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# An ecological and social approach to the distribution of vector and nuisance mosquito species across residential land use types

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Mosquito abundance and distribution are related to environmental variables like rainfall and land cover which shape available aquatic habitat for oviposition and juvenile development. Many mosquito species rely on natural water sources for oviposition and juvenile development. However, others have evolved to occupy urban niches and artificial habitats associated with urbanization and human-dominated environments, like tires or storm drains. Additionally, as land cover changes over rural–urban gradients, mosquito species richness decreases via reduced habitat heterogeneity. Human exposure to mosquitoes is a product of environmental processes, and human behaviors related to mosquito control and personal protection. To understand mosquito distribution from both perspectives, we conducted a study with paired entomological and behavioral science data collection. We collected mosquitoes at 40 sites across a rural–urban gradient of 30 residential properties and 10 recreational forest sites in Bangor, Maine, and conducted a juvenile habitat assessment on the residential properties. Additionally, a Knowledge, Attitudes and Practice survey was administered among property owners to understand factors that affect engagement in mosquito control and protective behaviors. Mosquito abundance was highest in forested and rural residential sites. Nuisance species abundance was highest at rural residential sites, while vector species abundance was highest in urban residential sites. Despite 54% respondents reporting mosquitoes as a nuisance, only 10.5% and 5.3% reported frequent engagement in preventative behaviors such as wearing mosquito repellent or protective clothing, respectively. This study builds on literature demonstrating patterns of vector mosquito abundance in residential areas and exploration of resident mosquito control practices.

*Keywords:* Eastern equine encephalomyelitis, landscape, surveillance, vector ecology, West Nile virus

## Introduction

Mosquito species distributions and the risk of human exposure to mosquitoes as disease vectors and nuisance pests are driven by complex environmental and social dynamics. Due to human creation and modification of juvenile mosquito habitats and subsequent human interactions with adult mosquitoes, insect distributions can be approached as products of a social–ecological system, in which human and environmental factors interact and feedback to each other at various spatial scales (Colding and Barthel 2019). Social dynamics at large scales (eg urbanization, globalization, commercial and residential development) and small scales (eg decisions about property and landscape management, and personal protective behaviors) affect mosquito ecology through the alteration of available mosquito habitat (Gratz 1999, Bowden et al. 2011). Some disease vector species have spread across the globe as a result of these human processes, such as *Aedes aegypti* and *Aedes albopictus* (Moore and Mitchell 2009, Powell and Tabachnick 2013).

The distribution of mosquito species, which may be disease vectors, biting pests, or both, is a consequence of the available aquatic habitat for oviposition and larval development and terrestrial habitat to support adult mosquitoes (Reiskind et al. 2017, Wilke et al. 2019). It is of public health and pest management interest to integrate the investigation of ecological and social drivers of mosquito species distribution to understand disease risk implications across regional landscapes, where human behavior can contribute to and change in response to the abundance of mosquitoes. Previous studies that explicitly integrate social and biophysical drivers of mosquito distributions at the residential scale are limited. While more common in countries with a higher mosquito-borne disease (MBD) burden, the first United States (US) study that reports integrating household social and entomological data collection found that perceptions, but not knowledge, of West Nile Virus (WNV) were related to the presence of larvae-positive containers on properties among participants in suburban upstate New York (Tuiten et al. 2009). A subsequent study integrating social science surveys and entomological assessments was conducted in the Baltimore–Washington, DC metropolitan area (Dowling et al. 2013). The researchers found that reported engagement in mosquito larvae source reduction was correlated with lower observations of *Culex pipiens* and *Ae. albopictus* larvae-positive containers on participant properties. It is important to continue to unravel this social and biophysical link at varying spatial scales and across diverse US regions to add context to our understanding of mosquito distributions and the implications for public health and pest management.

In the northeastern US mosquitoes are both pests and vectors of disease. In the state of Maine, where our study took place, there are more than 45 documented mosquito species. About half of these species have been shown to be competent disease vectors in laboratory and experimental studies, and among these, several species are recognized as key amplifying and bridge vectors of zoonotic pathogens. WNV, first reported in New York in 1999, has become endemic in the 2 decades since its introduction and is the most common MBD in the US (Ronca et al. 2021). In the northeast US, WNV is maintained in enzootic and epizootic cycles by *Culex restuans*, *Cx. pipiens*, and *Cx. salinarius*, with the latter 2 species serving as the main bridge vectors of WNV to humans in this region (Andreadis 2004). Eastern equine encephalitis virus (EEEV) is predominantly transmitted by *Culiseta melanura* (McMillan et al. 2020). EEEV is maintained in an avian enzootic cycle, but occasionally EEEV cases spillover into livestock and humans (Armstrong and Andreadis 2013). Jamestown Canyon virus (JCV) is vectored by several boreal mosquito species, notably *Aedes vexans* and *Ochlerotatus canadensis* (Crans 2004, McMillan et al. 2020). The reservoir hosts of JCV in the northeast are white-tailed deer, and although human cases are generally rare, the increase in cases in recent decades is of public health concern (Andreadis et al. 2008). In addition to their ability to transmit diseases, more than half of the mosquito species in this region are known to be aggressive human-biters, such as *Aedes japonicus,* and *Oc. canadensis* (Holman et al. 2006). Studies have documented that residents and visitors in the northeast perceive mosquitoes as nuisance pests, including a study conducted in New Jersey in which 59.5% of resident participants reported that mosquitoes prevented their enjoyment of outdoor activities (Halasa et al. 2014). Additionally, in research conducted at Acadia National Park, Maine, 60% of park visitors indicated that they perceived increased presence of mosquitoes to be an important impact of climate change within the park (De Urioste-Stone 2016).

Human exposure to mosquitoes is in part a consequence of mosquito species distributions in the landscape, which is driven largely by environmental factors; land cover, and human land use patterns can alter the risk of MBD (Franklinos et al. 2019, Ortiz et al. 2021). For example, in New Haven, CT, *Cx. pipiens*, the primary vector of WNV to humans, is more strongly associated with urban land use compared to *Culex* species that only act as enzootic vectors (Brown et al. 2008). Reduced landscape heterogeneity in urban landscapes has also been associated with low mosquito species diversity in Chicago, IL, where WNV infection rates in *Cx. pipiens* increased in flat landscapes with high impervious surface cover (Chavez et al. 2011). More broadly, review studies have examined how water retention systems, deforestation, agricultural development, and urbanization have been associated with risk of MBD transmission on a global scale (Norris 2004).

Mosquito species distributions are dependent on the types of available habitat for mosquito breeding due to differences in the oviposition habitat use of gravid female mosquitoes. For example, oviposition by some species such as *Cx. pipiens* is associated with artificial human-made containers of water such as storm drain infrastructure, trash cans, and garden equipment in urban environments (Marini et al. 2020, Leisnham et al. 2021). Other urban mosquitoes like *Aedes albopictus* and *Ae. aegypti* are more strongly associated with smaller artificial human-made containers like planters, buckets, and tarps (Carrieri 2003, LaDeau et al. 2013). *Culiseta melanura* and *Coquillettidia perturbans* are associated with oviposition in natural aquatic habitat such as rural wetland or floodplain landscapes (Bowden et al. 2011, Skaff et al., 2017). As land cover changes from more to less forested, some adult mosquito species such as *Cx. territans* may decrease in abundance as a function of canopy cover and host presence (Burkett-Cadena 2013). However, in Virginia field collections, adult *Cx.* spp. and *Ae. albopictus* abundance were shown to not be significantly correlated with canopy cover (Deichmeister and Telang 2011). In general, mosquito species diversity tends to be lower in urban habitats compared to rural habitats due to higher concentration of impervious surface cover, limited diversity of breeding habitat, and higher temperatures (LaDeau et al. 2013, Gardner et al. 2014, de Valdez 2017, Zettle et al. 2022). Urban environments also tend to have a higher density of vector species compared to rural environments due to the availability of suitable habitat that disease vectors such as *Cx. pipiens* have evolved to occupy in human-dominated environments, such as in buckets, tires, or storm drain infrastructure (Becker et al. 2014). Human behaviors, such as those which affect larval mosquito habitat sources, can also impact mosquito abundance, species distributions, and exposure to mosquitoes in a landscape (Schrama et al. 2020).

In turn, the abundance and species distributions of mosquitoes may also affect human interaction with the landscape (Tangena et al. 2017). In residential neighborhoods, household mosquito abundance can be driven not only by landscape context but also by household management practices, such as emptying artificial water containers (Pai et al. 2005). While reducing mosquito abundance through habitat modification is an option on one's private residence, human exposure to mosquitoes and mosquito bites also occurs in recreational outdoor settings, such as wooded areas that support large mosquito populations (Healy et al. 2014). This exposure to mosquitoes can be altered by preventive health behaviors such as use of protective clothing, personal repellent, or avoiding the outdoors altogether (Prabaningrum et al. 2020). Individuals decide whether to engage in mosquito control or exposure prevention behaviors based on factors such as personal experience with and knowledge of mosquito ecology, attitudes surrounding effectiveness of mosquito control and exposure prevention strategies, and perceptions of social norms (Bosnjak et al. 2020). Additionally, exposure to mosquitoes in recreation settings may influence individuals' perceptions and ultimate engagement in control practices at home, and vice versa. These dynamics of landscape–human interactions that determine decision-making processes can be measured using resident surveys

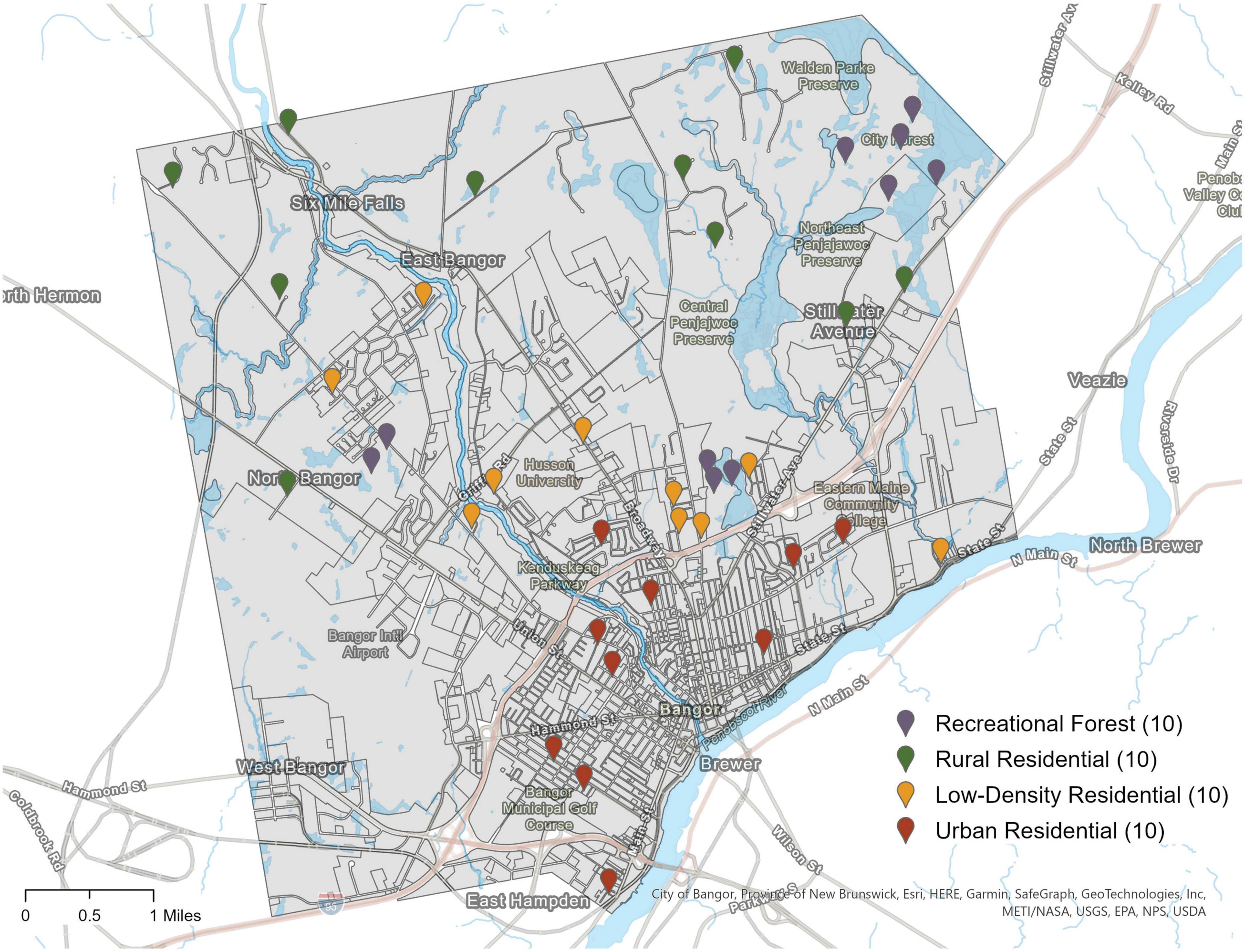


**Fig. 1.** Map of the study area in Bangor, Maine, showing the locations of 40 mosquito trapping sites along an urban–rural gradient. Trapping sites were categorized into 3 residential land use classes—urban, low-density, and rural residential (30 sites total)—and included 10 additional sites in recreational forested areas (Brown Woods, Essex Woods, and Bangor City Forest). LUC were assigned based on the City of Bangor land parcel classification.

that apply psychosocial theories to test a priori hypotheses about determinants of behavior.

This study aimed to document mosquito species distributions over residential land use categories (LUC) and human behavioral responses to mosquitoes and is novel in its application of integrated biophysical and social science methodology in a dominantly rural landscape. The study had 2 main objectives: first to assess whether there are differences in mosquito abundance, further classified into (i) vector species abundance, (ii) nuisance species abundance, and/or (iii) artificial container-breeding species abundance across residential LUC in Bangor, Maine, and second, to investigate residents' knowledge, attitudes, and practices (KAP) surrounding mosquito control and prevention behaviors, and the association between reported behaviors, observed mosquitoes and available mosquito habitat.

## Materials and Methods

### Site Selection and Property Recruitment

We conducted our study on residential properties and recreational forests in Bangor, Maine (44.80°N, 68.77°W), a US city of 34.26 miles$^2$ and a population of 31,191 with a population density of 927 people per square mile (U.S. Census Bureau 2021). The city of Bangor and the urban to rural gradient it encompasses is a novel case for the study of mosquito species distributions due to its location in the largely rural and forested state of Maine, which has no statewide mosquito control program. To assess the relationship between mosquito distributions and land use we selected 40 sites throughout Bangor for data collection. Thirty of the sites were randomly selected residential properties along an urban to rural gradient, with 10 sites from each of the following residential LUC: urban residential, low-density residential, and rural residential (Fig. 1). Residential land parcel data were acquired from the Bangor City Planning Office. To understand the types of mosquitoes that Bangor residents are exposed to in public areas, an additional 10 sites were selected within recreational city forests: 2 within Brown Woods, 3 within Essex Woods, and 5 within Bangor City Forest (Fig. 1). Participants were recruited from the randomly selected residential properties by approaching property owners with a request to participate in the study. If property owners from the randomly selected list were not home, or otherwise unable to participate, we instead recruited a neighboring property within the same land use category.

### Mosquito Trapping

Mosquitoes were trapped from the week of 7 June 2021 through the week of 6 September 2021, for a total of 14 consecutive trapping weeks. Mosquitoes were trapped weekly at all 40 sites. Sites were randomly assigned to 1 of 4 groups, with 1 group sampled each of the 4 trap nights every week. Each week the sampling order was randomly determined. One of each gravid and light traps were set at each site. Traps were set between the hours of 3 PM to 11 AM on 4 trap nights each week. CDC Gravid Traps (catalog #6545-01-457-5511, John W. Hock Company, Florida, USA) were baited with 1 gallon of grass-clipping infused tap water, which was allowed to infuse for 24 to 48 h prior to deployment. Gravid traps were placed on the ground near low vegetation in a shaded area. Unbaited CDC Miniature Light Traps (catalog #3740-01-106-0091, John W. Hock Company, Florida) were hung on a tree branch 4.5 to 5 ft above the ground. Upon collection, mosquito traps were immediately placed in freezers at −30 °C to maintain sample integrity for identification. Mosquitoes were sorted from bycatch and sexed. Males and females were counted, and females were identified to species using a dichotomous key (Andreadis et al. 2005).

All identified mosquitoes were categorized by property as vector vs nonvector species, nuisance vs nonnuisance species and artificial container breeding vs nonartificial container species, based on literature review (Supplementary Table S1). A nuisance mosquito species was defined as any species known to bite humans. Vector mosquitoes were defined as any species capable of transmitting WNV, EEEV, or JCV in nature. Artificial container-breeding mosquito species were defined as any species which prefers to oviposit in small human-made containers. Mosquito species were assigned to more than 1 category, where applicable. The number of vector species, nuisance species, and artificial container-breeding species collected were calculated for each property. Mosquito abundance was calculated as the average number of mosquitoes collected each week at each site. For the recreational forest LUC, only abundance data are reported due to the large number of specimens.

To quantify the differences in mosquito diversity across sites, we calculated Shannon's Diversity Indices, including the overall species diversity index and the equity index across LUC. The equations used were:

Shannon's diversity index ($H'$):

$$H' = -\sum_{i=1}^{s} p_i \ln p_i$$

where $S$ is the total number of species, $p_i$ is the proportion of individuals belonging to species $i$ ($p_i = n_i/N$). $n_i$ is the number of individuals of species $i$, and $N$ is the total number of individuals across all species.

Shannon's evenness index ($E$):

$$E = \frac{H'}{\ln S}$$

where $H'$ is the Shannon diversity index and $S$ is the total number of species. The evenness index ranges from 0 to 1. Values closer to 1 indicate a more even distribution of individuals among species.

## Microclimate Monitoring

Temperature (°C) and relative humidity (%) were monitored at each mosquito collection site. Microclimate conditions were recorded using BlueMaestro TempoDisc Dataloggers (catalog #DSCTHD001, Blue Maestro, London, UK), deployed on tree branches at breast height. Dataloggers were programmed to collect data hourly and data were offloaded weekly during mosquito trap collection.

## Larval Habitat Assessment

To explore a potential mechanism to explain adult mosquito abundance, all residential sites were assessed once for potential larval mosquito habitat, and presence of juvenile mosquitoes within those habitats. Any natural (eg trees holes) or artificial (eg tires, bird baths, children's toys) vessel that could support water collection was observed and recorded. The estimated volume of the container, container type category, and whether the container was positive for juvenile mosquito presence was recorded. Container type was categorized by function (eg ornamental, recreational). Larval habitat assessments occurred once on each property from the week of 12 July 2021 through the week of 23 August 2021. Assessments occurred on days when the latest precipitation event occurred at least 2 to 4 d prior to avoid a bias toward observation of larvae-positive containers.

## Survey Design and Implementation

A knowledge, attitudes, and practices survey instrument was designed using the Theory of Planned Behavior (Azjen 1991) to measure behaviors related to mosquito control and protection that property participants engage in and the factors that determine those behaviors. The factors measured by the survey instrument included: knowledge, attitudes, subjective norms, perceived behavioral control and practices associated with mosquito control and exposure prevention. The knowledge construct was composed of right/wrong questions addressing knowledge of mosquitoes and MBD systems (Tuiten et al. 2009, Duval et al. 2023). The attitudes, subjective norms, perceived behavioral control, and practices constructs were comprised of Likert-type questions addressing assessments about different types of mosquito control and protection practices and intentions to perform mosquito control and protection practices (Faqah et al. 2015, Paz-Soldán et al. 2016, Wang et al. 2018, Jacob et al. 2019, Hamilton et al. 2020). The final section included sociodemographic questions about age, race, education, and income. To increase survey response rates, we used the Dillman Tailored Design Method and a mixed-mode survey approach (Dillman 2016) whereby participants received up to 2 email reminders and once via phone to complete the survey instrument, and a paper version was available if participants had limited internet access. Survey data collection occurred between 28 September 2021 and 22 March 2022. Only households participating in the ecological mosquito surveillance were invited to complete the KAP survey. We restricted participation to these households because our primary objective was to directly link household-level KAP responses to site-specific mosquito abundance data.

All study participants provided written and oral consent before conducting the survey described above. The survey design and distribution were approved to be compliant with the University of Maine Institutional Review Board for the Protection of Human Subjects under protocol No. 2021_07_07.

## Data Analysis

To test the hypotheses that there are differences in (i) overall mosquito abundance, (ii) vector species abundance, (iii) nuisance species abundance, and/or (iv) artificial container-breeding species abundance across residential LUC, data were analyzed using R version 4.2.1 (R Core Team 2022). Each response variable was analyzed using separate hurdle regression models due to zero-inflated data (pscl package; Zeileis et al. 2008). Hurdle models consist of 2 stages for analyzing zero-inflated data and are particularly relevant for count data analysis. In the first stage, presence versus absence of mosquitoes was modeled using a binomial distribution. The second stage is the conditional model, which modeled counts given that mosquitoes were present using a Poisson distribution (Feng 2021). Model predictors included fixed effects of LUC, site ID, and week

**Table 1.** Number of female, male, and unidentifiable mosquitoes collected, with summary of female mosquito species collected across residential LUC in Bangor, Maine

| | Rural | | | Low-density | | | Urban | | | Grand total | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Gravid | Light | Total | Gravid | Light | Total | Gravid | Light | Total | Gravid | Light | Total |
| Total Mosquitoes | 1,464 | 734 | 2,198 | 1,008 | 505 | 1,513 | 1,425 | 157 | 1,582 | 3,897 | 1,396 | 5,293 |
| Unidentifiable mosquitoes | 122 | 20 | 142 | 124 | 21 | 145 | 122 | 6 | 128 | 368 | 47 | 415 |
| Male mosquitoes | 25 | 90 | 115 | 7 | 26 | 33 | 12 | 24 | 36 | 44 | 140 | 184 |
| Identifiable female mosquitoes | 1,317 | 624 | 1,941 | 877 | 458 | 1,335 | 1,291 | 127 | 1,418 | 3,485 | 1,209 | 4,694 |
| Species identified | | | | | | | | | | | | |
| *Aedes cinereus* | 10 | 21 | 31 | 3 | 3 | 6 | 0 | 1 | 1 | 13 | 25 | 38 |
| *Aedes japonicus* | 81 | 2 | 83 | 142 | 7 | 149 | 165 | 4 | 169 | 388 | 13 | 401 |
| *Aedes vexans* | 28 | 11 | 39 | 21 | 7 | 28 | 8 | 12 | 20 | 57 | 30 | 87 |
| *Aedes/Ochlerotatus sp.* | 9 | 1 | 10 | 16 | 0 | 16 | 1 | 0 | 1 | 26 | 1 | 27 |
| *Anopheles punctipennis* | 18 | 45 | 63 | 8 | 23 | 31 | 13 | 6 | 19 | 39 | 74 | 113 |
| *Anopheles quadrimaculatus* | 13 | 9 | 22 | 7 | 37 | 44 | 5 | 2 | 7 | 25 | 48 | 73 |
| *Anopheles sp.* | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| *Anopheles walkeri* | 1 | 14 | 15 | 2 | 18 | 20 | 0 | 1 | 1 | 3 | 33 | 36 |
| *Coquillettidia perturbans* | 227 | 213 | 440 | 101 | 170 | 271 | 45 | 27 | 72 | 373 | 410 | 783 |
| *Culex sp.* | 675 | 28 | 703 | 362 | 67 | 429 | 887 | 41 | 928 | 1924 | 136 | 2,060 |
| *Culiseta melanura* | 25 | 31 | 56 | 66 | 20 | 86 | 56 | 8 | 64 | 147 | 59 | 206 |
| *Culiseta morsitans* | 74 | 173 | 247 | 44 | 81 | 125 | 25 | 11 | 36 | 143 | 265 | 408 |
| *Culiseta sp.* | 2 | 0 | 2 | 0 | 0 | 0 | 2 | 0 | 2 | 4 | 0 | 4 |
| *Ochlerotatus aurifer* | 3 | 3 | 6 | 32 | 5 | 37 | 7 | 0 | 7 | 42 | 8 | 50 |
| *Ochlerotatus canadensis* | 24 | 3 | 27 | 35 | 0 | 35 | 22 | 0 | 22 | 81 | 3 | 84 |
| *Ochlerotatus cantator* | 0 | 8 | 8 | 3 | 1 | 4 | 2 | 1 | 3 | 5 | 10 | 15 |
| *Ochlerotatus excrucians* | 16 | 1 | 17 | 20 | 0 | 20 | 20 | 0 | 20 | 56 | 1 | 57 |
| *Ochlerotatus hendersoni* | 1 | 0 | 1 | 1 | 1 | 2 | 2 | 0 | 2 | 4 | 1 | 5 |
| *Ochlerotatus intrudens* | 47 | 15 | 62 | 0 | 3 | 3 | 1 | 1 | 2 | 48 | 19 | 67 |
| *Ochlerotatus provocans* | 4 | 9 | 13 | 0 | 1 | 1 | 3 | 1 | 4 | 7 | 11 | 18 |
| *Ochlerotatus punctor* | 1 | 8 | 9 | 2 | 0 | 2 | 0 | 0 | 0 | 3 | 8 | 11 |
| *Ochlerotatus triseriatus* | 24 | 6 | 30 | 4 | 1 | 5 | 19 | 5 | 24 | 47 | 12 | 59 |
| *Ochlerotatus trivittatus* | 2 | 3 | 5 | 5 | 0 | 5 | 1 | 0 | 1 | 8 | 3 | 11 |
| *Uranotaenia sapphirina* | 1 | 3 | 4 | 1 | 1 | 2 | 2 | 2 | 4 | 4 | 6 | 10 |
| *Wyeomyia smithii* | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Totals | 1,320 | 621 | 1,940 | 877 | 458 | 1,335 | 1,295 | 123 | 1,418 | 3,492 | 1,202 | 4,694 |

of collection. Temperature and rainfall were included as covariates in the models due to their established associations with mosquito abundance. For significant conditional regression models, pairwise comparisons among means for LUC were analyzed using a Tukey's test for significant differences among estimated marginal means (emmeans package; Lenth 2022). Mosquito abundance metrics for each LUC were calculated as the average number of mosquitoes collected each trap night on properties from each LUC.

Participant knowledge was measured through answers to the KAP survey knowledge questions. Answers were scored as +1 for correct answers, and −1 for incorrect answers. Knowledge question scores were aggregated into a single score, and knowledge scores were further categorized in High, Medium, and Low levels of knowledge. Analysis of the correlation between resident knowledge scores and presence of larval habitat containers on residential properties was conducted using Kendall's Tau statistic in R (stats package; R Core Team 2022). To test the associations between constructs in the Theory of Planned behavior model, Fisher's exact test was used due to small sample size (Nowacki 2017).

## Results

### Mosquito Summary

Over the course of the study, 16,582 mosquitoes were collected, including male mosquitoes and those which were unidentifiable due to poor condition (Table 1). Overall, mosquitoes were most abundant in the forest sites (9,560), followed by rural residential sites (3,830), urban residential sites (2,084), and low-density residential sites (1,790). Species data are only reported herein for residential sites and for female mosquitoes that were identifiable to genus ($N$ = 4,694). The most abundant species, accounting for 43.89% ($N$ = 2,060) of total mosquitoes captured across sites, were *Cx. restuans* and *Cx. pipiens*, followed by *Cq. perturbans* accounting for 16.68% ($N$ = 783), and *Cs. morsitans* and *Ae. japonicus* comprising 8.69% ($N$ = 408) and 8.54% ($N$ = 401), respectively. The remaining 22% of the identifiable female mosquitoes captured comprised 23 species across 5 genera, for a total of 23 species across 7 genera identified (Table 1). Of the 459 trap nights across all 40 sites, 8.06% ($N$ = 37) of gravid trap nights and 24.84% ($N$ = 114) of light trap nights had zero mosquitoes at 26 and 30 sites, respectively. Figure 2 summarizes mosquito classification across LUC. Gravid traps collected mostly vector and artificial container-breeding mosquitoes, while light traps captured mostly vector species across all LUC (Fig. 2).

### Mosquito Diversity and Abundance

Results of the Shannon's diversity index calculations across LUC show that the species diversity index ($H$) was lower in urban sites ($H$ = 1.41) than in low-density ($H$ = 2.17) or rural sites ($H$ = 2.09). Additionally, the equity index of diversity, or evenness, was lowest at urban sites (0.41) compared to low-density (0.64) and rural (0.61) sites.

In the conditional model, the portion of the hurdle model that models mosquito abundance at the sites where mosquitoes were

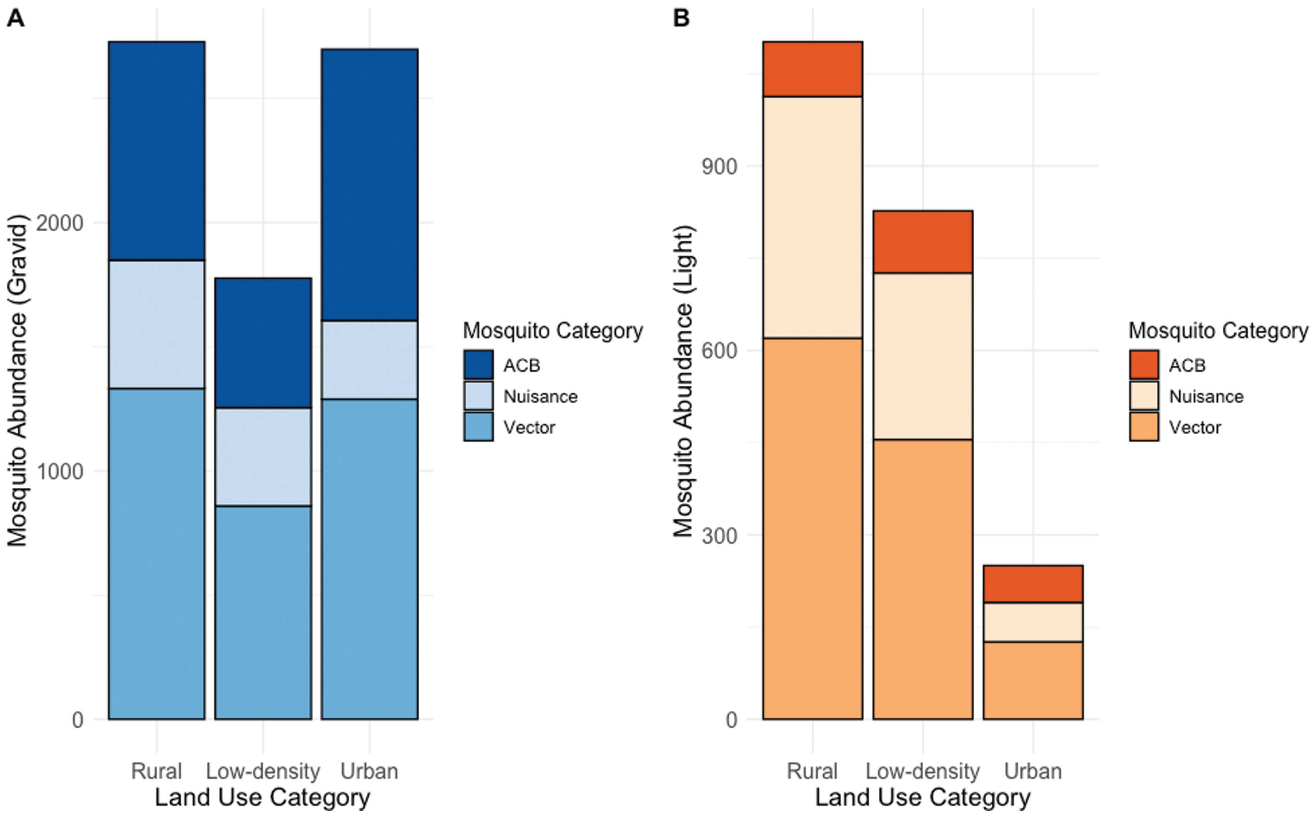


**Fig. 2.** Relative abundance of mosquitoes classified as vector species, nuisance species, and artificial container-breeding species across the 30 residential trapping sites from 1 June to 21 September 2021. Stacked bars represent the proportion of total mosquitoes trapped that fall into each classification group within urban, low-density, and rural residential LUC.

**Table 2.** Hurdle model comparison of weekly trap night mosquito abundance in gravid and light traps across residential land use category

| Trap | Effect | Estimate | SE | *Z* | *P*-value |
|---|---|---|---|---|---|
| Gravid | Conditional model | | | | |
| | Intercept | 1.871 | 0.130 | 14.343 | 1.18E–46* |
| | Land use category (rural/low density) | 0.357 | 0.042 | 8.426 | 3.58E–17* |
| | Land use category (urban/low density) | 0.312 | 0.042 | 7.423 | 1.15E–13* |
| | Property | –0.017 | 0.002 | -9.029 | 1.73E–19* |
| | Week | 0.057 | 0.006 | 9.736 | 2.12E–22* |
| | Temperature | 0.024 | 0.006 | 3.863 | 0.00011* |
| | Precipitation | –0.691 | 0.070 | -9.878 | 5.20E–23* |
| Light | Conditional model | | | | |
| | Intercept | –0.075 | 0.197 | -0.383 | 0.702 |
| | Land use category (rural/low density) | 0.377 | 0.058 | 6.561 | 5.34E–11* |
| | Land use category (urban/low density) | –0.717 | 0.084 | –8.511 | 1.72E–17* |
| | Property | –0.018 | 0.003 | –6.235 | 4.52E–10* |
| | Week | –0.029 | 0.009 | –3.366 | 0.000764* |
| | Temperature | 0.122 | 0.009 | 14.127 | 2.58E–45* |
| | Precipitation | 0.070 | 0.087 | 0.808 | 0.419 |

Asterisk indicates significance at $P < 0.05$.

present, land use category was associated with a significant difference in mosquito abundance per trap night in gravid traps (Table 2). Mosquito abundance in gravid traps differed significantly across LUC (Fig. 1). The highest mean number of mosquitoes were captured at rural residential sites, followed by forested sites and urban residential sites, and the fewest mosquitoes were captured in gravid traps at low-density residential sites. For light traps, the conditional model indicated significant differences in mosquito abundance between LUC (Table 2). The highest mean number of mosquitoes were trapped at recreational forest sites, followed by rural, low-density and urban residential sites (Fig. 3).

## Vector Species Mosquito Abundance

### WNV Vector Species

When mosquitoes were present, there were differences in the mean abundance of WNV vectors (ie *Cx. pipiens*, *Cx. restuans*, *Ae.*

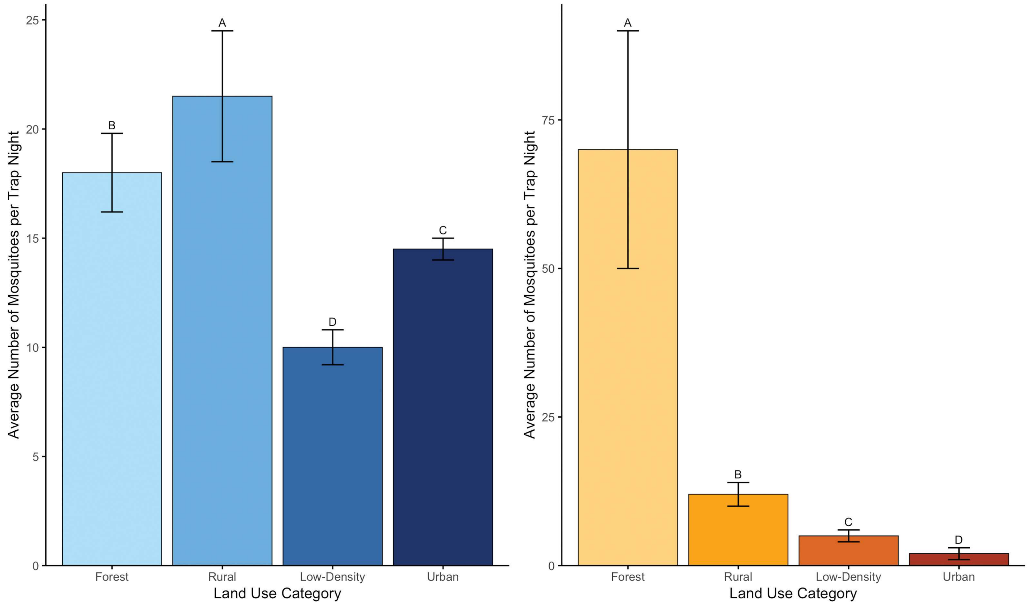


**Fig. 3.** Average number of mosquitoes (±standard error) captured per weekly trap night in gravid traps (left) and light traps (right) across the 30 residential trapping sites from 1 June to 21 September 2021. Mosquito abundance was highest in rural residential sites, followed by low-density and urban residential sites. Letters indicate significant differences ($P < 0.05$) between residential LUC based on posthoc Tukey's HSD tests of estimated marginal means from the conditional hurdle models presented in Table 2. Note the different *y*-axis scales between trap types.

*japonicus*) trapped in gravid traps between residential LUC (Table 3). The highest mean number of WNV vectors were captured at urban residential sites and rural residential and the lowest mean number of WNV vectors were trapped in gravid traps at low-density residential sites (Fig. 4). In light traps, the conditional model shows a relationship between residential LUC and the mean number of WNV vectors collected (Table 3). The highest mean number of WNV vectors in light traps were captured at rural residential sites, followed by low-density residential and the lowest mean number at urban residential sites (Fig. 4).

### EEEV Vector Species

For the mean number of EEEV vectors (ie *Cs. melanura*, *Cs. mortisans*, *Ae. vexans*) captured in gravid traps there were significant differences between residential LUC in the conditional model (Table 4). The highest mean number of EEEV vectors in gravid traps were captured at urban residential and rural residential sites and the lowest at low-density residential sites (Fig. 4). In light traps, using the conditional model, the mean number of EEEV vectors captured per trap night differed across residential land use (Table 4). The highest mean number of EEEV vectors were captured at rural residential sites, followed by low-density residential sites, and the lowest number of EEEV vectors were captured in light traps at urban residential sites (Fig. 4).

### JCV Vector Species

In the conditional model of mean JCV vector species (ie *Och. excrucians*, *Och. communis*, *Ae. abserratus*, etc.) abundance in gravid traps, there was significant differences between residential LUC (Table 5). Based on Tukey's test, the highest number of JCV vectors in gravid traps were captured at rural residential sites, followed by low-density residential sites, with the lowest mean number of JCV vectors in gravid traps captured at urban residential sites (Fig. 2). For the mean number of JCV vectors captured in light traps, the conditional model shows significant differences between residential LUC (Table 5). The most JCV vector mosquitoes captured in light traps were at rural residential sites, followed by low-density residential sites, and the lowest mean number of JCV vectors in light traps were captured at urban residential sites (Fig. 4).

### Nuisance Species Mosquito Abundance

Mean abundance of nuisance mosquito species in gravid traps was significantly different between residential LUC (Table 6). The residential land use category with the highest mean abundance of nuisance mosquitoes in gravid trap was rural, followed by low-density residential, and the lowest mean number of nuisance mosquitoes captured in gravid traps was at urban residential sites (Fig. 5). For nuisance mosquitoes captured in light traps, the conditional model showed a significant difference between residential land use (Table 6). The most nuisance mosquitoes in light traps were captured at rural residential sites, followed by low-density residential sites, and the lowest mean number of nuisance mosquitoes captured in light traps was at urban residential sites (Fig. 5).

### Artificial Container-Breeding Species Mosquito Abundance

In the conditional model, for artificial container-breeding mosquitoes captured in gravid traps, there were significant differences between low-density and urban residential sites, and between urban and rural sites, but no significant difference between low-density and rural residential land use (Table 7). The highest mean number of artificial container-breeding mosquitoes were captured in gravid traps at urban residential sites, and the lowest number of artificial container breeding species captured in gravid traps were collected at rural residential sites and low-density residential sites (Fig. 6). In both the binomial and conditional models, mean abundance of artificial container-breeding mosquitoes captured in light traps was not significantly different between residential LUC (Fig. 6 and Table 7).

## Artificial Container Survey

Across the 30 residential properties, 212 containers were identified as potential larval habitat. The average number of observations

**Table 3.** Hurdle model comparison of weekly trap night WNV vector mosquito abundance in gravid and light traps across residential land use category

| Trap | Effect | Estimate | SE | *Z* | *P* |
|---|---|---|---|---|---|
| Gravid | Conditional model | | | | |
| | Intercept | 1.493 | 0.154 | 9.710 | 2.73E-22* |
| | Land use category (rural/low density) | 0.209 | 0.050 | 4.147 | 3.37E-05* |
| | Land use category (urban/low density) | 0.313 | 0.048 | 6.458 | 1.06E-10* |
| | Property | −0.013 | 0.002 | −5.917 | 3.29E-09* |
| | Week | 0.050 | 0.007 | 7.269 | 3.62E-13* |
| | Temperature | 0.030 | 0.007 | 4.127 | 3.68E-05* |
| | Precipitation | −0.785 | 0.094 | −8.332 | 7.95E-17* |
| Light | Conditional model | | | | |
| | Intercept | −0.362 | 0.242 | −1.497 | 0.134 |
| | Land use category (rural/low density) | 0.200 | 0.066 | 3.017 | 0.0026* |
| | Land use category (urban/low density) | −1.196 | 0.125 | −9.591 | 8.74E-22* |
| | Property | −0.021 | 0.004 | −5.788 | 7.12E-09* |
| | Week | −0.072 | 0.010 | −6.958 | 3.44E-12* |
| | Temperature | 0.145 | 0.010 | 14.530 | 7.84E-48* |
| | Precipitation | 0.174 | 0.103 | 1.679 | 0.093 |

Asterisk indicates significance at $P < 0.05$.

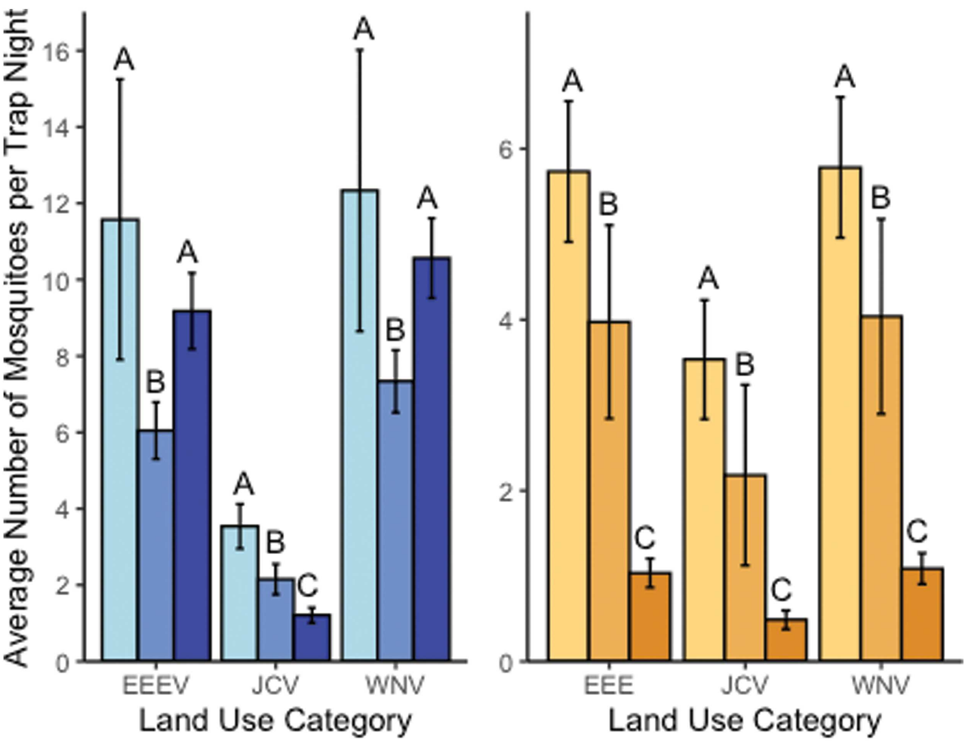


**Fig. 4.** Average abundance (±standard error) of mosquitoes classified as vectors of EEEV, JCV, and WNV, captured per weekly trap night in gravid traps (left) and light traps (right) across the 30 residential trapping sites from 1 June to 21 September 2021. Vector species abundance was highest in urban residential sites, with lower numbers in low-density and rural residential sites. Letters indicate significant differences ($P < 0.05$) between residential LUC based on posthoc Tukey's HSD tests of estimated marginal means from hurdle models presented in Tables 3 to 5. Note the different *y*-axis scales between trap types.

was 7.07 ± 0.950 containers per property, the maximum number of containers observed on a single residential property site was 22 and the minimum was 0. The most common type of container observed were planters, comprising 12.34% of observations ($n = 26$), followed by tarps (9.43%, $n = 20$) (Supplementary Table S2). Of the 212 containers observed, 14.14% ($n = 30$) were positive for mosquito larvae (Supplementary Table S3). The highest proportion of households with positive containers were in the low-density residential LUC, and lowest in the rural LUC. The highest proportion of positive containers found on properties were at sites in the low-density LUC, and the lowest in the rural LUC as well (Supplementary Table S3). There was no significant correlation between the number of containers observed on a residential property and resident mosquito knowledge, as measured through a Knowledge, Attitudes and Practice survey.

## KAP Survey Results

Of the 30 property owners who gave us permission for mosquito collections, 76.67% ($N = 23$) responded to the KAP survey. Of these

**Table 4.** Hurdle model comparison of weekly trap night EEE vector mosquito abundance in gravid and light traps across residential land use category

| Trap | Effect | Estimate | SE | *Z* | *P* |
|---|---|---|---|---|---|
| Gravid | Conditional model | | | | |
| | Intercept | 1.681 | 0.163 | 10.324 | 5.50E–25* |
| | Land use category (rural/low density) | 0.236 | 0.054 | 4.395 | 1.11E–05* |
| | Land use category (urban/low density) | 0.290 | 0.052 | 5.553 | 2.82E–08* |
| | Property | −0.014 | 0.002 | −6.055 | 1.40E–09* |
| | Week | 0.032 | 0.007 | 4.384 | 1.17E–05* |
| | Temperature | 0.023 | 0.008 | 3.047 | 0.0023* |
| | Precipitation | −0.909 | 0.111 | −8.230 | 1.88E–16* |
| Light | Conditional model | | | | |
| | Intercept | −0.318 | 0.242 | −1.313 | 0.189 |
| | Land use category (rural/low density) | 0.210 | 0.067 | 3.150 | 0.0016* |
| | Land use category (urban/low density) | −1.235 | 0.128 | −9.642 | 5.31E–22* |
| | Property | −0.021 | 0.004 | −5.701 | 1.19E–08* |
| | Week | −0.076 | 0.010 | −7.350 | 1.98E–13* |
| | Temperature | 0.143 | 0.010 | 14.347 | 1.12E–46* |
| | Precipitation | 0.195 | 0.104 | 1.886 | 0.059 |

Asterisk indicates significance at $P < 0.05$.

**Table 5.** Hurdle model comparison of weekly trap night JCV vector mosquito abundance in gravid and light traps across residential land use category.

| Trap | Effect | Estimate | SE | Z | P |
|---|---|---|---|---|---|
| Gravid | Conditional model | | | | |
| | Intercept | 2.131 | 0.309 | 6.896 | 5.35E–12* |
| | Land use category (rural/low density) | 0.391 | 0.088 | 4.414 | 1.01E–05* |
| | Land use category (urban/low density) | −0.535 | 0.121 | −4.432 | 9.32E–06* |
| | Property | −0.028 | 0.004 | −6.282 | 3.34E–10* |
| | Week | 0.036 | 0.015 | 2.378 | 0.017* |
| | Temperature | −0.019 | 0.015 | −1.308 | 0.191 |
| | Precipitation | −1.123 | 0.234 | −4.803 | 1.56E–06* |
| Light | Conditional model | | | | |
| | Intercept | −0.718 | 0.332 | −2.163 | 0.031* |
| | Land use category (rural/low density) | 0.253 | 0.093 | 2.727 | 0.0064* |
| | Land use category (urban/low density) | −1.154 | 0.184 | −6.275 | 3.50E–10* |
| | Property | −0.038 | 0.005 | −7.178 | 7.08E–13* |
| | Week | −0.138 | 0.013 | −10.384 | 2.93E–25* |
| | Temperature | 0.182 | 0.014 | 13.152 | 1.66E–39* |
| | Precipitation | 0.320 | 0.135 | 2.376 | 0.018* |

Asterisk indicates significance at $P < 0.05$.

respondents, 81.3% were female, 64.5% were aged 60+, and 100% identified as white (Supplementary Table S4). Education level of at least a bachelor's degree was reported by 70.6% of participants, and 94.1% owned their home. Most respondents (66.7%) had no children in the home, and 53.3% of respondents identified as politically liberal.

The mean participant knowledge score was 10.23, the maximum score was 16, and the minimum score was −2 out of a possible 16. Based on the sample, scores 14 and up were categorized as high, scores 9 to 13 were categorized as mid, and scores below 9 were considered low. Given a list, participants were most likely to know that mosquitoes can transmit dengue fever virus (82.6% correct) and malaria (78.3% correct), and least likely to know that mosquitoes can transmit EEEV (52.2% correct) and JCV (0.0% correct). Participants were most likely to identify stormwater catch basins (95.7% correct) and stagnant water (91.3% correct) as mosquito-suitable habitats, and least likely to identify vernal pools (47.8% correct). Given a true/false prompt, 85.7% of participants correctly associated aquatic habitat with juvenile mosquitoes, while 50.0% of respondents knew that some mosquito species do not bite humans (Supplementary Table S5).

When measuring attitudes, respondents reported high perceived efficacy for some practices to reduce mosquito bites, such as wearing protective clothing (95.2% and 85.7% perceived long shirts, and long pants as effective, respectively), and treating clothing with insect repellent (90.5% reported perceived efficacy), and low perceived efficacy for other practices such as electric rackets (36.8%) and citronella candles (47.6%). Similarly, some practices were reported to have high perceived efficacy for reducing mosquito abundance (eg eliminating standing water [90.0%], keeping lids on water containers [90.0%]), while respondents reported lower perceived efficacy for others (eg using chemical mosquito dunks to treat water [50%]).

Eighty-one percent of respondents indicated that they did not think they were likely to contract an MBD in Maine, but 100% reported that they were likely to get mosquito bites in Maine, and 90.5% reported that they were likely to be bitten on their properties.

**Table 6.** Hurdle model comparison of weekly trap night nuisance mosquito abundance in gravid and light traps across residential land use category

| Trap | Effect | Estimate | SE | *Z* | *P* |
|---|---|---|---|---|---|
| Gravid | Conditional model | | | | |
| | Intercept | 1.693 | 0.255 | 6.651 | 2.92E−11* |
| | Land use category (rural/low density) | 0.363 | 0.072 | 5.027 | 4.99E−07* |
| | Land use category (urban/low density) | -0.335 | 0.085 | −3.942 | 8.07E-05* |
| | Property | −0.025 | 0.004 | −7.062 | 1.64E−12* |
| | Week | 0.078 | 0.012 | 6.237 | 4.47E−10* |
| | Temperature | −0.007 | 0.012 | −0.535 | 0.593 |
| | Precipitation | −0.699 | 0.144 | −4.854 | 1.21E−06* |
| Light | Conditional model | | | | |
| | Intercept | −0.559 | 0.329 | −1.701 | 0.089 |
| | Land use category (rural/low density) | 0.244 | 0.088 | 2.778 | 0.0055* |
| | Land use category (urban/low density) | −1.094 | 0.172 | −6.367 | 1.92E−10* |
| | Property | −0.041 | 0.005 | −8.077 | 6.66E−16* |
| | Week | −0.123 | 0.013 | −9.448 | 3.45E−21* |
| | Temperature | 0.172 | 0.014 | 12.468 | 1.12E−35* |
| | Precipitation | 0.487 | 0.117 | 4.154 | 3.26E−05* |

Asterisk indicates significance at $P < 0.05$.

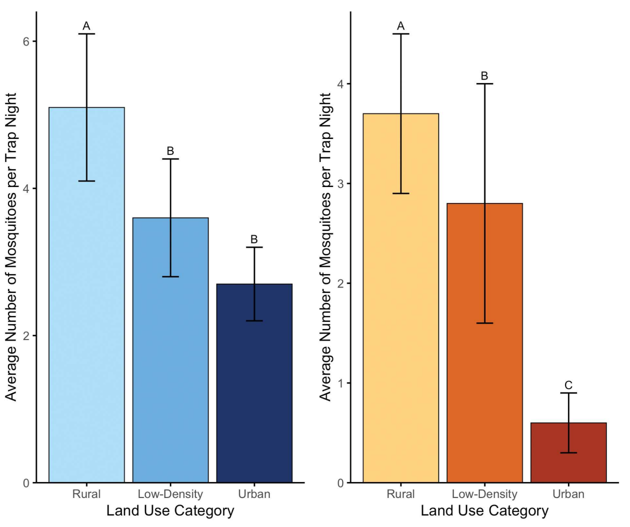


**Fig. 5.** Average abundance (±standard error) of nuisance (ie human-biting) mosquitoes captured per weekly trap night in gravid traps (left) and light traps (right) across the 30 residential trapping sites from 1 June to 21 September 2021. Nuisance species abundance was highest in rural residential sites, followed by low-density and urban residential sites. Letters indicate significant differences ($P < 0.05$) between residential LUC based on post-hoc Tukey's HSD tests of estimated marginal means from hurdle models presented in Table 6.

However, only 52.4% reported mosquitoes on their property as a nuisance (Supplementary Table S6). In terms of social norms, most survey participants (85%) reported that people who are important to them would not support spraying pesticides on their property to reduce mosquitoes. Additionally, 65% of participants reported that people who are important to them would not support them avoiding spending time outdoors to reduce mosquito encounters (Supplementary Table S7).

When measuring control and prevention practices, the only mosquito reduction behaviors that respondents reported frequent engagement in were cleaning rain gutters and storm drains and removing standing water from containers on their property. For participant engagement in practices that reduce mosquito encounters, 100% of respondents reported sometimes or always wearing protective clothing, sometimes or always using mosquito repellent. Additionally, 73.7% of respondents reported sometimes avoiding spending time outdoors to avoid mosquito encounters (Supplementary Table S8).

There were no significant relationships detected between attitudes or reported engagement in behaviors with land use category, and no relationship detected between participant knowledge and attitudes. When we tested the relationships between constructs using Fisher's exact tests, we found 2 significant associations. One significant association was detected between respondent's reported subjective norms and engagement in treating their properties with pesticide spray ($P = 0.0196$, $Z = 2.33$). A second significant association was detected between respondent attitudes and engagement in the practice of wearing long pants while outdoors ($P = 0.0526$, $Z = 1.94$).

## Discussion

Our study found that residential land use category has a significant effect on several variables relating to mosquito species distributions including mosquito abundance, species diversity, vector species abundance, nuisance species abundance, and artificial container breeding species abundance. In particular, sites in rural and low-density LUC had more mosquitoes overall, more nuisance species mosquitoes, and a higher species diversity of mosquitoes collected. Sites in the urban residential land use category had more vector and artificial container-breeding species and lower species diversity compared to other less urban LUC. These results are consistent with results from other mosquito studies which show similar patterns of vector concentration and lower species diversity in urban landscapes (Chavez 2011, de Valdez 2017, Zettle et al. 2022). This study builds upon prior work by showing that the effect of an urban to rural gradient on mosquito distributions is present even in smaller US towns with less urban sprawl than where much of prior work has taken place (eg Chicago, Baltimore, Washington D.C., San Antonio) and that lower mosquito species diversity is observed compared to rural sites in this less populated urban setting. Additionally, this study adds to the growing body of interdisciplinary approaches to mosquito research, by integrating a larval mosquito habitat survey with social science

**Table 7.** Hurdle model comparison of weekly trap night artificial container-breeding mosquito abundance in gravid and light traps across residential land use category

| Trap | Effect | Estimate | SE | *Z* | *P* |
|---|---|---|---|---|---|
| Gravid | Conditional model | | | | |
| | Intercept | 0.9548 | 0.1909 | 5.0021 | 5.67E–07* |
| | Land use category (rural/low density) | −0.0383 | 0.0662 | −0.5785 | 0.563 |
| | Land use category (urban/low density) | 0.5083 | 0.0574 | 8.8613 | 7.91E–19* |
| | Property | −0.0027 | 0.0027 | −0.9653 | 0.334 |
| | Week | 0.0432 | 0.0083 | 5.2270 | 1.72E–07* |
| | Temperature | 0.0379 | 0.0086 | 4.3819 | 1.18E–05* |
| | Precipitation | −0.6458 | 0.1075 | −6.0071 | 1.89E–09* |

Asterisk indicates significance at $P < 0.05$.

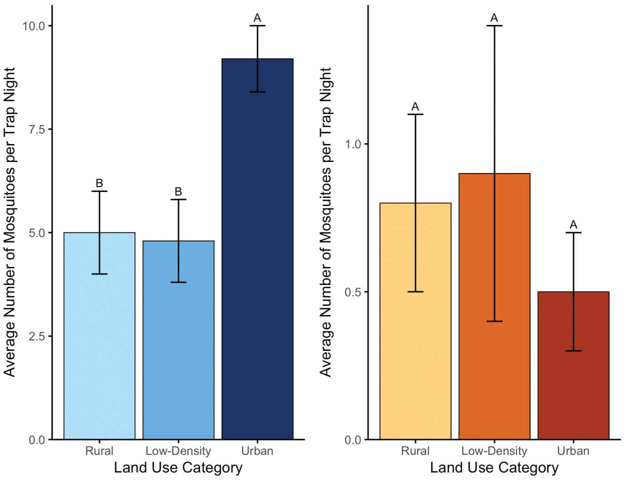


**Fig. 6.** Average abundance (±standard error) of artificial container-breeding mosquitoes captured per weekly trap night in gravid traps (left) and light traps (right) across the 30 residential trapping sites from 1 June to 21 September 2021. Artificial container-breeding species were most abundant in urban residential sites, with lower numbers in low-density and rural residential sites. Letters indicate significant differences ($P < 0.05$) between residential LUC based on posthoc Tukey's HSD tests of estimated marginal means from hurdle models presented in Table 7. Note the different *y*-axis scales between trap types.

survey data to test the association of resident knowledge with the number of containers at each collection site.

The highest mosquito abundance was observed in forested sites compared to residential sites, and within residential LUC, rural sites had the highest mosquito abundance. This association of more mosquitoes in less-developed areas is consistent with known mosquito ecology. Mosquito species such as *Ae. vexans*, *Ae. triseriatus*, *Ps. ferox*, *Oc. Canadensis*, and *Cq. peturbans* oviposit in floodplains, or areas with high likelihood of flooding, which provide temporary fresh water sources (Aziz and Hayes 1987, Horsfall et al. 1975). Mosquito species with this oviposition habitat use tend to hatch and develop in large numbers compared to mosquito species that lay eggs in smaller water sources (Horsfall et al. 1975). In addition, since oviposition occurs in dry areas, before flooding occurs, these eggs are especially resilient to desiccation and may remain dormant in the environment until flooding aids in embryonic development (Curtisi 1985). Adult female floodplain mosquitoes are also multivoltine (Lundström et al. 2013, Östman et al. 2015). Due to these traits, floodplain mosquito species, especially *Ae. vexans* and *Och. canadensis* are considered nuisance pests for both humans and livestock and are also aggressive human-biting mosquitoes (Schäfer et al. 2008). Indeed, the highest number of nuisance species mosquitoes on residential sites in this study were also observed at sites in the rural land use category. Rural residential sites also had the highest Shannon's diversity and evenness indices compared to low-density and urban LUC. This is consistent with prior literature that attributes lower species diversity in more urbanized areas to the decreased variety in aquatic and semiaquatic habitat available for oviposition and development in landscapes that are less human dominated (LaDeau et al. 2013, Little et al. 2017).

While the smallest number of mosquitoes found on residential sites were in the urban land use category, urban sites had the most WNV and EEEV vectors, the most artificial container species and the lowest Shannon's diversity and evenness indices. This is likely due to biological and ecological mechanisms described in previous studies. Human dominated and urbanized landscapes are more associated with the presence of artificial containers which some disease vector species prefer for oviposition. These mosquito species, notably *Cx. pipiens*, *Cx. restuans*, *Ae. japonicus* in the northeast US, hatch in smaller broods compared to floodplain mosquitoes, but have evolved to occupy the aquatic and semiaquatic niche environments provided by urbanized landscapes, such as in stormwater basins, gutter drains, and items on resident properties such as tires or buckets (LaDeau et al. 2013, Little et al. 2017, Marini et al. 2020). The results of our study show that observation of the number of artificial containers on residential properties did not vary by LUC, but the proportion of containers found positive for juvenile mosquito presence were higher on urban and low-density residential sites than rural sites.

Among KAP survey results, resident knowledge scores did not significantly vary among LUC, and knowledge scores were not significantly correlated with the number of containers found on resident properties. Additionally, attitudes toward mosquito practices tended to be positive, indicating that people believe these control and protective methods work to reduce mosquito encounters or mosquito abundance. However, when asked how often they engaged in these methods, participants reported low engagement in control and protective behaviors. This indicates that metrics beyond level of knowledge and perception of effectiveness may be important to better understand and predict behaviors that influence risk of mosquito exposure.

In our study, we detected a significant association between participant subjective norms and reported engagement in the use of pesticide spray, and between reported attitudes toward and engagement in wearing protective clothing. While our sample size ($N = 23$) was too small to draw conclusions about the directions of these associations, we can draw on inferences based on prior studies that use the KAP and TPB frameworks. Attitudes have consistently been found to be significant predictors of behavioral intention when studying a myriad of practices related to pro-environmental behavior, health practices, conservation decisions, etc. since Azjen first published the framework in 1991 (Bosnjak et al. 2020). In a meta-analysis of 206 studies that used the TPB to explain factors in health behavior decision-making, attitudes were found to be the most important predictor of behavioral intention, and the second-most important predictor of behavioral engagement (McEachan et al. 2011).

While our sample size was too low to generalize our results, we included survey questions on attitudes, subjective norms, and perceived behavioral control to try to further explain reported engagement in mosquito control behaviors. Other US studies have employed a similar quantitative social science approach and found that socioeconomic status is related to mosquito and mosquito control knowledge (Tuiten et al. 2009, Dowling et al. 2013, Parker 2019). In addition, perceptions of high mosquito activity have been positively associated with reported engagement in preventive mosquito measures among participants in upstate New York (Tuiten et al. 2009) and mosquito knowledge was associated with reported engagement in source reduction behaviors among residents of the Baltimore–Washington metropolitan area (Dowling et al. 2013). Further, a qualitative study conducted in a suburban city in southeast India, showed that while there were no differences in mosquito abundance metrics across sites of different LUC, there were differences among participant perception of mosquitoes, and these differences were largely explained by differences in individuals' engagement with outdoor space, and their hazard vulnerability (Evans et al. 2022).

As evidenced by Evans et al. (2022), reported human experiences with and perceptions of mosquito presence, abundance and risk of disease transmission may not match entomological data collection, pointing to a potential mismatch in engagement with mosquito control behaviors. For example, in our study, vector mosquito abundance was highest at urban sites, which had the lowest total mosquito abundance. If human experiences with high mosquito abundance, such as those in recreational forested areas, drive their motivation to control mosquitoes, then they may be less motivated to control mosquitoes or use protective measures when they experience them in lower numbers, such as on their own property or within their residential neighborhood. This could lead to engagement in mosquito control and protection behaviors when mosquitoes are a nuisance, but not when people are at a higher risk of exposure to vector species.

It is important to note several limitations within our methodological approach. First, carbon dioxide was not included in the deployment of light traps. This likely contributed to the differences in mosquito abundance patterns observed in the light versus gravid traps, particularly in the urban environments where light pollution may have been competing with the light traps. This is illustrated by the mosquito abundance results, which show that light traps collected significantly fewer mosquitoes than gravid traps at all sites, except recreational forests, and the pattern is most pronounced in the urban sites, supporting the effect of light pollution on trap effectiveness. Prior research shows that light pollution may compete with light trap attractiveness (Justice and Justice 2016) and that light pollution may increase photoperiod which has implications for mosquitoes such as nutrient accumulation and diapause initiation in adult *Cx. pipiens* (Wolkhoff 2023), and the nighttime biting activity of *Ae. aegypti* (Wolkhoff 2023). Additionally, unpublished data collected for our lab's mosquito surveillance efforts show that light traps baited with carbon dioxide in 2022 collected more mosquitoes in Bangor than observed in our nonbaited study (Unpublished data, 2022). One main objective of this study was to collect ecological and social variables at the same sites to make direct conclusions about resident behaviors, container presence, and mosquito distributions. A well-known problem in social–ecological research is that the sample size requirements vary widely for social and environmental data (Cumming 2006). While this study was adequately powered to make inferences about mosquito abundance, the social science sample size was insufficient to generalize to the broader population or test inferences about the relationship between constructs. This issue of scale is a common one in SES studies which rely on time and resource consuming data collection. Future SES studies of entomological pests and vectors might employ survey data collection from a larger sample size and limit entomological data collection as resources allow. Additionally, KAP survey response rate was 76.67% overall ($N = 23/30$) but as low as 60% ($N = 6/10$) from the low-density residential LUC. This likely had an effect on the variation in the sample and reflects the importance of added measures to increase response rate. Lastly, participants were approached about the study and ecological data collection began before conducting the KAP survey. No information was provided regarding mosquitoes, but participant perceptions of mosquitoes may have been primed to perceive mosquitoes as more of a risk based on the information provided on the aims of the mosquito collection component during the recruitment conversation (Filonik and Winters 2020).

The mosquito classification system (vector versus nuisance versus artificial container breeding mosquitoes) employed for this study allowed us to identify general patterns of mosquito distribution as a nonexpert audience might best understand. While this general classification does not distinguish between enzootic, bridge, or primary vectors within the WNV, JCV, or EEEV systems, allowing nuances of these vector distributions to be lost, it allowed us to consider mosquito distribution generally, as it best relates to human experiences. In conclusion, this study adds to the current state of knowledge on mosquito abundance and species distributions across residential and recreational land use. We employed a social–ecological data collection approach, expanding known patterns of mosquito abundance across rural to urban gradients to a smaller US urban setting than typically studied. This research underlines the importance of integrating data types across disciplines to understand how interactions between people and their environment affect mosquito distributions and motivates further social–ecological mosquito studies with more power to detect these complex relationships.

## Supplementary material

Supplementary material is available at *Journal of Medical Entomology* online.

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## Author contributions

Megan Schierer (Conceptualization [equal], Data curation [lead], Formal analysis [lead], Project administration [lead], Writing—original draft [lead], Writing—review & editing [lead]), Allison Gardner (Conceptualization [equal], Funding acquisition [lead], Writing—review & editing [equal]), and Sandra De Urioste-Stone (Conceptualization [equal], Funding acquisition [lead], Writing—review & editing [equal])

*Conflicts of interest.* None declared.

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