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The influence of urban, socio-economic, and eco-environmental aspects on COVID-19 cases, deaths and mortality: A multi-city case in the Atlantic Forest, Brazil

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ABSTRACT

Urban, socio-economic and eco-environmental influences on people’s health are widely studied and well-known. Their relation to COVID-19, however, is still a novel research topic. Thus, we investigated if COVID-19 parameters are higher in cities with higher urbanization, worst socio-economic conditions, and less vegetation cover, considering 3,052 municipalities in the Atlantic Forest, Brazil. Brazil is the second country most affected by COVID-19, and the Atlantic Forest is its most urbanized, populous, and deforested region. Indexes were created through multivariate principal components analysis using secondary official data: population, demographic density, absolute built area, and relative built area as urbanization parameters; average per capita income, relative people vulnerable to poverty, illiteracy rate of the population aged 18 or over, and human development index (HDI) as socio-economic parameters; and absolute and relative vegetation cover, absolute and relative forest cover as eco-environmental parameters. These indexes were correlated with absolute and relative confirmed COVID-19 cases, absolute and relative confirmed deaths, and mortality rate via Spearman’s and Kendall’s coefficients. Strong correlations (>0.50) were found between COVID-19 and urbanization. Socio-economic and eco-environmental aspects, although weaker predictors of COVID-19, presented meaningful relations with the health parameters. This study contributes to the evidence regarding COVID-19 incidence in the Brazilian population.

1. Introduction

Most people in the world (55 %) today live in urban areas which gather adverse conditions to their health (UNESCO and UN-WATER, 2020). Among these conditions are the ones that influence disaster risk (Kabisch et al., 2017). In addition to infrastructural damages, essential services interruption, and economic impacts that indirectly affect human health, disasters can also cause deaths, accidents, and diseases like cholera, leptospirosis, dengue, and malaria (UNDRR, 2019).

Moreover, people living in cities more likely have sedentary lifestyles, bad eating habits, and chronic stress, leading to obesity, high blood pressure, type 2 diabetes, anxiety, and depression (Beyer et al., 2014; Haahreta et al., 2019; Kabisch et al., 2017; Ulmer et al., 2016; WHO, 2017). Urbanization along with few natural spaces interferes with the human microbiota diversity necessary for a balanced immune function, which is also affected by dietary and exercise practices (Flandroy et al., 2018; Haahreta et al., 2019).

However, studies mention noise, air temperature, and air pollution as the urban conditions most problematic to human health (Aerts et al., 2018; Arantes et al., 2019; Franco et al., 2017; Gronlund et al., 2015; Haahreta et al., 2019; James et al., 2015; Van den Bosch and Sang, 2017; WHO, 2017). Noise is related to stress, sleep disorders, mental discom- fort, attention and memory decline, and even elevated blood pressure, increased risk of myocardial infarction, and other cardiovascular problems (Franco et al., 2017; Van den Bosch and Sang, 2017). High air temperature increases both the susceptibility to new diseases and the risk of worsening existing ones and is associated with cardiovascular and respiratory mortality (Gronlund et al., 2015; Van den Bosch and Sang, 2017). Air pollution in general, and fine particle pollutants in particular, cause heart and lung damages, favoring cardiovascular and respiratory diseases, such as heart disease, stroke, asthma, tuberculosis, chronic

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obstructive pulmonary disease, and pneumonia (Du et al., 2016; Fares et al., 2020; Haathela et al., 2019; Ulmer et al., 2016). Lung and alveolus exposed to air pollution may have a weaker response to respiratory viruses thereby increasing the likelihood of adverse outcomes (Becchetti et al., 2020).

There is evidence already that both high air temperature and pollution accentuate disease prevalence and patient reaction to the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) (Auler et al., 2020; Bashir et al., 2020; Kodera et al., 2020; Li et al., 2021; Liu et al., 2021; Prata et al., 2020; Wu et al., 2020; Zhu et al., 2020).

These urban impacts on human health can be exacerbated by socio-economic factors. Poverty is influenced by urbanization and natural environment deprivation and is related to higher mortality rates in general (Kivimäki et al., 2020; Sloggert, 1994).

Nature can help attenuate adverse urban conditions and benefits people’s health mainly through cultural and regulatory ecosystem services (Aerts et al., 2018; Franco et al., 2017; Gascon et al., 2016; Kabisch et al., 2017; MEA, 2005; Van den Berg et al., 2015; Van den Bosch and Sang, 2017; WHO and CBD, 2015). Cultural services refer to the aesthetic, spiritual, inspirational, and recreational aspects of ecosystems, including open spaces for the practice of physical activities (Caldeira and Chroni 2014; Hartig et al., 2014; James et al., 2015; Kabisch et al., 2017; Kondo et al., 2018; MEA, 2005; WHO, 2017). Regulatory services comprehend climate, air, water, flood, noise, and disease regulation (Hartig et al., 2014; Kabisch et al., 2017; MEA, 2005; Van den Bosch and Sang, 2017).

There is a substantial body of evidence that indicates how urban ecosystems relieve stress and fatigue, improve self-esteem and mental health, and reduce anxiety and depression (Barton et al., 2012; Beil and Hanes, 2013; Brooks et al., 2017; Cox et al., 2017; Hartig et al., 2014; James et al., 2015; James et al., 2016; Kabisch et al., 2017; Lee et al., 2017; Shanahan et al., 2016; Van den Berg et al., 2015; Van den Bosch and Sang, 2017; WHO, 2017); influences child-birth and newborn health, and the visual and motoric development of children (Banan et al., 2017; Casey et al., 2016; Grazuleviciene et al., 2015; James et al., 2015; Kabisch et al., 2016); decreases obesity, high blood pressure, high blood glucose, high cholesterol, type 2 diabetes, myocardial infarction, heart disease, and stroke (Beil and Hanes, 2013; Gronlund et al., 2015; James et al., 2015; James et al., 2016; Kondo et al., 2018; Kardan et al., 2015; Paquet et al., 2014; Shanahan et al., 2016; Tsao et al., 2014); and lower deaths associated with cardiovascular, cerebrovascular, diabetes, respiratory and all-cause mortality (Crouse et al., 2017; Gascon et al., 2016; James et al., 2015; James et al., 2016; Kondo et al., 2018; Kondo et al., 2020; Mitchell and Popham, 2008; Rojas-Rueda et al., 2019; Van den Bosch and Sang, 2017; Villeneuve et al., 2012; Wilker et al., 2014).

Urban forest improves air quality by removing air pollutants (Fares et al., 2020; Kabisch et al., 2017), which reduces incidences of acute respiratory symptoms, respiratory diseases and mortality, and promote respiratory health (Crouse et al., 2017; Edwards and Woods, 2018; Haathela et al., 2019; James et al., 2016; Liddicoat et al., 2018; Lovasti et al., 2013; Nowak et al., 2014; Shen and Lung, 2017; Tomita et al., 2017; Van den Berg et al., 2015; Villeneuve et al., 2012). Since SARS-CoV-2 causes the COVID-19, a respiratory disease with a high association with cardiovascular diseases (Clerkin et al., 2020), and mostly concentrated in cities (Mishra et al., 2020), the urban forest may influence it.

Most ecosystem-related COVID-19 studies approach the impact of social distancing in the current perception and use, and future design and management of urban green areas (Fisher et al., 2020; Honey-Ross et al., 2020; Rice and Pan, 2020; Samuelsson et al., 2020; Venter et al., 2020). Research exploring the possible influence of urban and nature aspects in COVID-19, however, are few (Becchetti et al., 2020). Here, we assess COVID-19 cases, deaths, and mortality from the perspective of the urban forest and its benefits to human health. Since the connection between respiratory diseases and urbanization, socio-economic conditions, and nature is well established in the scientific literature, our research hypothesis is that the number of confirmed cases and deaths, and the mortality rate from COVID-19 are higher in (a) more urbanized cities, (b) cities with worst socio-economic conditions, and (c) cities with less vegetation cover. Thus, we contribute to further the knowledge about COVID-19 and the influences of urban, socio-economic, and eco-environmental aspects on people’s health.

2. Methods

2.1. Study area

By October 7th, 2020, the 225th day since the first reported case on February 26th, Brazil is one of the countries most affected by COVID-19, with 4,969,141 confirmed cases, after the United States (7,501,869 cases) and India (6,757,131 cases), and 147,494 confirmed deaths, second only to the United States (210,918 deaths) (Cota, 2020; JHU CSSE, 2020), even though Brazil is the sixth most populous country in the world, with nearly 212 million inhabitants (UN DESA, 2019).

We selected the Brazilian Atlantic Forest (Fig. 1) as our study area since it is the most populated and urbanized biome in Brazil. Almost 120 million people (57% of the country’s population) live on its 1,107,419 km² (13% of the country’s territory), mostly in urban areas, which represent 57% of this land use in the country (IBGE, 2020; MAPBIO, 2020). Biome is a term used for large-scale ecosystems and its biotic community, shaped by climatic factors and characterized by physiognomy and functional aspects (MUCINA, 2019). In Brazil, the word is often used as a synonym for morphoclimatic and phyto-geographical domain and is used to officially designate the regions Amazon, Atlantic Forest, Caatinga, Cerrado, Pampas and Pantanal.

The Atlantic Forest originally covered 15 of the 27 Brazilian states and 3081 of the 5570 country’s municipalities (IBGE, 2019). Considered a biodiversity hotspot (Myers et al., 2000), the biome suffers from high habitat fragmentation and biodiversity and ecosystem services loss. Currently, Atlantic Forest’s native remnants sum 314,557 km², only 28.40% of its original cover (FBDS, 2020).

For this research, we considered the 3052 Atlantic Forest municipalities with confirmed COVID-19 cases and 2482 municipalities with confirmed COVID-19 deaths, as shown in Table 1. Furthermore, we also selected the 205 municipalities with a population of over 100,000 inhabitants, all with confirmed COVID-19 cases and deaths.

Our study area concentrates 2,795,584 cases and 95,359 deaths, representing 56.26% of all Brazilian COVID-19 cases and 64.65% of all Brazilian COVID-19 deaths, respectively.

2.2. Data collection and preparation

We did a quantitative assessment of the impact of urban, socio-economic, and eco-environmental parameters on COVID-19 in the Atlantic Forest municipalities, as shown in Fig. 2. Microsoft Excel 365 software was used for data curation and visualization, while IBM SPSS Statistics 25 was used for statistical analysis.

The dependent variables selected as COVID-19 parameters were absolute confirmed cases, confirmed cases per 100,000 inhabitants, absolute confirmed deaths, confirmed deaths per 100,000 inhabitants, and mortality rate (Table 1). All COVID-19 data are from the Brazilian Unified Health System (SUS) until August 9th, 2020, made available by Cota (2020).

The following independent variables that could influence the COVID-19 parameters were selected (Table 2): population, demographic density, absolute built area, and built area relative to municipality area as urbanization parameters; average per capita income, number of people vulnerable to poverty in relation to total municipality inhabitants, illiteracy rate of the population aged 18 or over, and human development index (HDI) as socio-economic parameters; and absolute vegetation cover, vegetation cover relative to municipality area, absolute forest cover, and forest cover relative to municipality area as eco-
environmental parameters, selected to represent nature influences on human health. Urban and eco-environmental data were collected from the Brazilian Foundation for Sustainable Development (FBDS, 2020), and socio-economic data from the Brazilian Institute of Geography and Statistics (IBGE, 2020).

These variables were selected to represent urbanization, socio-economic status, and eco-environmental conditions based on scientific literature. Both all-type vegetation and forest covers were considered as eco-environmental parameters because evidence shows that forests in particular positively affect human health and well-being the most when in comparison to other vegetation types (Astell-Burt and Feng, 2019; Reid et al., 2017). Furthermore, both absolute and relative values were considered to help distinguish distinct realities, since the Atlantic Forest municipalities differ greatly from each other.

We considered two sets of data to perform the statistical analysis: first, including all the 3052 municipalities with confirmed COVID-19 cases; and second, regarding only the municipalities with a population over 100,000 inhabitants, which is considered a “big city” by Brazilian standards (IBGE, 2020). This second set comprehends 205 municipalities.

To avoid issues associated with multicollinearity between variables, we performed principal components multivariate analysis (PCA) for both sets of data (total and >100,000 inhabitants) and for each group of parameters composed by independent variables (urban, socio-economic, and eco-environmental), resulting in Table 3. PCA is an exploratory data analysis method widely used in studies with large datasets to increase its interpretability by reducing its dimensionality while preserving as much
variability as possible (Jolliffe and Cadima, 2016). Here, PCA was used to create urban, socio-economic, and eco-environmental indexes as linear combinations or mixtures of the previously listed parameters. These indexes were found through the standardization of data, the elaboration of a covariance matrix, and the computation of eigenvalues of the covariance matrix on SPSS (as presented in Abdi and Williams, 2010).

For all municipalities, the PCA created two urban indexes from its four original parameters. The first index represents population and absolute built area, and the second index represents demographic density and relative built area. Both indexes combined describe 95.160 % of the four original urban parameters. Communalities were 0.963 for population; 0.939 for demographic density; 0.960 for absolute built area; and 0.944 for relative built area. Communalities range between 0 and 1, where the closest to 1, the better the component explains the variable’s variance.

For municipalities with a population above 100,000 inhabitants, the results were similar. Two urban indexes were created, representing the same variable combinations from above. Both indexes combined describe 96.021 % of the original parameters. Communalities were 0.969 for population; 0.952 for demographic density; 0.969 for absolute built area; and 0.951 for relative built area.

Only one socio-economic index was necessary to represent the four original parameters both for all municipalities and for the ones with a population above 100,000 people, describing 90.187 % and 83.983 % respectively. This index represents better socio-economic conditions,
Table 2
Secondary data available for the study area and data from principal components analysis considered in the COVID-19 health assessment.

| Code | Variables | Unit or measure | Parameter |
|------|-----------|-----------------|-----------|
| id1  | Geocode   | Number          | –         |
| id2  | Municipality name | Name | –         |
| id3  | State     | Name            | –         |
| area | Municipality total area | km² | –         |
| cases | COVID-19 absolute cases | Number | Health |
| cases.inhab | COVID-19 relative cases per 100,000 inhabitants | Health |
| Deaths | COVID-19 absolute deaths | Number | Health |
| deaths.inhab | COVID-19 relative deaths per 100,000 inhabitants | Health |
| mortality | COVID-19 mortality rate | % deaths/cases | Health |
| urb1 | Municipality population | Number | Urban |
| urb2 | Demographic density | population/km² | Urban |
| urb3 | Absolute built area | km² | Urban |
| urb4 | Relative built area | % built area/total area | Urban |
| soc.ec1 | Average per capita income | BRL/population | Socio-economic |
| soc.ec2 | Relative poverty | % vulnerable/population | Socio-economic |
| soc.ec3 | Illiteracy rate | % literate/population | Socio-economic |
| soc.ec4 | Human development index (HDI) | 0 low - 1 high | Socio-economic |
| eco.env1 | Absolute vegetation cover | km² | Eco-environmental |
| eco.env2 | Relative vegetation cover | % vegetation cover/total area | Eco-environmental |
| eco.env3 | Absolute forest cover | km² | Eco-environmental |
| eco.env4 | Relative forest cover | % forest cover/total area | Eco-environmental |
| index.urb1 | C1 urban index | Number | Urban |
| index.urb2 | C2 urban index | Number | Urban |
| index.soc.ec | Socio-economic index | Number | Socio-economic |
| ec | index.eco.env1 | C1 environment index | Number | Eco-environmental |
| index.eco.env2 | C2 environment index | Number | Eco-environmental |

Legend: BRL = Brazilian Real; C1 = component 1; C2 = component 2; Geocode = municipality identification number given by the Brazilian Institute of Geography and Statistics (IBGE).

with a positive relation with income and HDI, and a negative relation with poverty and illiteracy. Communalities were 0.858 for per capita income; 0.931 for poverty; 0.872 for illiteracy; and 0.947 for HDI for all municipalities, and 0.744 for per capita income; 0.889 for poverty; 0.787 for illiteracy; and 0.938 for HDI for municipalities with a population above 100,000.

Two eco-environmental indexes were generated by the PCA for all municipalities using its four original parameters as well. The first index is primarily composed of the absolute vegetation and forest cover variables, while the second index is of relative vegetation and forest cover. Both indexes combined describe 97.026 % of the four original environmental parameters. Communalities were 0.981 for absolute vegetation cover; 0.959 for relative vegetation cover; 0.977 for absolute forest cover; and 0.965 for relative forest cover. For municipalities with more than 100,000 inhabitants, two environmental indexes were also created, but with the first component representing relative covers, and the second component representing absolute covers. Both indexes combined describe 98.460 % of the original parameters. Communalities were 0.980 for absolute vegetation cover; 0.989 for relative vegetation cover; 0.978 for absolute forest cover; and 0.990 for relative forest cover.

2.3. Correlation analysis

We applied a bivariate non-parametric correlation between every COVID-19 parameter and urban, socio-economic, and eco-environmental indexes, with the application of Spearman’s and Kendall’s correlation coefficients (Eqs (1) and (2), respectively), both considered robust and efficient statistic methods (Croux and Dehon, 2010). Correlation analysis is used to measure the association of two variables to investigate possible connections between them, with a coefficient that varies from -1 to +1 (Kozak, 2009) (Table 4).

\[ r_s = 1 - 6 \sum \frac{d_i^2}{n(n^2 - 1)} \]  
\[ \tau = \frac{[(\text{concordant}) - \text{(discordant)}]}{0.5n(n-1)} \]

Where \( r_s \) = Spearman’s rho; \( d_i \) = difference between the ranks of two parameters; \( n \) = number of alternatives.

Where \( \tau \) = Kendall’s tau; concordant = number of concordant pairs; discordant = number of discordant pairs; \( n \) = number of pairs.

3. Results

Of the 100 bivariate correlations performed (considering five health parameters and five urban, socio-economic, and eco-environmental indexes; all municipalities and municipalities with a population above 100,000 inhabitants data sets; and Spearman’s and Kendall’s correlation coefficients), 23 were not statistically significant, with a calculated error above 5%, and therefore are not considered for this study (Table 5). Municipalities with more than 100,000 inhabitants data set presented more inadmissible errors, possibly due to sample size. Spearman’s and Kendall’s coefficients gave analogous results.

For all municipalities, the strongest correlation was between COVID-19 reported cases and the C1 urban index, which represents population and absolute built area (\( r_s = 0.657; \tau = 0.491 \)). Correlation between deaths and C1 urban index (\( r_s = 0.568; \tau = 0.466 \)), cases and C2 urban index (\( r_s = 0.414; \tau = 0.293 \)), and deaths and C2 urban index, came next (\( r_s = 0.403; \tau = 0.293 \)). For municipalities with a population above 100,000 inhabitants, correlation between cases and the C1 urban index was also the strongest (\( r_s = 0.564; \tau = 0.401 \)), followed by the C2 urban index, that represents demographic density and relative built area, mainly related to COVID-19 reported deaths (\( r_s = 0.493; \tau = 0.339 \)), the mortality rate (\( r_s = 0.434; \tau = 0.294 \)), and deaths per 100,000 inhabitants (\( r_s = 0.404; \tau = 0.275 \)).

Some correlation was found between health parameters and the socio-economic index, that represent positive socio-economic conditions, considering both all municipalities and those above 100,000 inhabitants. The strongest one was found considering the mortality rate for municipalities > 100,000 inhabitants (\( r_s = -0.301; \tau = -0.207 \)), possibly indicating a smaller mortality rate in big cities with better socio-economic conditions. Moreover, the socio-economic index was also correlated with cases (all municipalities \( r_s = 0.268; \tau = 0.185 \); municipalities > 100,000 inhabitants \( r_s = 0.261; \tau = 0.181 \)), and cases per 100,000 inhabitants (all municipalities \( r_s = 0.235; \tau = 0.165 \); municipalities > 100,000 inhabitants \( r_s = 0.213; \tau = 0.143 \)). The positive correlation between better socio-economic parameters and cases was unexpected.

No strong correlations between health parameters and the eco-environmental indexes were found considering all municipalities, but there may be some association, nonetheless. The C1 environmental index, which represents absolute vegetation and forest covers, presented a correlation of \( r_s = 0.248 \) and \( \tau = 0.169 \) with COVID-19 cases; and of \( r_s = 0.233 \) and \( \tau = 0.165 \) with COVID-19 deaths. For municipalities above 100,000 inhabitants, on the other hand, the C2 environment index, that also represents absolute vegetation and forest covers,
The positive correlation presented for all municipalities, however, were significant evidence from literature associating higher urbanization with important or weak correlations at most, which was not expected. Our findings were different from other studies that find socio-economic variables as strong predictors of health (Kabisch et al., 2017). Specifically, Marmot et al. (2020) found a strong correlation between worse socio-economic conditions with higher COVID-19 mortality in England, while Sannigrahi et al. (2020) found associations between poverty and higher COVID-19 cases throughout Europe, although with different degrees depending on the country. Moreover, Das et al. (2021) found a correlation between worse living conditions and higher COVID-19 transmissions in Kolkata, India; and Hu et al. (2021) found associations between housing quality, living conditions, and race with COVID-19 death rates in Washington D.C, USA.

Table 4

| Interpretation of correlation coefficients values. | Correlation value |
|---------------------------------------------------|------------------|
| Correlation meaning                              | KMO              |
| Very strong inverse                              | -1.00 < -0.70    |
| Strong inverse                                   | -0.70 < -0.50    |
| Weak inverse                                     | -0.50 < -0.20    |
| Non-important                                    | -0.20 - 0.20     |
| Weak positive                                    | > 0.20 - 0.50    |
| Strong positive                                  | > 0.50 - 0.70    |
| Very strong positive                             | > 0.70 - 1.00    |

Reference: adapted from Kozak (2009).

showed some correlation with COVID-19 deaths per 100,000 inhabitants (r = -0.316; τ = -0.211), and the mortality rate (τ = -0.387; τ = -0.263). The inverse correlation found between vegetation and forest covers and COVID-19 in big cities was expected due to the body of evidence of health associated ecosystem services presented in Section 1. The positive correlation presented for all municipalities, however, were unexpected - even if the correlation is weak.

4. Discussion

This study aimed to answer if the number of confirmed cases, deaths, and the mortality rate from COVID-19 are related to urbanization, socio-economic conditions, and vegetation cover. The results showed that yes, associations were found, although in different proportions. Urbanization was the factor with the strongest correlations, possibly indicating that both cases and deaths from COVID-19 are higher when the population, demographic density, and absolute and relative built areas are higher. This result was expected since (a) COVID-19 started and is still concentrated mostly in big cities in the study area, and (b) there is significant evidence from literature associating higher urbanization with worst respiratory and cardiovascular health, as presented in Section 1. Studies including Kodera et al. (2020) in Japan, Das et al. (2021) in Kolkata, India, Li et al. (2021) in Huangzhou, China, and Mansour et al. (2021) in Oman, already show an association between urban parameters, such as population density, and COVID-19.

Regarding socio-economic aspects, we found non-important or weak correlations at most, which was not expected. Our findings were different from other studies that find socio-economic variables as strong predictors of health (Kabisch et al., 2017). Specifically, Marmot et al. (2020) found a strong correlation between worse socio-economic conditions with higher COVID-19 mortality in England, while Sannigrahi et al. (2020) found associations between poverty and higher COVID-19 cases throughout Europe, although with different degrees depending on the country. Moreover, Das et al. (2021) found a correlation between worse living conditions and higher COVID-19 transmissions in Kolkata, India; and Hu et al. (2021) found associations between housing quality, living conditions, and race with COVID-19 death rates in Washington D.C, USA.

We speculate that we have not found strong correlations between the socio-economic index and COVID-19 cases, deaths, and mortality rate in Brazil because we evaluated municipalities and not individual cases, and believe that a more detailed approach, when possible, will show a stronger relationship between them. Nevertheless, the results indicate that lower per capita income and HDI, and higher poverty and illiteracy, may indicate higher COVID-19 parameters in municipalities with more than 100,000 inhabitants. Moreover, evidence shows that areas with worse socio-economic aspects benefit from nature’s benefits to human health the most (Kondo et al., 2020; Van den Berg et al., 2015; WHO, 2017).

Even though the correlation may be considered weak, absolute vegetation and forest covers partially predicted COVID-19 deaths per 100,000 inhabitants and mortality, when assessing municipalities with a population above 100,000 people. This may indicate that nature’s benefit to human health is more important in big cities. The results found here add to the wide body of evidence that shows the correlation between urban forest and other aspects of human health (Aerts et al., 2018; Arantes et al., 2019; Franco et al., 2017; Gascon et al., 2016; Hartig et al., 2014; James et al., 2015; Kabisch et al., 2017; Kondo et al., 2018; Rojas-Rueda et al. 2019; Van den Berg et al., 2015; Van den Bosch and Sang, 2017).

Since COVID-19 still is a recent subject, few studies explored the disease in the context of nature’s benefits to people’s health. In Italy, for example, one of the most affected countries along with Brazil, Becchetti et al. (2020) found that municipalities located in environmentally...
Table 5
Non-parametric bivariate correlation analysis between COVID-19 health parameters and urban, socio-economic, and eco-environmental indexes as predictor variables, for all municipalities and for municipalities > 100,000 inhabitants.

| All municipalities (n = 3052) | Predictor variables | cases | cases. inh. | deaths | deaths. inh. | mortality |
|------------------------------|--------------------|-------|-------------|--------|--------------|-----------|
| Spearman                     | index.urb1         | 0.657 | 0.155       | 0.608  | 0.197        | 0.140     |
|                              | (0.000)            | (0.000) | (0.000) | (0.000) | (0.000)***  |
|                              | index.urb2         | 0.414 | 0.257       | 0.403  | 0.289        | 0.138     |
|                              | (0.000)            | (0.000) | (0.000) | (0.000) | (0.000)***  |
|                              | index.soc.ec       | 0.268 | 0.235       | 0.173  | 0.055        | -0.083    |
|                              | (0.000)            | (0.000) | (0.000) | (0.000) | (0.000)***  |
|                              | index.urban1       | 0.169 | -0.039      | 0.165  | 0.039        | -0.055    |
|                              | (0.000)            | (0.000) | (0.000) | (0.000) | (0.000)***  |
|                              | index.urban2       | 0.062 | -0.025      | -0.085 | -0.069       | -0.063    |
|                              | (0.000)            | (0.000) | (0.000) | (0.000) | (0.000)***  |

| Kendall                      | index.urb1         | 0.491 | 0.106       | 0.466  | 0.142        | 0.099     |
|                              | (0.000)            | (0.000) | (0.000) | (0.000) | (0.000)***  |
|                              | index.urb2         | 0.293 | 0.172       | 0.293  | 0.195        | 0.094     |
|                              | (0.000)            | (0.000) | (0.000) | (0.000) | (0.000)***  |
|                              | index.soc.ec       | 0.185 | 0.165       | 0.121  | 0.039        | -0.055    |
|                              | (0.000)            | (0.000) | (0.000) | (0.000) | (0.000)***  |
|                              | index.urban1       | 0.191 | -0.022      | 0.239  | 0.275        | 0.294     |
|                              | (0.000)            | (0.000) | (0.000) | (0.000) | (0.000)***  |
|                              | index.urban2       | 0.141 | 0.143       | 0.015  | -0.120       | -0.207    |
|                              | (0.000)            | (0.000) | (0.000) | (0.000) | (0.000)***  |

Municipalities > 100,000 inhabitants (n = 205)

| Predictor variables | cases | cases. inh. | deaths | deaths. inh. | mortality |
|--------------------|-------|-------------|--------|--------------|-----------|
| Spearman           | index.urb1 | 0.564 | 0.145 | 0.363 | -0.109 | -0.203 |
|                    | (0.000) | (0.039) | (0.000) | (0.121) | (0.004)** |
|                    | index.urb2 | 0.298 | -0.031 | 0.493 | 0.404 | 0.434 |
|                    | (0.000) | (0.657) | (0.000) | (0.000) | (0.000)*** |
|                    | index.soc.ec | 0.261 | 0.213 | 0.025 | -0.167 | -0.301 |
|                    | (0.000) | (0.002)** | (0.721) | (0.017)** | (0.000)*** |
|                    | index.urban1 | -0.005 | -0.009 | 0.030 | 0.076 | 0.115 |
|                    | (0.939) | (0.899) | (0.674) | (0.281) | (0.101) |
|                    | index.urban2 | 0.022 | 0.083 | -0.197 | -0.316 | -0.387 |
|                    | (0.759) | (0.235) | (0.005)** | (0.000) | (0.000)*** |

Kendall

| Predictor variables | cases | cases. inh. | deaths | deaths. inh. | mortality |
|--------------------|-------|-------------|--------|--------------|-----------|
| index.urb1         | 0.401 | 0.092 | 0.248 | -0.073 | -0.135 |
| (0.000)            | (0.049) | (0.000) | (0.121) | (0.004)** |
| index.urb2         | 0.199 | -0.022 | 0.339 | 0.275 | 0.294 |
| (0.000)            | (0.635) | (0.000) | (0.000) | (0.000)*** |
| index.soc.ec       | 0.181 | 0.143 | 0.015 | -0.120 | -0.207 |
| (0.000)            | (0.002)** | (0.750) | (0.011)** | (0.000)*** |
| index.urban1       | -0.002 | -0.006 | 0.022 | 0.049 | 0.075 |
| (0.959)            | (0.900) | (0.633) | (0.293) | (0.112) |
| index.urban2       | 0.015 | 0.057 | -0.128 | -0.211 | -0.263 |
| (0.750)            | (0.222) | (0.006)** | (0.000) | (0.000)*** |

Legend: cases = COVID-19 confirmed cases; cases.inh = COVID-19 confirmed cases per 100,000 inhabitants; deaths = COVID-19 confirmed deaths; deaths.inh = COVID-19 confirmed deaths per 100,000 inhabitants; mortality = COVID-19 mortality rate; index.urban1 = C1 urban index; index.urban2 = C2 urban index; index.soc.ec = socio-economic index; index.env1 = C1 environment index; index.env2 = C2 environment index. Correlation coefficients are shown with standard error in brackets. Significance * = p-value < 0.05; ** = p-value < 0.01; *** = p-value < 0.001.
5. Conclusion

Urbanization is the strongest COVID-19 predictor among the parameters considered in this study for the Brazilian Atlantic Forest. More urbanized cities, with a higher population, demographic density, and absolute and relative built areas, have higher COVID-19 confirmed cases and deaths. Socio-economic conditions have not presented strong correlations with COVID-19 parameters considered in this study for the Brazilian Atlantic Forest. More absolute and relative built areas, have higher COVID-19 total and relative cases.

Eco-environmental aspects were more meaningful when considering the big cities data set (municipalities with a population above 100,000), rather than all municipalities with COVID-19 confirmed cases. Less absolute vegetation and forest covers were to some degree related to higher deaths per 100,000 inhabitants and mortality.

This study contributes to the knowledge about the COVID-19 spread and nature’s contribution to people’s health. These findings could be useful for urban planning for resilient cities.

Declaration of Competing Interest

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

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