes demonstrate a similar pattern, where precipitation in the weeks prior to sampling increases adult abundance by providing habitat for adult females to lay egg rafts. Alternatively, this relationship between high *Culex* abundance following rain events might have more to do with favorable ambient conditions for adults (eg, higher humidity reducing desiccation risk), which could promote activity and increase trapping success. Though the gravid traps can themselves act as a larval habitat because of the water availability in those traps, we found positive relationships between prior rainfall and *Culex* spp. abundance estimates in both light and gravid traps, without an indication that gravid traps collected more mosquitoes during dry periods.

Wind speed affects mosquito host-seeking activities and flight direction. In this study, the maximum average wind speed of the same week of capture was negatively associated with *Culex* abundance in light traps but not gravid traps. The reason for this difference may be associated with trap placement. CDC light traps were set approximately 1.5 m above the ground, whereas gravid traps were placed directly on the ground: it is possible that this subtle difference in trap height may have exposed host-seeking and adult females to different wind conditions.⁵⁶ Indeed, Hamer et al found that *Culex* spp. may move as far as 2.48 km, but that this dispersal was likely mediated by wind.⁴² Similarly, Lebl et al found that average wind speed three weeks prior to capture was negatively associated with *Culex* abundance.²¹

Landscape features may also affect mosquito production through variation in breeding habitat and resting places for adult mosquitoes. We found that in light traps, more *Culex* spp. mosquitoes were captured in natural areas than in residential areas, whereas in the gravid traps, this variability was negligible. Availability of hosts and competition with natural container habitats, respectively, may modify these relationships. For example, more birds in natural areas could result in more host-seeking mosquitoes being present and thus available for light trap capture. Lower numbers of *Culex* mosquitoes in light traps in residential areas may also be related to mosquito abatement practices that target those areas, such as pesticide treatments for adult mosquitoes and the placement of larvicides in urban catch basins.⁵⁷ In a study conducted in Suffolk County, New York, the highest abundance of *C. pipiens* was in areas where WNV was mostly prevalent in birds, not in humans, and this may be the case in the current study region as well.⁵⁸ Further, comparison of our findings to other studies is somewhat confounded by how landscapes are defined. Our study occurred within an urban area, and our semi-natural areas were relatively small patches within a highly urbanized landscape. If we had used the same index of urbanization that was used to assess *Culex* spp. abundance in New York, for example, all our sites would have been classified as “urban”.⁵⁹

The estimated abundance of mosquitoes was not clearly correlated with mosquito infection rates or negative public health outcomes. The Illinois Department of Public Health reported only one human WNV case in Cook County Illinois in 2009 when abundance estimates from gravid traps were higher than any of the four years. There were 30 cases of WNV reported in 2010, 22 cases in 2011, and 174 cases in 2012, clearly indicating that 2012 was a locally notable WNV outbreak year.⁶⁰ During 2012, temperatures were above average (hot) and rainfall was below average (dry), supporting prior patterns of higher MIR observed by Ruiz et al.⁶¹ The MIR was also higher in 2012 in Cook County at large, but the local MIR in 2012 in our smaller study area was higher in 2009 and 2010 than in 2012, highlighting the variability of the WNV transmission potential and surveillance outcomes at different scales. Messina et al found that MIR in the Chicago area was not associated spatially with human illness after controlling for other factors in a multivariate regression, and differences in mosquito abundance or a failure to capture temporal and spatial dynamics may have accounted for this.⁶² It was not possible to compare the relationship between mosquito abundance, MIR, and the reported WNV human illness at a broader level due to the lack of comprehensive mosquito abundance data at that scale. Future work should include the collection of additional abundance estimates and consider alternative spatio-temporal approaches.

Mosquito vector abundance is an important theoretical predictor of human infection, especially for multi-host pathogens. The weak correlation between the fine-scale mosquito abundance estimates and regional measures of human WNV illnesses observed in our study area may be related to the differences in the geographic scale of analysis. Our data demonstrate that in the Cook County, Illinois, gravid and light traps set at the same time in similar conditions do not produce identical abundance estimates. These findings highlight both the importance of local weather and landscape features in combination with the trapping methods for the development of mosquito abundance measures that are relevant to public health. Our findings indicate that abundance estimates obtained from only one type of trap, for a short period of time, and from a limited sampling of landscape types, may not truly represent mosquito abundance. Consequently, investment into long-term surveillance that accounts for different habitats within a control district, and that implements different trapping methods, will give better estimates of mosquito abundance for use in the assessment of arboviral transmission risk in human populations.

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Author Contributions

Conceived and designed the experiments: SK, MOR. Analyzed the data: SK, MOR, TKA, GLH. Wrote the first draft of the manuscript: SK, MOR. Contributed to the writing of the manuscript: SK, MOR, TKA, GLH. Agreed with manuscript results and conclusions: UDK, EDW. Made critical revisions and approved the final version: TLG, BLK. All the authors reviewed and approved the final manuscript.

REFERENCES

- World Health Organization. Vector-borne diseases; 2015. Available at: <http://www.who.int/mediacentre/factsheets/fs387/en/>. Accessed February 15, 2016.
- Weaver SC, Reisen WK. Present and future arboviral threats. *Antiviral Res.* 2010;85(2):328–45.
- Anderson JR, Rico-Hesse R. *Aedes aegypti* vectorial capacity is determined by the infecting genotype of dengue virus. *Am J Trop Med Hyg.* 2006;75(5):886–92.
- Ceccato P, Vancutsem C, Klaver R, Rowland J, Connor SJ. A vectorial capacity product to monitor changing malaria transmission potential in epidemic regions of Africa. *Re Dai Yi Xue Za Zhi.* 2012;2012:1–6.
- Garrett-Jones C, Shidrawi G. Malaria vectorial capacity of a population of *Anopheles gambiae*: an exercise in epidemiological entomology. *Bull World Health Organ.* 1969;40(4):531–45.
- Scott TW, Morrison AC. *Aedes aegypti* density and the risk of dengue-virus. In: Takken W, Scott TW, eds. *Ecological Aspects for Application of Genetically Modified Mosquitoes*. Vol 2. Dordrecht: FRONTIS; 2003:187.
- Ciota AT, Kramer LD. Vector-virus interactions and transmission dynamics of West Nile virus. *Viruses.* 2013;5(12):3021–47.
- Kilpatrick AM, Kramer LD, Campbell SR, Alleyne EO, Dobson AP, Daszak P. West Nile virus risk assessment and the bridge vector paradigm. *Emerg Infect Dis.* 2005;11(3):425–9.
- Gujral IB, Zielinski-Gutierrez EC, LeBailly A, Nasci R. Behavioral risks for West Nile virus disease, northern Colorado, 2003. *Emerg Infect Dis.* 2007;13(3):419.
- Bolling BG, Barker CM, Moore CG, Pape WJ, Eisen L. Seasonal patterns for entomological measures of risk for exposure to *Culex* vectors and West Nile virus in relation to human disease cases in northeastern Colorado. *J Med Entomol.* 2009;46(6):1519–31.
- Kilpatrick AM, Pape WJ. Predicting human West Nile virus infections with mosquito surveillance data. *Am J Epidemiol.* 2013;178(5):829–35.
- Reisen WK. Landscape epidemiology of vector-borne diseases. *Annu Rev Entomol.* 2010;55:461–83.
- Andreadis TG. The contribution of *Culex pipiens* complex mosquitoes to transmission and persistence of West Nile virus in North America. *J Am Mosq Control Assoc.* 2012;28(4 s):137–51.
- Hamer GL, Kitron UD, Brawn JD, et al. *Culex pipiens* (Diptera: Culicidae): a bridge vector of West Nile virus to humans. *J Med Entomol.* 2008;45(1):125–8.
- Mutebi JP, Savage HM. Discovery of *Culex pipiens pipiens* form molestus in Chicago. *J Am Mosq Control Assoc.* 2009;25(4):500–3.
- Crans WJ. A classification system for mosquito life cycles: life cycle types for mosquitoes of the northeastern United States. *J Vector Ecol.* 2004;29:1–10.
- Vinogradova EB. *Culex pipiens pipiens* Mosquitoes: Taxonomy, Distribution, Ecology, Physiology, Genetics, Applied Importance and Control. Sofia, Bulgaria: Pensoft Publishers; 2000.
- Hartley DM, Barker CM, Le Menach A, Niu T, Gaff HD, Reisen WK. Effects of temperature on emergence and seasonality of West Nile virus in California. *Am J Trop Med Hyg.* 2012;86(5):884–94.
- Ciota AT, Matacchiero AC, Kilpatrick AM, Kramer LD. The effect of temperature on life history traits of *Culex* mosquitoes. *J Med Entomol.* 2014;51(1):55–62.
- Andreadis S, Dimotisiou O, Savopoulou-Soultani M. Variation in adult longevity of *Culex pipiens* f. *pipiens*, vector of the West Nile Virus. *Parasitol Res.* 2014;113(11):4315–9.
- Lebl K, Brugger K, Rubel F. Predicting *Culex pipiens/restuans* population dynamics by interval lagged weather data. *Parasit Vectors.* 2013;6:129–39.
- Carrieri M, Fariselli P, Maccagnani B, Angelini P, Calzolari M, Bellini R. Weather factors influencing the population dynamics of *Culex pipiens* (Diptera: Culicidae) in the Po Plain Valley, Italy (1997–2011). *Environ Entomol.* 2014;43(2):482–90.
- DeGaetano AT. Meteorological effects on adult mosquito (*Culex*) populations in metropolitan New Jersey. *Int J Biometeorol.* 2005;49(5):345–53.
- Walsh AS, Glass GE, Lesser CR, Curriero FC. Predicting seasonal abundance of mosquitoes based on off-season meteorological conditions. *Environ Ecol Stat.* 2008;15(3):279–91.
- Chase JM, Knight TM. Drought-induced mosquito outbreaks in wetlands. *Ecol Lett.* 2003;6(11):1017–24.
- Cailly P, Balenghien T, Ezanno P, Fontenille D, Toty C, Tran A. Role of the repartition of wetland breeding sites on the spatial distribution of *Anopheles* and *Culex*, human disease vectors in Southern France. *Parasit Vectors.* 2011;6:65–72.
- Jones CE, Lounibos LP, Marra PP, Kilpatrick AM. Rainfall influences survival of *Culex pipiens* (Diptera: Culicidae) in a residential neighborhood in the mid-Atlantic United States. *J Med Entomol.* 2012;49(3):467–73.
- Gardner AM, Hamer GL, Hines AM, Newman CM, Walker ED, Ruiz MO. Weather variability affects abundance of larval *Culex* (Diptera: Culicidae) in storm water catch basins in suburban Chicago. *J Med Entomol.* 2012;49(2):270–6.
- Gardner AM, Anderson TK, Hamer GL, et al. Terrestrial vegetation and aquatic chemistry influence larval mosquito abundance in catch basins, Chicago, USA. *Parasit Vectors.* 2013;6:9–19.
- Gardner AM, Allan BF, Frisbie LA, Muturi EJ. Asymmetric effects of native and exotic invasive shrubs on ecology of the West Nile Virus vector *Culex pipiens* (Diptera: Culicidae). *Parasit Vectors.* 2015;16:329–37.
- Brown H, Diuk-Wasser M, Andreadis T, Fish D. Remotely-sensed vegetation indices identify mosquito clusters of West Nile virus vectors in an urban landscape in the northeastern United States. *Vector Borne Zoonotic Dis.* 2008;8(2):197–206.
- Crowder DW, Dykstra EA, Brauner JM, et al. West Nile virus prevalence across landscapes is mediated by local effects of agriculture on vector and host communities. *PLoS One.* 2013;8(1):e55006.
- Chuang T-W, Hockett CW, Kightlinger L, Wimberly MC. Landscape-level spatial patterns of West Nile virus risk in the Northern Great Plains. *Am J Trop Med Hyg.* 2012;86(4):724–31.
- Landau KI, van Leeuwen WJ. Fine scale spatial urban land cover factors associated with adult mosquito abundance and risk in Tucson, Arizona. *J Vector Ecol.* 2012;37(2):407–18.
- Trawinski PR, Mackay DS. Identification of environmental covariates of West Nile virus vector mosquito population abundance. *Vector Borne Zoonotic Dis.* 2010;10(5):515–26.
- Reisen W, Pfuntner A. Effectiveness of five methods for sampling adult *Culex* mosquitoes in rural and urban habitats in San Bernardino County, California. *J Am Mosq Control Assoc.* 1987;3(4):601–6.
- Dimenna MA, Bueno R Jr, Parmenter RR, et al. Comparison of mosquito trapping method efficacy for West Nile virus surveillance in New Mexico. *J Am Mosq Control Assoc.* 2006;22(2):246–53.
- Moore CG, McLean R, Mitchell CJ, et al. *Guidelines for Arbovirus Surveillance Programs in the United States*. Vol 500. Atlanta, GA: Department of Health and Human Services. Division of Vector-Borne Infectious Diseases; 1993.
- Williams GM, Gingrich JB. Comparison of light traps, gravid traps, and resting boxes for West Nile virus surveillance. *J Vector Ecol.* 2007;32(2):285–91.
- Hribar LJ, Vlach JJ, Demay DJ, et al. Mosquitoes infected with West Nile virus in the Florida Keys, Monroe County, Florida, USA. *J Med Entomol.* 2003;40(3):361–3.
- Krebs BL, Anderson TK, Goldberg TL, et al. Host group formation decreases exposure to vector-borne disease: a field experiment in a 'hotspot' of West Nile virus transmission. *Proc Biol Sci.* 2014;281(1796):20141586.
- Hamer GL, Anderson TK, Donovan DJ, et al. Dispersal of adult *Culex* mosquitoes in an urban West Nile virus hotspot: a mark-capture study incorporating stable isotope enrichment of natural larval habitats. *PLoS Negl Trop Dis.* 2014;8(3):e2768.
- Hamer GL, Walker ED, Brawn JD, et al. Rapid amplification of West Nile virus: the role of hatch-year birds. *Vector Borne Zoonotic Dis.* 2008;8(1):57–68.
- Harrington LC, Poulson RL. Considerations for accurate identification of adult *Culex restuans* (Diptera: Culicidae) in field studies. *J Med Entomol.* 2008;45(1):1–8.
- Hamer GL, Kitron UD, Goldberg TL, et al. Host selection by *Culex pipiens* mosquitoes and West Nile virus amplification. *Am J Trop Med Hyg.* 2009;80(2):268.
- Centers for Disease Control and Prevention. Software for mosquito surveillance. Fort Collins, Colorado; 2006. Available at: <http://www.cdc.gov/ncidod/dvbid/westnile/software.htm>. Accessed January 15, 2015.
- Akaike H. A new look at the statistical model identification. *IEEE Trans Autom Control.* 1974;19(6):716–23.
- Jacob BG, Gu W, Caamano EX, Novak RJ. Developing operational algorithms using linear and non-linear squares estimation in Python® for the identification of *Culex pipiens* and *Culex restuans* in a mosquito abatement district (Cook County, Illinois, USA). *Geospat Health.* 2009;3(2):157–76.
- Mulatti P, Ferguson HM, Bonfanti L, Montarsi F, Capelli G, Marangon S. Determinants of the population growth of the West Nile virus mosquito vector *Culex pipiens* in a repeatedly affected area in Italy. *Parasit Vectors.* 2014;7(1):26–36.
- Paz S, Albersheim I. Influence of warming tendency on *Culex pipiens* population abundance and on the probability of West Nile Fever outbreaks (Israeli case study: 2001–2005). *Ecohealth.* 2008;5(1):40–8.



51. Pecoraro HL, Day HL, Reineke R, et al. Climatic and landscape correlates for potential West Nile virus mosquito vectors in the Seattle region. *J Vector Ecol.* 2007;32(1):22–8.
52. Wang J, Ogden NH, Zhu H. The impact of weather conditions on *Culex pipiens* and *Culex restuans* (Diptera: Culicidae) abundance: a case study in Peel region. *J Med Entomol.* 2011;48(2):468–75.
53. Hagstrum DW, Workman EB. Interaction of temperature and feeding rate in determining the rate of development of larval *Culex tarsalis* (Diptera, Culicidae). *Ann Entomol Soc Am.* 1971;64(3):668–71.
54. Roiz D, Ruiz S, Soriguer R, Figuerola J. Climatic effects on mosquito abundance in Mediterranean wetlands. *Parasit Vectors.* 2014;7:333–45.
55. Mordecai EA, Paaijmans KP, Johnson LR, et al. Optimal temperature for malaria transmission is dramatically lower than previously predicted. *Ecol Lett.* 2013;16(1):22–30.
56. Darbro JM, Harrington LC. Bird-baited traps for surveillance of West Nile mosquito vectors: effect of bird species, trap height, and mosquito escape rates. *J Med Entomol.* 2006;43(1):83–92.
57. Harbison JE, Henry M, Xamplas C, Berry R, Bhattacharya D, Dugas LR. A comparison of FourStar™ briquets and Natular™ XRT tablets in a North Shore suburb of Chicago, IL. *J Am Mosq Control Assoc.* 2014;30(1):68–70.
58. Rochlin I, Ginsberg HS, Campbell SR. Distribution and abundance of host-seeking *Culex* species at three proximate locations with different levels of West Nile virus activity. *Am J Trop Med Hyg.* 2009;80(4):661–8.
59. Drummond CL, Drobnack J, Backenson PB, Ebel GD, Kramer LD. Impact of trap elevation on estimates of abundance, parity rates, and body size of *Culex pipiens* and *Culex restuans* (Diptera: Culicidae). *J Med Entomol.* 2006;43(2):177–84.
60. IDPH. West Nile Virus; 2015. Available at: <http://www.dph.illinois.gov/topics-services/diseases-and-conditions/west-nile-virus>. Accessed January 15, 2016.
61. Ruiz MO, Chaves LF, Hamer GL, et al. Local impact of temperature and precipitation on West Nile virus infection in *Culex* species mosquitoes in northeast Illinois, USA. *Parasit Vectors.* 2010;3(1):19–34.
62. Messina JP, Brown W, Amore G, Kitron UD, Ruiz MO. West Nile virus in the Greater Chicago area: a geographic examination of human illness and risk from 2002 to 2006. *URISAJ.* 2011;23:5–22.