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Seasonal mosquito (Diptera: Culicidae) dynamics and the influence of environmental variables in a land use gradient from Yucatan, Mexico

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ABSTRACT

Mosquito-borne diseases constitute a significant global impact on public and animal health. Climatic variables are recognized as major drivers in the mosquitoes' life history, principally rainfall and temperature, which directly influence mosquito abundance. Likewise, urbanization changes environmental conditions, and understanding how environmental variables and urbanization influence mosquito dynamics is crucial for the integrated management of mosquito-borne diseases, especially in the context of climate change. In this study, our aim was to observe the effect of temperature, rainfall, and the percentage of impervious surface on the abundance of mosquito species over a temporal scale of one complete year of fortnightly samplings, spanning from June 2021 to June 2022 in Yucatan, Mexico. We selected nine localities along an urbanization gradient (three natural, three rural, and three urban) from Mérida City to Reserva de la Biosfera Ría Celestún. Using BG-traps, mosquitoes were collected biweekly at each locality. Additionally, we estimated the percentage of impervious surface. Daily data of the maximum, mean and minimum temperatures, diurnal temperature range and rainfall were accumulated weekly. We calculated the accumulated quantities of temperatures and rainfall and lagged from one to four weeks before sampling for each locality. Generalized linear mixed models were then performed to study the influence of environmental variables and percentage of impervious surfaces on each of the 15 most abundant species. A total of 131,525 mosquitoes belonging to 11 genera and 49 species were sampled with BG-Sentinel traps baited with BG-lure and dry ice. The most frequently significative variable is the accumulated precipitation four weeks before the sampling. We observed a positive relationship between *Cx. quinquefasciatus* and *Cx. thriambus* with the diurnal temperature range. For *Ae. aegypti*, we observed a positive relationship with minimum temperature. Conversely, the percentage of impervious surface serves as a proxy of anthropogenic influence and helped us to distinguishing species exhibiting habitat preference for urban and rural environments, versus those preferring natural habitats. Our results characterize the species-specific effects of environmental variables (temperature, rainfall and impervious surface) on mosquito abundance.

1. Introduction

Mosquito-borne diseases (MBDs) with constantly emerging and re-emerging outbreaks constitute a significant global impact on public and animal health (Kilpatrick and Randolph 2012). MBDs such as malaria, dengue fever, Zika virus, West Nile Virus, among others, lead to substantial socio-economic consequences, primarily affecting developing countries in tropical and subtropical regions (Wilson et al., 2020; Diagne et al., 2021). Furthermore, the effects of global warming and climate change are expected to alter the geographic ranges of these diseases. In some cases, these changes may result in expansion, as observed with dengue and Zika or may shift the spatial range, moving to higher latitudes, as for malaria (Baker et al., 2022). Understanding the vector context is crucial for effective control, thereby posing frequent

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challenges in public and animal health (Mordecai et al., 2019; Roche et al., 2020).

Several species of mosquitoes have represented a public concern worldwide including *Aedes aegypti* that serves as the principal vector for Dengue, Chikungunya, and Zika viruses, and *Aedes albopictus* is a secondary vector (Wilson et al., 2020). *Anopheles* species are the principal vectors of malaria (Hurtado et al., 2018; Pinault and Hunter, 2012). The genus *Culex* are associated with the transmission of the West Nile Virus, Saint Louis encephalitis, Japanese encephalitis, and equine encephalitis viruses among other pathogens (Soh and Aik, 2021; Tolsá et al., 2023), and *Haemagogus* and *Sabethes* genera are implicated in sylvatic transmission of Yellow Fever and Mayaro viruses in the neotropics (Talaga et al., 2023; Kilpatrick and Randolph, 2012).

Environmental conditions are widely recognized as major drivers in the life history of mosquitoes, shaping population and community structure and affecting the potential for disease transmission (Arora et al., 2022; Baril et al., 2023; Reisen, 2010; Wilke et al., 2021). Multiple studies have found rainfall and temperature to be key drivers of mosquito abundance and seasonality (Mordecai et al., 2019). Rainfall principally affects the quantity of available breeding sites, egg viability, and, consequently influencing mosquito abundance (Baril et al., 2023; Kraemer et al., 2015.; Ng et al., 2018). Meanwhile, temperature is considered the principal climatic variable that directly influences mosquito dynamics, affecting fecundity and survival rates, as well as limiting the geographic range and transmission of MBD (Blagrove et al., 2017; Chadee and Martinez, 2016). In general, a reduction in the extrinsic incubation period and increase in vectorial capacity are associated with higher temperatures (Mordecai et al., 2019; Couper et al., 2021). However, experimental reports have associated lower temperatures with higher infection and transmission rates of Dengue and Chikungunya viruses by *Ae. aegyti* and *Ae. albopictus,* respectively (Bellone and Failloux, 2020). Despite the advancements, there are still gaps in understanding the influence of temperature on the dynamics of mosquitoes and pathogens (Mordecai et al., 2019). Given the significant variation in mosquitoes' life history, including their immature development stages, between species, it is important to consider the lagged effect of rainfall and temperature on adult mosquito abundance (Scott et al., 2000; Soh and Aik, 2021).

The influence of environmental variables can be exacerbated by other factors such as human activities (Couper et al., 2021; Wilke et al., 2021). Urbanization, changes environmental conditions, favoring synanthropic species and consequently decreasing species richness (Wilke et al., 2021; Talaga et al., 2020). Conversely, natural habitats like mangroves and marshes maintain a high species diversity (Wilke et al., 2021; Bond et al., 2014). Understanding how the environmental variables and urbanization influence mosquito dynamics is crucial for the surveillance and control of vectors and MBD, especially in the context of climate change (Ramírez-González et al., 2023; Arora et al., 2022).

Throughout its history, the state of Yucatan, Mexico, has experienced various outbreaks of MBDs. The first documented yellow fever epidemics date back to 1648 (Gubler, 2004), likely associated with the presence of *Ae. aegypti*, which, in conjunction with *Ae. albopictus,* is widely distributed in the region (Brady and Hay, 2019; Garcia-Rejón et al., 2021). These mosquitoes are constantly reported to be vectors for Dengue, Zika and Chikungunya viruses (Lopez-Apodaca et al., 2022; Cigarroa-Toledo et al., 2016). Additionally, *Cx. quinquefasciatus,* the principal vector of Saint Louis encephalitis and West Nile Virus (WNV), is present in the region. Previous serologic reports of WNV in horses and wild birds suggest the virus circulation in Yucatan; however, the role of *Cx. quinqufasciatus* as vector in the region remains uncertain (Chavez et al., 2016; Loroño-Pino et al., 2003).

In urban and *peri* urban areas near to Mérida city, there are records of the black salt marsh mosquito *Aedes taeniorhyncus* testing positive for Zika virus and Bunyavirus, specifically Cache Valley and Kairi virus relevant to livestock and occasionally reported in humans (Nuñez-Avellaneda et al., 2021; Farfan-Ale et al., 2009). In Mexico Venezuelan Equine Encephalitis virus has been reported in *An. pseudopunctipennis, Cx. nigripalpus*, and *Coquilletidia nigricans* (Adams et al., 2012). Additionally, it has been reported in *Ae. taeniorhynchus* from Guatemala and Costa Rica (García-Rejón et al., 2023). Recent reports of RNA Alphavirus in *Ae. taeniorhynchus, An. crucians, and An. pseudopunctipennis* in the mangroves of the Yucatan indicated the possible circulation of medically important Alphavirus (García-Rejón et al., 2023).

Previous records also highlight the presence of other species capable of transmitting pathogens, such as those belonging to the *Culex* (*Melanoconion*) subgenus, as well as species of the genera *Mansonia, Psorophora, Haemagogus, Sabethes, Deinocerites,* and additional species of the genera *Aedes* and *Anopheles*, are present in the region (Talaga et al., 2023).

The climate change threat modifies the thermal limits, seasonality, and distribution range of mosquitoes and pathogens (Mordecai et al., 2019). However, little information is available on the mosquito species from Yucatan and their relationship with the environment and climate along the year and the influence of human activities.

To understand this relationship, we designed a study aiming to observe the influence of environmental variables (temperature, rainfall, and impervious surfaces as a proxy to anthrophization) on the abundance of mosquito species in the Yucatán state. This study aims to contribute with field information that can be used in risk modelling, mosquito surveillance and control strategies.

2. Material and methods

Study area: The state of Yucatan is located in the north of the Yucatan peninsula in southern Mexico. The landscape is a mosaic of diverse habitats, including mangroves, marshes, coastal lagoons, coastal dunes towards the coastline, savannas, and tropical dry forest to the south, mixed with crops, grasslands, and secondary forest resulting from human activities. Yucatan state is mostly flat with an altitude below 200 m. The region is characterized by a warm tropical climate, with a mean annual temperature of 26 °C. Annual precipitation in the area range is between 1000 and 1200 mm, with a typical rainy season occurring from June to October (Hernández-Stefanoni et al., 2011; Morrone, 2006; Vázquez-Domínguez and Arita, 2010).

Study design: We selected nine sampling localities along an urbanization gradient, with three replicates of each land use type (natural, rural, and urban). Specifically, the three urban localities were chosen in Mérida city, three in rural areas (Hunucmá, Tetiz, and Kinchil), which are immersed in a matrix of tropical deciduous and semi-deciduous forest mixed with crops and human settlements, and three within the natural area of the Reserva de la Biosfera Ría Celestún (RBRC). These correspond principally to mangroves, coastal dunes vegetation, and salt marshes (Fig. 1). The trap locations were selected based on logistical criteria (safety of the traps and accessibility) and situated at a minimum distance of 2 km between them, determined by the average mosquito flight range, to ensure spatial independence in the sampling (Verdonschot and Besse-Lototskaya, 2014).

To characterize the natural, rural, and urban gradient in a quantitative manner, we established a 1 km diameter buffer around each locality and extracted the land cover and land use data using the National Forest Inventory land cover data (INEGI 2020). Subsequently, we grouped the land-cover categories into forested and impervious lands. Finally, based on previous works, we estimated the percentage of forested and impervious surface (IS) for the buffer around each locality as a proxy of anthropization (Kaminski et al., 2021; Ng et al., 2018; Talaga et al., 2020). In characterizing the natural, rural, and urban gradient, we identified 14 types of land cover. An evident gradient was observed from the localities within Mérida city (100 % IS) to the rural zones of Rural1 (89 % IS), Rural2 (54 % IS) and Rural3, (26 % IS), ending in the sampling localities of the RBRC with 0 % IS (Fig. 2).

Mosquito sampling: Mosquitoes were captured using BG-sentinel

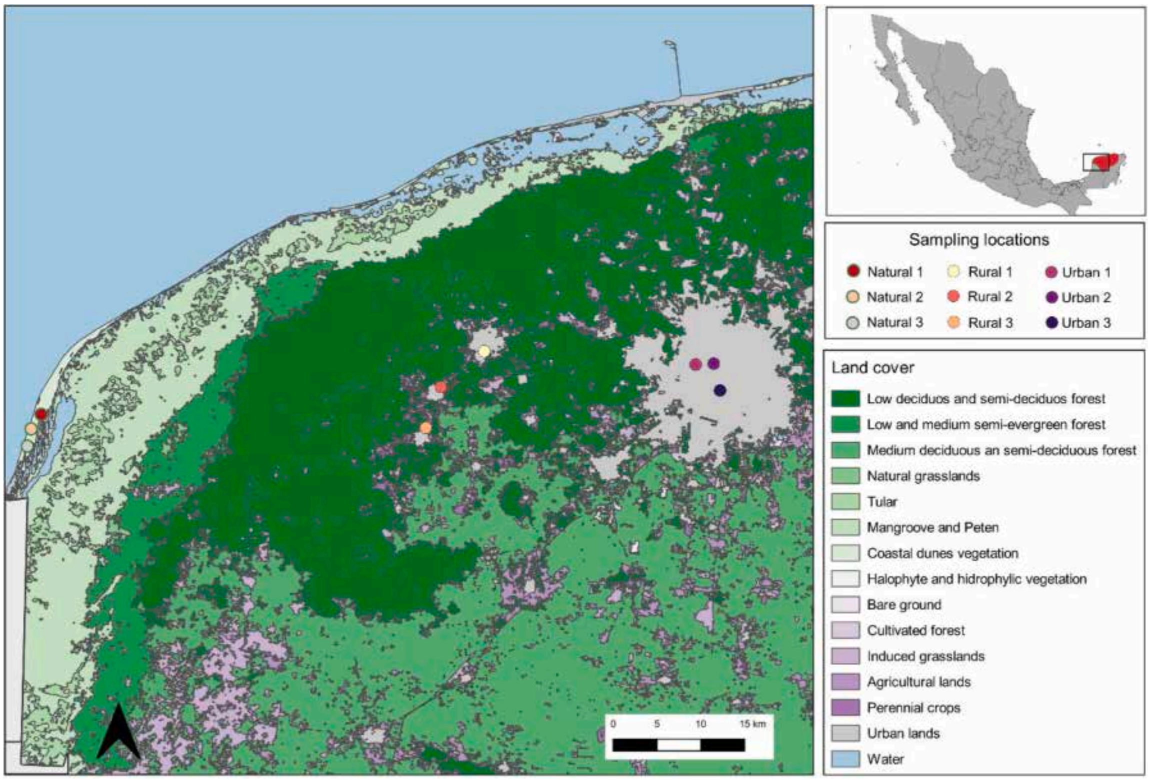

Fig. 1. Distribution of sampling localities along an urbanization gradient (natural, rural, and urban) in the Yucatan state, Mexico. Land cover type is shown according to the National Forest Inventory INEGI-2020.

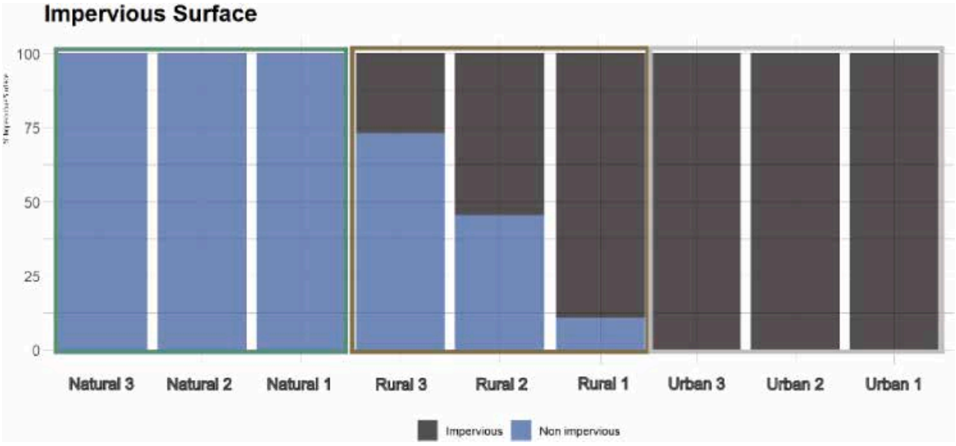

Fig. 2. Land use gradient based on the percentage of impervious surface for each locality (estimated using data National Forest Inventory INEGI-2020).

traps baited with BG-lure (Biogents AG, Regensburg, Germany) and supplemented with 1.5 kg of dry ice as a source of CO_2. Each BG-sentinel trap was located at the center of each locality and operated 24 h biweekly from June 2021 to June 2022, summing up a total of 234 trapping nights. All captures were preserved in dry ice and stored at −40 °C until identification in the laboratory. The mosquito collection was conducted following the official standards protocols of the Institutional Animal Care and Use Subcommittee (SICUAE) of the Universidad Nacional Autónoma de México (UNAM) and the study was conducted in accordance with local authorities.

Mosquito identification: Mosquitoes were identified on a chill table using a taxonomic key of Clark-Gil and Darsie (1983) adapted in line with the recent review of the mosquito fauna occurring in the Yucatan peninsula (Talaga et al., 2023). Considering the difficulty of accurately identifying *Culex* (*Melanoconion*) species based only on external features of adults, specimens of this subgenus were not identified to species.

Environmental variables: Temperature was measured throughout the year at each locality, using a data logger HOBO-Pendant UA-002–64, (Onset Computer Corporation, Bourne, MA). With the obtained data, the maximum temperature (Tmax), mean temperature (Tmean), minimum temperature (Tmin), and diurnal temperature range (DTR) were calculated from one to four weeks before sampling (Paaijmans et al., 2010; Blagrove et al., 2017). Daily precipitation data were obtained from CHIRPS-2.0 (Funk et al., 2014) and the weekly sum was aggregated from one to four weeks before the sampling week (1wbs to 4wbs).

Statistical analysis: The analysis was arbitrarily performed for the 15 most abundant mosquito species. The environmental variables were tested with Sperman rank correlation to avoid collinearity. Generalized linear mixed models (GLMM) with a negative binomial distribution were performed to test the effect of environmental variables on the abundance of mosquito species (Bolker et al., 2019). We used temperature variables (Tmean, Tmax, Tmin, DTR) and accumulated precipitation calculated at one to four weeks before the sampling, and the impervious surface percentage as fixed effect. To control for the seasonality effect, the epidemiological week of the sampling was used as the random effect variable. All statistical analysis and figures were carried out using the R software, v4.2. The glmm-TMB package was used for the negative binomial GLMM (Bolker et al., 2019). We conducted forward model selection using Akaike's information criterion (AIC), with the function AICctab from the bbmle package, and the likelihood ratio test was employed to compare similar nested models (Bolker, 2012).

3. Results

During the 234 days of trapping, we captured a total of 131,525 mosquitoes belonging to 11 genera and 49 species. We excluded from the analysis 25,269 specimens (14,225 males and 11,044 damaged females) as their identification to species was uncertain, resulting in a total of 106,256 mosquitoes for data analysis (Table 1). The two most abundant species throughout the year were *Aedes taeniorhynchus*, representing 74.5 % of the total captures, and *Culex quinquefasciatus* comprising 19 % of the samples. The 13 other species included in the analysis were: *Anopheles crucians, Aedes aegypti, Culex interrogator, Aedes bimaculatus, Aedes albopictus, Culex coronator, Culex* (*Melanoconion*) spp., *Anopheles albimanus, Psorophora ferox, Culex thriambus, Aedes serratus, Anopheles pseudopunctipennis,* and *Coquillettidia nigricans*.

Culex quinquefasciatus was captured in all localities throughout the year, being less abundant in two natural localities of the RBRC, and increasing in rural and urban localities, particularly in Rural 2 and Urban 3. The month of peak abundance for this species varied according to habitat type for different months: natural in December, rural in May and urban in January (Fig. 3).

Aedes aegypti was captured in all localities except in one (Natural 1). It was more abundant in urban and secondarily, in rural habitats, with a peak of abundance during the rainy season. Nevertheless, in the urban habitat two additional abundance peaks were observed, one in November after the end of the rainy season and another one in May before the next rainy season (Fig. 4).

Aedes taeniorhynchus, An. crucians and *An. albimanus* were primarily collected in natural localities, but *Ae. taeniorhynchus* was also secondarily captured in rural habitats, with a few individuals collected in urban habitats. *Anopheles crucians* was also found in rural localities closer to the RBRC. *Aedes taeniorhynchus* was more abundant after the end of the rainy season, whereas *An. crucians,* and *An. albimanus* showed an abundance peak several weeks after than *Ae. taeniorhynchus* being more abundant during the dry season (Fig. 4).

In contrast, *Cx. interrogator, Cx. thriambus* and *Cx. coronator* were captured mainly in rural habitats during the rainy season. On the other hand, *Ae. bimaculatus, Ae. serratus, Cx.* (*Melanoconion*) spp. *and Ps. ferox* were collected in natural habitats, principally displaying a peak of abundance at the end of the rainy season, except for *Ae. bimaculatus,* which was more abundant at the beginning of the rainy season (Fig. 4).

We found a positive relationship between the abundance of *Cx. quinquefasciatus* and the diurnal temperature range four weeks before the sampling ($z = 3.587$, $p < 0.001$) and the percentage of impervious surface ($z = 5.598$, $p < 0.001$) (Table 2, Fig. 3). Conversely, this species had a negative relationship with accumulated precipitation four weeks before the sampling ($z{=}{-}4.169$, $p < 0.001$). Abundance of *Ae. aegypti* was positively related to the minimum temperature one week before the sampling ($z = 3.504$, $p < 0.001$) and accumulated precipitation one week before the sampling, although the effect was small ($z = 2.035$, $p < 0.05$) (Fig. 5). *Culex thriambus* was positively related to the diurnal temperature range three weeks before the sampling ($z = 2.459$, $p < 0.05$) and accumulated precipitation three weeks before the sampling ($z = 5.598$, $p < 0.05$). Additionally, some species exhibited a negative relationship with the percentage of impervious surface: *Ae. taeniorhynchus* ($z{=}{-}17.343$, $p{=}{<}0.001$), *An. crucians* ($z{=}{-}3.572$, $p < 0.005$), *and Ps. ferox* ($z{=}{-}2.991$, $p < 0.001$). *Aedes taeniorhynchus* had a positive relationship with minimum temperature one week before the sampling ($z = 2.975$, $p < 0.01$) and *An. crucians* was negatively related to accumulated precipitation four weeks before the sampling ($z{=}{-}2.866$, $p < 0.01$). *Anopheles albimanus* was negatively related to the maximum temperature four weeks before the sampling ($z{=}{-}2.782$, $p < 0.01$) and accumulated precipitation four weeks before the sampling ($z{=}{-}3.225$, $p < 0.01$). *Anopheles pseudopunctipennis* was negatively related to the diurnal temperature range two weeks before the sampling ($z{=}{-}4.066$, $p < 0.001$) and accumulated precipitation two weeks before the sampling ($z{=}{-}3.058$, $p < 0.01$). *Aedes bimaculatus* was negatively related to the mean temperature four weeks before the sampling ($z{=}{-}2.003$, $p < 0.001$) and positively related to accumulated precipitation four weeks before the sampling ($z = 2.357$, $p < 0.05$). Additionally, two species were positively related only to accumulated precipitation one week before the sampling: *Ae. serratus* ($z = 2.015$, $p < 0.01$) and *Cq. Nigricans* ($z = 5.5331$, $p < 0.001$). Finally, *Cx.* (*Melanoconion*) spp. were positively related to accumulated rainfall three weeks before the sampling ($z = 5.159$, $p < 0.001$). We did not find any relationship between accumulated precipitation, maximum, minimum, and mean temperatures for *Cx. interrogator, Ae. albopictus,* and *Cx. coronator*.

4. Discussion

To our knowledge, this is the first work focusing on the influence of climatic and environmental variables in the Yucatan peninsula, Mexico for several mosquito species, other than *Ae. aegypti* and *Ae. albopictus.*

Table 1

Total mosquito abundance per locality of the 15 most abundant species used in the data analysis.

Mosquito species	Natural1	Natural2	Natural3	Rural1	Rural2	Rural3	Urban1	Urban2	Urban3	Total
Ae. aegypti	2	32	0	197	71	273	90	306	416	1387
Ae. albopictus	1	12	0	211	38	167	1	0	41	471
Ae. bimaculatus	142	363	117	0	5	1	0	0	0	628
Ae. serratus	20	47	7	13	1	14	0	0	1	103
Ae. taeniorhynchus	24,094	29,970	23,598	231	160	1040	10	5	10	79,118
An. albimanus	59	157	26	0	0	0	0	0	0	242
An. crucians	1314	754	168	0	4	8	0	0	0	2248
An. pseudopunctipennis	9	86	6	0	0	2	0	0	0	103
Cq. nigricans	21	32	34	0	0	3	0	0	0	90
Cx. (Melanoconion) spp.	53	56	116	2	1	27	0	0	0	255
Cx. coronator	0	0	1	109	42	84	0	2	20	259
Cx. interrogator	233	31	13	198	77	107	0	0	0	659
Cx. quinquefasciatus	7	1525	7	1806	4313	372	491	988	10,840	20,349
Cx. thriambus	29	8	9	1	34	28	0	0	0	109
Ps. ferox	114	90	3	1	2	6	0	0	0	216

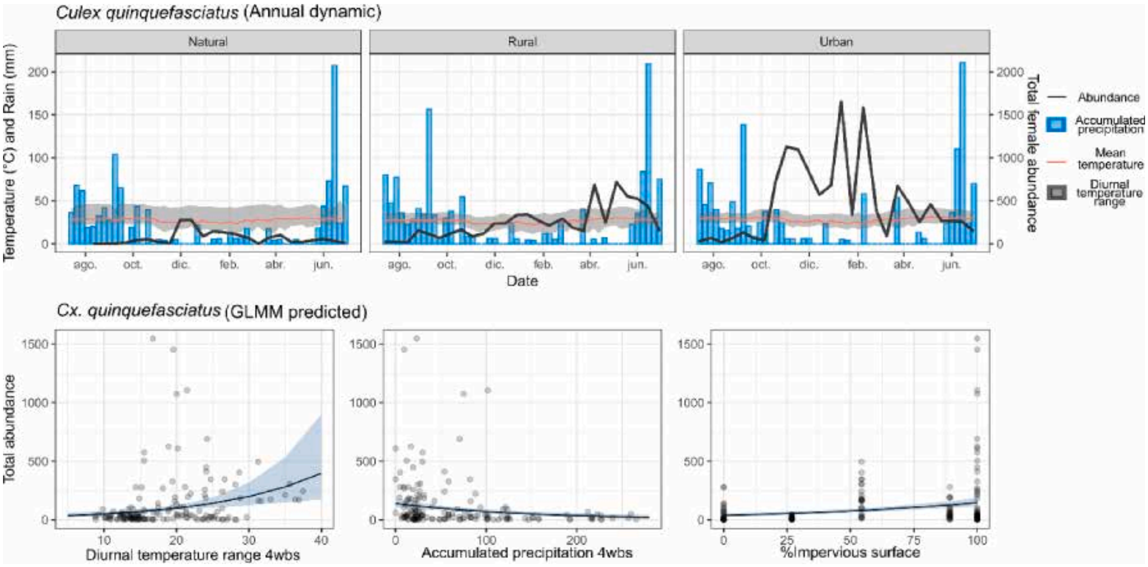

Fig. 3. (a) Annual dynamic of *Cx. quinquefasciatus* abundance and weekly accumulated climatic variables (black line: total abundance, blue bars: accumulated precipitation, red line: mean temperature and, gray area: diurnal temperature range. (b) Plotted predictions of the generalized linear mixed models showing the effect of the climatic variables and the percentage of impervious surface on the *Cx. quinquefasciatus* abundance. Gray points: weekly abundance data, black line: model prediction, and blue area confidence intervals at 95%.

Our results emphasize the fact that the effects of temperature and precipitation on mosquito abundance are species-specific. Therefore, generalist statements of the effect of climate and climate change on mosquito abundance or MBDs are not adequate for mosquito species in this region. Throughout an intensive longitudinal field work and a careful analysis of temporal patterns, we demonstrated how the key variables might vary depending on mosquito species and habitat types.

Culex quinquefasciatus, An. crucians, and *An. albimanus* showed a negative relationship with rainfall, being more abundant during periods with less than 50 mm of accumulated precipitation. Our results are in line with other studies; for *Cx. quinquefasciatus,* heavy rainfall overflows human-made-larval habitats (as anthropic containers), producing a flushing effect on immature mosquitoes and/or diluting organic material needed for larval development, diminishing the mosquito abundance (Soh and Aik, 2021). In contrast, another sylvatic species exploits natural resources such as bromeliads and tree holes as larval habitats (Wilke et al., 2017). Additionally, the availability of these larval habitats depends on the amount or rain (Baril et al., 2023). This was observed in our findings for *Ae. bimaculatus* and *Cx. (Melanoconion) spp*., which showed a positive relationship with accumulated precipitation at four and three weeks before the sampling, with the highest abundance near to 200 mm or rain. Similarly, *Ae. serratus, and Cq. nigricans,* exhibited a positive relationship with accumulated precipitation at one week before the sampling, with peak abundances occurring near to 22 mm of rain. The increases in the abundance of *An. crucians* and *An. albimanus* at the late rainy season, and the low abundances in the dry season, aligns with previous reports (Grieco et al., 2006; Hurtado et al., 2018). Similar findings are reported for *An. marajoara* larvae from Brazil (Galardo, et al., 2009). The negative relationship with accumulated precipitation four weeks before sampling might be related with several mechanisms, as flushing, but further studies are needed to clarify these findings.

We observed a positive relationship between *Cx. quinquefasciatus* abundance and the diurnal temperature range. Some studies reported the positive influence of mean temperature on larval and adult abundance (Moser et al., 2023; Rueda et al., 1990a; Soh and Aik, 2021). A significant abundance was described when the diurnal temperature range fluctuated between 15 °C and 25 °C, corresponding to the cooler months in Yucatan (October to February), which exhibit temperatures ranging from a minimum of 10 °C to 40 °C of maximum.

According to Rueda et al. (1990b), the optimal range for the development of *Cx. quinquefasciatus* is between 15 °C and 27 °C. Probably during these months, favorable conditions prevailed for the development of *Cx. quinquefasciatus*, as warm temperatures contribute to enhancing larval survival rates and adult longevity (Moser et al., 2023). Conversely, in our study area, the lag in the temporal effect in this case is four weeks, two weeks more than in other studies (Soh and Aik, 2021). A similar pattern was found for *Cx. thriambus* with a lag effect of three weeks before the sampling. There is limited knowledge about the climatic preferences of *Cx. thriambus,* and more studies are needed to clarify the effect of temperature on the life cycle of this species (Nelms et al., 2016).

In the case of *Ae. aegypti,* we observed a positive relationship with minimum temperature, consistent with other studies that have reported a positive relationship with the mean temperature (Scott et al., 2000). However, we noted a time lag in the influence on abundance, manifesting one week before the sampling. We observed greater abundances at warm temperatures, specifically when minimum temperatures exceeded 20 °C. It has been reported that warm temperatures favor larval development rates reducing the development time from egg to adult in a temperature range of 25–34 °C (Bellone and Failloux, 2020b; Chadee and Martinez, 2016).

We observed an increase in the *Ae. taeniorhynchus* abundance corresponding to rising minimum temperatures. This pattern aligns with the findings of Qualls et al. (2021). However, they reported a lag effect one month before the sampling, while our data showed a more immediate effect of one week before sampling. For *An. albimanus* we observed a decrease in abundance correlating to increasing maximum temperatures in the four weeks before the sampling. Members of genus *Anopheles* are generally associated high temperatures accelerating the development cycle; however, temperatures exceeding 34 °C are reported to delay larval development and increasing larval mortalities (Agyekum et al., 2021).

Concerning *Ae. bimaculatus*, we identified a negative relationship with the mean temperature four weeks before the sampling. Also, we observed a negative relationship of diurnal temperature range two weeks before the sampling on *An. pseudopunctipennis* abundance. This negative effect of temperatures on *An. albimanus* and *An. pseudopunctipennis* may reflect the negative effect of high temperatures on mosquito longevity and life expectancy (Tabachnik et al., 2010). Therefore, we propose that these two mosquito species may be more sensitive to high

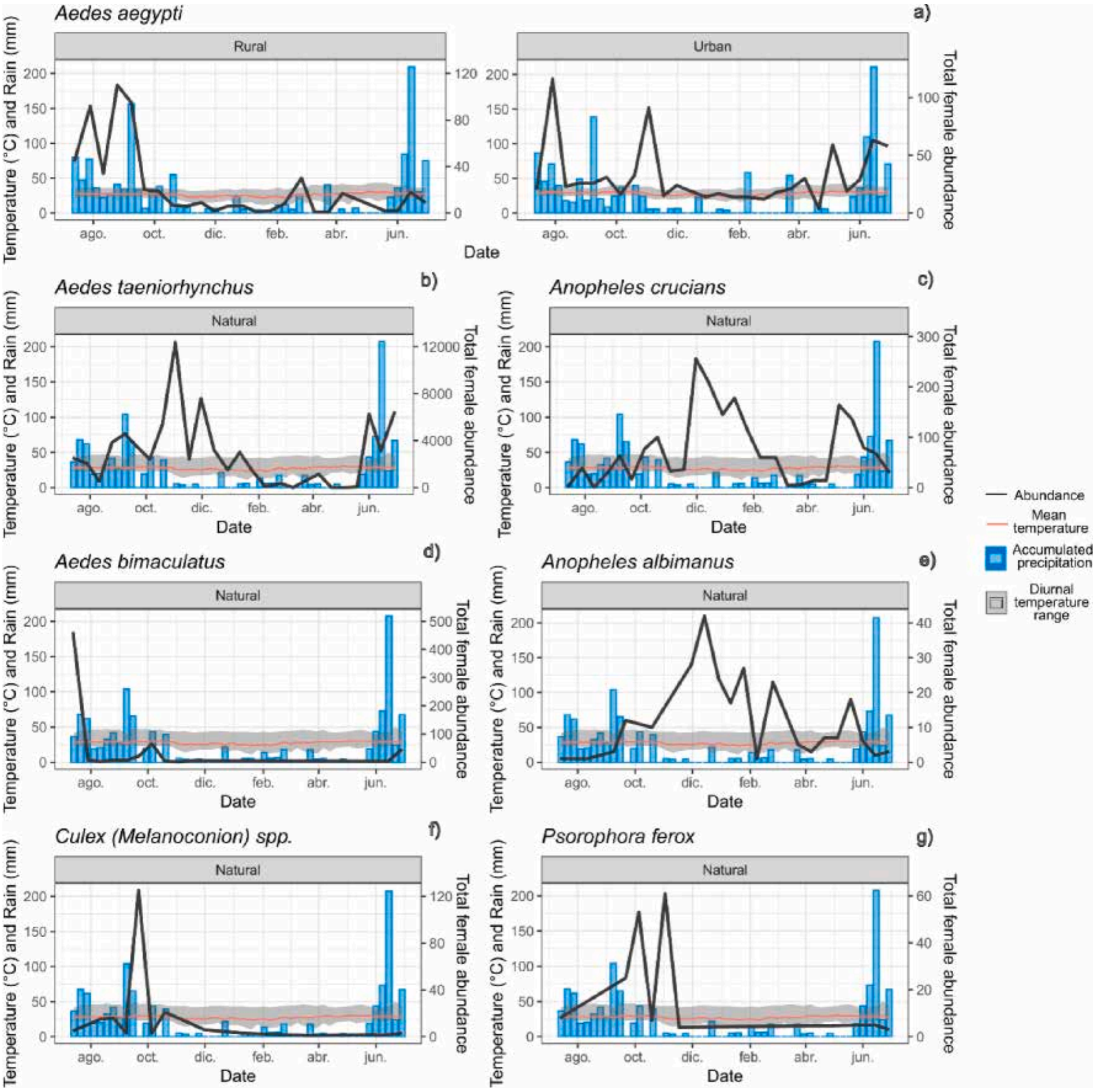

Fig. 4. Annual dynamics of mosquito species in the habitat type in which each species presented the highest abundance (black line: total abundance, blue bars: accumulated precipitation, red line: mean temperature and, gray area: diurnal temperature range). *Aedes aegypti* was mainly captured in the urban and rural habitats, whereas the other species were mostly captured in natural habitats. The high variation in abundance magnitude is evident on the secondary Y-axis (right side), ranging from 40 individuals captured for *An. albimanus* to 12,000 individuals captured of *Ae. taeniorhynchus.*

temperatures. Limited knowledge is available regarding the bionomics data of these species and therefore, more studies are needed to confirm these conclusions.

In addition, the percentage of impervious surface is a proxy of anthropization and helped us to distinguish species with urban and rural habitat preference from those with natural habitat preference, as observed in the case of introduced species *Ae. aegypti* and *Cx. quinquefasciatus.* These species are urban and rural as reported in other works, as they depend principally on artificial larval habitats (Talaga et al., 2020; Wilke et al., 2019). Additionally, they exhibit a preference for human blood meals and animals close to humans, thereby increasing the potential for urban and rural cycle of several important arboviral diseases, as dengue, chikungunya, West Nile or Saint Louis encephalitis (Rose et al., 2020). Nevertheless, we found a few specimens of these species in natural habitats throughout the year, likely due to human activities in the region encroaching on natural land (tourism, irregular settlements, and primary activities). This highlights the plasticity and the capacity of these species to invade natural habitats (Chadee and Martinez, 2016; Wilke et al., 2021). Finally, *Ae. taeniorhynchus, An. crucians* and *Ps. ferox* are species mainly associated with natural habitats and therefore, their abundance is reduced with anthropization (Navarrete-Carballo et al., 2022). However, the preference of *Ae. taenyorhyncus* and *An. crucians* for habitats associated with coastal ecosystems should be taken into account (Talaga et al., 2023; Dale et al., 2023).

The study has some limitations. The use of BG- sentinel traps as the capture method, primarily attracting mammophilic species, may limit the capture of certain species, especially those with lower abundance. Furthermore, considering the seasonal and inter-annual variation of rainfall and temperature, alongside the constant increase in the urbanization in the region, a long-time perspective is needed to clarify the influence their influence on mosquito abundance.

The effect of global change is accelerating worldwide, and the Yucatan peninsula is a clear example (Andrade-Velázquez et al., 2021). Temperatures are increasing, rainfall patterns are changing and the impervious surface due to urbanization is rising at a high rate in recent years (Andrade-Velázquez et al., 2021; Cinco-Castro and Herrera-Silveira, 2020; Hernández-Stefanoni et al., 2011). All these changes will have a marked impact in favoring and reducing certain

Table 2

Summary of generalized linear mixed models output for the most abundant species, showing the estimated, value for the coefficient z, standard error, and p-value for each species. (***P*** *< 0.05, **< 0.01, ***< 0.001). Additionally, the Akaike Information Criterion AIK, and the Bayesian Information Criterion BIC for each model. The variables represent time lagged from one to four weeks before the sampling (wbs).

Specie	Variable	Estimate	Std. Error	Z	P-value	AIC	BIC
Ae. aegypti	Minimum temperature 1wbs	0.094439	0.026951	3.504	0.000458***	772.3	786.2
	Accumulated precipitation 1wbs	0.018875	0.009276	2.035	0.041866*		
Ae. bimaculatus	Mean temperature 4wbs	−0.44086	0.22011	−2.003	0.0452*	198.6	205.4
	Accumulated precipitation 4wbs	0.01348	0.00572	2.357	0.0184*		
Ae. serratus	Accumulated precipitation 1wbs	0.02997	0.01487	2.015	0.0439*	134.4	139.6
Ae. taeniorhynchus	Minimum temperature 1wbs	0.225342	0.07574	2.975	0.00293**	1582.9	1597
	% Impervious surface	−0.056932	0.003283	−17.343	< 2e-16***		
An. crucians	Accumulated precipitation 4wbs	−0.011036	0.003851	−2.866	0.004157**	642.4	656.3
	% Impervious surface	−0.05249	0.014695	−3.572	0.000354***		
An. albimanus	Maximum temperature 4wbs	−0.083375	0.029974	−2.782	0.00541**	211.6	219.6
	Accumulated precipitation 4wbs	−0.006297	0.001952	−3.225	0.00126**		
An. pseudopunctipennis	Diurnal temperature range 2wbs	−0.190603	0.046879	−4.066	0.0000479***	91.2	95.3
	Accumulated precipitation 2wbs	−0.028041	0.009171	−3.058	0.00223**		
Cq. nigricans	Accumulated precipitation 1wbs	0.07883	0.01479	5.331	0.0000000976**	81.4	84.8
Cx. (Melanoconion) spp.	Accumulated precipitation 3wbs	0.017094	0.003313	5.159	0.000000248***	165.9	171.5
Cx. quinquefasciatus	Diurnal temperature range 4wbs	0.068717	0.019156	3.587	0.000334***	1771	1789.5
	Accumulated precipitation 4wbs	−0.00683	0.001638	−4.169	0.0000305***		
	% Impervious surface	0.013495	0.00241	5.598	0.0000000216***		
Cx. thriambus	Diurnal temperature range 3wbs	0.13204	0.0537	2.459	0.0139*	82.5	84.9
	Accumulated precipitation 3wbs	0.02286	0.01133	2.018	0.043*		
Ps. ferox	% Impervious surface	−0.03754	0.01255	−2.991	0.00278**	139	143.4

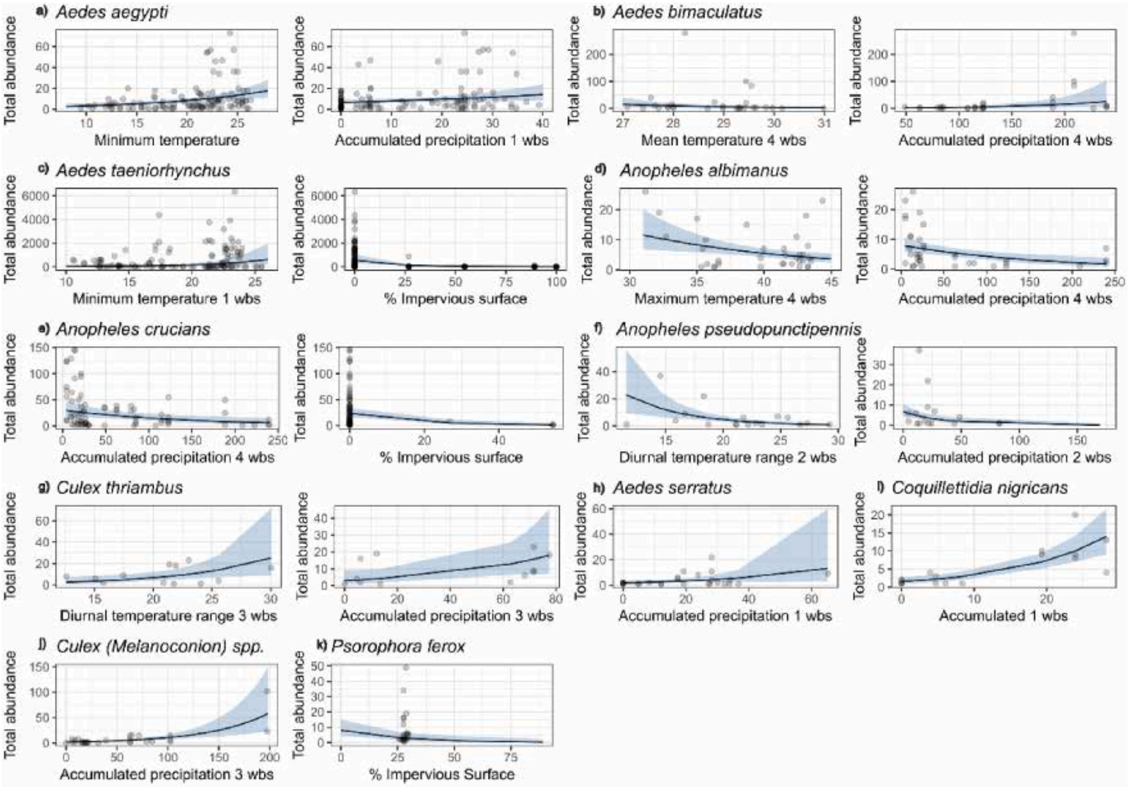

Fig. 5. Results of the generalized linear mixed models, with a negative binomial distribution, showing the effect of the climatic variables and the percentage of impervious surface on the mosquito abundance. Gray points: weekly abundance data, black line: model prediction, and blue area confidence intervals at 95 %.

mosquito species. In particular, urban species such as *Ae. aegypti* and *Cx. quinquefasciatus* might increase their abundance, favored by increased urbanization and habitat availability, as well as higher temperatures (Talaga et al., 2020). Conversely, the abundance of some species might be reduced, in particular for natural species most sensitive to high temperatures, like *An. albimanus* and *An. pseudopunctipennis* (Soh and Aik, 2021). Additionally, species exhibiting a marked seasonality, such as *Ae. bimaculatus, Ae. serratus* or *Cq. nigricans,* may also be affected by changes in rainfall patterns (Wilke et al., 2017).

Our results show that there is a species-specific response to climatic variables on mosquito abundance. The impervious surface is a helpful proxy to differentiate the species within natural, rural, and urban habitats. These findings providing valuable field information for the less known species other than the synanthropic ones, which have been more extensively studied. Nevertheless, more species-specific research is needed to understand the effect of climate on mosquito species and predict the effect of climate change on MBDs.

CRediT authorship contribution statement

O. García-Suárez: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M.J. Tolsá-García:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **R. Arana-Guardia:** Writing – review & editing, Data curation. **V. Rodríguez-Valencia:** Writing – review & editing, Data curation. **S. Talaga:** Writing – review & editing, Data curation. **P.A. Pontifes:** Writing – review & editing, Formal analysis. **C. Machain-Williams:** Writing – review & editing, Investigation. **G. Suzán:** Writing – review & editing, Validation, Supervision. **D. Roiz:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data is available in Fig Share with the doi:10.6084/m9.figshare.25818769.

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