The influence of urban heat islands and socioeconomic factors on the spatial distribution of *Aedes aegypti* larval habitats

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Abstract

We addressed the potential associations among the temporal and spatial distribution of larval habitats of *Aedes* (*Stegomyia*) *aegypti*, the presence of urban heat islands and socioeconomic factors. Data on larval habitats were collected in Santa Bárbara d'Oeste, São Paulo, Brazil, from 2004 to 2006, and spatial and temporal variations were analysed using a wavelet-based approach. We quantified urban heat islands by calculating surface temperatures using the results of wavelet analyses and grey level transformation from Thematic Mapper images (Landsat 5). *Ae. aegypti* larval habitats were geo-referenced corresponding to the wavelet analyses to test the potential association between geographical distribution of habitats and surface temperature. In an inhomogeneous spatial point process, we estimated the frequency of occurrence of larval habitats in relation to temperature. The São Paulo State Social Vulnerability Index in the municipality of Santa Barbára d'Oeste was used to test the potential association between presence of larval habitats and social vulnerability. We found abundant *Ae. aegypti* larval habitats in areas of higher surface temperature and social vulnerability and fewer larval habitats in areas with lower surface temperature and social vulnerability.

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Introduction

Intensive urbanisation since the 1950s has altered the natural landscape in Brazil and severely impacted communities of plants and animals in these areas (McKinney, 2008; Knapp *et al.*, 2017). Urbanisation has generally been most severe in economically deprived areas and is frequently accompanied by poor urban planning and reduced levels of sustainability (Haughter and Hunter, 1994). The resulting changes of the environment can create ecological conditions that, coincidentally, favour the presence of mosquito vectors of human pathogens and thus the establishment of epidemics of vector-borne diseases (Lafferty, 2009; Misslin *et al.*, 2016). Among the mosquito vectors most strongly associated with urban environments is *Aedes* (*Stegomyia*) *aegypti* (Linnaeus, 1762) (Foratini, 2002), which plays a key role in the transmission of dengue and yellow fever viruses (Foratini, 2002; Jentes *et al.*, 2011; Simmons *et al.*, 2012), chikungunya virus (Leparc-Goffart *et al.*, 2014; Vega-Rúa *et al.*, 2014) and zika virus (Freitas *et al.*, 2015; Zanluca *et al.*, 2015). Consequently, the Brazilian public health system has been continuously challenged by the risk of arboviruses, particularly dengue (Braga and Valle, 2007; Barcellos and Lowe, 2014) and, more recently, zika (Faria *et al.*, 2017), chikungunya (Cardoso *et al.*, 2017) and urban yellow fever (Possas *et al.*, 2018) epidemics.

Ae. aegypti was reintroduced into Brazil in the 1970s, after being previously eradicated in the 1950s (Araújo *et al.*, 2015). The species has since colonised most of the country, facilitated by intensive commerce, urbanisation, social vulnerabilities and human migration (Gubler, 1998; Chang *et al.*, 2014) making this species a major public health threat (Guzman and Harris, 2015). Urban environments are a particularly important habitat for *Ae. aegypti*, as they provide an abundance of suitable containers for larval development, such as plates, plant pots, cans, bottles, recyclable containers and swimming pools (Piovezan *et al.*, 2012; Kraemer *et al.*, 2015). *Ae. aegypti* is also strongly associated with poor sanitary conditions and lack of waste residual recycling typical of rapidly expanding urban areas and seen as important contributory factors to epidemics of vector-borne diseases (Costa *et al.*, 2017).

The fact that mosquitoes are insects, and therefore exothermic, makes temperature a fundamentally important factor in the dynamics of transmission of vector-borne diseases (Meineke *et al.*, 2013; Xu *et al.*, 2017). This kind of transmission dynamics is highly dependent on temperature because the latter not only affects mosquito survivorship and the duration of its life cycle but also the extrinsic incubation period of the pathogen (Yang *et al.*, 2009; Bhatt *et al.*, 2013; Naish *et al.*, 2014). For example, temperatures above 30 °C can reduce the extrinsic replication cycle of the dengue virus from 12 to 7 days and alter infection rates from 67 to 95% (Watts *et al.*, 1987). A particularly important phenomenon that affects temperatures in urban environments is the concept known as urban heat island (UHI). An UHI increases surface temperature in urban areas relative to the surrounding countryside and impacts human wellbeing and public health negatively (Mohajerani *et al.*, 2017). Urbanisation and the intensive use of man-made materials significantly increases anthropogenic heat production, interfering with wind dynamics, physical and thermal properties of heat absorption and heat dissipation (Landsberg, 1981; Oke, 1995). This urban climate is characterised by temperatures that can be 1 or 2 °C higher than the surrounding countryside and may in some cases be 3 ºC higher (Tyson *et al.*, 1972) as frequently occurs in metropolitan areas. These variations in the surface temperatures brought about by UHIs can favour the occurrence of vector-borne disease epidemics (Misslin *et al.*, 2016), including Brazil's dengue epidemics (Araujo *et al.*, 2015).

The current study aims to establish the spatial distribution of *Ae. aegypti* and explore the potential associations among vector larval habitat frequency, UHIs and the social vulnerability index in the city of Santa Barbara d'Oeste, Sao Paulo, Brazil. The study should provide a greater understanding of social vulnerability index and weather factors associated with the occurrence of *Ae. aegypti* larval habitats and the potential risk of arbovirus exposure in the urban environment. It should also assist dengue surveillance programmes in the development of more effective public health and urban development strategies.

Materials and Methods

Sampling area

The sampling area is located in the Santa Bárbara d'Oeste municipality, in the Atlantic Forest biome, between the geographical coordinates 22°44'09" - 22°51'43" South and 47°20'27" - 47°30'36" West (Figure 1). Its total area covers 271 km^2 and its population is estimated at 190,769 inhabitants by Fundação Sistema Estadual de Dados (SEADE), a non-profit Government-related organization that collects, organizes and processes data on population, education, health, finance for the State of Sao Paulo (SEADE, 2010). The study area has an undulating terrain, and its climate, according to Centro de Pesquisas Meteorológicas e Climáticas Aplicadas à Agricultura (CEPAGRI) is characterised by dry winters with moderate temperatures and wet summers with moderately high temperatures (CEPAGRI, 2013).

Field collections

In the present study, we used data collected by the Zoonoses Control Center of the Municipal Health Department of the Municipality of Santa Bárbara d'Oeste (SP). Field collections in the urban area were carried out daily from February 2004 to February 2006. During the period, we estimated that more than 300,000 houses were inspected, resulting in the collection of 1,891 mosquito larvae (Piovezan *et al.*, 2012).

Mosquito identification and data base

Larvae were identified using the morphological key introduced by Forattini (2002). The information was stored in a hierarchically organised database by larval habitat type (1-tire; 2- plant pot and drip tray; 3- tin, jar, bottle; 4- bucket, washtub, barrel; 5- water tank; 6- bottle; 7- other removable container; and 8- other non-removable container), collection date and the geographical coordinates of the site of collection.

Spatial analysis

The periodicity and seasonality of larval habitats were defined based on the protocols proposed by Cazelles *et al.* (2007), Nagao and Koelle (2008), Johansson *et al.* (2009), Chowell *et al.* (2011), Cuong *et al.* (2011) and Thai and Anders (2011) using wavelets *f*(t) statistics (Weng and Lau, 1994; Daubechies, 1988), expressed by:

$$\omega_{l,t'}(f) = \int f(t)\Psi^{*}_{l,t'}(t)dt \qquad \text{Eq.1}$$

where *l* is the parameter of dilation, *t'* is the parameter of translation, and * the conjugated complex of the wavelets Ψ*l, t'*.

$$\Psi_{l,t'}(l) = \frac{1}{\sqrt{l}}\Psi\left(\frac{t-t'}{l}\right) \qquad \text{Eq.2}$$

Ψ *(t)* is the mother wavelet, and the transformation of the wavelet is expressed by:

$$f(t) = \frac{1}{C_{\Psi}}\iint W_{(l,t')}(f)\Psi_{l,t'}(t)dt'\frac{dl}{l^2} \qquad \text{Eq.3}$$

C_Ψ is a normalization factor expressed by:

$$C_{\Psi} = 2\pi\int_0^{\infty}\frac{|\Psi(\omega)|^2}{\omega}d\omega < \infty \qquad \text{Eq.4}$$

The non-stationary signals of larval habitats were addressed through breakdown of the temporal series and frequency to verify

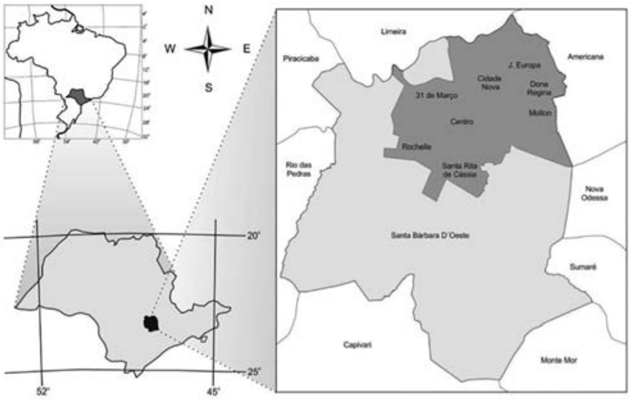

Figure 1. The sampling area located in the Santa Bárbara d'Oeste Municipality in the Atlantic Forest biome, São Paulo state, Brazil.

cycles and time of occurrence. The wavelet statistics yield a scalegram, which is a graphic representation of wavelet coefficients, showing the cyclical behaviour of variables (Torrence and Compo, 1998) and a global wavelet spectrum. The results of the wavelet analyses were employed to assess the statistical correlation between the surface temperature and spatial distribution of *Ae. aegypti*. For the analyses we chose dates when the number of larval habitats positive for *Ae. aegypti* was high. We employed Landsat-5 satellite images available at National Institute of Spatial Research (http://www.dgi.inpe.br/CDSR/). Images were selected for the larval collection date. Four surface temperature maps for the period February 2004-February 2006 were generated for Santa Bárbara d'Oeste. The Idrisi Geographical Information System (Eastman, 1999) was employed to estimate the surface temperature using the SEBAL algorithm, based on Steinke *et al.* (2010) and Moreira *et al.* (2011). The apparent temperatures were transformed from the digital signal of the satellite into radiance (w/m^2.sr.μm). The digital number of each pixel image (resolution of 120 m) was converted into monochromatic spectral radiance. After adjusting the radiance, the atmospheric noise was corrected and thus the planetary and the surface albedo. Emissivity was calculated using Planck's inverted function (https://ncc.nesdis.noaa.gov/data/planck.html) that allows the use of blackbody temperatures (K). Surface temperature (Ts) was then calculated using the parameters obtained in the spectral radiance of the thermal band and emissivity according to the following function:

$$T_s = \frac{K_2}{\ln\left(\frac{\epsilon_{NB} K_1}{L_{\lambda,6}} + 1\right)} \qquad \text{Eq.5}$$

where K_1=607.76 Wn-22r^{-1}μm^{-1} and K_2=1260.56; these are calibration constants of Landsat-5's thermal band.

Statistical spatial correlation between surface temperature and localities with the highest probability of standing larval habitats of *Ae. aegypti* was assessed using the inhomogeneous K function model. This model can be used to verify spatial correlations in point patterns and determine the impact of UHIs on the abundance of *Ae. aegypti* larval habitats. The kernel ratio for temperature, with a covariate for point intensity, generated a smoothed surface, which estimates the value of the larval habitat rate for an area.

Statistical tests were carried out to determine the potential correlation between the local point intensity of larval habitats of *Ae. aegypti* and São Paulo State Social Vulnerability Index for Santa Barbara d'Oeste (SEADE, 2010). For correlation analysis we employed the spatial and temporal distribution of geo-referenced larval habitats determined by the wavelet analysis. These data were homogenised by the area of the sectors of occurrence determined according to the social vulnerability index levels. Further, the same procedure adopted for the spatial analysis of surface temperature was employed to assess the importance of social vulnerability on the abundance of larval habitats. All analyses were performed using SPATSTAT package in R software (Baddeley *et al.*, 2015).

Results

The wavelet analysis of larval habitat occurrence (Figure 2) showed a clear annual periodicity of about 365 days (red colour in the figure). This periodicity is only detectable during the months of December to March of each year, a period that coincides with hotter and wetter summer months when larval habitat occurrence is greatest (Figure 3). No other signal of periodicity is detectable in the time series.

Monthly periodicity showed a sinusoidal pattern (Figure 3) with the largest number of habitats occurring in the months with higher temperatures (January-April); the number of larval habitats recorded during the field collections had a peak of 92, 93 and 75 on February 6th 2004, February 3rd 2005 and February 17th, 2006, respectively, while numbers dramatically declined during winter, reaching zero for some winter days in both 2004 and 2005.

When assessing the correlation between larval habitats and UHIs, we used the temperatures registered on 4th February and 14th August 2004 and 14th February and 22nd June 2005. The surface temperature varied from 15 to 31°C within the urban area of Santa Bárbara d'Oeste (Figure 4).

The charts drawn with the help of the Landsat-5 satellite images showed that a warm front reached the municipality at the beginning of February 2004 reducing the cloud cover and thus the probability of precipitation, and thus creating conditions for UHIs. In the first fortnight of August 2004, a high-pressure area was recorded, resulting from a polar anticyclone and Atlantic polar air mass that caused increased air moisture in the atmosphere and humidity on the ground, leading to reduced cloud cover and the creation of UHIs. At the end of February 2005, a high-pressure system caused by a tropicalized polar air mass reduced ground and

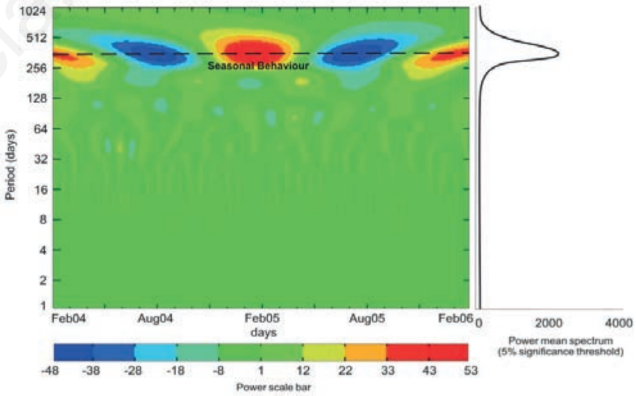

Figure 2. Wavelet analyses of larval habitat frequency per week sampled in Santa Bárbara d'Oeste, São Paulo, Brazil from January 2004 to February 2006. The wavelet period is given in days on a log scale (vertical axis). The colour code for power ranges from low (dark blue) to high values (red).

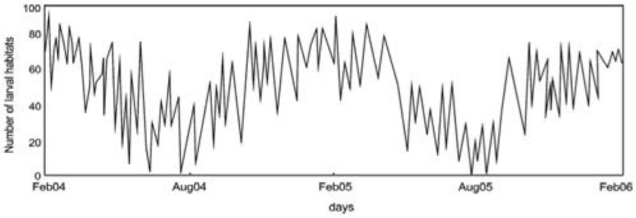

Figure 3. Temporal distribution of larval habitats occupied by *Aedes aegypti* in Santa Bárbara d'Oeste, São Paulo, Brazil from January 2004 to February 2006.

atmospheric humidity, thus intensifying the formation of heat islands. The overall conditions observed in the second fortnight of August 2005, with the presence of a high-pressure system caused by a polar anticyclone and cold Atlantic air, also permitted the development of UHIs. The results of inhomogeneous *K* function model analysis (Figure 5) showed a spatial correlation between the temperature and frequency of occurrence of larval habitats (Z-score 4.99; Z-score critical with 2.59, 95% of significance). As such, the areas with the highest risk of occurrence of *Ae. aegypti* habitats were identified in the neighbourhoods of Jardim Europa and Mollon.

The distribution of the larval habitats in relation to the São Paulo State Social Vulnerability Index (Figure 6) showed that the highest frequency of larval habitats occurs in the eastern part of the city, in the conurbation of Santa Bárbara d'Oeste and the Americana municipality. Another area presenting a high number of

Figure 4. Map of surface temperature with the habitats of *Aedes aegypti* in the urban area of Santa Bárbara d'Oeste, São Paulo, Brazil from February 2004 to February 2006.

larval habitats was situated in the central part of the Santa Barbara d'Oeste, but it was lower than in the region of conurbation with the municipality of Americana. The inhomogeneous point pattern analysis (Figure 7) showed spatial autocorrelation (Z-score 9.11, Z-score critical with 2.58, 95% of significance) between larval habitat occurrence and level of social vulnerability. The areas with the highest risk of *Ae. aegypti* larval habitat were those of high social vulnerability, located in Jardim Europa, Dona Regina and Mollon.

The existence of larval habitats in the areas of high social vulnerability was likely due to these areas having greater numbers of potential larval breeding substrates, a wide variety of which were found across the study area (Figure 8).

Discussion

UHIs can influence the life cycle of *Ae. aegypti* by providing conditions favourable with respect to this mosquito's occurrence and development, even when surface temperatures are adverse (Misslin *et al.*, 2016). In a preliminary study on this subject in the city of Santa Bárbara d'Oeste, São Paulo, Azevedo *et al.* (2013) found breeding sites of *Ae. aegypti* at air temperatures that were lower than the species survival threshold. Similar results were found in recent studies carried out in the city of São Paulo (Araujo *et al.*, 2015) and in Thailand (Chaves *et al.*, 2014) further supporting the hypothesis that the occurrence of UHIs is favourable for the proliferation of *Ae. aegypti*.

The results of the current study in the city of Santa Bárbara d'Oeste demonstrated that, even when temperature conditions were adverse to the occurrence and development of *Ae. aegypti*, UHI-related oscillations in microclimates were responsible for alterations in the usual pattern of mosquito dispersal and activity. Temperatures between 20 and 31°C can increase the metabolic rate of the mosquito, shorten the duration of period of larval development and optimise foraging and egg-laying behaviour leading to increased mosquito abundance when larval habitats are available (Scott *et al.*, 2000; Araujo *et al.*, 2015; Misslin *et al.*, 2016; Murdock *et al.*, 2017). In addition, high temperature may have a positive impact on vector competence. Results of experiments performed under laboratory conditions have demonstrated that great oscillations in temperature can diminish the viral load of mosquitoes (Watts *et al.*, 1987; Turell and Lundström, 1990). Daily temperature range can also impact vector competence and the capacity of a mosquito species to transmit the dengue virus, as shown by Lambrechts *et al.* (2011) in experiments using *Ae. aegypti* and two different dengue serotypes.

UHIs can play an important role in the dynamics of dengue virus transmission because this phenomenon may maintain a more stable surface temperature, narrow daily temperature fluctuations

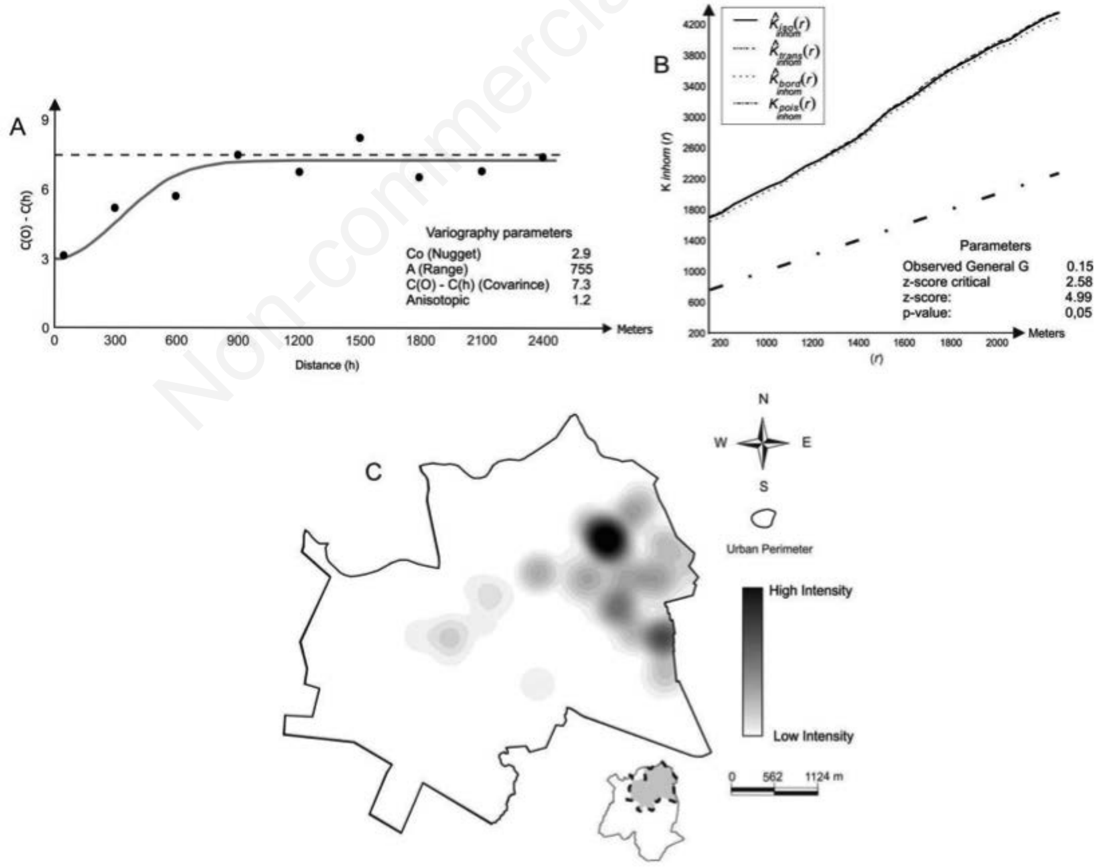

Figure 5. Inhomogeneous spatial point pattern analysis of *Aedes aegypti* larval habitat occurrences and surface temperatures in Santa Bárbara d'Oeste, São Paulo, Brazil from February 2004 to February 2006.

and maintain transmission even during the coldest months of the year (Misslin *et al.*, 2016). In this context, UHIs can be used as an abiotic indicator of the risk of dengue virus transmission by mosquitoes. In addition, it can help describe the heterogeneity of dengue distribution in areas where the mosquito vector is present, but where disease transmission is absent, due to, for example, inadequate temperatures for conservation of the circulation of the virus.

Socioeconomic factors have been shown to play a significant role in supporting *Ae. aegypti* reproductive rates (Reiter, 2014). According to Kuno (1995), social factors that influence the occurrence of larval habitats depend on two distinct pillars. The first is human community behaviour, which is related to factors such as education, income, occupation and population density in an area. The second is the condition of human dwellings, including sanitation of the surrounding environment. Urban areas with bad sanitary conditions, especially in areas with little or no service for recycling waste materials, tend to create larval habitats for *Ae. aegypti* (Souza-Santos and Carvalho, 2000; Ferreira and Chiaravalloti Neto, 2007; Scandar *et al.*, 2010; Teixeira and Cruz, 2011; Tipayamongkholgul and Lisakulruk, 2011). Studies carried out in Jeddah, Saudi Arabia (Misslin *et al.*, 2016) and Delhi, India (Khormi and Kumar, 2012) found the presence of *Ae. aegypti* larval habitats in areas of high social vulnerability, which tend to have a high human population density (Chang *et al.*, 1971; Anno *et al.*, 2015), poor sanitary conditions and precarious or absent waste recycling services, factors that also favour larval habitat abundance and high mosquito population density (Huang *et al.*, 2011; Araujo *et al.*, 2015; Misslin *et al.*, 2016). In line with this, we found that in Santa Barbara d'Oeste the incidence of larval habitats was high-

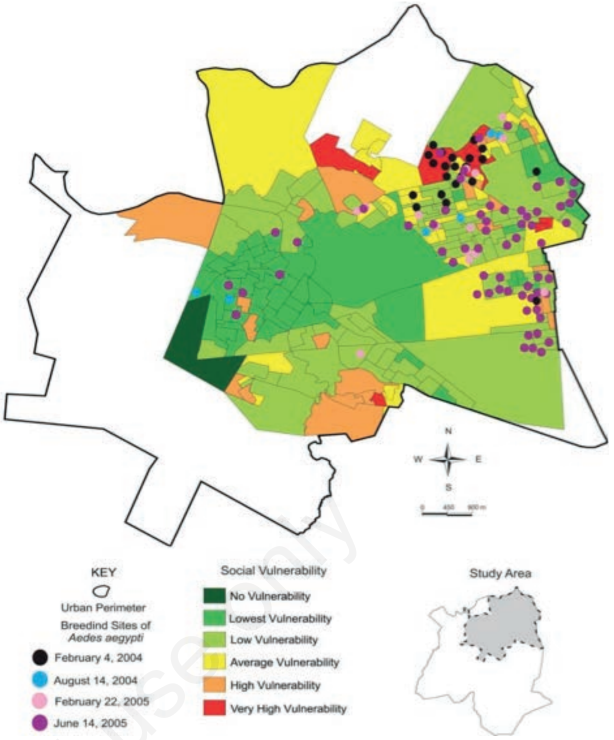

Figure 6. Map of *Aedes aegypti* larval habitats and the social vulnerability index in the urban area of Santa Bárbara d'Oeste, São Paulo, Brazil from February 2004 to February 2006.

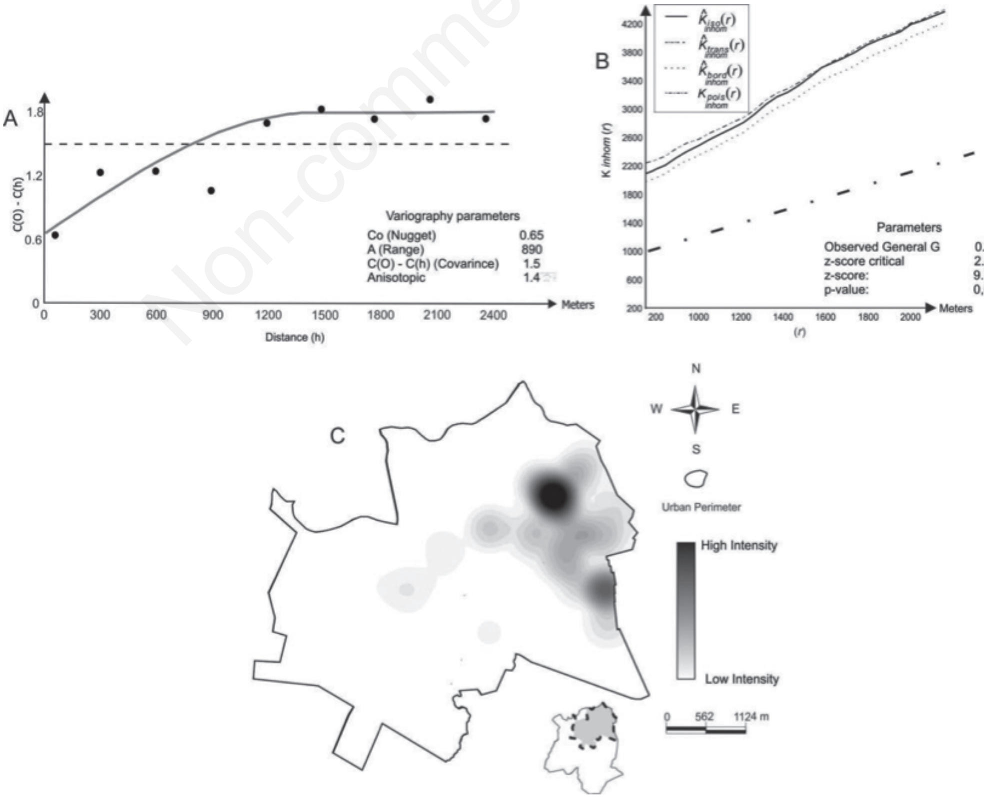

Figure 7. Inhomogeneous spatial point pattern analysis of *Aedes aegypti* larval habitat density and São Paulo State Social Vulnerability Index in Santa Bárbara d'Oeste, São Paulo, Brazil from February 2004 to February 2006.

er in areas of high social vulnerability, such as Jardim Europa, Dona Regina, and Mollon.

Taking all results together, our findings highlight the importance of a robust and sustainable surveillance and vector control programme throughout the year. The success of dengue control in urban areas will demand the implementation of social programmes designed to increase the quality of life, education and income of socially vulnerable communities. Furthermore, a sustainable vector control programme will require environmental management and the development of education programmes that will promote the participation of local communities (Piovezan *et al.*, 2014). In addition, the development of urban parks with tree plantations would provide shade to help diminish the occurrence of UHIs, the presence of mosquito larval habitats and the risk of dengue epidemics (Araujo *et al.*, 2015). In our study, the statistical correlation analysis between larval habitat presence and both the occurrence of UHIs and the social vulnerability index helps to explain the spatial and temporal distribution and abundance of *Ae. aegypti* mosquitoes in urban areas. This information can be important in delineating vector control programmes, while also emphasizing the need for continuous surveillance activities throughout the year, including periods when dengue is less intense. This is particularly relevant given that during these periods both mosquito control programmes and the local communities may interrupt or diminish control measures focusing on the reduction of *Ae. aegypti* larval habitats.

In dengue endemic countries, temperature and precipitation during winter months may constrain mosquito vector populations and viral development to such a degree as to eliminate or control viral transmission. The occurrence of UHIs, however, provides temperature conditions suitable for maintaining dengue virus transmission at low levels, potentially allowing the virus to circulate unnoticed, and thus unregistered, by surveillance programmes. Maintaining transmission in this way can have the effect of intensifying transmission in more favourable seasons, for example during the summer when the weather conditions better support both mosquito populations and virus development.

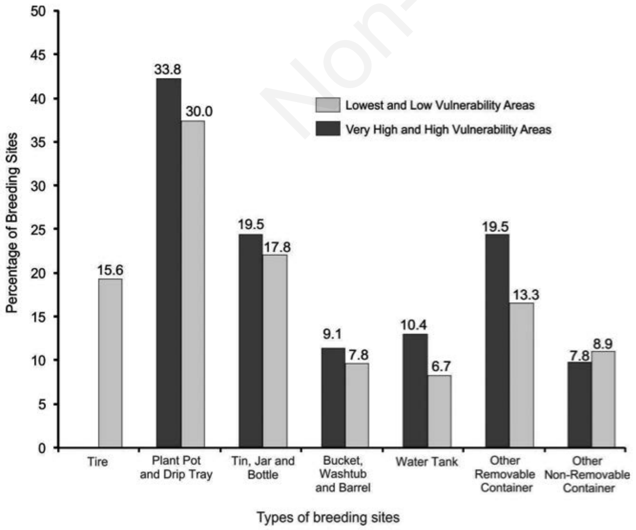

Figure 8. Percentage of *Aedes aegypti* in different larval habitats located in areas of low and high social vulnerability in Santa Bárbara d'Oeste, São Paulo, Brazil, February 2004 to February 2006.

Conclusions

The wavelet analysis in vector-borne diseases was used to extract information from a time series of field collections focusing on the larval habitats of *Ae. aegypti*. Our analysis demonstrates the cyclical occurrence of larval habitats, and their dependence on both local weather events and levels of social vulnerability, which can be useful to delineate vector surveillance and control programs. High social vulnerability is correlated with an increase in the number of *Ae. aegypti* larval habitats because of poor or lacking sanitary conditions. The absence or discontinuity of waste recycling programmes and fresh water distribution results in increased use of artificial containers, which are often left with some water inside and can therefore represent larval habitats for urban populations of vector mosquitoes. In addition, the occurrence of UHIs favour the presence of *Ae. aegypti* in the urban landscape. In conclusion, the findings reported here may also be useful for management strategies in other urban areas with similar ecological conditions and levels of social vulnerability where urban areas favourable for *Ae. aegypti* can be identified and the circulation of the dengue virus offset.

Susceptible urban areas can be targeted for more intensive and specific mosquito control measures, and for education programmes focused on local community involvement. The participation of local communities in the control program would guarantee the sustainability of the programme that needs to be robust to avoid any negative impact caused by political and economical interferences. Finally, a sustainable vector control programme demands the implementation of measures that eliminate the extreme poverty that is associated with high social vulnerability and increased exposure to vector-borne diseases. As largely discussed in the published literature, extreme poverty is a determinant of the dynamics of vector-borne transmission and its elimination is essential for reaching sustainable global development (WHO, 2017).

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