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ORIGINAL RESEARCH ARTICLE

Influence of abiotic factors on the oviposition of *Aedes (Stegomyia) aegypti* (Diptera: Culicidae) in Northern Paraná, Brazil

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Abstract

Aedes aegypti is the main vector of dengue in the Americas and is also a transmitter of urban yellow fever arboviruses, Zika, and Chikungunya, all of which have substantial economic impacts on the affected countries. Through mathematical models, the influence of climatic factors on the oviposition of *Ae. aegypti* was determined. The data were collected in the city of Apucarana, Paraná State, using oviposition traps. Daily data were submitted to a negative binomial regression model ($p < 0.05$). The analyses were performed using the R statistical program to determine the climatic factors that most influenced oviposition. A Poisson regression showed that the variables temperature, atmospheric pressure, humidity, and precipitation significantly increased the number of eggs. However, using the semi-normal probability graph with a simulation envelope, it was determined that the Poisson regression model was not adequate to explain the relationships between the variables. Thus, a negative binomial regression model was used, which overcame the problem of overdispersion, and showed that only temperature affected the increase in the number of eggs, where an increase of 1 °C was expected to result in a 54.03% increase in the number of *Ae. aegypti* eggs.

Keywords Ovitrap · Vector monitoring · Climatic factors · Poisson Regression · Negative Regression

Introduction

Being an exotic species of African origin, *Aedes* (*Stegomyia*) *aegypti* Linnaeus, 1762 currently has a high degree of anthropoly and domiciliation in Brazil and is the main vector of the dengue, Chikungunya, Zika, and urban yellow fever viruses in the Americas. Dengue is the most important arbovirus in the world, with a 30-fold increase in the number of cases registered annually over the last 50 years, exposing almost half of the global population to the risk of contagion with an estimated 50 to 100 million cases per year being in more than 100 countries where it is endemic (WHO 2017). In 2019, American countries registered 3 million dengue cases, the highest number in history (PAHO 2020a). In the first 5 months of 2020, more than 1.6 million dengue cases were recorded in the Americas, even in the face of the COVID-19 pandemic (PAHO 2020b). This situation became even more worrisome in September 2014 with the introduction of Zika and Chikungunya, causing a triple epidemic in the Brazil (Carvalho and Moreira 2017). Chikungunya fever presents 1.5 million cases on the South America, and Zika is a new challenge for nations, with cases reported mainly in Brazil and Colombia (Araújo et al. 2018). These mosquito-borne pathogens affect the economy by debilitating the workforce and creating the need to treat numerous patients, which can congest the public health system, possibly causing it to collapse (Calvo et al. 2016).

Currently, the breeding grounds for *Ae. aegypti* are all places that can accumulate water from anthropic actions and are contained within the urban environment. This factor is crucial for delivering etiological agents to humans and animals (Gubler 1998). During oviposition, females deposit eggs in many breeding sites (jumping oviposition) to ensure reproductive success, and the eggs can remain viable for more than 1 year. An infected female is capable of transmitting the arbovirus for the rest of her life after virus incubation (Carvalho and Moreira 2017; Powell and Tabachnick

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2013). Normally, 3 d after engorgement, the females can lay, with between 60 and 125 eggs laid at a time (Christophers 1960). The eggs are black, with a center of mass at 0.47 of the egg length and an average value of 0.012 ± 0.002 mm^3 (Morais et al. 2019).

Climatic conditions are factors that contribute to the reproductive success of mosquitoes and may include temperature, rainfall, humidity, wind speed, and atmospheric pressure. Santos et al. (2020) observed a relationship between increased precipitation, decreased wind speed, and increased humidity with an increase in the number of eggs collected in the northeastern region of Brazil. Other factors can directly affect the oviposition dynamics of the *Ae. aegypti* mosquito, such as human population density, socioeconomic factors, and geographical characteristics of the study site.

The development of an egg to an adult mosquito occurs in approximately 8 to 12 d, allowing a change in the metabolism of the insects as the climate warms, causing increased proliferation when exposed to higher temperatures. Eggs are very sensitively affected by temperature, diapause phenomenon occurring when subjected to lower temperatures in the laboratory and in the field (Hanson and Craig 1995).

Currently in Brazil, one of the monitoring methods for controlling this vector is based on determining its presence at breeding sites using the Rapid Survey of Indexes for *Aedes aegypti* and the use of an ovitrap, which is widely used to identify the site-specific presence of *Ae. aegypti*. According to Technical Note 3/2014/IOC-FIOCRUZ (2014), the trap is the most sensitive method to detect the vector. However, ovitraps allow the counting and identification of eggs and are also an economical, accessible, and sensitive detection method for *Ae. aegypti* (Braga and Valle 2007).

Mathematical modeling of epidemics is of great importance for epidemiological studies. It allows a better understanding of the development of the epidemic besides the search for efficient measures for its prevention and more effective monitoring and control strategies. With this current context, the goal of this study was to demonstrate the influence of climatic factors, including temperature, precipitation, relative humidity, wind speed, and atmospheric pressure, on the oviposition behavior of mosquitoes by using mathematical models.

Material and methods

Data collection

Egg collection was conducted using oviposition traps (ovitraps), consisting of a dark plastic container (15×25 cm) with 500 mL capacity. In each trap, 300 mL of an attractive substance, composed of 270 mL of water and 30 mL of hay water (water tanned in *Brachiraria* sp. grass for 15 d at a 1: 5 ratio), and a duratree reed (12×2.5 cm) partially submerged in the solution to allow oviposition. Each container received 1 g of larvicide temephos to prevent the larvae from developing.

In total, 107 traps were installed on the Apucarana campus of the Federal Technological University of Paraná (UTFPR-AP) (23°33′04″S; 51°25′43″W, 864 m altitude), including indoor and outdoor environments. The traps were installed at a minimum distance of 3 m from each other and remained exposed for 7 d, being replaced on the last day by another trap in the same place. The straws were collected and taken to the Microbiology Laboratory at UTFPR-AP, where they were dried for 24 h at room temperature. The eggs were counted with the aid of an Opton®Tim-2BR stereoscopic microscope and subsequently eliminated with a sodium hypochlorite solution and 5% water. For this study, oviposition from March 2016 to February 2017 was analyzed using the egg density index (IDO).

Meteorological data

Meteorological data for the period from March 2016 to February 2017 were obtained from the Paraná Meteorological System (SIMEPAR) (23°51′75″S; 51°53′02″W). Daily data on temperature, precipitation, humidity, atmospheric pressure, and wind speed were provided. The daily data for each variable were grouped into a single value consisting of the arithmetic mean, which represented the week corresponding to that of egg collection.

Data analysis

The weekly data on the number of eggs, temperature (°C), precipitation (mm), relative humidity (%), atmospheric pressure (Pa), and wind speed (m/s) were submitted to a negative binomial regression model ($p < 0.05$), which considers that the average rate of occurrences of the number of eggs is a random variable. The analyses were performed in the R statistical program (R Development Core Team 2018) to determine the climatic factor that most influenced the oviposition of *Ae. aegypti*.

Results and discussion

Scatter diagram

Before conducted the statistical analysis of the data, to identify which climatological variables could affect or explain the quantity of *Ae. aegypti* eggs, an exploratory multiple regression analysis was conducted. Thus, it was possible to evaluate the relationships between the response variable, the number of eggs, and explanatory variables, including temperature, relative humidity, precipitation, wind speed, and atmospheric pressure.

The dispersion diagram (Fig. 1) shows that only the temperature variable was related to the response variable, i.e., increases in the average temperature increased the number of eggs. The other variables were not related to the number of eggs. Upon the examination of the diagram, it was noted that the atmospheric pressure variables remained constant with respect to the temperature. However, wind speed, humidity, and precipitation had no relationship with the response variable, i.e., the behavior of the points did not follow any convergence.

Poisson regression model

The Poisson regression model was proposed to explain which variables were related to an increase in the number of eggs because of the behavior of the response variable, which resulted from a counting process within a given time interval. This probabilistic model has two important mathematical properties: the occurrence of the counts is independent and the average rate of occurrence per week is constant.

Table 1 shows that the variables temperature, atmospheric pressure, humidity, and precipitation were significant for the increase in the number of eggs of *Ae. aegypti*.

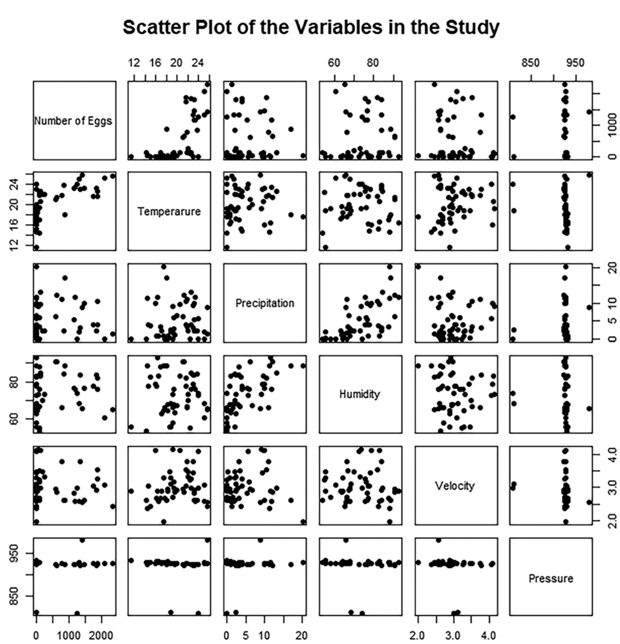

Fig. 1 Diagram of dispersion of oviposition of *Ae. aegypti* collected with ovitraps in relation to temperature, precipitation, humidity, wind speed, and atmospheric pressure from March 2016 to February 2017 in Apucarana, Paraná, Brazil

Table 1 Results of the Poisson regression model for *Aedes aegypti* oviposition in relation to abiotic factors from March 2016 to February 2017 in Apucarana, Paraná, Brazil

Variable	Estimate	Standard Error	P-value
Intercept	-6.5706899	0.2479018	< 2e-16 ***
Temperature	0.4497455	0.0036064	< 2e-16 ***
Wind speed	-0.0053913	0.0144708	0.70947
Atmospheric pressure	-0.0007074	0.0002213	0.00139 ***
Relative humidity	0.0504169	0.0009513	< 2e-16 ***
Precipitation	0.0121095	0.0018437	6.47e-11***

To verify whether the Poisson regression model was suitable for the data, a residual analysis was performed, which considers the random error caused by random variation. A semi-normal probability plot with a simulation envelope was used. It was found (Fig. 2) that all points were not included in the simulated envelope, suggesting that the Poisson regression model was not adequate to explain the relationships between the variables.

The simulated envelope graph indicated the presence of an overdispersion phenomenon, which is related to the "excess" in data variability, that is, the variance of the data was greater than the average. This excess of dispersion occurred because the average rate of occurrence of eggs was not constant for every week, such that one of the properties of the Poisson distribution was violated This explained the lack of suitability of the data.

To solve the problem of overdispersion, it was necessary to consider the average rate of egg occurrence as a

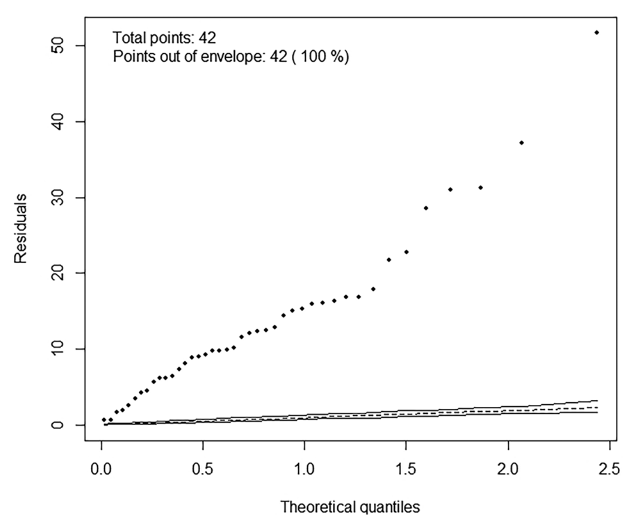

Fig. 2 Semi-normal probability graph with a simulation envelope for the Poisson regression model for *Aedes aegypti* oviposition in relation to abiotic factors from March 2016 to February 2017, Apucarana, Paraná, Brazil

random variable. The average rate began to have a gamma distribution; consequently, the variable number of eggs followed a negative binomial distribution. Assuming that the average number of occurrences of a Poisson distribution has a random portion, it was described by Eq. 1:

$$\lambda i = ui.Vi \tag{1}$$

Negative binomial regression model

To explain which variables influenced the increase in the number of eggs and overcome the problem regarding the overdispersion of data, a negative binomial regression model was proposed.

Negative binomial regression model

In Table 2, it is noted that only temperature significantly influenced the increase in the number of eggs.

Again, a semi-normal probability plot with a simulation envelope was constructed to verify whether the negative binomial regression model was adequate for the data (Fig. 3).

Figure 3, shows that 100% of the points were contained in the simulated envelope, and it can be concluded that the negative binomial regression model was adequate to explain the relationships between the variables. Thus, the negative binomial model can be adjusted to contain only the explanatory variable that influenced the response variable, i.e., temperature. The results are shown in Table 3.

When interpreting the negative binomial regression model as adjusted, the number of eggs given the temperature is represented by:

$$\theta(\mathrm{T}) = e^{(-3.21341+0.43202x\mathrm{T})} \tag{2}$$

Adjusted negative binomial regression model

Thus, it can be concluded that with an increase in temperature of 1 °C, the expected increase in the number of mosquito eggs is given by:

Table 2 Results of the negative binomial regression model for the analysis of *Aedes aegypti* oviposition in relation to abiotic factors from March 2016 to February 2017, Apucarana, Paraná, Brazil

	Estimate	Standard Error	P-value
Intercept	0.0808149	10.6652596	0.994
Temperature	0.3785252	0.0781601	1.28e-06 ***
Wind speed	-0.4603225	0.6235616	0.460
Atmospheric pressure	0.007476	0.0103693	0.943
Relative humidity	-0.0252038	0.0314448	0.423
Precipitation	0.082548	0.0686951	0.230

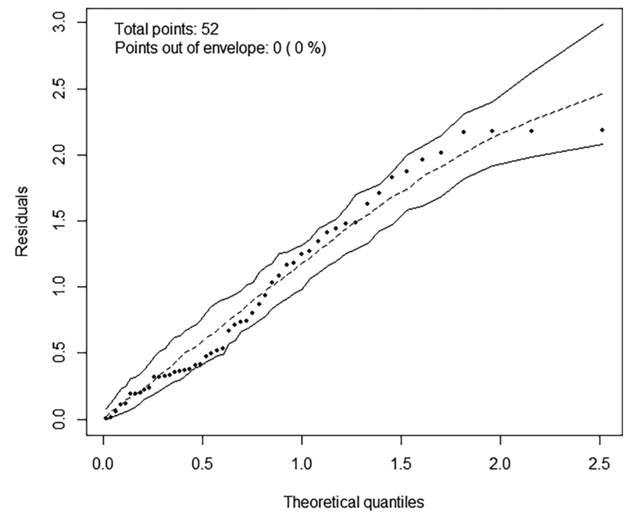

Fig. 3 Semi-normal probability graph with simulation envelope for the negative binomial regression model

$$\theta\frac{\mathrm{T}+1}{\theta}(\mathrm{T}) = e^{(0.43202)} = 1.54036 \tag{3}$$

Negative binomial regression model adjusted to the increase of 1 °C

A 1 °C increase in temperature is expected to increase the number of *Ae. aegypti* eggs oviposited by 54.03%. When applying the negative binomial model represented by Eq. 2, a graph can be constructed that shows the exponential increase in the number of eggs in relation to the increase in temperature (Fig. 4).

Temperature is an important factor that influences the establishment of insect populations, either directly through their development or indirectly through their feeding because they are poikilothermic and their body temperature varies according to the temperature of the environment. For *Ae. aegypti*, temperature interferes with flight, feeding, reproduction, pathogen transmission, and several other morphological and physiological factors in its life cycle (Delatte et al. 2009; Marchoux et al. 1903; Rowley and Graham 1968).

Within its life cycle, the development of immature forms may accelerate as the temperature increases. Beserra et al. (2006) concluded that the development of eggs, larva, pupa,

Table 3 Results of the negative binomial regression model with only temperature variable to explain the oviposition of *Aedes aegypti*, from March 2016 to February 2017, Apucarana, Paraná, Brazil

	Estimate	Standard Error	P-value
Intercept	-3.21341	1.38370	0.0202 *
Temperature	0.043202	0.06811	2.25e-10 ***

*significant for $p < 0.05$

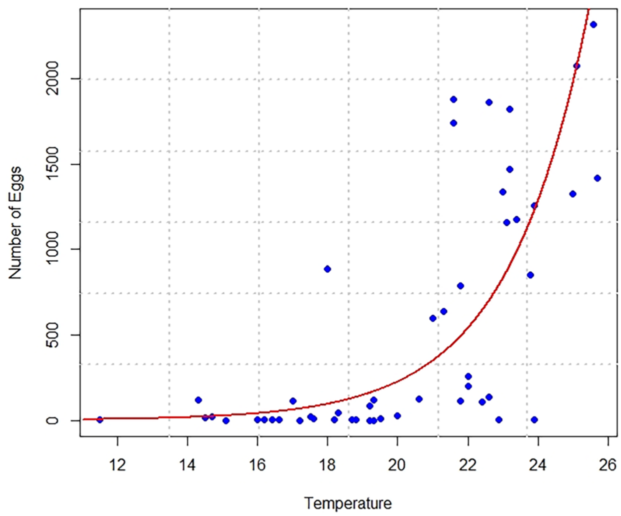

Fig. 4 Number of eggs × temperature (°C) in *Aedes aegypti* oviposition collected with oviposition traps between February 2016 to March 2017 in Apucarana, Paraná, Brazil

and the time from egg to adult decreased with thermal elevation, being recorded for the extremes in temperatures of 18 °C and 34 °C. The same authors detected significant interactions between temperature, longevity, and fertility of adults, with a decrease in longevity with an increase in temperature to 28 °C, being significantly higher at 26 °C for females and 22 °C and 26 °C for males. Based on the development time and viability of the eggs, larva, pupa, and fecundity phases of adults, it was determined that the temperature favorable to the vector was above 22 °C and below 32 °C. Even in hot environments, *Aedes* has adapted to human landscapes by hibernating in sewers and selecting shaded areas during the day in warm environments (Ebi and Nealon 2016).

Temperature affects not only the development of the vector but also the speed of transmission of the dengue virus. The time between feeding and detection of the virus in the salivary glands of *Ae. aegypti* decreased from 9 d at 26 °C and 28 °C to 5 d at 30 °C for the dengue strains DENV-1 and DENV-4 (Rohani et al. 2009), that is, an increase of only 2 °C may further increase the risk of contagion.

These data are worrisome because the Intergovernmental Panel on Climate Change (IPCC 2007) concluded that Earth's temperature will increase by an average of approximately 2 °C to 6.5 °C by 2099. In Brazil, the forecasted increase is from 1 °C by 2040 and possibly up to 6 °C by 2100. This temperature variation may interfere with the life cycle of insects and increase viral circulation. Kraemer et al. (2015) reported that the global distribution of *Aedes* has never been considered as important as it is today because *Ae. aegypti* has greatly expanded its geographic distribution over the past 30 years. It is estimated that in the context of climate change, regions with adequate environmental conditions for the development of the *Aedes* (high number of breeding sites, regions with greater frequency and intensity of rainfall and air humidity, adequate temperature, and availability of food) will increase by 50% by the end of the century, putting another 30 million people at risk (Glasser and Gomes 2002; Rochlin et al. 2013).

Conclusion

The negative binomial regression model ($p < 0.05$) determined that temperature was the only variable that influenced the increase in the number of eggs of *Ae. aegypti*, with an increase of 1 °C in temperature expected to increase the number of *Ae. aegypti* eggs deposited by 54.03%. Therefore, it was concluded that seasons with higher temperatures, such as summer, present a greater incidence of dengue because of the influence of temperature on oviposition. This factor is intrinsically related to global warming predicted by the IPCC, which may contribute to a greater density of this vector.

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Declarations

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