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Greenness and Hospitalization for Cardiorespiratory Diseases in Brazil

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Background: The potential health benefits of exposure to vegetation, or greenness, are well documented, but there are few nationwide studies in Brazil, a country facing challenges related to land-use planning, deforestation, and environmental health risks.

Objectives: In this study, we investigated the association between greenness and hospitalizations for cardiorespiratory diseases in Brazil.

Methods: We accessed hospital admissions data from 967,771 postal codes (a total of 26,724,624 admissions) covering Brazil for the period between 2008 and 2018. We used Normalized Difference Vegetation Index (NDVI) data from the Moderate Resolution Imaging Spectroradiometer (MODIS) to measure greenness at the postal-code level. First, we applied a quasi-Poisson regression model to estimate the association between greenness and hospitalizations for circulatory and respiratory diseases, adjusted for air pollution, weather variables, and area-level socioeconomic status. We stratified the analyzes by sex, age group, health outcome, and Brazilian regions. In the second stage, we performed a meta-analysis to estimate pooled effects across the Brazilian regions.

Results: The national meta-analysis for the whole population, incorporating both urban and nonurban areas, showed that higher levels of greenness were associated with a lower risk of hospitalizations for circulatory diseases. An interquartile range (IQR = 0.18) increase in average NDVI was associated with a 17% (95% confidence interval: 8%, 27%) lower risk of cardiovascular admissions. In contrast, there was no association found between greenness and respiratory admissions. When specifically examining urban areas, the results remained consistent with the overall findings. However, the analyses of nonurban areas revealed divergent results, suggesting that higher levels of greenness in rural regions are associated with a lower risk of hospital admissions for both circulatory and respiratory diseases.

Discussion: The findings emphasize the importance of prioritizing the preservation and creation of green spaces in urban areas as a means of promoting cardiovascular health in Brazil. https://doi.org/10.1289/EHP13442

Introduction

Cardiovascular and respiratory diseases are the leading causes of morbidity and mortality worldwide.[1] In Brazil, these diseases are responsible for a significant number of hospital admissions and deaths. In 2022, cardiovascular and respiratory diseases accounted for 9.7% and 10% of all deaths in Brazil, respectively. These diseases also represent a significant burden for the health care system, with a total of 1.2 million hospital admissions for cardiovascular diseases and 1.2 million for respiratory diseases in Brazil in 2022.[2]

Over the past several decades, urbanization has led to the transformation of the natural environment, with the reduction of green spaces and increases in air pollution, which have been associated with adverse health outcomes.[3,4] These environmental changes could be contributing to the high rates of cardiovascular and respiratory diseases observed in Brazil, which are major causes of morbidity and mortality.

The potential positive effects of green spaces on human health have been widely documented in the literature.[5–8] Access to nature and green spaces has been shown to be associated with better mental[9] and physical health[10] outcomes and better cognitive function.[5,9,11] Potential mechanisms through which green spaces may improve health are by reducing exposure to air pollution,[12] improving thermal comfort,[13] reducing stress and anxiety,[9,11] providing opportunities for social interaction, and improving physical activities.[10,14]

The Normalized Difference Vegetation Index (NDVI) is a widely used remote sensing tool that measures the amount of greenness in an area. Several studies have used the NDVI to investigate the association between greenness and health outcomes, including hospitalizations for cardiovascular and respiratory diseases.[15–18] However, most of these studies have focused on high-income countries, and little is known about the association between greenness and health outcomes in low- and middle-income countries, such as Brazil (particularly, investigations at a national scale),[19] where the burden of disease is higher. Our research addresses this gap by estimating the nationwide association between greenness and hospitalizations for circulatory and respiratory diseases in Brazil between 2008 and 2018.

Methods

Hospital Admission Data

We obtained hospital admission data for circulatory (ICD-10 codes I00-I99) and respiratory (ICD-10 codes J00–J99) diseases that occurred in Brazil between 1 January 2008 and 31 December 2018. These data were accessed from an open-access dataset provided by the Brazilian Ministry of Health—from the Hospital Information System of Sistema Único de Saúde—(SIH/SUS). Although these hospitalization admission data do not cover all hospitalizations nationwide, the data include admissions from both public hospitals and a portion of private hospitals reimbursed by the Ministry of Health. These hospitalization data cover ∼80% of total hospitalizations in Brazil (https://bvsms.saude.gov.br/).

Hospitalization information included the date of the event, sex and age of the hospitalized patient, and the postal code of the patient

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(based on centroids of the postal code). The average distance between postal code points was 170.42 m [standard deviation (SD) = 1,412.56 m]. In the supplemental material, Table S1 shows the descriptive statistics for the distance between postal code centroids for the whole Brazil and stratified by urban and nonurban areas. In this study, there was no missing data in the hospital admission dataset obtained from the Brazilian Ministry of Health. The dataset includes hospital admissions records from 967,771 postal codes, totaling 26,724,624 admissions for circulatory and respiratory diseases. All variables of interest were complete for analysis.

The hospital admission data were grouped by aggregating the number of admissions for each postal code and date during the study period. We also categorized the number of hospitalizations by sex and age group (15–45, 46–65, and over 65 y of age). The decision to use broader age groups, such as 15–45, was made based on a balance between statistical considerations and biological mechanisms. The use of wider age groups allows for a sufficient sample size within each category, ensuring statistical robustness, especially given the granularity of the hospitalization data available. The hospital admission counts are presented as daily counts per postal code. In Table S2, we show the descriptive characteristics of hospital admissions across the years (2008–2018).

Greenness Data

We used the NDVI to estimate the level of greenness at the postal-code level. This vegetation index is calculated as the normalized ratio of the near-infrared (NIR) and red reflectance bands obtained from satellite imagery.[18] The NDVI has been widely used as a reliable indicator of greenness on the ground in epidemiological studies.[18,20,21] Negative values of the NDVI indicate water, dead plants, or urban areas, whereas values near zero correspond to barren areas of rock or sand. Positive values correspond to more vegetated or greener regions, with 1 representing the greenest area.

In this study, we obtained NDVI data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Terra and Aqua satellites. The MODIS NDVI data (MOD13Q1 and MYD13Q1 products) is available on a 250 m × 250 m grid with a temporal resolution of 16 d. We calculated the quarterly average NDVI for Brazil between 2008 and 2018. The choice of quarterly data was made to capture potential seasonality and variations in greenspace exposure throughout the year. In regions with distinct seasons, such as Brazil, the amount of green vegetation can exhibit significant fluctuations between different quarters because of factors like rainfall, temperature, and vegetation growth cycles.[22] To match the temporal resolution of hospitalizations, admissions occurring during the first quarter of a year (1 January to 31 March) were aggregated with the NDVI data from the first quarter. Similarly, hospitalizations occurring during the second quarter (1 April to 30 June) were aggregated with the NDVI data from the second quarter, and so on for hospitalizations occurring during the third and fourth quarters (1 July to 30 September, and 1 October to 31 December, respectively).

To estimate the average NDVI exposure at the postal-code level, we first removed all zero and negative NDVI values. Given that our objective is to focus solely on vegetated areas' impact on health outcomes, this filter avoids the offset of the positive NDVI values by the negatives in the NDVI. Then, we extracted the NDVI values for all the pixels corresponding to the locations of the postal code centroids, as represented in a point shapefile. In addition, we calculated the average NDVI in buffers of different sizes (500 m, 1,000 m, 1,500 m, and 2,000 m) around the postal code centroid. Given that our postal codes were represented as points, rather than large geographic areas, the choice of buffer sizes was made to reflect the spatial context and distribution of green spaces around these points. The buffers were used to capture the potential effect of greenness beyond the immediate surroundings of the postal code. To address concerns about buffer overlap and land area coverage in our spatial analysis, we conducted a detailed assessment of overlap statistics for the buffers used in our study. Descriptive statistics for the area (m^2) of overlapping buffers are provided in Table S3 in the supplementary materials.

Covariates

Covariates were included in the model to account for potential confounding factors. The following variables were considered: air pollution [particulate matter (PM) with aerodynamic diameter ≤ 2.5 μm ($PM_{2.5}$), NO_2, and O_3], weather (temperature and relative humidity), and postal code–level socioeconomic status (SES; average family income and education).

Data on air pollution were obtained from the Copernicus Atmosphere Monitoring Service (CAMS), which is implemented by the European Center for Medium-Range Weather Forecasts (ECMWF). We used both CAMS-reanalysis and CAMS Near Real Time (CAMS-NRT) predictions to obtain $PM_{2.5}$ ($\mu g/m^3$), NO_2 (ppb), and O_3 (ppb) data. The data had a spatial resolution of 12 km and a temporal resolution of 6 h. Weather data were also obtained from ECMWF and had the same spatial and temporal resolution as the air pollution data. We calculated the daily mean $PM_{2.5}$, NO_2, O_3, temperature (°C), and relative humidity (percentage). For each postal code point, we extracted the pixel values of air pollution ($PM_{2.5}$, NO_2, and O_3), as well as weather variables (temperature and relative humidity), at the corresponding latitude and longitude coordinates. For the buffer zone around each postal code point, we used the following approach: *a*) for buffers that entirely fell within a single grid cell of weather or air pollution data (mostly the buffers $\leq 1{,}000$ m), we extracted values based on the intersection of the buffer with that grid cell; and *b*) for larger buffers (mostly $>1{,}000$ m) whose boundaries extended across at least two grids of weather or air pollution data, an area-weighted mean values of air pollutants and weather variables was calculated within the buffer zone.

Finally, SES variables were accessed from the 2010 Brazilian Census, providing data at the census tract level, which were subsequently aggregated at the postal-code level. This aggregation was performed by spatially joining the census tract polygons with the postal code points to associate SES data with postal code locations. For the buffer zones around postal codes, we calculated the area-weighted mean of intersecting SES polygons to account for SES variations within these areas. The SES variables considered included per capita income and years of schooling. In addition, the census data provide information distinguishing between urban and nonurban areas. This land use information was employed in our subgroup analysis to stratify the data based on the urbanization status of each postal code.

Statistical Analyses

Statistical analysis was conducted in two stages. In the first stage, we employed quasi-Poisson regression models to estimate the association between greenness (as measured by NDVI) and hospital admissions for circulatory and respiratory diseases at the regional level in Brazil (North, Northeast, South, Southeast, and Midwest). We controlled the model for air pollutants ($PM_{2.5}$, NO_2, and O_3), weather variables (temperature and humidity), and SES (per capita income and education, represented by years of schooling). To characterize potential nonlinear relationships, the air pollutant variables and the weather parameters were modeled with natural cubic splines. The confounding effect of seasonality was modeled through smooth function (natural spline) with 3

Table 1. Descriptive characteristics of hospital admissions for circulatory and respiratory diseases in Brazil, 2008–2018.

		Number of hospital admissions		
Health outcome	Age (y)	Men	Women	Both sexes
Circulatory hospital admissions	15–45	862,461	1,109,840	1,972,301
	46–65	2,617,714	2,271,212	4,888,926
	>65	2,658,598	2,692,422	2,617,714
	All ages	6,244,331	6,163,129	12,407,460
Respiratory hospital admissions	15–45	1,126,441	1,114,231	2,240,672
	46–65	1,156,212	1,064,890	2,221,102
	>65	1,847,446	1,826,250	3,673,696
	All ages	7,559,356	6,757,808	14,317,164

degrees of freedom per year. To address potential clustering of postal codes within the same 12-km grid cell and to ensure valid statistical inference, we applied robust standard errors clustered at the level of grid cells. Finally, we included in the model the log of the population size of the postal code as an offset.

The analyses were stratified by buffer size (500 m, 1,000 m, 1,500 m, and 2,000 m), sex (female and male), age group (15–45, 46–65, and over 65 y of age), health outcome (respiratory and circulatory), and Brazilian region (North, Northeast, South, Southeast, and Midwest). These regions follow the official administrative divisions set by the Brazilian government. For each subgroup analysis, we estimated the relative risks (RRs) and 95% confidence intervals (CIs) associated with an interquartile range (IQR) increase in NDVI during our study period, which spans from 2008 and 2018.

In the second stage, we conducted a meta-analysis to estimate the national RR of hospital admissions associated with greenness. We considered random effects to account for variability between regions. These random effects were used to model the average effect size of greenness on hospital admissions, assuming that this effect varied randomly from region to region within the Brazilian population.[23] This approach allowed us to account for regional differences and potential heterogeneity in the relationship between greenness and hospitalization outcomes across the country. Heterogeneity was examined using the *I*-square (I^2) statistic. A *p*-value >0.05 and/or I^2 <50% were considered homogeneous.

All analyses were performed on the Cloud Academic Platform. We used the R software (version 4.0.2; R Development Core Team), including the R package "glm" (generalized linear model) for the quasi-Poisson regression model. The software ArcGIS was used to create the maps.

Sensitivity Analysis

To assess the robustness of our findings, we conducted several sensitivity analyses aimed at examining the impact of different model specifications and variable exclusions. First, we tested a model without any covariates to evaluate the independent effect of greenness on hospital admissions. Second, given that the primary model included $PM_{2.5}$, NO_2, and O_3 as covariates, we tested three additional models, each including one air pollutant at a time, to assess the individual contributions of these pollutants. Furthermore, we evaluated the impact of excluding weather variables and SES variables (per capita income and education, represented by years of schooling) separately to understand their influence on the association between greenness and hospitalizations. In addition, we conducted analyses distinguishing between urban and nonurban areas to explore potential differences in the relationship across different geographical settings. Finally, we assessed the impact of excluding observations with NDVI values <0.2, considering this threshold as a sensitivity check on the inclusion of lower greenness levels.

Results

Table 1 shows the descriptive characteristics of hospitalizations for circulatory and respiratory diseases in Brazil during the study period. Our study population includes 26,724,624 hospitalizations for cardiorespiratory diseases in Brazil between 2008 and 2018. Among those, 12,407,460 (46.43%) were circulatory diseases and 14,317,164 (53.57%) were respiratory diseases. The number of male hospitalizations was slightly higher for both respiratory and circulatory diseases, representing 50.27% and 50.77% of total hospitalizations, respectively. For the age groups, the highest proportion was for patients over 65 y of age, with 43.82% hospitalized for circulatory diseases and 45.16% for respiratory diseases. In Excel Table S3, we show the descriptive characteristics of hospital admissions stratified by Brazilian regions and years (2008–2018), with the number of postal codes. In Table S4, we present the descriptive characteristics of hospital admissions for circulatory and respiratory diseases stratified by urban and nonurban areas.

Table 2 shows the summary statistics for NDVI and covariates in Brazil between 2008 and 2018. Considering the NDVI at the postal code points (buffer 0 m), we estimated a mean (with standard deviations) of 0.35 (0.16). The average NDVI across the buffers of 500 m, 1,000 m, 1,500 m, and 2,000 m increased gradually. Mean concentrations of $PM_{2.5}$, NO_2, and O_3 during the study period in Brazil were 17.66 (23.69) $\mu g/m^3$, 3.47 (4.61) ppb, and 21.40 (7.58) ppb, respectively (Table 2). For the meteorological variables, we estimated an average of 22.71 (4.06) °C for temperature and 77.40 (12.93) % for relative humidity (Table 2).

Figure 1 illustrates the spatial distribution of the annual mean NDVI for the years 2008, 2013, and 2018 (year of beginning, middle, and end of the study period, respectively) in Brazil and the national count of respiratory and circulatory admissions during the study period.

Table 2. Summary statistics for NDVI and covariates (air pollution, weather, and SES variables) in Brazil, 2008–2018.

Variable	Min	Q1	Mean	SD	Q3	Max
NDVI buffer: 0 m	0.00	26	0.36	0.15	0.44	1.00
NDVI buffer: 500 m	0.00	0.28	0.38	1.14	0.46	1.00
NDVI buffer: 1,000 m	0.00	0.30	0.41	0.14	0.50	1.00
NDVI buffer: 1,500 m	0.00	0.32	0.43	0.14	0.53	1.00
NDVI buffer: 2,000 m	0.00	0.33	0.44	0.15	0.55	1.00
NO_2 (ppb)	2×10^{-4}	0.82	3.32	4.48	3.60	118.10
O_3 (ppb)	1.3×10^{-7}	15.75	20.94	7.58	25.50	118.45
$PM_{2.5}$ ($\mu g/m^3$)	4.87×10^{-5}	5.95	17.07	23.19	17.38	282.20
Temperature (°C)	1.25	20.30	22.73	4.07	25.70	34.85
Humidity (%)	20.00	70.25	77.26	13.03	87.00	100.00
Income (R$)	102.20	948.71	1,608.27	483.41	2,263.09	3,100.84
Education (y)	0.00	0.00	0.91	1.38	1.00	8.00

Note: All the covariates shown in this table were measured at the census tract level. Max, maximum; Min, minimum; ppb, parts per billion; Q1, first quartile; Q3, third quartile; SD, standard deviation; SES, socioeconomic status.

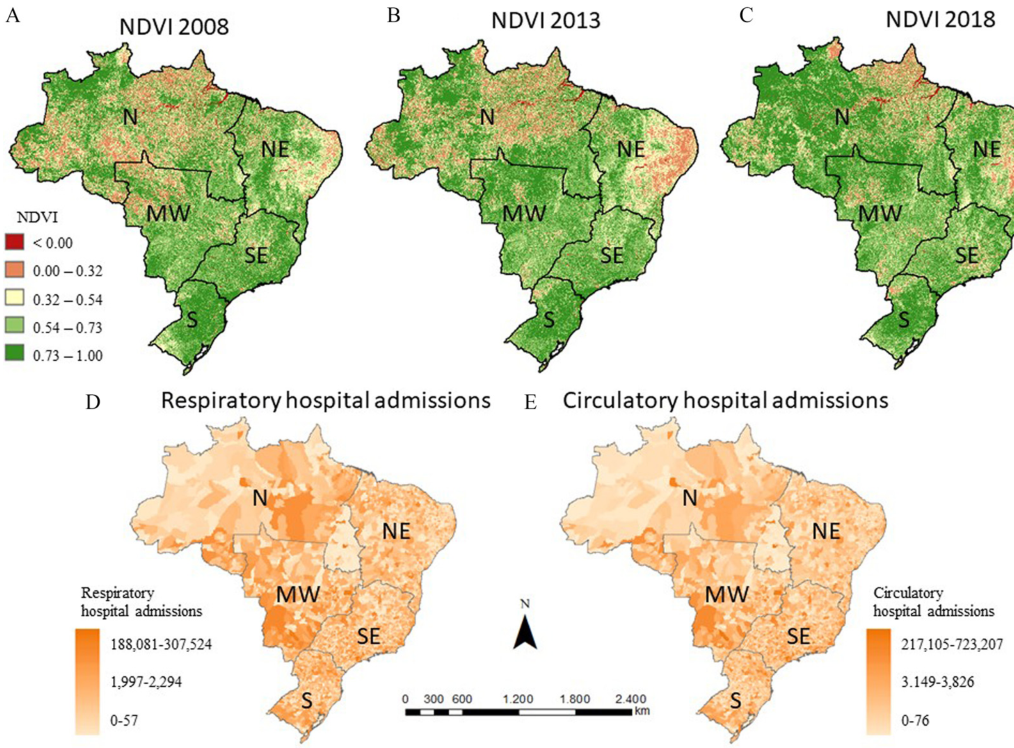

Figure 1. Spatial distribution of the annual average NDVI for the years 2008, 2013, and 2018 (year of beginning, middle, and end of the study period, respectively) in Brazil and the national count of respiratory and circulatory hospitalizations (2008–2018). The black and gray polygons represent the Brazilian regions: North (N); Northeast (NE); Midwest (CM); Southeast (SE), and South (S). Dark green in (A), (B), and (C) represent the regions in Brazil with NDVI above 0.73, whereas regions in red represent negative NDVI. In 2008, the average NDVI per region was: 0.48-N, 0.36-NE, 0.35-MW, 0.33-SE, 0.41-S. In 2013, it was: 0.43-N, 0.33-NE, 0.34-MW, 0.32-SE, 0.40-S. In 2018, it was: 0.44-N, 0.39-NE, 0.36-MW, 0.33-SE, 0.43-S. Note: NDVI, Normalized Difference Vegetation Index.

Figure 2 shows the national RR of hospital admissions for circulatory and respiratory diseases associated with greenness. In Excel Table S1 (supplementary materials), we show all national RR from the primary analysis, for all subgroup analyses, and health outcomes along with the estimated heterogeneity test from the meta-analysis.

The national meta-analysis for the entire dataset (without stratification by sex and age) showed an IQR increase (IQR = 0.18) in average NDVI (at the postal code point, represented by buffer 0) were associated with lower hospitalizations for circulatory diseases, with an RR of 0.83 (95% CI: 0.74, 0.92) (Figure 2). In contrast, for respiratory hospital admissions, the associations did not reach statistical significance (Figure 2). The benefits of green spaces in reducing respiratory admissions (considering buffer 0) were observed in only men (all ages) and women >65 y of age (Figure 2).

The inverse association for greenness tended to be stronger and more consistent (across age and sex groups) in smaller buffers, especially for circulatory admissions. For respiratory admissions, we found positive associations (suggesting the negative impact of greenness) for some age/sex groups in larger buffers, including buffers of 1,000, 1,500, and 2,000 (Figure 2).

In Figures 3 and 4, we show the results stratified by region. Overall, greenness was associated with lower risk of hospitalization for circulatory diseases in the North, Northeast, Midwest, and South regions (Figure 3). Some subgroup analyses (for age and sex) in the North, Midwest, and South suggested negative effects of greenness on health, especially the largest buffers. Southeast was the region with the most inconsistent RR and positive associations (Figure 3). For respiratory admissions (Figure 4), North and South were the regions where the benefits from greenness occurred in most of the analyses. Northeast, Midwest, and Southeast had several inconsistent and positive associations (Figure 4).

The results of the sensitivity analyses for the national meta-analysis were generally consistent. The models including one air pollutant at a time (Figures S1, S2, and S3), model excluding meteorological variables (Figure S4), and model excluding the income SES variable (Figure S5) presented similar results in comparison with the primary model (Figure 2). However, the effects observed in the sensitivity analyses stratified by age group and sex exhibited more significant variations or differences in comparison with the effects observed in the primary analyses. Sensitivity analysis without the education variable (Figure S6) showed an inverse association of greenness on hospitalizations for circulatory and respiratory diseases.

In the stratification analyses by urban and rural areas, noteworthy differences in the observed associations between greenness and hospital admissions for circulatory and respiratory diseases were identified. The supplemental figures (S7–S18) and Excel Table S2 present the detailed results of these stratified analyses. In particular, when focusing on rural areas, the analysis revealed several negative associations, suggesting that higher levels of greenness in rural regions are associated with a lower risk of hospital admissions for both circulatory and respiratory diseases. This finding contrasts with the findings from the primary model, which included both urban and rural areas together and showed several insignificant and positive associations, especially for respiratory admissions.

Discussion

Our findings indicate substantial inverse associations of greenness with hospitalization for cardiovascular diseases in Brazil. The

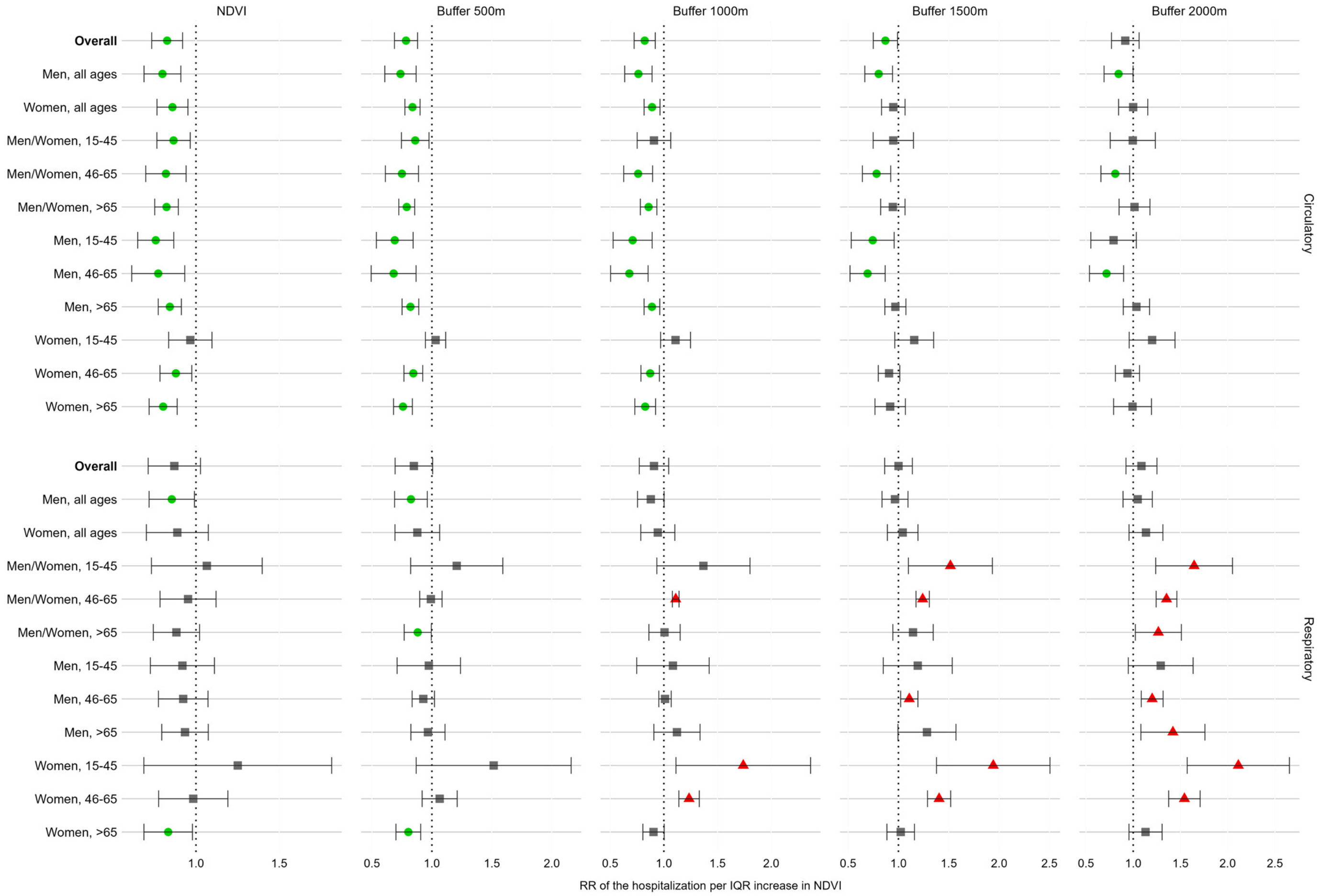

Figure 2. Relative risks (95% CI) by IQR for each increase of 1 NDVI unit in hospitalizations for circulatory and respiratory diseases in Brazil (meta-analysis results) between 2008 and 2018, stratified by health outcomes, age, and sex. Total of postal codes: 1,096,636. Total hospital admissions: 26,724,624. The gray square represents negligible coefficients (whose RR includes the value 1), the red triangle represents significant positive associations, and the green circle represents significant negative associations. Model adjusted for $PM_{2.5}$, NO_2, O_3, temperature, humidity, year, income, and education. This figure is mentioned in the "Results" section. The numeric data used to create this figure can be found in Excel Table S3. Note: CI, confidence interval; IQR, interquartile range; RR, relative risk.

associations with hospitalization for respiratory diseases did not reach statistical significance. Apart from this difference between the health outcomes (cardiovascular and respiratory admissions), the robustness of the RR and the effect size varied significantly by buffer size and region.

The difference in the risk between cardiovascular and respiratory diseases can be explained by the following hypotheses. First, the association with respiratory diseases may be less clear, because the inverse effect of greenness on respiratory health could be offset by the negative effects of allergenic and irritant airborne particles found in green vegetation, especially in larger buffers.[16] These negative effects are associated with pollen exposure. Pollen from trees and other vegetation contains allergenic proteins that, when inhaled, can trigger immune responses in susceptible individuals.[24] This immune response can lead to a range of respiratory symptoms, including sneezing, nasal congestion, and wheezing.[25] For individuals with preexisting respiratory conditions such as asthma or allergic rhinitis, exposure to pollen can exacerbate these conditions, leading to increased severity of symptoms and potentially necessitating medical treatment or hospitalization.[24,25] Second, in this study, we did not specify the type of respiratory diseases. The group of respiratory diseases has different etiologies and pathologies, and some may be more strongly linked to green spaces than others. Some respiratory diseases, such as chronic obstructive pulmonary disease (COPD), asthma, and bronchitis, are well known to be associated with environmental factors, including air pollution.[26] Other respiratory conditions such as pneumonia and tuberculosis present more intricate origins, encompassing infectious agents, host factors, and environmental elements.[27] In addition, sociodemographic factors such as income and education level can influence the association between greenness and health outcomes.[28] For example, individuals with lower SES may be more likely to live in areas with higher levels of environmental hazards, which could mask the benefits of greenness.[29] Furthermore, these individuals may have limited access to health care and resources for preventative measures, which could lead to higher rates of hospitalization for respiratory diseases in comparison with circulatory conditions.[30] Even after adjusting for socioeconomic variables in our models, there may still be residual confounding due to unmeasured or inadequately measured factors, given that we could only adjust for SES at the postal-code level and not at the individual level, and the effects of socioeconomic variables may vary by age and sex. These are possible hypotheses that may explain the lack of significant association (and some positive associations) between greenness and respiratory admissions.

The difference between the risk for circulatory and respiratory admissions was also found in previous studies. In a study conducted in the United States, an IQR (0.27) increase in NDVI was negatively associated with hospitalizations for circulatory

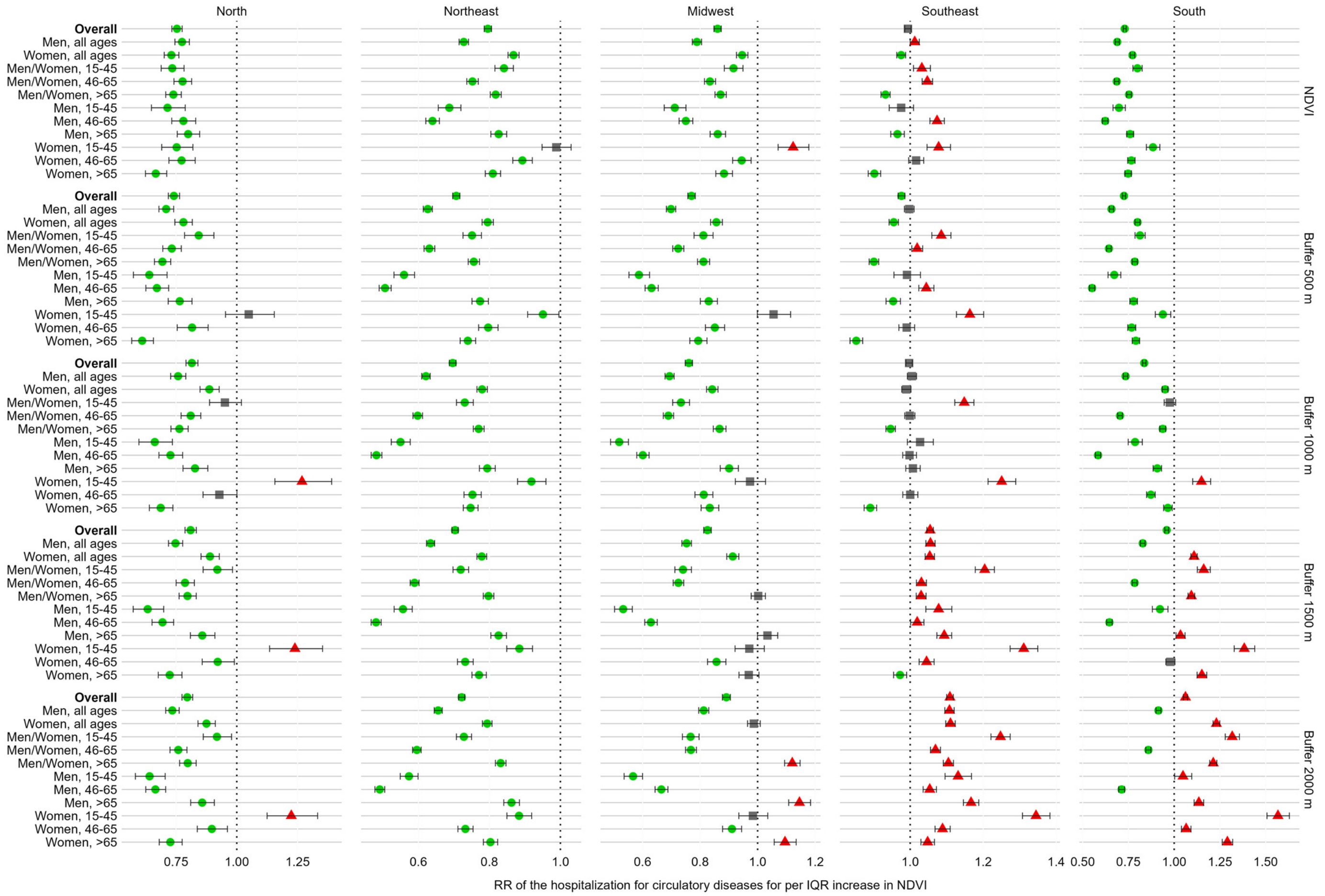

Figure 3. Relative risks (95% CI) of the primary model for circulatory hospitalizations in Brazil stratified by age, sex, and region between 2008 and 2018. Total of postal codes: 559,324. Total hospital admissions: 12,407,460, including 567,101 hospital admissions in the North, 2,606,533 in the Northeast, 2,444,689 in the South, 5,248,379 in the Southeast, and 1,540,758 in the Midwest. Of the total hospital admissions, 6,244,331 are from the group of men of all ages; 6,163,129 from the group of women of all ages; 1,972,301 with individuals of both sexes and between 15 and 45 y of age; 4,888,926 with individuals of both sexes and between 46 and 65 y of age; 5,351,020 individuals of both sexes and over the age of 65 y; 862,461 men between 15 and 45 y of age; 2,617,714 men between 46 and 65 y of age; 2,658,598 men over the age of 65 y; 1,114,231 women between 15 and 45 y of age; 1,064,890 women between 46 and 65 y of age; and 1,826,250 women over 65 y of age. The gray square represents negligible coefficients (whose RR includes the value 1), the red triangle represents significant positive associations, and the green circle represents significant negative associations. Model adjusted for $PM_{2.5}$, NO_2, O_3, temperature, humidity, year, income, and education. This figure is mentioned in the "Results" section. The numeric data used to create this figure can be found in Excel Table S3. Note: CI, confidence interval; RR, relative risk.

diseases [hazard ratio (HR) = 0.97; 95% CI: 0.96, 0.97] but not with hospitalizations for respiratory diseases (HR = 0.99; 95% CI: 0.98, 1.00).[31] A study conducted in South Korea[10] reported that people residing in areas with greater greenness coverage had a reduced risk of circulatory disease events, with an RR of 0.85 (95% CI: 0.81, 0.89).[10] In Lithuania, Tamosiunas et al. estimated that people exposed to the third tertile of distance to green space (≥629.61 m) had a higher RR of cardiovascular disease (1.36; 95% CI: 1.03, 1.80) than those in the second tertile, with a distance between 347.81 and 629.6 m (RR = 1.20; 95% CI: 0.90, 1.61).[14] In China, similar results were found, suggesting beneficial associations of green spaces in reducing circulatory diseases, including hypertension and stroke.[32] Another study in China[33] examined how the combination of exposure to air pollution and residential vegetation affects the risk of respiratory mortality in a large cohort. The results indicated that having more vegetation in residential areas can reduce the negative effects of air pollution on respiratory health. Other research[34] looked at how exposure to air pollution and residential vegetation affects the risk of hospitalizations for pediatric respiratory illnesses. The results showed that the presence of vegetation in residential areas can mitigate the harmful effects of air pollution on children's respiratory health.[35] In contrast, high levels of green areas are associated with a higher risk of dry cough at night among preschool children in China.[36] As we mentioned above, this positive association may be related to the adverse effects of allergenic and irritant airborne particles present in green vegetation, as we observed in our findings, particularly within larger buffer zones. On the other hand, in Italy, green areas were associated with a protective effect on children's respiratory health, including the incidence of wheezing, asthma, and bronchitis.[37]

We also estimated that the inverse association of greenness for hospitalizations for circulatory diseases is stronger in smaller buffer sizes. On the other hand, for respiratory admissions, the results were less consistent, and some age/sex groups showed positive associations (suggesting the negative impact of greenness) for larger buffer sizes. These results are consistent with the literature.[35,36,38] A potential explanation is that individuals who live closer to green spaces may be more likely to engage in physical activities such as walking or jogging in the park, which could help reduce the risk of cardiovascular diseases.[39] In addition, there is the stress pathway. This pathway encompasses psychological and physiological responses to stressors,[40] which can include factors related to the living environment.[41] Green spaces can serve as a direct and easily accessible

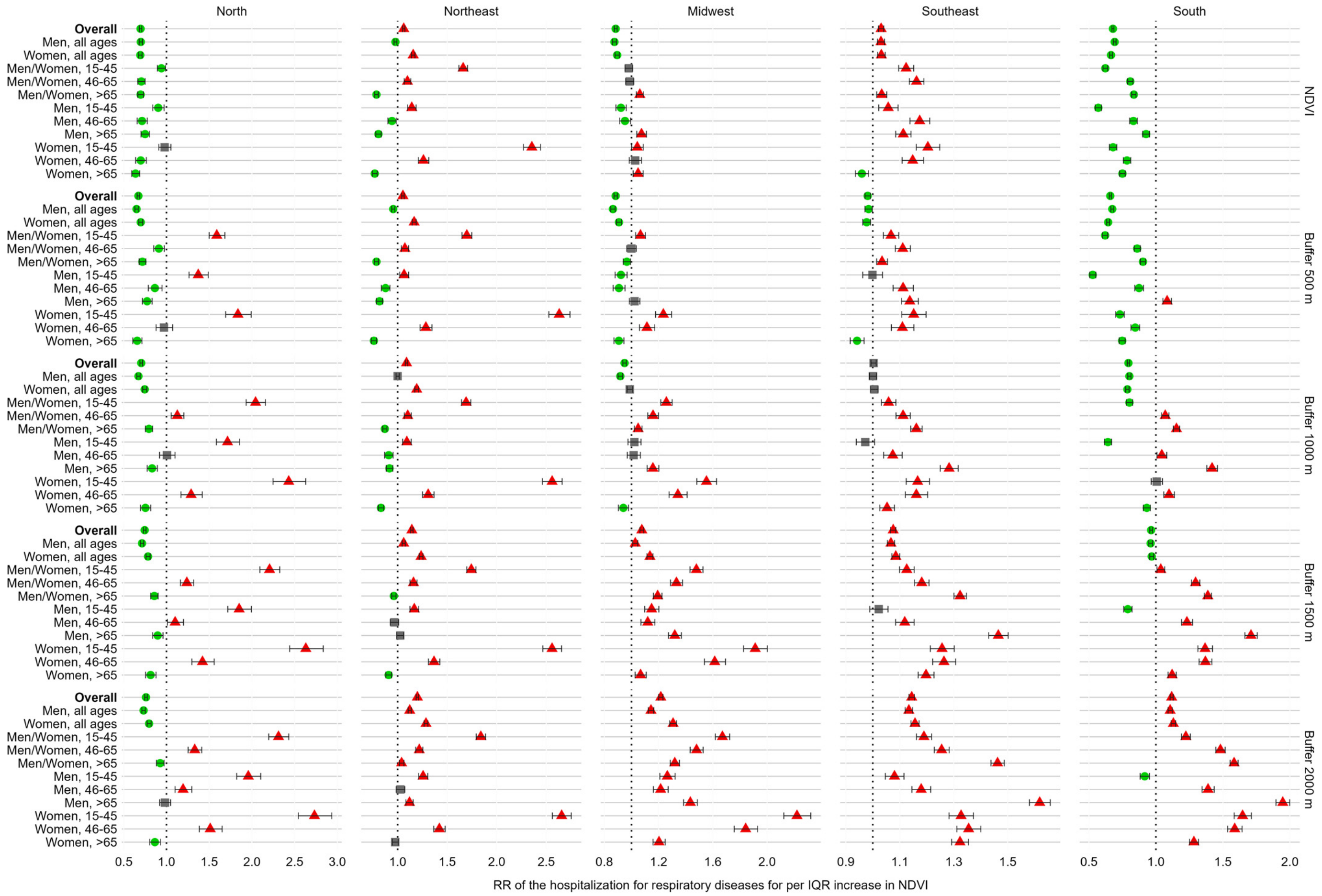

Figure 4. Relative risks (95% CI) of the primary model for respiratory hospitalizations in Brazil stratified by age, sex, and region between 2008 and 2018. Total of postal codes: 537,313. Total hospital admissions: 14,317,164, including 986,841 hospital admissions in the North; 3,634,601 in the Northeast; 2,794,086 in the South; 4,760,446 in the Southeast; and 2,141,190 in the Midwest. Of the total hospital admissions, 7,559,356 are from the group of men of all ages; 6,757,808 from the group of women of all ages; 2,240,672 with individuals of both sexes and between 15 and 45 y of age; 2,240,672 with individuals of both sexes and between 46 and 65 y of age; 3,673,696 individuals of both sexes and over the age of 65 y; 1,126,441 men between 15 and 45 y of age; 1,156,212 men between 46 and 65 y of age; 1,847,446 men over the age of 65 y; 1,114,231 women between 15 and 45 y of age; 1,064,890 women between 46 and 65 y of age; and 1,826,250 women over 65 y. The gray square represents negligible coefficients (whose RR includes the value 1), the red triangle represents significant positive associations, and the green circle represents significant negative associations. Model adjusted for $PM_{2.5}$, NO_2, O_3, temperature, humidity, year, income, and education. This figure is mentioned in the "Results" section. The numeric data used to create this figure can be found in Excel Table S3. Note: CI, confidence interval; RR, relative risk.

stress-buffering environment.[42] Individuals living in areas with green spaces may experience lower stress levels and, as a result, potentially lower the risk of hospitalizations because of circulatory diseases.[40,41] In addition, green spaces may have a greater impact on air quality and temperature regulation, which are known risk factors for cardiovascular diseases.[43] In contrast, regarding the different effects for respiratory admissions (suggesting the negative impact of greenness in larger buffers), this finding may be explained by the fact that larger buffer sizes may capture a wider range of environmental and socioeconomic factors that can affect respiratory health, including air pollution, traffic, and noise, which may offset the potential benefits of greenness.[29]

Particularity on the positive associations observed in specific subgroups, such as women 15–45 y of age in the North region (where there did not seem to be many positive associations between greenspace and circulatory hospitalizations for other groups), may reflect unique dynamics related to greenspace exposure and health outcomes in these populations.[44] Potential explanations for these findings could include differences in activity patterns[45] (e.g., women in the 15–45 age group engage in different outdoor activities or spend less time in greenspaces in comparison with other age groups), outdoor exposure[46] (e.g., women in this age group might have different patterns of outdoor exposure due to work, lifestyle, or family-related factors), or susceptibility to environmental factors among different demographic groups[44,47] (women in this age range may have unique physiological or genetic factors that make them less responsive to the positive effects of greenspace on health outcomes).

The observed shift in associations when stratifying by urban and rural areas underscores the nuanced relationship between greenness and health outcomes in distinct environments. The disparities between urban and rural areas in our findings may be attributed to the diverse characteristics of green spaces in these regions. Although urban areas may exhibit a mix of natural parks, urban green infrastructure, and landscaped areas, rural regions often feature more extensive natural landscapes, including forests and agricultural spaces. The negative associations identified in rural areas suggest that green spaces in such environments may offer inverse effects against hospital admissions for circulatory and respiratory diseases. In contrast, the positive or insignificant associations in the combined urban and rural analysis (primary model) might be influenced by complex interactions between urbanization, air quality, and socioeconomic factors. Urban green spaces, despite their potential benefits, may face challenges such as air pollution, noise, and limited accessibility, which could attenuate their positive impact on health. Understanding these distinctions emphasizes the need for context-specific urban planning and public health interventions tailored to the unique characteristics of urban and rural green spaces. Future research could examine the specific features and qualities of green spaces in different urban and rural environments to unravel the intricacies of their health-related effects.

Our findings suggest regional differences in the associations between greenness and cardiorespiratory admissions. Overall, greenness was found to be associated with a reduction in hospitalizations for circulatory diseases in all regions (except in the Southeast region, where there were some inconsistent RRs; in the South region, some inconsistent RRs were observed only for large buffers). However, the benefits of greenness on respiratory health were more varied across regions. The country is divided into five regions (North, Northeast, Midwest, Southeast, and South) with different geographic, environmental, climatic, and socioeconomic characteristics, which may affect the associations between greenness and health outcomes.[48,49]

These regional differences in the associations between greenness and cardiorespiratory admissions may also be due to variations in environmental exposures, including differences in air pollution levels, which can vary substantially between regions.[50] Brazil's extensive geographical diversity includes urbanized areas, natural forests, and various ecosystems, which impact the types of green spaces present across different regions. Note that Brazil exhibits a broad spectrum of landscapes and urbanization patterns.[51] For example, the Southeast region, including major cities like São Paulo and Rio de Janeiro, is more densely urbanized, featuring a higher concentration of urban parks and green spaces within metropolitan areas. In contrast, the North region encompasses the Amazon rainforest, one of the world's largest natural forests. This region is known for its exceptional biodiversity, lush vegetation, and extensive forested areas. The Northeast and Midwest regions are characterized by a mix of urban and rural areas, with the Caatinga and Cerrado biomes prevalent in these regions.[51] The geographical distribution of these diverse green spaces, coupled with the varying levels of urbanization and vegetation types, can introduce unique dynamics into the relationships between greenness and health outcomes.[52] These distinctions may affect factors such as air quality, temperature regulation, and exposure to specific types of vegetation, which, in turn, influence cardiorespiratory health outcomes. Considering this context, we suggest the hypothesis that it is not just the mere amount of vegetation in an area (which is measured by NDVI) but rather the diversity of that vegetation (which is not measured by NDVI) that may matter.[52] Therefore, the green spaces in areas with high biodiversity, such as the Amazon rainforest in the North region, may have a more beneficial effect on health[53] (note that in the North region, we found a significant negative association with respiratory admissions in most of the subgroup analyses) due to their ability to absorb pollutants and provide cleaner air, in comparison with other regions with more urban or agricultural landscapes.[54,55]

These differences in greenspace exposure in Brazil, as in comparison with other regions of the globe, are multifaceted and rooted in the country's distinctive geographical and socioeconomic context.[56] These characteristics can introduce unique dynamics to the relationships between greenness and health outcomes, which is essential for a comprehensive interpretation of our results. One of the most distinguishing features of Brazil is the presence of the Amazon rainforest, an ecological marvel known for its unparalleled biodiversity.[51] This vast rainforest not only contributes significantly to Brazil's green cover but also plays a vital role in global environmental health. The Amazon's rich and diverse flora and fauna have the potential to enhance air quality and overall environmental well-being. In contrast, although other regions (e.g., North America and Europe) host their own green spaces, they lack the sheer scale and ecological diversity found in the Amazon. Moreover, Brazil faces environmental challenges that set it apart from many other regions.[56] Deforestation, in particular, has been a significant concern. Brazil's struggle with deforestation, driven by factors such as agricultural expansion, mining, and urbanization, has led to a rapid loss of forest cover.[51] This loss directly affects the availability of green spaces in urban areas and, consequently, the health of the population.[57]

The impact from deforestation on green space is not uniform across all regions. Larger cities like Rio de Janeiro or São Paulo may have maintained their levels of greenspace over time. In contrast, in specific areas experiencing rapid urbanization and deforestation, this impact on green space can result in a fragmented urban landscape characterized by disparities in green space distribution and accessibility. Low-income and marginalized communities often endure the worst of these environmental injustices, facing limited access to green areas and increased exposure to the adverse health impacts of urbanization and deforestation.[58] In contrast, some regions in North America,[59] Europe,[60] and Asia[61] have made substantial efforts to preserve and expand green spaces within urban areas. These efforts often include the creation of urban parks, green belts, and green infrastructure initiatives. Although these regions face their own unique environmental challenges, such as air pollution and urbanization, the extent and nature of these challenges can differ significantly from those in Brazil. Understanding these distinctions in greenspace exposure and the associated environmental challenges is crucial for contextualizing our findings and their relevance to global research on greenness and health outcomes. It underscores the significance of local nuances in shaping the relationship between green spaces and population health, allowing for more targeted and region-specific urban planning and public health interventions.

Our study has some limitations. First, despite adjusting for potential confounders, including air pollution, temporal factors, and SES, there is a possibility of residual confounding bias. Although we cannot definitively establish the direction of bias, it is essential to acknowledge that residual confounding may affect the robustness of our associations. To improve future research in this regard, more extensive data collection, including variables on individual health behaviors, access to health care, green space usage, and specific sources of air pollution, could enhance the precision of our findings. Moreover, employing advanced statistical methods, such as causal inference techniques, could be valuable in further mitigating potential confounding. Second, our study was done at the ecological level and not the individual level, which only allows us to suggest associations between greenness and hospitalizations for respiratory and cardiovascular diseases, but not establish causality.[62] Future studies that incorporate individual-level data and a longitudinal approach can provide stronger evidence of causality. Third, the study relied on administrative hospitalization records, which may not capture all cases of diseases of interest and may be subject to underreporting or misclassification. We acknowledge the possibility that certain populations, such as those seeking care in primary health care facilities or not seeking medical attention, may not be fully represented in these records, leading to a potential source of bias. The extent of this bias, especially concerning differential underreporting between urban and rural populations, remains a consideration worth exploring in future research efforts. Fourth, we only accounted for one measure of green areas, NDVI, which does not capture the quality of the green space. Incorporating data on green space characteristics and accessibility could provide more comprehensive insights into the health benefits of different types of green spaces.[31,62] There is also a potential limitation of using MODIS. Although the use of MODIS data allowed us to conduct a nationwide analysis, it is important to acknowledge that the coarser spatial resolution of MODIS (250 m × 250 m) could introduce some exposure misclassification, particularly when assessing fine-scale variations in greenspace. Future research may benefit from incorporating higher-resolution data sources, such as Landsat (30 m × 30 m), in areas where detailed spatial analysis is paramount to capture localized effects of greenspace on health outcomes. Another limitation is that we may not have fully accounted for fine-grained variations in greenspace exposure that could exist within the same region. Although our approach allowed us to capture broad-scale geographical differences in greenspace exposure and health outcomes, it did not explicitly address spatial variation within regions at the postal-code level. Another limitation is the lack of detailed information on the definition and characteristics of postal codes. Given that the spatial data representing the postal codes that we used in our study were provided in the form of a shapefile represented by points, we were unable to calculate the specific land areas or demographic characteristics of individual postal-code regions. We also were unable to estimate how close people live to the point that represents their postal code. This variation in population density and land area within and between postal codes may have implications for the spatial granularity at which greenspace exposure is assessed and the interpretation of our findings. This issue led to differential exposure measurement error. Finally, we did not have information on SES varying over time at the level of the postal code, limiting our ability to account for these temporal fluctuations in SES.

Our study has some strengths. First, to our knowledge, our study is the first to look at the association of greenness on risks of hospitalizations nationwide in Brazil. Second, by using a validated measure of greenness (NDVI), we were able to objectively assess the number of green spaces in each region, and our use of different buffer sizes allowed for a more detailed investigation of the spatial distribution of greenness and its effects on health. Third, we assessed the relationship between greenness and hospitalization at the postal-code level in Brazil. The study population is a valid representative sample of individuals. Stratifying by age and gender enabled the identification of the most affected gender and age group.

Conclusions

Our study provides evidence of a potential beneficial association between greenness and reduced hospitalizations for circulatory diseases in Brazil. This evidence for circulatory admissions was observed in certain buffer sizes and regions. The findings suggest that the availability and accessibility of green spaces may play a role in promoting population health and reducing the burden of disease. Because this study is one of the initial nationwide studies in Brazil, additional research is warranted to enhance our understanding of the mechanisms influencing the observed associations. Further investigation will contribute valuable insights for informing policies directed at promoting the provision and equitable distribution of green spaces for public health benefits.

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