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Spatial analysis of Dengue through the reproduction numbers relating to socioeconomic features: Case studies on two Brazilian urban centers

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A B S T R A C T

The study of the propagation of infectious diseases in urban centers finds a close connection with their population's social characteristics and behavior. This work performs a spatial analysis of dengue cases in urban centers based on the basic reproduction numbers, R_0, and incidence by planning areas (PAs), as well as their correlations with the Human Development Index (HDI) and the number of trips. We analyzed dengue epidemics in 2002 at two Brazilian urban centers, Belo Horizonte (BH) and Rio de Janeiro (RJ), using PAs as spatial units. Our results reveal heterogeneous spatial scenarios for both cities, with very weak correlations between R_0 and both the number of trips and the HDI; in BH, the values of R_0 show a less spatial heterogeneous pattern than in RJ. For BH, there are moderate correlations between incidence and both the number of trips and the HDI; meanwhile, they weakly correlate for RJ. Finally, the absence of strong correlations between the considered measures indicates that the transmission process should be treated considering the city as a whole.

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1. Introduction

Dengue is a viral disease caused by an arbovirus, with four known serotypes: DENV-1, DENV-2, DENV-3, and DENV-4 (Guzman & Harris, 2015). It is transmitted to humans by the bite of *Aedes genus* mosquitos, adapted to the urban environment and developed in tropical and subtropical areas (Simmons et al., 2012). Its incidence has increased in the last decades, with an estimated 390 million dengue infections worldwide yearly, of which 96 million manifest clinically (Bhatt et al., 2013). It affects five WHO Regions, of which the Americas, Southeast Asia, and Western Pacific are the most seriously affected (World Health Organization - WHO, 2022).

The 2030 Agenda for Sustainable Development, unanimously adopted by all United Nations Member States in 2015, presents a comprehensive framework that fosters peace, prosperity, and sustainability for people and the planet, both in the present and the future. This agenda encompasses 17 Sustainable Development Goals (SDGs) that aim to eradicate poverty, promote better health care and education, reduce inequality, and promote economic growth (United Nations - Department of Economic and Social Affairs, 2022). SDG 3 refers to health, and its sub-goal (SDG 3.3) is to "End the epidemics of AIDS, tuberculosis, malaria, and neglected tropical diseases and combat hepatitis, water-borne diseases, and other communicable diseases' (United Nations - Department of Economic and Social Affairs, 2022). Dengue is one of those diseases that are of concern to governments of many countries, among which Brazil.

Three conditions are necessary for a dengue outbreak or epidemic to occur: a circulating serotype of the disease virus, a population susceptible (without antibodies) to this circulating virus, and a transmitter, in this case, the Aedes aegypti mosquito. A dengue epidemic was reported in Roraima, North Region of Brazil, due to DENV-1 and DENV-4 in 1981–82. However, the explosion of cases in the country occurred in 1986, after their introduction in Rio de Janeiro State, Southeast Region. In the same state, in 1990 and 2001, DENV-2 and DENV-3 were introduced, respectively, spreading epidemics in 24 other states (Nogueira et al., 2007). In 2002, Brazil was responsible for 78.6% of 986,699 cases reported in The Americas WHO Region (PAHO / WHO, 2002), when the DENV-3 serotype caused epidemics of great magnitude, especially in the Southeast Region. The southeast region comprises about 40% of the entire Brazilian population, and it is where the three main metropolises of Brazil, São Paulo, Rio de Janeiro, and Belo Horizonte, are located. (IBGE, 2002b).

The characteristics of these large urban centers, where socioeconomic inequalities are evident, offer spaces for the spread of infectious diseases such as dengue and hinder its control. This difficulty lies in a combination of factors: high population density; disorderly growth of cities, resulting in poor housing and lack of infrastructure for basic sanitation and garbage collection; lack of water supply, causing storage in open containers at home (Cordeiro et al., 2011); increasing density of *Aedes* mosquitos due to urban environments with tropical climate (Teixeira et al., 2009); difficulty of access to vacant lots by health professionals for larval and mosquito control; absence of a safe vaccine and resistance of mosquitoes to insecticides.

The investigation of a relation between the occurrence of dengue fever and socioeconomic/environmental indexes for a better understanding of the disease has been the subject of several studies (Almeida et al., 2009; Natal & Costa, 1998; Teixeira et al., 2002; Teixeira & Medronho, 2008; Vasconcelos et al., 1998; Mondini & Neto, 2008; Freitas et al., 2020a, 2020b; Santos et al., 2019). Although most of them associate socioeconomic levels with the occurrence of dengue, there is no consensus about it (Mulligan et al., 2014).

Another critical factor in the spreading of dengue is the daily mobility of people, which favors the spatial spread of the disease (Gubler, 1998). It is well known from the literature that human mobility facilitates the transmission of viruses and proliferation to other urban spaces as long as there is a vector presence (Gil et al., 2016). The movement of adults from more vulnerable and affected peripheral areas, who develop work activities in urban centers in the daytime far from their residences, contributes to the dispersion of the virus where the circulation of people is intense (Falcón-Lezama et al., 2017; MacPherson & Gushulak, 2001; Telle et al., 2016). The relevance of human mobility is also pointed out by (Barmak et al., 2011): his stochastic model in a city-simulating network shows the effects of urban mobility on the spread of disease. Even in the case where the movement of an individual across the network is only considered, the epidemic spreads much more rapidly than when only driven by mosquitoes; human mobility is far-reaching and frequent, while mosquito mobility is short-range and becomes long-range only when it accompanies urban mobility through the means of transport.

To analyze the dengue epidemics during the summer of 2001–2002, we selected the cities of Rio de Janeiro (RJ), capital of the state with the same name, and Belo Horizonte (BH), capital of the state of Minas Gerais, since DENV-3 entered in these cities respectively in December of 2001 and in February of 2002 (Almeida et al., 2008; Bezerra et al., 2021; Nogueira et al., 2005). These cities are located in the same geographic region but have characteristics that differentiate one from each other, such as geographic, climatic, vegetation, and urban organization. Rio de Janeiro is a coastal city known for its tourist attractions and enormous slums. Meanwhile, Belo Horizonte is surrounded by mountains and is known for being Brazil's first planned city.

Besides dengue incidence, this study employs the concept of basic reproduction number, R_0, another relevant measure for epidemics spreading. R_0, introduced in the 50s but mathematically formalized in the 90s (Diekmann et al., 2010), measures the mean number of secondary cases caused by a single case in a fully susceptible population. If $R_0 < 1$, there is no epidemic; the infection can not spread in the host population. We use the expression based on the mathematical model presented in Pinho et al. (2010), which considers the model dynamics and the force of infection obtained from the time series of actual dengue cases. This method of estimating R_0 for vector-borne transmitted diseases was applied in other contexts, for instance, for comparing Zika and dengue epidemics spreading (Villela et al., 2017), for the co-circulating-viruses model (de Araújo et al., 2023).

However, in this work, for the first time, as far as we know, this method of calculating R_0 is applied to intra-urban spatial units and relates them to urban mobility. Therefore, R_0 is a good measure of the velocity of transmission disease for DENV3 epidemics in 2002 for both the cities as a whole and their intra-urban units, which may help the strategies of infection control. Public health interventions aim to reduce it to values less than one (Ridenhour et al., 2014).

In light of the preceding, this research endeavors to analyze the occurrence of dengue epidemics by investigating the reproduction numbers associated with the Human Development Index (related to SDG 1 - No poverty), as well as urban mobility (correlated with SDG 11 - Sustainable cities and communities) (United Nations - Department of Economic and Social Affairs, 2022).

2. Materials and methods

In this section, we describe the elements used for our analysis: the urban centers of Rio de Janeiro (RJ) and Belo Horizonte (BH) and the characteristics of their regions, the urban measures related to urban mobility and human development, and the reproduction number considered for the vector-borne transmission model. According to our proposed methodology, we calculate correlations between dengue measures and urban measures for regions of the selected Brazilian urban centers. By dengue measures, we mean incidence and basic reproduction number, and by urban measures, we select the Human Development Index (HDI) and the number of trips.

2.1. Study areas

This study uses data on dengue cases and urban measures of Rio de Janeiro and Belo Horizonte, both cities of the Brazilian Southeast Region. Rio de Janeiro had a population of 5.937.251 in 2002 and a population density of 4946.35 hab/km^2. Belo Horizonte registered 2.284.469 inhabitants in the same year, with a population density of 6894.34 hab/km^2 (IBGE, 2002a). Both cities have official administrative divisions: municipality limits, districts, planning areas, and neighborhoods. In this study, we consider the Planning Areas (PA) as spatial units, which correspond to a group of neighborhoods, as Fig. 1 shows. Besides the quantitative analysis, their characteristics are detailed below to help understand their role in dengue spreading.

2.1.1. Rio de Janeiro's planning areas

Rio de Janeiro has 10 PAs coded as 1, 2.1, 2.2, 3.1, 3.2, 4, 5.1, 5.2, and 5.3, as Table 1 and Fig. 1C present.

- PA1 is a hub of business, boasting commercial establishments that attract a high influx of people, leading to problems such as garbage collection and homeless population (Rio de Janeiro, 2018).
- PA2 is renowned for its tourist attractions and vertical development, particularly in the neighborhood of Copacabana. Although it is the wealthiest region of the city, it has high rates of violence and informal occupation of hillsides.
- PA3 boasts crucial highways connecting the urban center and the international airport on Governador Island, which also serves as a departure point for boats. However, PA3.1 experiences the lowest income levels of the city, with neighborhoods like Complexo do Alemão and Maré (Rio de Janeiro, n.d.).
- PA4 encompasses environmental protection areas and presents challenges related to pond pollution. It also exhibits a disparity in living conditions, with the affluent neighborhood of Barra da Tijuca coexisting alongside the economically disadvantaged Cidade de Deus (Rio de Janeiro, 2018).
- PA5 boasts the largest territorial expanse of the city with low population density, rural activities, and horizontal dwellings. It is a hub for mass transportation corridors and faces challenges due to the uncontrolled occupation of slopes, mangroves, and marginal strips of river channels (de Janeiro, n.d.).

2.1.2. Belo Horizonte's planning areas

Belo Horizonte has 9 PAs (PMBH. Dep.de Inf. Técnicas, 2003), as Table 2 and Fig. 1B show.

- PA1 is an industrial center that established services and retail to cater to the working population of the industries.
- PA2 is the most affluent region, with high-rise buildings and a substantial daily influx of people to administrative, financial, and commercial activities. However, it also features tourist attractions such as parks and squares.
- PA3 holds high-quality living conditions and has considerable commercial and residential value due to its proximity to the central region.
- PA4 encompasses middle-class neighborhoods with a notable flow of people. It exhibits a significant discrepancy in development degrees and housing characteristics.
- PA5 is the oldest and most traditional region of the city, home of Via Express Way, which connects to the city's Industrial District.
- PA6 is characterized by unsuitable housing occupations, primarily accommodating many low-income populations.
- PA7, located near the center, combines vacant spaces and the highest population density across slums.

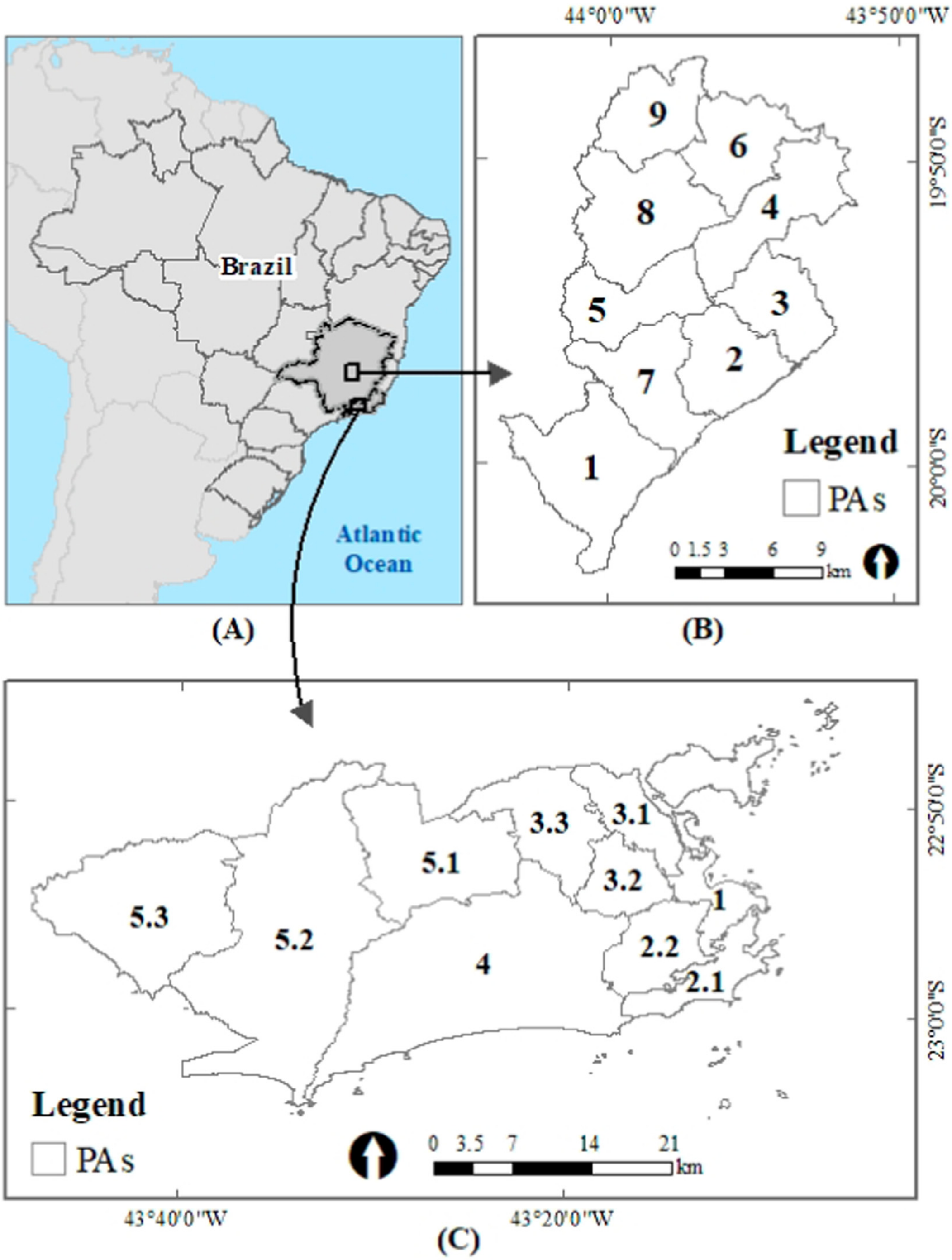

Fig. 1. (A) Location of study areas in Brazil; (B) PAs in Belo Horizonte; (C) PAs in Rio de Janeiro.

- PA8 comprises large buildings and tourist spaces but exhibits significant disparities with precarious conditions, making access to specific locations challenging.
- PA9 is the farthest region from the Center, characterized by disorderly growth and inadequate infrastructure.

Table 1
Planning Areas identifiers and examples of neighborhoods in PAs for the municipality of Rio de Janeiro. Source: Municipal Health Secretary of Rio de Janeiro.

Planning Areas Code	Neighborhoods names
1	Centro, Santa Teresa
2.1	Copacabana, Lagoa, Rocinha
2.2	Tijuca, Andaraí
3.1	Ilha do Governador, Complexo do Alemaõ, Maré
3.2	Méier, Jacarezinho
3.3	Madureira, Vista Alegre
4	Cidade de Deus, Barra da Tijuca
5.1	Realengo, Bangu
5.2	Campo Grande, Guaratiba
5.3	Santa Cruz, Sepetiba

2.2. Dengue data

The reported cases of dengue fever in both urban centers were obtained from the Notifiable Diseases Information System (SINAN) of the Brazilian Ministry of Health (MOH). Probable cases are reported by health professionals assisting patients in health services and then confirmed or discarded based on laboratorial or clinical criteria. Surveillance services criticize these data, and then they are available for public access without information that allows the identification of patients. Cases were analyzed by Epidemiological Week (EW), considering the date of onset of symptoms (Brasil. Ministério da Saúde. Dep. Inf. do SUS, 2002). Concerning datasets of dengue epidemics in Rio de Janeiro, we also use the database available at the Municipal Health Department of Rio de Janeiro (Municipal Secretary of Health and Civil Defense, 2002).

Dengue data - number of dengue cases by PA - for RJ and BH are shown in column 4 of Tables 3 and 4, respectively (Section 3). In addition, the incidence is shown in column 5 of the same tables for PAs of RJ and BH, respectively.

2.3. Urban indices

As Section 2.1 pointed out, the characteristics of PAs reveal differences concerning urban mobility and human development features. Due to that, we use the number of trips and The Human Development Index (HDI) for both cities' PA. They are shown in columns 6 and 7 of Table 3 (RJ's PAs) and Table 4 (BH's PAs) in Section 3.

2.3.1. Urban mobility

Urban mobility data come from Origin and Destination (OD) Surveys conducted within the analyzed municipalities. We consider the number of trips, which represents the cumulative journeys undertaken by residents for various purposes using any mode of transportation. Each trip refers to the starting and ending points of an individual's commute without considering intermediate stops. To calculate the total number of trips for a particular PA, we sum up the commutes entering and leaving that PA, accounting for both trips generated and trips attracted by each PA.

The State Department of Transportation conducted the OD survey in Rio de Janeiro from October 2002 to December 2003. During this period, survey agents visited 40,000 households and interacted with 99,310 individuals across the metropolitan region of Rio de Janeiro (Rio de Janeiro, 2003). The survey questionnaire collected information on the neighborhoods of origin and destination for each commute, encompassing both motorized and non-motorized trips. Trips with the exact origin and destination were grouped for analysis (Santos, 2014).

Similarly, the Belo Horizonte Metropolitan Region Development Agency (MRBH Agency) conducted a household OD Survey in all 34 municipalities of the MRBH in 2012. The research employed homogeneous areas and macro mobility units (MMUs) as spatial units of analysis (MRBH Agency, 2012). The MMUs, which align with the PAs, define the geographic boundaries for this study. In this analysis, we focus on the nine MMUs as units for urban mobility analysis, explicitly considering the trips made by residents of Belo Horizonte and trips originating and terminating within this same municipality.

2.3.2. The human development index (HDI)

Although the PAs are not homogeneous regions concerning their population, they have a set of characteristics that differentiate them from the others. Therefore, it is relevant to investigate the participation of socioeconomic variables, such as the Human Development Index (HDI).

This index is calculated to illustrate the human development of regions based on three dimensions: long and healthy life, knowledge, and a decent standard of living. It considers the indicators of life expectancy at birth, expected years of schooling, mean years of schooling, and the gross national income per capita to generate the index. The results are classified into four categories: low (<0.550), medium (0.550–0.699), high (0.700–0.799), and very high (>0.800), as suggested by UNDP (2022).

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Table 2
Planning Areas identifiers and their names for the municipality of Belo Horizonte. Source: Municipal Health Secretary of Belo Horizonte.

Planning Area Code	Name
1	Barreiro
2	Centro-Sul
3	Leste
4	Nordeste
5	Noroeste
6	Norte
7	Oeste
8	Pampulha
9	Venda Nova

Table 3
Variables related to dengue epidemics in 2002 for ten planning areas of the city of Rio de Janeiro.

PA	Force of infection	R_0	# of cases	Incidence (100,000 inh.)	# of trips	HDI
1	0.535 ± 0.013	3.36 ± 0.21	9854	3958.89	190,657	0.778
2.1	0.179 ± 0.015	1.76 ± 0.15	12,532	1954.83	229,211	0.847
2.2	0.354 ± 0.025	2.61 ± 0.30	8492	2385.15	92,474	0.868
3.1	0.492 ± 0.028	3.00 ± 0.06	18,328	2008.88	160,001	0.732
3.2	0.155 ± 0.017	1.67 ± 0.15	9548	1730.01	118,312	0.773
3.3	0.461 ± 0.029	3.25 ± 0.47	10,752	1104.17	176,336	0.760
4	0.465 ± 0.010	2.98 ± 0.17	27,510	3298.70	214,572	0.787
5.1	0.311 ± 0.060	2.94 ± 0.86	8154	1169.49	92,526	0.744
5.2	0.214 ± 0.038	2.12 ± 0.39	11,151	1552.90	85,275	0.710
5.3	0.245 ± 0.041	2.57 ± 0.75	23,054	6431.13	35,858	0.694

Table 4
Variables related to dengue epidemics in 2002 for nine planning areas of the city of Belo Horizonte.

PA	Force of infection	R_0	# of cases	Incidence (100,000 inh.)	# of trips	HDI
1	0.491 ± 0.107	2.92 ± 0.45	994	379.11	665, 733	0.660
2	0.248 ± 0.043	1.87 ± 0.15	630	236.84	2, 142, 635	0.849
3	0.329 ± 0.107	2.19 ± 0.40	1, 074	431.16	695, 114	0.739
4	0.287 ± 0.126	2.02 ± 0.45	1, 581	576.88	847, 890	0.722
5	0.455 ± 0.051	2.75 ± 0.21	2, 038	604.12	901, 593	0.749
6	0.402 ± 0.084	2.51 ± 0.33	560	289.01	552, 738	0.664
7	0.373 ± 0.114	2.38 ± 0.44	1, 098	408.64	962, 527	0.757
8	0.426 ± 0.058	2.62 ± 0.24	1, 011	708.97	834, 701	0.766
9	0.287 ± 0.037	2.02 ± 0.14	1, 216	497.21	692, 470	0.660

We have set up a database with the HDI of each PA of Rio de Janeiro using data from the IPP (2002). For Belo Horizonte, we collected data of each PA at Brasil (2000).

2.4. The basic reproduction number

Besides incidence, we estimate the basic reproduction numbers, R_0, for the considered urban centers and for their PAs. For that proposal, we consider the differential equations model studied by Pinho et al. (2010) to simulate dengue spreading, which establishes a relationship between R_0 and the force of infection obtained from the actual data. By force of infection Λ, we mean the exponent associated with the initial exponential increase of cases, which may be obtained as the linear coefficient between new and cumulative cases.

Regarding the dynamical model and the main steps of calculating R_0, also developed by Pinho et al. (2010), we forward the reader to the Appendix. Getting (7) from the Appendix, R_0 is presented in terms of the parameters of the model and the force of infection Λ derived by epidemic data:

$$R_0^2 = \left(\frac{\Lambda}{\theta_m + \mu_m + c_m} + 1\right)\left(\frac{\Lambda}{\theta_h + \mu_h} + 1\right)\left(\frac{\Lambda}{\mu_m + c_m} + 1\right)\left(\frac{\Lambda}{\alpha_h + \mu_h} + 1\right) \quad (1)$$

where θ_m and θ_h are the transition rates from susceptible to exposed mosquito and from susceptible to exposed human, respectively; c_m is the mosquito control parameter; μ_h is the human birth and death rates, α_h is the human recovered rate.

To calculate the values of R_0 for the PAs of both cities, we apply the same procedure adopted for the entire city, checking the exponential number of cases and obtaining the force of infection as the slope of the graphics between the number of new dengue cases versus the cumulative cases.

Estimating R_0 for each PA will help us to observe in which regions the transmission of the disease has more significant initial growth with a higher velocity of the disease spreading. Dengue incidence is the ratio of the number of dengue cases and the resident population by PA, multiplied by 100,000 inhabitants, and R_0 by PA may provide complementary information about the disease spreading. The data and codes used are available in the GitHub repository (Silva, 2023).

2.5. Pearson's coefficients

The correlations between dengue measures and urban measures are calculated through Pearson's coefficients given:

$$r = \frac{N\left(\sum_{i=1}^{N} x_i y_i\right) - \left(\sum_{i=1}^{N} x_i\right)\left(\sum_{i=1}^{N} y_i\right)}{\sqrt{\left[N\sum_{i=1}^{N} x_i^2 - \left(\sum_{i=1}^{N} x_i\right)^2\right]\left[N\sum_{i=1}^{N} y_i^2 - \left(\sum_{i=1}^{N} y_i\right)^2\right]}} \tag{2}$$

for which x_i corresponds to the HDI or the number of trips, y_i corresponds to R_0 or incidence, and N is the number of spatial units that are the PAs of each considered urban center. Since HDI and the number of trips may be correlated, we also calculate their correlations.

As well known, Pearson's coefficient varies in the interval $[-1, 1]$; two variables present a linear correlation if their Pearson's coefficient is 1; they anti-correlate to each other if it is -1; the smaller their absolute value, the weaker the correlations. For epidemiological systems, in general, it is considered that when $|r| < 0.25$, it is considered very weak. When $0.25 < |r| < 0, 5$, it is weak; when $0.5 < |r| < 0, 75$, it is moderate and when $0.75 < |r| < 1, 0$, it is strong (Colton, 1974).

3. Results

Our results focus on how dengue epidemics' reproduction numbers and incidence behave in relation to the urban indices for the PAs of urban centers. To do that, first, we present the reproduction numbers for the cities (as a whole) and their PAs; then, we perform a comparative analysis of R_0 and incidence related to urban indices for both cities.

3.1. R_0 for dengue epidemics

From the time series of dengue cases in the cities of Rio de Janeiro and Belo Horizonte in 2002 (see Fig. 2A and C), we set up the relation between the number of new cases per cumulative case (Fig. 2B and Fig. 2D), we obtain the respective forces of infection $\Lambda = (0.570 \pm 0.004)$ weeks^{-1} and $\Lambda = (0.420 \pm 0.017)$ weeks^{-1}.

We consider the more pessimistic situation to estimate the R_0 values (Equation (1)), assuming that there was no practical adult phase of vector control, $c_m \approx 0$. We used $\mu_h = 4 \times 10^{-5}$ days^{-1} and $\alpha_h = 0.125$ days^{-1} for the human parameters (Pinho et al., 2010). As the entomological parameters vary with temperature, we used the mean temperature for Rio de Janeiro in 2002 provided by the National Institute of Meteorology (INMET), $(25{,}13 \pm 2{,}73)^0$C, obtaining for the mosquito mortality rate, $\mu_m = 0.0337$ days^{-1} (values range from 0.0284 to 0.3105 days^{-1}) and extrinsic incubation, $\theta_m = 0.0957$ days^{-1} (values range from 0.00938 to 0.0977 days^{-1}), leading to the value of R_0 for Rio de Janeiro, $R_0 = 3.28 \pm 0.01$. Analogously the mean temperature for Belo Horizonte in 2002 provided by INMET is $(23, 0 \pm 5{,}5)^0$C, obtaining for the mosquito mortality rate, $\mu_m = 0.0365$ days^{-1} and extrinsic incubation, $\theta_m = 0.0833$ days^{-1} in the same year, leading $R_0 = 2.59 \pm 0.01$. Due to the temperature difference between cities in 2002 and the different forces of infection in the two cities, the R_0 for dengue epidemics in Belo Horizonte is almost 25% bigger than its value for Rio de Janeiro in 2002.

3.2. Spatial analysis of dengue

This section exhibits and analyses the results of dengue measures and urban indices for each PA in both cities.

3.2.1. Spatial distribution for case studies

Tables 3 and 4 summarize the results for PAs of RJ and BH, respectively. The columns of these tables represent (1) the PAs identifier; (2) the estimated value of the force of infection based on dengue data; (3) the calculated values of R_0 based on Equation (1); (4) the number of dengue cases; (5) the incidence; (6) the total number of trips; (7) the Human Development Index (HDI). The values of R_0 for Rio de Janeiro's PAs vary from 1.67 to 3.36; meanwhile, the range for Belo Horizonte is 1.87–2.92.

Figs. 3 and 4 exhibit the spatial distribution of quantitative measures of dengue epidemics in 2002 in Rio de Janeiro and Belo Horizonte, respectively. There are relevant differences between the spatial distribution of R_0 and incidence for both cities.

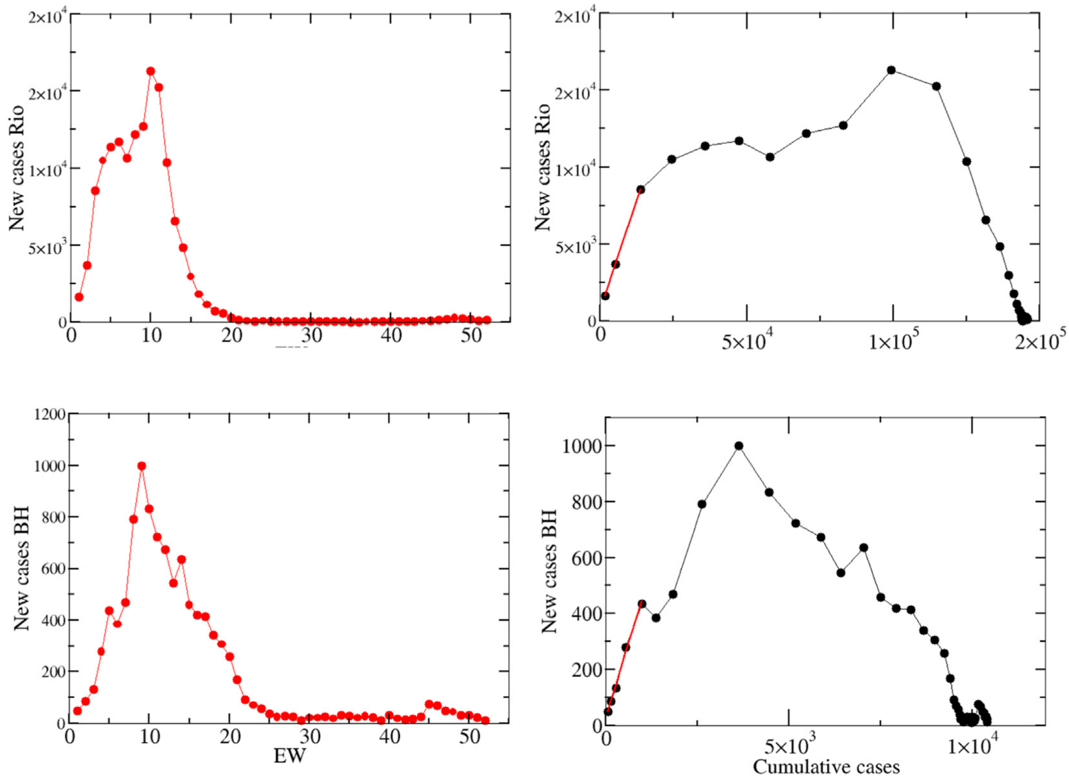

Fig. 2. (a) Time series of dengue cases in RJ in 2002, where *EW* is epidemiological week; (b) Number of new cases per cumulative cases for RJ; (c) Time series of dengue cases in BH in 2002 and (d) Number of new cases per cumulative cases for BH.

3.2.2. Mobility and socioeconomic conditions related to dengue epidemics

We analyze how R_0 and incidence behave in relation to the number of trips, plotting their values versus the number of trips exhibited in Tables 3 and 4.

Fig. 5A and Fig. 5B shows the plots for RJ; meanwhile, Fig. 5C and Fig. 5D for BH. The results indicate that the correlations between incidence and the number of trips in RJ are very weak. However, they correlate moderately in BH with a Pearson coefficient of 0.6, considering PA2 an outlier.

Analogously, we analyze how R_0 and incidence behave concerning HDI, plotting their values versus those exhibited in Tables 3 and 4. Fig. 6A and Fig. 6B shows the plots for RJ; meanwhile, Fig. 6C and Fig. 6D for BH. The results also indicate that R_0 weakly correlates to HDI in RJ and BH. However, considering PA2 as an outlier for dengue epidemics in BH, incidence correlates moderately with HDI, whose Pearson coefficient is 0.6. For regions with high values of HDI - [0.7, 0.8] - R_0 is strongly correlated with HDI with a Pearson coefficient of 0.77; assuming the same regions, R_0 also correlates with the number of trips with a Pearson coefficient of 0.77.

The regions PA1, PA6, and PA9 with moderate HDI (lower than 0.7) compose another group with different behavior for which similar values of HDI are associated with low, intermediate, and high values of R_0.

Table 5 summarizes the list of Pearson correlation coefficients (r) between the variables related to the dengue epidemics in both cities in 2002 and the number of trips and HDI, except for the outlier PA2 for BH epidemics.

4. Discussion

The differences between the spatial distribution by PA for each urban center revealed in our results emphasize that the considered measures, incidence and R_0 complement the understanding of epidemics. Although these measures are heterogeneous for both urban centers, the range of R_0 values for RJ is more extensive than its range for BH, showing that the level of heterogeneity in RJ is more prominent than in BH. We show a complementary map of R_0 for dengue epidemics in 2002 in RJ with a finer scale based on neighborhoods in Fig. 7 to illustrate how heterogeneous the spatial distribution of R_0 is. Even though R_0 was calculated by PAs, there are differences within their perimeters, with significant discrepancies in income, housing conditions, access to water, and sanitation.

The results of correlations also confirm this heterogeneity. It is worth noting that the very weak Pearson's correlation between HDI and the number of trips in RJ makes evident the mixed character of population distribution in this urban center.

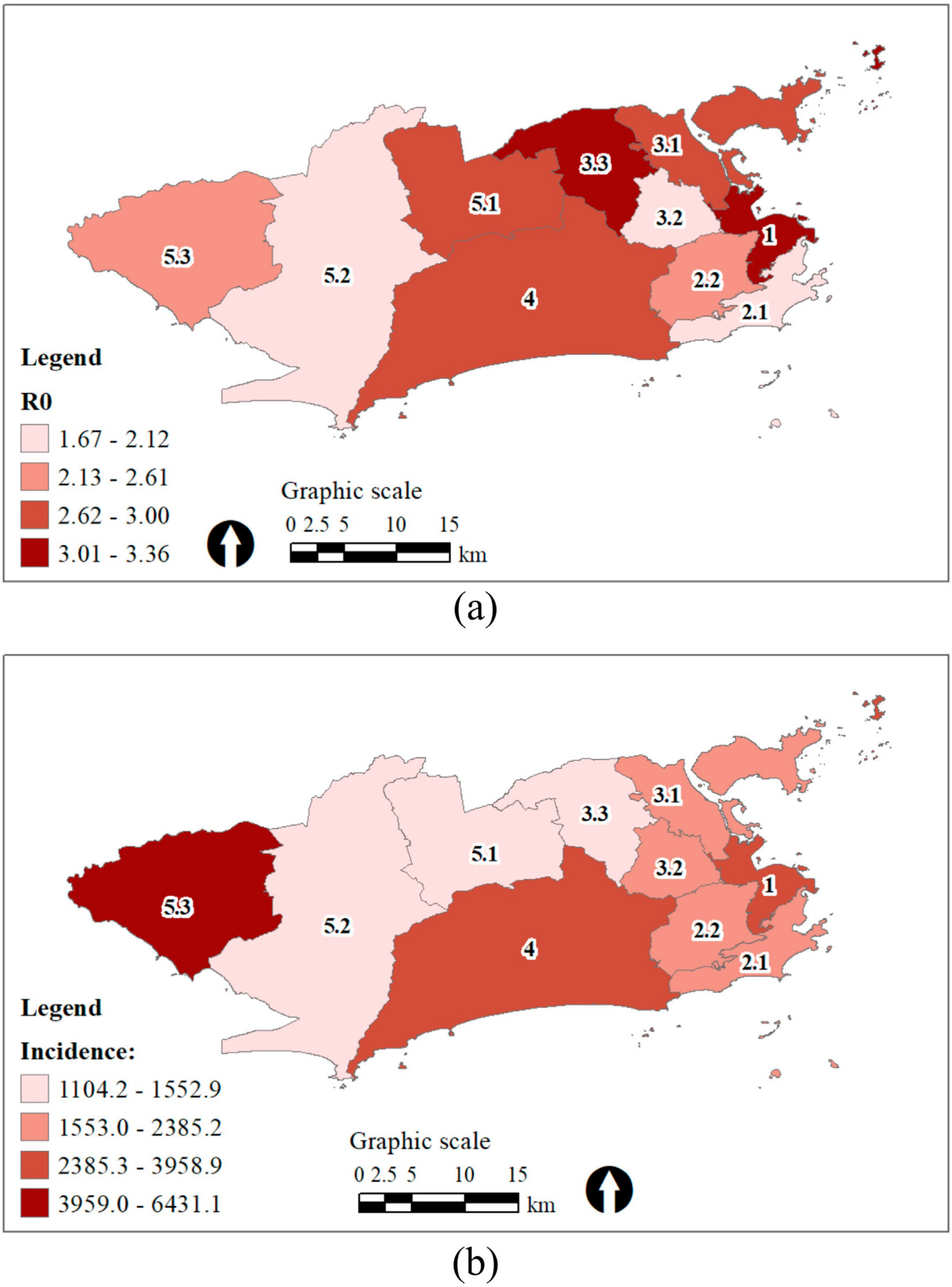

Fig. 3. Spatial distribution of Dengue epidemics by PA in 2002 in RJ: (a) R_0; (b) Incidence.

For BH, our results indicated moderate correlations between incidence and both HDI and number of trips, assuming PA2 as an outlier to avoid bias since it is an atypical region with high values of HDI and trips. It is also a tourist and financial center where people circulate despite not living. Conversely, concerning R_0, our results indicate weak correlations with both the number of trips and HDI in BH. However, limited to regions of high HDI (higher than 0.8), R_0 strongly correlates with both HDI and number of trips.

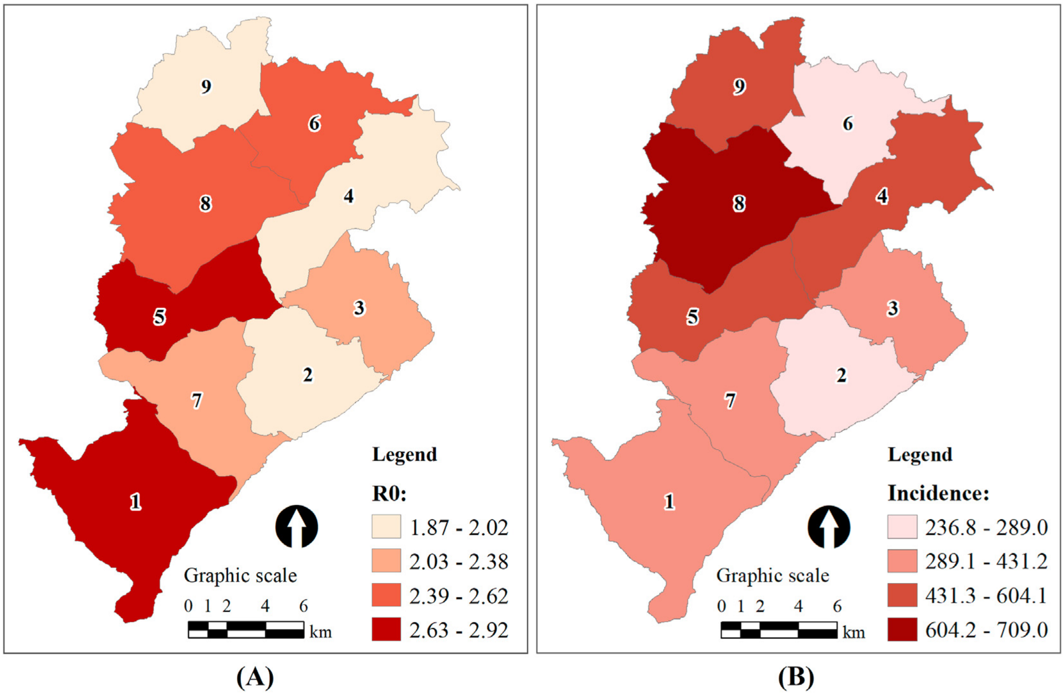

Fig. 4. Spatial distribution of Dengue epidemics by PA in 2002 in BH: (a) R_0; (b) Incidence.

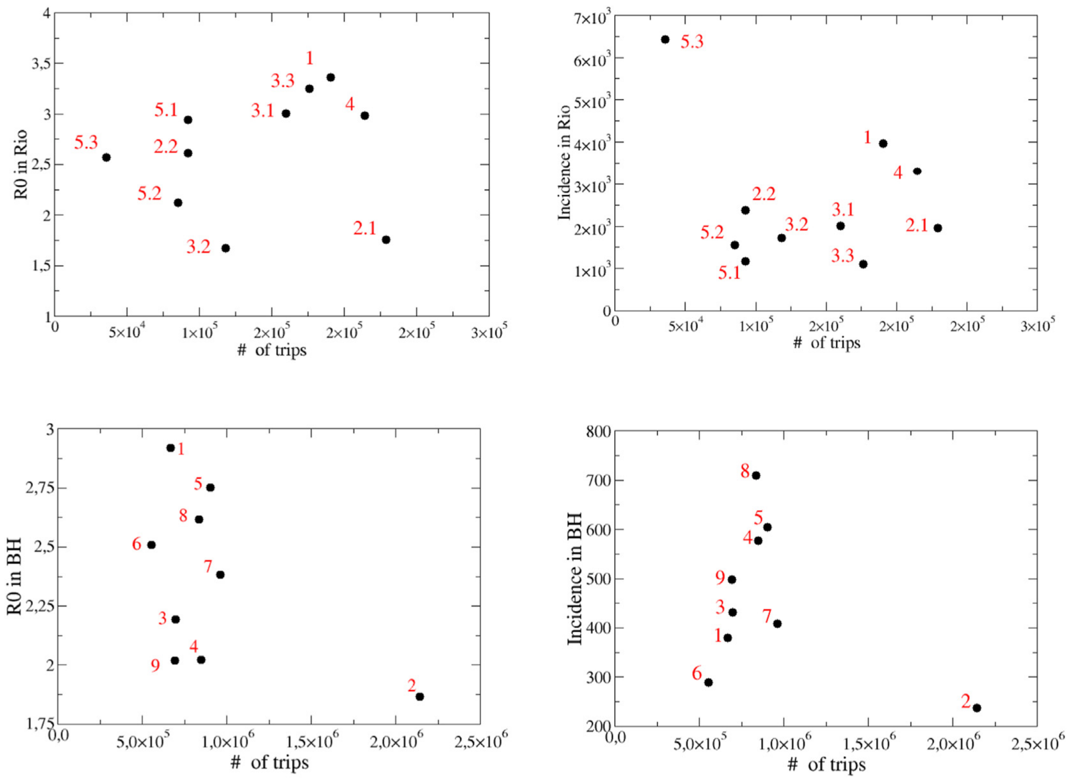

Fig. 5. (a) R_0 × trips by PA in RJ; (b) Incidence × trips by PAs in RJ; (c) R_0 × trips by PA in BH; (d) Incidence × trips by PAs in BH.

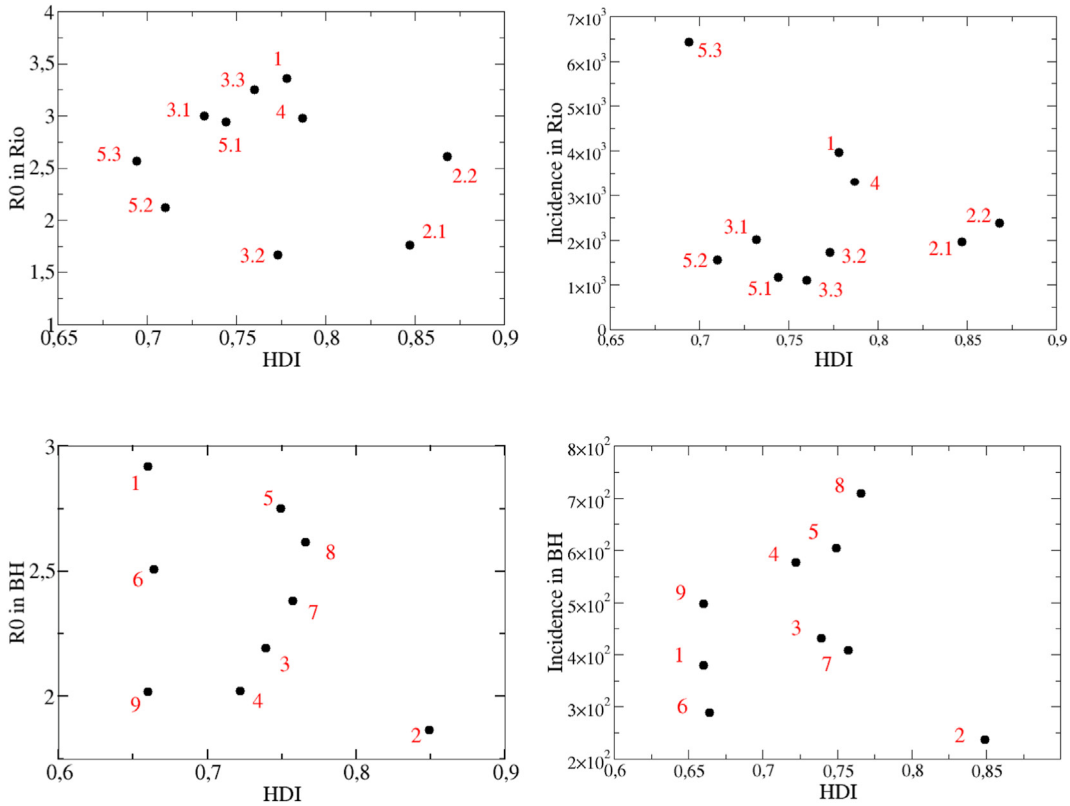

Fig. 6. (a) R_0 × HDI by PA in RJ; (b) Incidence × HDI by PAs in RJ; (c) R_0 × HDI by PA in BH; (d) Incidence × HDI by PAs in BH.

Despite the differences between both cities, the very weak correlations between R_0 and HDI, as well as between R_0 and the number of trips, highlight a particular feature of the global behavior of dengue dynamical measures such as R_0 related to the initial transmission process. It indicates that those measures should be considered for the entire urban center. However, to figure out some features of the propagation dynamics of disease in the urban center, it is vital to associate dengue measures with the specific characteristics of its regions. For instance, R_0 was the lowest value in PA2 in BH, and its force of infection was not so expressive as PA1 and PA6, even in the presence of the absurdly higher number of trips. As PA2 is a commercial and administrative center of BH, where people circulate during business time (about 8 a.m. to 6 p.m.), which produces an accumulation of garbage, the daily cleaning does not provide breeding sites for mosquitoes. In addition, the households of this region have good sanitation and verticalization, which does not facilitate access to the vector, given its low flight ability. People living in ground houses are at greater risk than those living in apartments (Braga et al., 2010; Mondini & Chiaravalloti-Neto, 2008).

It is noteworthy that HDI combines socioeconomic variables to express a region's development, whose relation to dengue fever is a relevant issue in the literature, as pointed out in the Introduction section. Results about dengue epidemics in some Brazilian urban centers in Salvador by (Teixeira et al., 2002) and in the city of Rio de Janeiro Teixeira and Cruz (2011) revealed high seroprevalence for all socioeconomic strata. However, (Mondini & Neto, 2008) in São José do Rio Preto (in the State of São Paulo) in 2002 and (Siqueira et al., 2004) in Goiânia (in the State of Goiás) in 2004 have found a good agreement between higher incidence of dengue fever and lower socioeconomic levels.

In our study, as it was observed in the description of PAs of RJ, it is a city of great socioeconomic diversity, with neighborhoods with better living conditions near places with low socioeconomic status and poor sanitation and garbage collection, as well as slums distributed throughout the city (Teixeira & Cruz, 2011), which may reflect on very weak of correlation between R_0 and HDI. In Belo Horizonte, a study carried out by (Cunha et al., 2008) evidenced higher seroprevalence of dengue in low-income populations living in horizontal buildings in PA3 and PA9 ($0.5 < \text{HDI} < 0.7$), where more vectors were found, when compared to PA2, the area with better living conditions, with very high HDI ($\text{HDI} > 0.8$). However, it must be considered that the place of residence does not necessarily mean the place of infection. In large urban centers where the vector population is disseminated everywhere, it is impossible to identify precisely where the infection occurred.

Concerning the effect of mobility in dengue epidemics in PAs of Rio de Janeiro, the highest value of R_0, shown in Fig. 3 found in PA1, is compatible with the literature (Municipal Secretary of Health and Civil Defense, 2002) since the highest number of cases was registered by the Health Department in the center of the city (PA1) at the beginning of the epidemics,

Table 5
Pearson's coefficients for correlation between variables for both cities.

Variables	city	Pearson's coefficient (r)	outlier
$R_0 \times \#oftrips$	RJ	0.22	-
Incidence $\times$ *#oftrips*	RJ	−0.25	-
$R_0 \times \#oftrips$	BH	−0.33	PA2
Incidence $\times$ *#oftrips*	BH	0.59	PA2
HDI $\times$ *#oftrips*	RJ	0.22	-
HDI $\times$ *#oftrips*	BH	0.80	PA2
$R_0 \times HDI$	RJ	−0.18	-
Incidence $\times$ *HDI*	RJ	−0.25	-
$R_0 \times HDI$	BH	−0.34	PA2
Incidence $\times$ *HDI*	BH	0.61	PA2

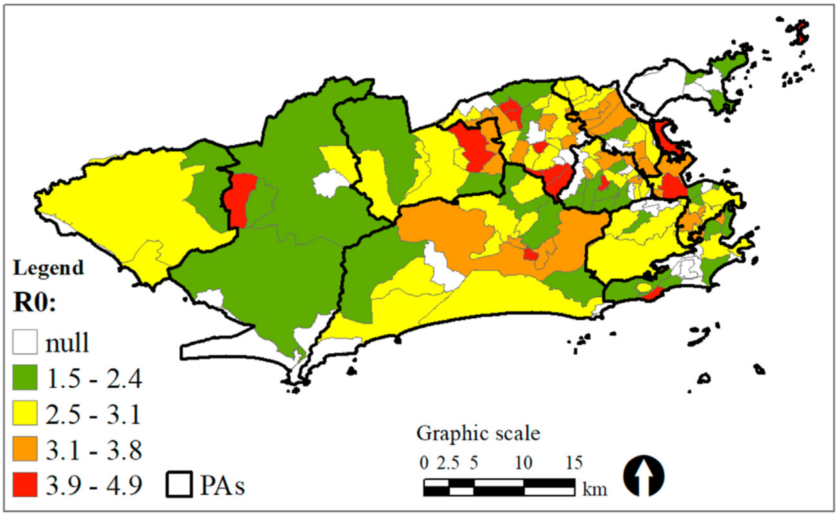

Fig. 7. R_0 of dengue epidemics in 2002 in Rio de Janeiro by neighborhoods.

spreading rapidly towards the west and north. However, PA1 is neither among the regions with a higher number of cases nor among the regions with higher incidence. In addition, the PAs with the highest R_0 values (PA1, PA3.1, PA3.3, and PA4) of Rio de Janeiro are directly interconnected, with ample avenues passing through their neighborhoods, reinforcing the hypothesis that human mobility, mainly due to work activities, facilitates the transmission of viruses as it was emphasized in the introduction section from the literature.

According to Barmak et al. (2011), based on his stochastic model, the rapid performance of entomological surveillance services in places with a significant movement of people at the beginning of the epidemic can contribute to eliminating mosquito breeding sites in that region and hinder the spread of the disease throughout the city. Even though, making evident the complex behavior of dengue dynamics in urban centers, the region PA2 in BH and PA2.1 in RJ with the highest number of trips had the lowest value and the second lowest value of R_0, respectively.

Finally, we reinforce that regions with higher R_0 values do not necessarily correspond to higher incidence values, as highlighted in Fig. 3A and Fig. 3B, as well as in Fig. 4A and 4. R_0 takes into account the force of infection that measures the initial exponential growth of dengue cases, considering some parameters to quantify the dynamics of dissemination and transmission. On the other hand, the incidence considers the number of cases and population, which makes sense when analyzed in temporal curves as a measure of the risk of the disease.

5. Concluding remarks

Studies such as this point to the importance of knowing the participation of human mobility in the dispersion of dengue, thus strengthening the surveillance and containment of cases in regions where the incidence and the R_0 are higher, mainly when associated with social determinants.

Following our methodology - to calculate R_0 based on dengue data and modeling and to relate R_0 and incidence with HDI and the number of trips for spatial units (PAs) of urban centers with different features - we emphasize how complex is dengue dynamics in urban centers, even if our results reinforce the relevance of diversity of socioeconomic strata and the human mobility for dengue spreading. The calculation of R_0 per PA allows us to verify which sites in the city have the larger capacity of infection at the beginning of an epidemic, pointing to the areas that require more rigorous control measures, intending to avoid its spread throughout the rest of the city.

Although our methodology provides insights about dengue spreading in urban centers, it is a first-glance spatial analysis of dengue measures based on data and dynamic model considering their correlations with a socioeconomic index and human mobility. For instance, regarding the technical aspects, we can gain precision by setting up the end of exponential phase of the epidemic curve to estimate the force of infection based on dengue data and to estimate other coefficients, such as Spearman coefficients, to estimate the correlations between the variables. Applying the method in other urban centers to investigate different scenarios is also important.

Finally, another limitation of our study is the number of investigated variables since many separated infrastructure factors, such as basic sanitation and garbage collection, and environmental factors, like temperature and rainfall, that influence vector dynamics may be examined (Xu et al., 2017). Furthermore, in our model, we did not consider the surveillance measures adopted by health services in an attempt to contain epidemics. The model proposed by Ghosh et al. (2019) demonstrated that active case surveillance for symptomatic and asymptomatic individuals significantly reduces the prevalence of dengue and the rate of bites and increases the reporting rate of cases and the mortality rate of vectors. Likewise, the isolation of cases is essential in interrupting the transmission cycle (Sanna et al., 2018).

Regarding work in progress (Rauh et al.), the focus is on the mathematical model as well as the estimation of basic and effective reproduction number studied in Pinho et al. (2010), performing numerical simulations based on the minimization of errors taking into account epidemics data, and sensitivity analysis to access the influence of model's parameters and climate variables.

Finally, as a future work, we intend to develop research with a suitable approach, considering a spatial meta-population model to investigate the number of exported cases from one spatial unit to another one, based on the basic and effective reproduction numbers as it was proposed by Jorge et al. (2022). Since the effective reproduction number corresponds to the reproduction number for any time t, it is a convenient tool to investigate an epidemic process providing more information about dengue dynamics.

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CRediT authorship contribution statement

Ana T.C. Silva: Validation, Writing – original draft, Writing – review & editing. **Rejane C. Dorn:** Formal analysis, Methodology. **Lívia R. Tomás:** Investigation, Validation, Writing – original draft, Writing – review & editing. **Leonardo B.L. Santos:** Investigation, Software, Writing – original draft. **Lacita M. Skalinski:** Conceptualization, Formal analysis, Investigation, Validation, Writing – original draft, Writing – review & editing, Funding acquisition. **Suani T.R. Pinho:** Conceptualization, Formal analysis, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that the research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix

The mathematical model used in this work was analyzed by Pinho et al. (2010). Regarding the variables, the mosquito population is divided into four compartments: A (aquatic phase), M_s (susceptible mosquitoes), M_e (exposed mosquitoes), and M_i (infected mosquitoes). The human population, considered constant, is divided into H_s (susceptible humans), H_s (exposed humans) and H_i (infected humans). The non-linear interactions between (H_i and M_s) and (H_s and M_i) are associated with the mechanism of vector-borne transmission of the virus. The system of ordinary differential equations of the model is given by:

$$
\begin{aligned}
\frac{dA}{dt} &= k\delta(t)\left(1-\frac{A}{C}\right)M-(\gamma_m(t)+\mu_a(t)+c_a(t))A\\
\frac{dM_s}{dt} &= \gamma_m(t)A-\frac{b(t)\beta_m(t)M_sH_i}{H}-(\mu_m(t)+c_m(t))M_s\\
\frac{dM_e}{dt} &= \frac{b(t)\beta_m(t)M_sH_i}{H}-(\theta_m(t)+\mu_m(t)+c_m(t))M_e,\\
\frac{dM_i}{dt} &= \theta_m(t)M_e-(\mu_m(t)+c_m(t))M_i\\
\frac{dH_s}{dt} &= \mu_h(H-H_s)-\frac{b(t)\beta_h(t)H_sM_i}{H}\\
\frac{dH_e}{dt} &= \frac{b(t)\beta_h(t)H_sM_i}{H}-(\theta_h+\mu_h)H_e,\\
\frac{dH_i}{dt} &= \theta_hH_e-(\alpha_h+\mu_h)H_i,
\end{aligned}
\tag{3}
$$

where the transition rates from A to M_s, from M_e to M_i, and from H_e to H_i are γ_m, θ_m and θ_h respectively; the number of mosquito bites is b, the contact rates mosquito-human and human-mosquito are β_m and β_h respectively.

The death rates for A, M and H are given, respectively by μ_a, μ_m and μ_h; the control parameters are c_a and c_m for A and M phases. The birth rate for A is the product of oviposition females rate δ and the number k of females that hatched eggs. The human birth rate is μ_h; H_i should be recovered with rate α_h. Although the entomological parameters may depend on the temperature of the urban center (Esteva & Yang, 2015), it is assumed as the average temperature. The model diagram is outlined in Fig. 8.

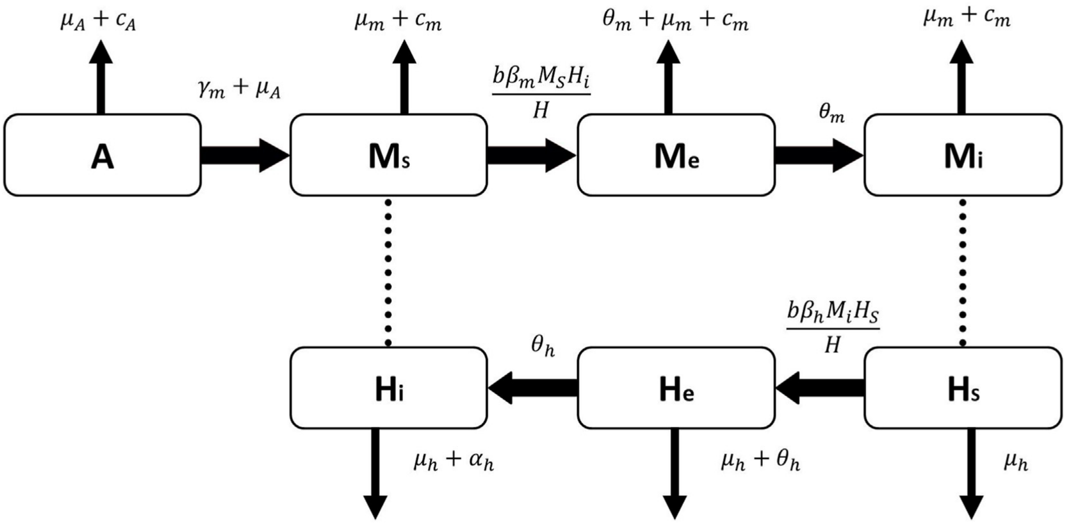

Fig. 8. Diagram of vector-borne model proposed in Pinho et al. (2010).

Using the next generation operator approach ((Diekmann et al., 2010; Driessche & Watmough, 2002) to the model), Pinho et al. (2010) have obtained the following expression for the basic reproductive number R_0 associated with the disease-free equilibrium:

$$
R_0=\sqrt{\frac{\theta_h\theta_m b^2\beta_h\beta_m}{(\theta_h+\mu_h)(\theta_m+\mu_m+c_m)(\alpha_h+\mu_h)(\mu_m+c_m)}\frac{\bar{M}_s}{H}}.
\tag{4}
$$

since the disease-free equilibrium is $E_0=(\bar{A},\bar{M}_s,0,0,H,0,0)$, where $\bar{A}$ and $\bar{M}_s$ are given by

$$\bar{A} = \frac{C}{(\mu_m + c_m)}\left(1 - \frac{1}{R_M}\right), \quad \bar{M}_s = \frac{\gamma_m \bar{A}}{(\mu_m + c_m)}, \tag{5}$$

where R_M, the "basic offspring" of the mosquito population, is given by

$$R_M = \frac{k\delta\gamma_m}{(\mu_m + c_m)(\gamma_m + \mu_a + c_a)}. \tag{6}$$

After that, they have considered the real epidemics data following Favier et al. (2006); Pinho et al. (2010) have assumed that, at the beginning of the epidemics, the cumulative number of cases grows exponentially, i.e., $H_I \propto \exp(\Lambda t)$, where Λ is the force of infection, as well as the other compartments with the pathogen (H_e, M_I, M_E). Then Pinho et al. (2010) have replaced those assumptions in (3), and after some calculations, they have obtained that (4) may be re-written in terms of Λ and some parameters of the model as

$$R_0^2 = \left(\frac{\Lambda}{\theta_m + \mu_m + c_m} + 1\right)\left(\frac{\Lambda}{\theta_h + \mu_h} + 1\right)\left(\frac{\Lambda}{\mu_m + c_m} + 1\right)\left(\frac{\Lambda}{\alpha_h + \mu_h} + 1\right) \tag{7}$$

References

Almeida, M., Assunção, R., Proietti, F., & Caiaffa, W. (2008). *Intra-urban dynamics of dengue epidemics in belo horizonte, minas gerais state, Brazil, 1996-2002, 24* pp. 2385–2395). Cad. Saúde Pública. https://doi.org/10.1590/s0102-311x2008001000019. URL: https://pubmed.ncbi.nlm.nih.gov/18949240/.

Almeida, A., Medronho, R., & Valencia, L. (2009). Spatial analysis of dengue and the socioeconomic context of the city of rio de janeiro (southeastern Brazil). *Revista de Saúde Pública, 43*, 666–673. https://doi.org/10.1590/S0034-89102009000400013. URL: https://www.revistas.usp.br/rsp/article/view/32649.

de Araújo, R. G., Jorge, D. C., Dorn, R. C., Cruz-Pacheco, G., Esteva, M. L. M., & Pinho, S. T. (2023). Applying a multi-strain dengue model to epidemics data, mathematical biosciences. *Mathematical Biosciences, 360*, Article 109013.

Barmak, D., Dorso, C., Otero, M., & Solari, H. (2011). Dengue epidemics and human mobility. *Physical Review E, 84*, Article 011901. URL: https://journals.aps.org/pre/abstract/10.1103/PhysRevE.84.011901.

Bezerra, J. M. T., de Sousa, S. C., Tauil, P. L., Carneiro, M., & Barbosa, D. S. (2021). Entry of dengue virus serotypes and their geographic distribution in brazilian federative units: A systematic review. *Revista Brasileira de Epidemiologia, 24*, Article E210020. https://doi.org/10.1590/1980-549720210020. URL: https://www.scielo.br/j/rbepid/a/z96xfD3n9nhNTqRqqPfwSYR/?lang=en.

Bhatt, S., Gething, P. W., Brady, O. J., Messina, J. P., et al. (2013). The global distribution and burden of dengue. *Nature, 496*, 504–507. https://doi.org/10.1038/nature12060. URL: https://www.nature.com/articles/nature12060#citeas.

Braga, C., Luna, C., Martelli, C., Souza, W., Cordeiro, M., & Alexander, N. (2010). Seroprevalence and risk factors for dengue infection in socioeconomically distinct areas of recife, Brazil. *Acta Tropica, 113*. https://doi.org/10.1016/j.actatropica.2009.10.021

Brasil, A. (2000). *Idhm por região administrativa de belo horizonte*. http://www.atlasbrasil.org.br. (Accessed 12 September 2022).

Brasil. Ministério da Saúde. Dep. Inf. do SUS. (2002). *Dengue. notificações registradas no sistema de informação de agravos de notificação. minas gerais*. http://tabnet.datasus.gov.br/cgi/deftohtm.exe?sinanwin/cnv/denguemg.def. (Accessed 28 September 2022).

Colton, T. (1974). *Statistics in medicine*. New York: Brown and Company.

Cordeiro, R., Donalisio, M., Andrade, V., Mafra, A., Nucci, L., Brown, J., et al. (2011). Spatial distribution of the risk of dengue fever in southeast Brazil, 2006-2007. *BMC Public Health [Internet], 11*, 355. https://doi.org/10.1186/1471-2458-11-355. URL: http://www.biomedcentral.com/1471-2458/11/355.

Cunha, M., Caiaffa, W., Oliveira, C., Kroon, E., et al. (2008). Associated factors to infection by dengue virus in the municipality of belo horizonte, state of minas gerais, Brazil: Individual characteristics and intra-urban differences. *Epidemiol. Serv. Saúde, 17*, 217–230. https://doi.org/10.5123/S1679-49742008000300007. URL: http://scielo.iec.gov.br/scielo.php?script=sci_arttext&pid=S1679-49742008000300007&lng=pt&nrm=iso&tlng=pt.

Diekmann, O., Heesterbeek, J., & Roberts, M. (2010). The construction of next-generation matrices for compartmental epidemics models. *Journal of The Royal Society Interface, 7*, 873–885. https://doi.org/10.1098/rsif.2009.0386. URL: https://pubmed.ncbi.nlm.nih.gov/19892718/.

Driessche, P., & Watmough, J. (2002). Reproduction numbers and sub-threshold endemic equilibria for compartmental models of disease transmission. *Mathematical Biosciences, 180*, 29–48. https://doi.org/10.1016/s0025-5564(02)00108-6. URL: https://pubmed.ncbi.nlm.nih.gov/12387915/.

Esteva, L., & Yang, H. (2015). Assessing the effects of temperature and dengue virus load on dengue transmission. *Journal of Biological Systems, 23*, 527–554. https://doi.org/10.1142/S0218339015500278. URL: https://www.ime.unicamp.br/hyunyang/publications/paper/2015_jbs_esteva.pdf.

Falcón-Lezama, J. A., Santos-Luna, R., Román-Pérez, S., Martínez-Vega, R. A., Herrera-Valdez, M. A., Kuri-Morales, A. F., Adams, B., Kuri-Morales, P. A., López-Cervantes, M., & Ramos-Castañeda, J. (2017). Analysis of spatial mobility in subjects from a dengue endemic urban locality in morelos state, Mexico. *PLoS One, 12*, 1–19. https://doi.org/10.1371/journal.pone.0172313

Favier, C., Degallier, N., Rosa-Freitas, M., Boulanger, J., Lima, J., Luitgards-Moura, J., Menkès, C., Mondet, B., Oliveira, C., Weimann, E., & Tsouris, P. (2006). Early determination of the reproductive number for vector-borne diseases: The case of dengue in Brazil. *Tropical Medicine and International Health, 11*, 332–340. https://doi.org/10.1111/j.1365-3156.2006.01560.x. URL: https://pubmed.ncbi.nlm.nih.gov/16553913/.

Freitas, V., Konstantyner, T., Feitosa, J., Sepetausjas, C., & Santos, L. (2020). The correspondence between the structure of the terrestrial mobility network and the emergence of covid-19 in Brazil. *Cadernos de Saúde Pública, 36*, Article e00184820. https://doi.org/10.1590/0102-311X00184820. URL: https://www.scielo.br/j/csp/a/bnx7jhGLfjbv7nXXtzjTb8t/?lang=en.

Freitas, V., Moreira, G., & Santos, L. (2020). Robustness analysis in an inter-cities mobility network: Modeling municipal, state and federal initiatives as failures and attacks toward sars-cov-2 containment. *PeerJ, 8*, Article e10287. https://doi.org/10.7717/peerj.10287. URL: https://peerj.com/articles/10287/.

Ghosh, I., Tiwari, P., & Chattopadhyay, J. (2019). Effect of active case finding on dengue control: Implications from a mathematical model. *Journal of Theoretical Biology, 464*, 50–62. https://doi.org/10.1016/j.jtbi.2018.12.027

Gil, J., Palacios, M., Krolewiecki, A., Cortada, P., Flores, R., & Jaime, C. (2016). Spatial spread of dengue in a non-endemic tropical city in northern Argentina. *Acta Tropica, 158*, 24–31. https://doi.org/10.1016/j.actatropica.2016.02.003

Gubler, D. J. (1998). Dengue and dengue hemorrhagic fever. *Clinical Microbiology Reviews, 11*, 480–496. URL: https://journals.asm.org/doi/10.1128/CMR.11.3.480?url_ver=Z39.88-2003&rfr_id=ori:rid:crossref.org&rfr_dat=cr_pub/20/200pubmed.

Guzman, M. G., & Harris, E. (2015). Dengue. *The Lancet, 385*, 453–465. https://doi.org/10.1016/S0140-6736(14)60572-9. URL: https://www.sciencedirect.com/science/article/abs/pii/S0140673614605729.

IBGE. (2002a). Brazilian population estimate. https://www.ibge.gov.br/estatisticas/sociais/populacao/9103-estimativas-de-populacao.html?=&t=o-que-e. (Accessed 10 March 2022).

IBGE. (2002b). *Cities and states*. https://www.ibge.gov.br/cidades-e-estados. (Accessed 11 September 2022).
IPP. (2002). Human development index. https://www.data.rio/documents/58186e41a2ad410f9099af99e46366fd/about. June, 2015.
de Janeiro, R., n.d. Description and maps of planning area-5. http://www.rio.rj.gov.br/dlstatic/10112/4290214/4105682/06.AnexoVIDescricaoeMapadaAreadePlanejamento5.pdf. Accessed June, 2015.
de Janeiro, R. (2003). *Master plan of urban transport of the metropolitan region of rio de janeiro. origin-destination research result.* http://www.central.rj.gov.br/pdtu/pesquisa-origem-destino.html. October, 2016.
de Janeiro, R. (2018). Decennial master plan 1992: Subsidies for its revision - 2005. https://www.data.rio/documents/a804aa95a66a4e30a8f18a1f1c24ddfd/explore. (Accessed 11 September 2022).
Jorge, D. C. P., Oliveira, J. F., Miranda, J. G. V., Andrade, R. F. S., & Pinho, S. T. R. (2022). Estimating the effective reproduction number for heterogeneous models using incidence data. *Royal Society Open Science, 9*, Article 220005. URL: https://royalsocietypublishing.org/doi/abs/10.1098/rsos.220005.
MacPherson, D., & Gushulak, B. (2001). Human mobility and population health: New approaches in a globalizing world. *Perspectives in Biology and Medicine, 44*, 390–401. https://doi.org/10.1353/pbm.2001.0053. URL: https://pubmed.ncbi.nlm.nih.gov/11482008/.
Mondini, A., & Chiaravalloti-Neto, F. (2008). Spatial correlation of incidence of dengue with socioeconomic, demographic and environmental variables in a brazilian city. *The Science of the Total Environment, 393*, 241–248. https://doi.org/10.1016/j.scitotenv.2008.01.010
Mondini, A., & Neto, F. (2008). Spatial correlation of incidence of dengue with socioeconomic, demographic and environmental variables in a brazilian city. *The Science of the Total Environment, 393*, 241–248. https://doi.org/10.1016/j.scitotenv.2008.01.010. URL: https://pubmed.ncbi.nlm.nih.gov/18262225/.
MRBH Agency. (2012). *Origin and destination survey*. http://www.agenciarmbh.mg.gov.br/pesquisa-od/. (Accessed 12 September 2022).
Mulligan, K., Dixon, J., CLJ, C. S., & Elliott, S. (2014). Is dengue a disease of poverty? A systematic review. *Pathogens and Global Health, 109*, 10–18. https://doi.org/10.1179/2047773214Y.0000000168. URL: https://pubmed.ncbi.nlm.nih.gov/25546339/.
Municipal Secretary of Health and Civil Defense. (2002). *Number of dengue cases per epidemiological week and planning areas, administrative regions and districts*. https://www.saude.rj.gov.br. June, 2015.
Natal, D., & Costa, A. (1998). Distribuição espacial da dengue e determinantes socioeconômicos em localidade urbana no sudeste do brasil. *Revista de Saúde Pública, 32*, 232–236. https://doi.org/10.1590/S0034-89101998000300005. URL: https://www.scielo.br/j/rsp/a/wvzJGdfCKHSQSzG5WYg8wYR/abstract/?lang=pt.
Nogueira, R. M. R., de Araújo, J. M. G., & Schatzmayr, H. G. (2007). Dengue viruses in Brazil, 1986-2006. *Revista Panamericana de Salud Públic, 22*, 358–363. https://doi.org/10.1590/s1020-49892007001000009. URL: https://www.scielosp.org/article/rpsp/2007.v22n5/358-363/en/.
Nogueira, R., Schatzmayr, H., Filippis, A., Santos, F., et al.C, R. (2005). Dengue virus type 3, Brazil, 2002. *Emerging Infectious Diseases, 11*, 1376–1381. https://doi.org/10.3201/eid1109.041043. URL: https://pubmed.ncbi.nlm.nih.gov/16229765/.
PAHO/WHO. (2002). *Dengue y dengue grave. casos y muertes para subregiones de las americas*. https://www3.paho.org/data/index.php/es/temas/indicadores-dengue/dengue-regional/506-449. (Accessed 11 September 2022).
Pinho, S., Ferreira, C., Esteva, L., Barreto, F., Silva, V., & Teixeira, M. (2010). Modelling the dynamics of dengue real epidemics. *Phil. Trans. R. Soc. A, 368*, 5679–5693. https://doi.org/10.1098/rsta.2010.0278. URL: https://pubmed.ncbi.nlm.nih.gov/21078642/.
PMBH. Dep.de Inf. Técnicas. (2003). *Anuário estatístico de belo horizonte*.
Rauh, C.S., Araujo, E.C., Ganem, F., Leandro, A.S., Freitas, R.M., Martins, C.A., Codeço, C.T., Bastos, L., Pinho, S.T., . Modeling dengue dynamics based on vector, climate and incidence data in foz do iguacu - Brazil. In progress.
Ridenhour, B., Kowalik, J., & Shay, D. (2014). Unraveling r0: Considerations for public health applications. *American Journal of Public Health, 104*, e32–e41. https://doi.org/10.2105/AJPH.2013.301704. URL: https://pubmed.ncbi.nlm.nih.gov/24328646/.
Rio de Janeiro, n.d. Technical annex i: Information on all planning areas. http://www.rio.rj.gov.br/dlstatic/10112/1529762/DLFE-220205.pdf/1.0. September 11, 2022.
Sanna, M., Wu, J., Zhu, Y., Yang, Z., Lu, J., & Hsieh, Y. H. (2018). Spatial and temporal characteristics of 2014 dengue outbreak in guangdong, China. *Scientific Reports, 8*, 2344. https://doi.org/10.1038/s41598-018-19168-6. URL: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5799376/.
Santos, L. (2014). *Territorial based complex networks (RCBT): Concept, characterization and its application potential in epidemiological modeling.* Ph.D. thesis. National Institute of Space Research.
Santos, L., Carvalho, L., Seron, W., Coelho, F., Macau, E., Quiles, M., & Monteiro, A. (2019). How do urban mobility (geo)graphs topological properties fill a map? *Applied Network Science, 4*, 1–14. https://doi.org/10.1007/s41109-019-0211-7. URL: https://appliednetsci.springeropen.com/articles/10.1007/s41109-019-0211-7#citeas.
Silva, A. T. C. (2023). *Data and code to calculate r0*. https://github.com/AnaTCSilva/Code-Data-to-calculate-R0.
Simmons, C. P., Farrar, J. J., van Vinh, c., Nguyen, & Wills, B. (2012). Dengue. *New England Journal of Medicine, 366*, 1423–1432. https://doi.org/10.1056/NEJMra1110265. URL: https://pubmed.ncbi.nlm.nih.gov/22494122/.
Siqueira, J., Martelli, C., Maciel, I., Oliveira, R., Ribeiro, M., Amorim, F., Moreira, B., Cardoso, D., Souza, W., & Andrade, A. (2004). Household survey of dengue infection in central Brazil: Spatial point pattern analysis and risk factors assessment. *The American Journal of Tropical Medicine and Hygiene, 71*, 646–654. URL: https://pubmed.ncbi.nlm.nih.gov/15569799/.
Teixeira, M., Barreto, M., Costa, M., Ferreira, L., Vasconcelos, P., & Cairncross, S. (2002). Dynamics of dengue virus circulation: A silent epidemic in a complex urban area. *Tropical Medicine and International Health, 7*, 757–762. https://doi.org/10.1046/j.1365-3156.2002.00930.x. URL: https://pubmed.ncbi.nlm.nih.gov/12225506/.
Teixeira, M. G., Costa, M. C. N. C., Barreto, F., & Barreto, M. L. (2009). *Dengue: Twenty-five years since reemergence in Brazil, 25* pp. S7–S18). Cad. Saúde Públiica. https://doi.org/10.1590/S0102-311X2009001300002. URL: https://www.scielo.br/j/csp/a/XbW35gmrDBmmLLgcytW5m3b/?lang=en.
Teixeira, T., & Cruz, O. (2011). Spatial modeling of dengue and socio-environmental indicators in the city of rio de janeiro, Brazil. *Cadernos de Saúde Pública, 27*, 591–602. https://doi.org/10.1590/S0102-311X2011000300019. URL: https://www.scielo.br/j/csp/a/gxkWMccQ8wGD648nL8qGqSs/?lang=en.
Teixeira, T., & Medronho, R. (2008). Indicadores sócio-demográficos e a epidemia de dengue em 2002 no estado do rio de janeiro, brasil. *Cadernos de Saúde Pública, 24*, 2160–2170. https://doi.org/10.1590/S0102-311X2008000900022. URL: https://www.scielo.br/j/csp/a/xHq4QWLqKHsrHKyFTpTrCqF/?lang=pt.
Telle, O., Vaguet, A., Yadav, N., Lefebvre, B., Cebeillac, A., & Nagpal, B. (2016). The spread of dengue in an endemic urban milieu—the case of Delhi, India. *PLoS One, 11*, Article e0146539. https://doi.org/10.1371/journal.pone.0146539
UNDP. (2022). Human development index (HDI). https://hdr.undp.org/data-center/human-development-index#/indicies/HDI. (Accessed 12 September 2022).
United Nations - Department of Economic and Social Affairs. (2022). *Sustainable development goals (SDG)*. https://sdgs.un.org/goals. (Accessed 25 May 2023).
Vasconcelos, P., Lima, J., Raposo, M., Rodrigues, S., Rosa, J., Amorim, S., Rosa, E., Moura, C., Fonseca, N., & Rosa, A. (1998). Inquérito soro-epidemiológico na ilha de são luis durante epidemia de dengue no maranhão. *Revista da Sociedade Brasileira de Medicina Tropical, 32*, 171–179.
Villela, D., Bastos, L., Carvalho, L. D., Cruz, O., Gomes, M., Durovni, B., & Codeço, C. (2017). Zika in rio de janeiro: Assessment of basic reproduction number and comparison with dengue outbreaks. *Epidemiology and Infection, 145*, 1649–1657.
World Health Organization - WHO. (2022). *Dengue and severe dengue*. https://www.who.int/news-room/fact-sheets/detail/dengue-and-severe-dengue. (Accessed 12 September 2022).
Xu, L., Stige, L. C., Chan, K. S., Zhou, J., Yang, J., Sang, S., Wang, M., Yang, Z., Yan, Z., Jiang, T., Lu, L., Yue, Y., Liu, X., Lin, H., Xu, J., Liu, Q., & Stenseth, N. C. (2017). Climate variation drives dengue dynamics. *Proceedings of the National Academy of Sciences, 114*, 113–118. URL: https://www.pnas.org/doi/abs/10.1073/pnas.1618558114.