Mercator, Fortaleza, v. 22, e22022, 2023. ISSN:1984-2201

GEOTECHNOLOGIES APPLIED TO THE BEHAVIORAL STUDY OF URBAN HEAT ISLANDS

https://doi.org/10.4215/rm2023.e22022

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Article history:
Received 08 October, 2023
Accepted 15 October, 2023
Published 30 October, 2023

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Abstract

Many cities are impacted by the effect of heat islands. In this context, the aim of this study was to analyze the spatial and temporal distribution of urban heat islands and the influence of green areas on the formation of urban microclimates in the city of Rio de Janeiro. As a result, it was observed that Rio de Janeiro city is under heat islands influence, in which the oldest and most urbanized areas of the city are the most affected by high temperatures. It was possible to verify the role of vegetation in the formation of urban microclimates through the negative correlation coefficient between surface temperature (Ts) and vegetation indexes (NDVI and EVI), along with the positive correlation coefficient between surface temperature (Ts) and the Index of Areas Built by Normalized Difference (NDBI), what demonstrates the influence of urbanization on the increase of temperature.

Keywords: Heat Island, city, Rio de Janeiro

Resumo / Resumen

GEOTECNOLOGIAS APLICADAS AO ESTUDO COMPORTAMENTAL DAS ILHAS DE CALOR URBANAS

Muitas cidades são impactadas pelo efeito das ilhas de calor. Neste contexto, objetivou-se com esse analisar a distribuição espacial e temporal das ilhas de calor urbanas e a influência das áreas verdes na formação dos microclimas urbanos no município do Rio de Janeiro. Como resultados, observou-se que Rio de Janeiro encontra-se sob influência das ilhas de calor, as áreas mais antigas da cidade e sobretudo mais urbanizadas são as mais acometidas pelas altas temperaturas. Foi possível constatar o papel da vegetação na formação dos microclimas urbanos por meio do coordenador de psicologia negativa entre a temperatura da superfície (Ts) e os índices de vegetação (NDVI) e (EVI), e ainda um coeficiente de transferência positiva entre Temperatura da Superfície (Ts) e Índice de Áreas Construídas por Diferença Normalizada (NDBI), demonstrando a influência da urbanização no aumento da temperatura.

Palavras-chave: Ilha de calor, cidade, Rio de Janeiro

GEOTECNOLOGÍAS APLICADAS AL ESTUDIO DEL COMPORTAMIENTO DE LAS ISLAS DE CALOR URBANO

Muchas ciudades se ven afectadas por el efecto de las islas de calor. En este contexto, el objetivo de este estudio fue analizar la distribución espacial y temporal de las islas de calor urbanas y la influencia de las áreas verdes en la formación de los microclimas urbanos en el municipio de Río de Janeiro, Brasil. Como resultados, se observó que Río de Janeiro está influenciada por las islas de calor, siendo las áreas más antiguas y urbanizadas las más afectadas por altas temperaturas. Se pudo constatar el papel de la vegetación en la formación de los microclimas urbanos mediante el coeficiente de correlación negativo entre la temperatura de la superficie (Ts) y los índices de vegetación (NDVI) y (EVI), así como un coeficiente de correlación positivo entre la temperatura de la superficie (Ts) y el Índice de Áreas Construidas por Diferencia Normalizada (NDBI), lo que demuestra la influencia de la urbanización en el aumento de la temperatura.

Palabras-clave: Palabras clave: Isla del Calor, ciudad, Río de Janeiro

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ARTICLE

INTRODUCTION

The growing urbanization has been identified as the main cause of green cover reduction and, consequent, surface temperature increase in cities (DWIVEDI; KHIRE, 2018). Due to the rapid urbanization process in the Brazilian territory, associated with unrestrained population growth, many cities have expanded without suitable urban planning or public policies concerning urban environmental quality (ORTIZ; AMORIM, 2012).

In view of the constant changes made for housing in the territory, where urban materials and equipment have replaced vegetation areas, cities started to have their own climate in terms of thermal and humidity conditions, resulting in temperature increase. According to Gunawardena, Wells e Kershaw (2017), human activities result in anthropogenic emissions that have the potential to increase the amount of thermal energy released into the urban climate, while the meteorological, urban and geographical characteristics influence the intensity and distribution of this release, causing a difference in temperature throughout the city.

This temperature difference found in urban centers is known as heat islands, a phenomenon in which cities become warmer places in relation to neighboring suburban areas. This is due to the high absorption of radiation by the constituent elements of the urbanized landscape, and as the city expand, it tend to intensify. The heat islands phenomenon has a series of implications for both population comfort and health, being pointed out as one of the major concerns for managers in large urban centers (GARTLAND, 2010; PERES et al., 2018).

The heat islands phenomenon appears in more urbanized cities as a source of many environmental problems and aggravates the urban living environment. Under the challenges and threats imposed by increasing urbanization and future climate change, there is an urgent need for sustainable strategies to adapt / mitigate its effects (YANG; WANG; KALOUSH, 2015).

On the other hand, recent studies have shown that the presence of green areas in the urban environment, such as forests, parks and afforestation, act to improve climatic conditions, reducing the effect of heat islands and contributing to the improvement of the urban microclimate (WONG; YU, 2005; ARMSON; STRINGER; ENNOS, 2012; MORAKINYO et al., 2017; ACERO; GONZÁLEZ-ASENSIO, 2018). According to Dimoudi and Nikolopoulou (2003), the presence of vegetation generates a phenomenon known as softening island, in which the existing vegetation presents several benefits and is capable of providing greater thermal comfort., being characterized as the opposite of heat islands.

The importance of studies related to mitigation of heat islands is increasing due to global climate change. Thus, studying the urban climate and understanding its dynamics allows to evaluate the impacts and influence of future changes in cities, what helps in the search for adaptive processes and alternatives that ensure the population life quality (SOUZA; SILVA, 2017).

A widely used approach to measure the effect of heat islands consists in the application of remote sensing to estimate the temperature of the Earth's surface. This technology allows to incorporate data from several satellites with different spectral, spatial and temporal resolutions, and has been successful to enable large-scale monitoring of heat islands (SHIRANI-BIDABADI et al., 2019). In vegetation monitoring studies, for example, remote sensing is one of the most used techniques, especially for allowing to consider the spatial aspect (GUEDES; SILVA, 2018).

Furthermore, as pointed out by Armson, Stringer and Ennos (2012), if the loss of urban vegetation is capable of increasing the effect of heat islands while the addition of vegetation may reduce its effects, it is justified to research and quantify the cooling effect caused by urban vegetation. In this context, the objective of this study is to analyze the spatial and temporal distribution of urban heat islands and the influence of green areas on the formation of urban microclimates in the Rio de Janeiro city, Brazil.

MATERIAL AND METHODS

STUDY AREA CHARACTERIZATION

The city of Rio de Janeiro, Brazil, with a total area of 1,255.3 km², is located between the geographic coordinates 22º44'54 "and 23º04'43" south latitude and 43º05'22 "and 43º47'59" west longitude (Figure 1). The estimated population is 6,688,927 inhabitants, with a demographic density of 5,265.82 inhabitants / km² (IBGE - Instituto Brasileiro de Geografia e Estatística, 2019),

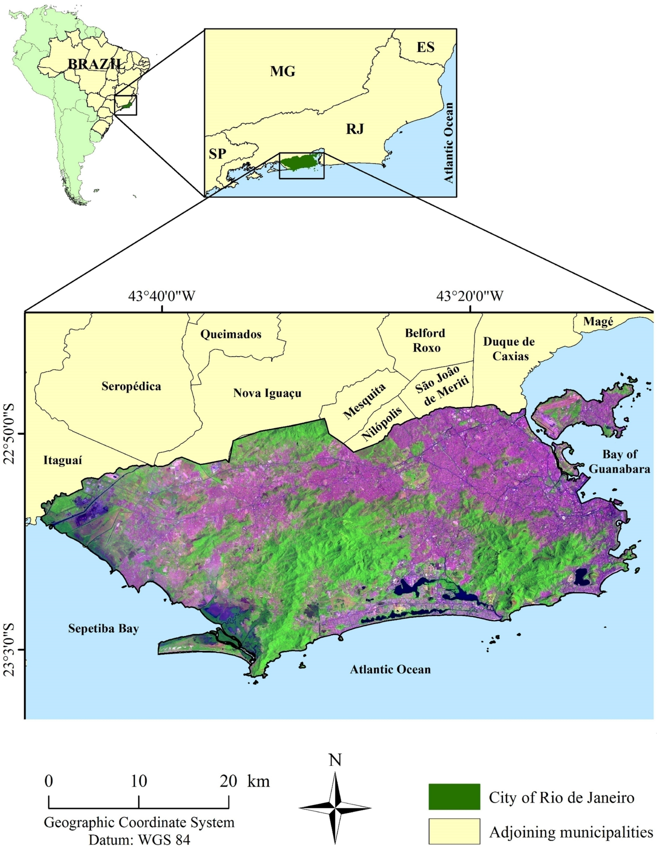


Figure 1 - Location of Rio de Janeiro city, Brazil.

The city's climate, according to the climate classification proposed by Koppen, has five climatic types: Af, humid tropical climate; Am, humid or sub-humid tropical climate; Aw, tropical climate with dry winter; Cfa, humid temperate climate with hot summer; Cfb, humid temperate climate with temperate summer (ALVARES et al., 2013). The region's average temperature is 23.8 °C during the year, with a maximum of 42 °C in December and a minimum of 21 °C in July (INMET, 2019). The predominant vegetation is the Atlantic Forest(MYERS et al., 2000).

METHODOLOGICAL PROCEDURES

The methodological flowchart containing the summary of all stages developed for this research is presented below:

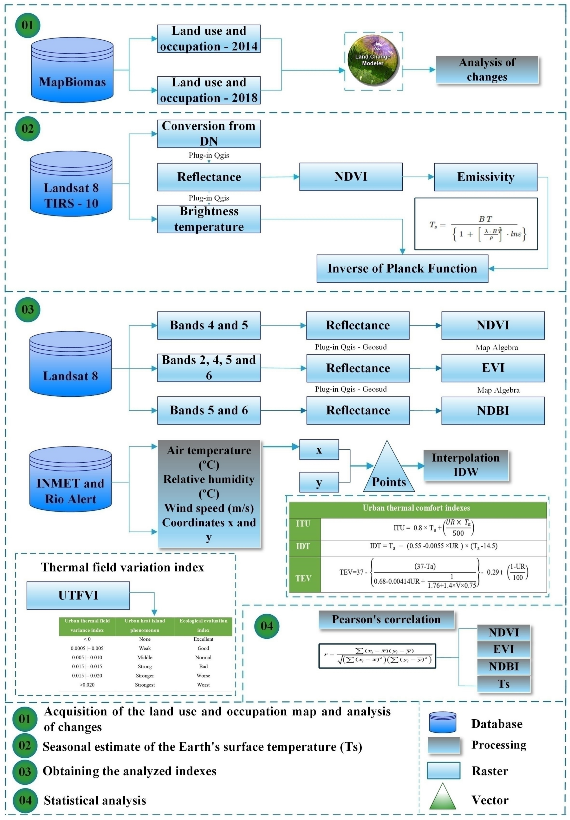


Figure 2 - Methodological flowchart containing all steps employed in the study

ACQUISITION OF THE LAND USE AND OCCUPATION MAP

The maps of land use and occupation for the years 2014 and 2018 were obtained free of charge on the Brazilian Annual Land Use and Land Cover Mapping Project (MAPBIOMAS) website (MAPBIOMAS, 2019).

ANALYSIS OF CHANGE IN LAND USE AND OCCUPATION

The obtained land use and occupation maps were incorporated into Land Change Modeler (LCM) module, available in the Terrset software, to obtain graphical and tabular analysis of gains and losses, as well as net changes for each class between studied years. Thus, it was possible to make a comparison in hectares and in percentage of the occurred changes.

SEASONAL ESTIMATE OF TERRESTRIAL SURFACE TEMPERATURE

Images from satellite Landsat-8 TIRS sensor (band10) were used, distributed over the last 5 years (2014-2018), prioritizing images with the least possible cloud interference, in different seasons (spring; summer; autumn and winter), for each studied year, totaling 20 images.The temperature of the earth's surface was obtained through The Land Surface Temperature Estimation Plugin, available in Qgis free software. This plug-in has the ability to extract the temperature from thermal images, according to the following steps, which are below described.

CONVERSION OF DIGITAL NUMBER (DN) TO SPECTRAL RADIANCE (LI)

First, the digital number (DN) values from the satellite image are converted to spectral radiance trough the equation developed by Markham and Barker (1985):

$$L_\lambda = M_L\, Q_{cal} + A_L \qquad \text{(Eq. 1)}$$

Where,

$L\lambda$: spectral radiance at the top of the atmosphere (W/m².sr.µm);

M_L: multiplying factor rescheduled for the specific band (radiance mult_ band_x), where x is the band number;

Q_{cal}: Digital number (ND) of the pixel;

A_L: radiated rescheduled additive factor for the specific band (radiance_add_band_x), where x is the band number.

CONVERSION FROM SPECTRAL RADIANCE (LI) TO REFLECTANCE (P)

For the calculation of vegetation indices and constructed areas, it is necessary to acquire the image reflectance, through the equation proposed by Markham and Barker (1985):

$$\rho\lambda = \frac{(M_\rho\, Q_{cal} + A\rho)}{\text{sen}\,(\theta SE)} \qquad \text{(Eq.2)}$$

Where,

ρ: planetary reflectance corrected at the top of the atmosphere;

M_ρ: scaled multiplicative factor of reflectance for the specific band (reflectance_mult_ band_x), where x is band number;

Q_{cal}: Digital number (ND) of the pixel;

$A\rho$: rescheduled additive factor of reflectance for the specific band específica (reflectance _add_ band_x), where x is band number;

θSE: local solar elevation angle equivalent to the sun_elevation value (degrees).

CONVERSION OF SPECTRAL RADIANCE (LL) TO BRIGHTNESS TEMPERATURE (T)

The calculation is performed using the Schott and Volchok (1985) (Eq.3).

$$T=\frac{K_2}{Ln\left(\frac{k_1}{L\lambda}+1\right)} \quad \text{(Eq.3)}$$

Where,

T: effective temperature of brightness in the sensor (K);

K_1: thermal constant of the specific band (k1_constant_band_x), where x is the band number, that is, bands 10 or 11;

K_2: thermal constant of the specific band (k2_constant_band_x), where x is the band number, that is, bands 10 or 11;

$L\lambda$: spectral radiance at the top of the atmosphere ($W/[m^2.sr.\mu m]$);

L_N: natural logarithm.

EMISSIVITY ESTIMATE

The emissivity estimate was performed according to the method proposed by Van de Griend and Owe (1993), in which, based on the range of values found for NDVI for each type of land use and occupation, an emissivity value is assigned. When the NDVI value varies from 0.157 to 0.727, the relationship between emissivity is expressed by the following equation: E In (NDVI)" (Eq. 4)

$$\in =1.0094 + 0.047 \times In\ (NDVI) \quad \text{(Eq. 4)}$$

For NDVI values outside the range of 0.157 to 0.727, they are divided into ranges as shown in Table 1 (ZHANG; WANG; LI, 2006).

NDVI	Emissivity of the surface
NDVI ? -0,185	0,995
-0,185 = NDVI ? 0,157	0,970
0,157 = NDVI = 0,727	1,0094 + 0,047 ln (NDVI)
NDVI ? 0,727	0,990

Table 1 - Estimate of emissivity based on NDVI. Source: Zhang, Wang and Li (2006).

OBTAINING THE EARTH'S SURFACE TEMPERATURE (INVERSE OF THE PLANCK FUNCTION)

The earth's surface temperature, in degrees Celsius, can be obtained by applying the Inverse of Planck Function (Eq. 5).

$$Ts = \frac{BT}{\left\{1 + \left[\frac{\lambda * BT}{\rho}\right] * \ln \epsilon\right\}} \quad \text{(Eq.5)}$$

Where,

T_s: earth's surface temperature (K);

BT: brightness temperature in the sensor (K);

λ: wave-length of the emitted radiation;

ρ: is the constant (1,438 x 10 $^{-2}$);

ε: emissivity of the thermal band (dimensionless).

CALCULATION OF NDVI AND EVI VEGETATION INDICES AS WELL AS BUILT-UP AREA INDEX (NDBI)

NDVI and EVI vegetation indices along with constructed area index (NDBI) were calculated through inserting their respective equations in the raster calculator function (map algebra - mapmatics) of the ArcGIS 10.3 software.

NDVI and EVI were considered as indicators of vegetation cover, while NDBI was used to map the built areas. All indices, NDVI, EVI and NDBI, were considered to be closely related to the Earth's surface temperature (Ts).

URBAN THERMAL FIELD VARIATION INDEX (UTFVI)

In order to characterize the effect of heat islands, the urban thermal field variation index (UTFVI) was used. It was calculated according to the equation of Zhang (2006).

$$UTFVI = \frac{T_s - T_{mean}}{T_{mean}} \quad \text{(Eq. 6)}$$

Where,

UTFVI: variation index of the urban thermal field (dimensionless);

T_s: Earth's surface temperature (K);

T_{mean}: average land surface temperature (K).

UTFVI	**Urban heat island phenomenon**	**Ecological Assessment Index**
< 0	Null	Great
0,0005 |– 0,005	Weak	Good
0,005 |– 0,010	Medium	Normal
0,015 |– 0,015	Strong	Bad
0,015 |– 0,020	Fortíssimo	Too bad
>0,020	Very strong	Terrible

Table 2 - Limit values of the ecological assessment index (UTFVI). Source: Zhang (2006).

URBAN THERMAL COMFORT INDICES

Three urban thermal comfort indexes were evaluated: Temperature and Humidity Index (ITU); Thermal Discomfort Index (IDT); and Effective Temperature Index as a function of Wind (VTE).

For estimating the parameters related to the equations of each index, meteorological data from six automatic meteorological stations distributed over the Rio de Janeiro city were used, which is made available free of charge by Instituto Nacional de Meteorologia (National Institute of Meteorology) - INMET and Sistema Alerta Rio da Prefeitura do Rio de Janeiro (Rio Alert system from Rio de Janeiro town hall).

TEMPERATURE AND HUMIDITY INDEX (ITU)

The temperature and humidity index (ITU) establishes three levels of comfort for the external environment. The calculation is performed according to the equation adopted by Nóbrega and Lemos (2011):

$$ITU = 0{,}8 \times T_a + \left(\frac{UR \times T_a}{500}\right) \quad \text{(Eq. 7)}$$

Where,

ITU: temperature and humidity index (°C);

T_a: air temperature (°C);

UR: relative humidity (%).

The thermal comfort levels were established according to the ITU intervals presented in Table 3.

Tracks	ITU (ºC)	Comfort levels
1	21 < ITU < 24	Comfortable
2	24 < ITU < 26	Slightly uncomfortable
3	ITU > 26	Extremely uncomfortable

Table 3 - Classification criteria for the Temperature and Humidity Index. Source: Nóbrega and Lemos (2011).

THERMAL DISCOMFORT INDEX (IDT)

The thermal discomfort index was proposed by Thom (1959). It is calculated according to the following equation:

$$IDT = T_a - (0{,}55 - 0{,}0055 \times UR) \times (T_a - 14{,}5) \quad \text{(Eq. 8)}$$

Where,

IDT: thermal discomfort index (°C);

T_a: air temperature (°C);

UR: relative humidity (%).

The thermal discomfort ranges were considered according to the classification presented in Table 4, with levels being adjusted to the tropical regions as proposed by Santos et al., (2012).

Tracks	IDT (ºC)	Thermal discomfort level
1	IDT < 24,0	Comfortable
2	24 = IDT = 26,0	Partly comfortable
3	26,0 < IDT < 28,0	Uncomfortable
4	IDT = 28,0	Very uncomfortable

Table 4 - Thermal discomfort rating ranges. Source: Santos et al., (2012).

EFFECTIVE TEMPERATURE INDEX AS A FUNCTION OF WIND (TEV)

This index is similar to the concept of effective temperature based on individual sensitivity, taking into account the wind speed. The index can be expressed according to Eq. (9), as proposed by Missenard (1937).

$$TEV = 37 - \left\{ \frac{(37-Ta)}{0,68-0,00414UR + \frac{1}{1,76+1,4*V*0.75}} \right\} - 0,29\ t\ \left(\frac{1-UR}{100} \right) \quad \text{(Eq.9)}$$

Where,

$T_{EV:}$ effective temperature depending on wind, air temperature and relative humidity (ºC);

T_a: average air temperature (ºC);

UR: relative humidity (%);

V: Wind speed (m/s).

Table 5 shows the comfort bands adopted for the analysis of TEV index, following the classification adopted by the meteorology laboratory of the University of São Paulo - USP.

Tracks	TEV (ºC)	Thermal sensation	Degree of physiological stress
1	< 05	Very cold	Extreme cold stress
2	05 |–10	Cold	Extreme cold stress
3	10 |– 13	Moderately Cold	tremble
4	13 |– 16	Slightly Cold	Body cooling
5	16 |– 19	A little cold	Slight cooling of the body
6	19 |– 22	Slightly Cool	Vasoconstriction
7	22 |– 25	Comfortable	Thermal neutrality
8	25 |– 28	Slightly Hot	Slight sweat, vasodilation
9	28 |– 31	Warm Moderate	Sweating
10	31 |– 34	Hot	Profuse sweat
11	> 34	Very hot	Thermoregulation failure

Table 5 - Thermal sensation bands adopted for TEV index. Source: Meteorology applied to regional weather systems (MASTER – IAG/USP).

STATISTICAL ANALYSIS

To understand the influence of green areas in the formation of urban microclimates, a comparison of vegetation (NDVI and EVI) and constructed area index (NDBI) with earth surface temperature (Ts) was done by means of Pearson's correlation Eq. (10).

$$r = \frac{\sum_{i=1}^{n}(x_{j-x}) \times (y_{i-y})}{\sqrt{\sum_{i=1}^{n}(x_i-x)^2} \times \sqrt{\sum_{i=1}^{n}(y_i-y)^2}} \qquad \text{(Eq.10)}$$

Where,

R: Pearson's correlation coefficient;

Xi: measured values of variable x;

Yi: measured values of variable y.

RESULTS

ASSESSMENT OF CHANGES IN LAND USE AND OCCUPATION

Land use and occupation mapping for Rio de Janeiro city in 2014 and 2018 can be seen in Figure 3.

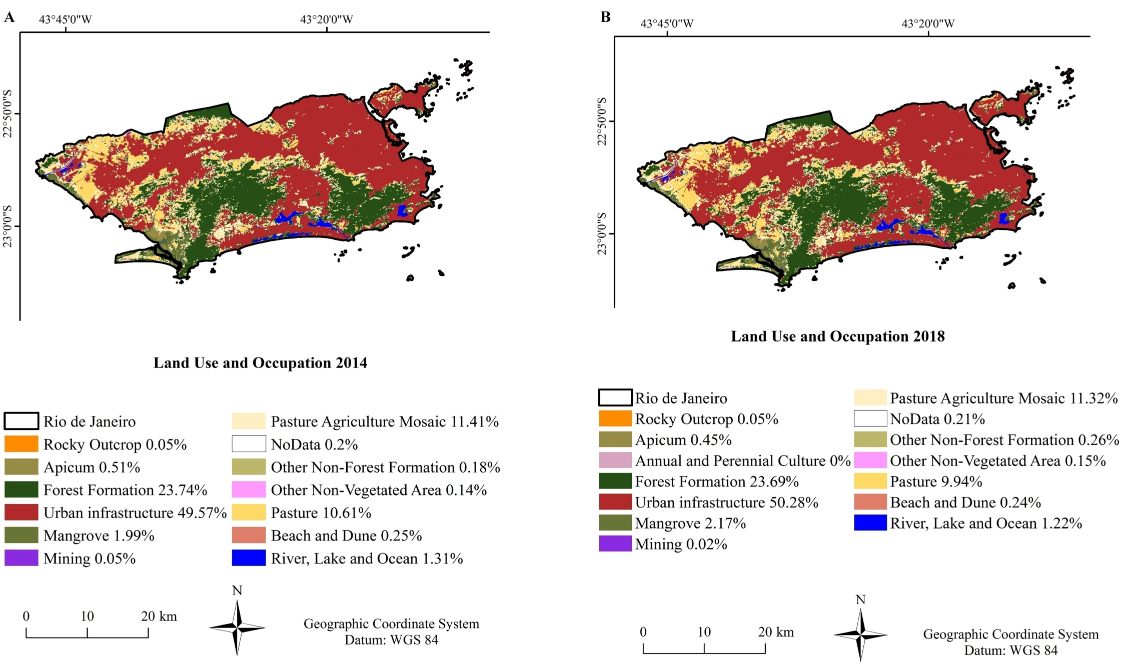
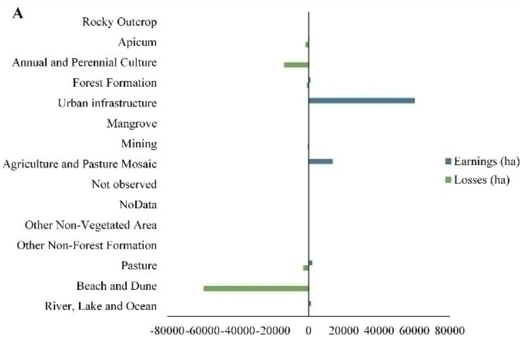


Figure 3 - (a) Map of Land Use and Occupation for 2014; (b) Map of Land Use and Occupation for the year 2018

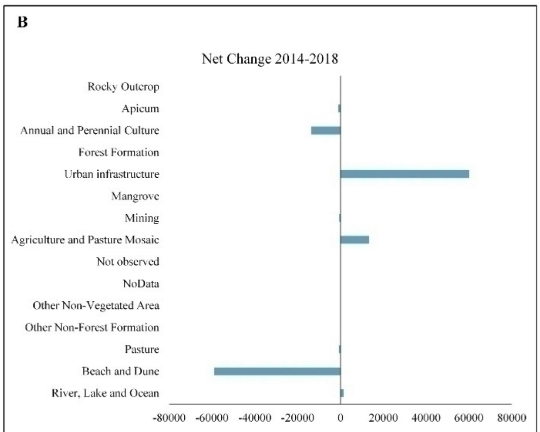
Analyzing the results of land use and occupation for the city, there is a significant urban occupation between the years 2014 and 2018, approximately half of the total city area is occupied by urban patches, what demonstrates the significant urbanization process that occurred in the city.

The second largest class for both years was Forest Formation, occupying 23.74% in 2014 and 23.69% in 2018. These forest formations are mainly located and distributed in Pedra Branca State Park, Tijuca Forest and in Conservation Units. Expressive urban density, in turn, is mainly observed in the North and Center regions, also corresponding to areas with less vegetation.

Little variation was observed among the identified classes, with only a few undergoing significant changes, such as Urban Infrastructure, which increased. These variations in land use and occupation can best be seen in Figure 4, which represent the graphical and tabular analysis of gains (blue) and losses (green), as well net changes (blue) for each class of land use between years 2014 and 2018.



	Losses (ha)	Earnings (ha)	Losses (%)	Earnings (%)
Rocky Outcrop	-56.0	62.0	0.07	0.08
Apicum	-1574.0	538.0	1.97	0.67
Annual and Perennial Culture	-13780.0	2.0	17.21	0.00
Forest Formation	-1048.0	989.0	1.31	1.24
Urban infrastructure	-158.0	60219.0	0.20	75.23
Mangrove	-83.0	292.0	0.10	0.36
Mining	-611.0	26.0	0.76	0.03
Agriculture and Pasture Mosaic	-296.0	13679.0	0.37	17.09
Not observed	0.0	0.0	0.00	0.00
NoData	-28.0	35.0	0.03	0.04
Other Non-Vegetated Area	-58.0	183.0	0.07	0.23
Other Non-Forest Formation	-88.0	183.0	0.11	0.23
Pasture	-2903.0	2096.0	3.63	2.62
Beach and Dune	-59368.0	279.0	74.16	0.35
River, Lake and Ocean	0.0	1467.0	0.00	1.83



Net Change (ha) 2014-2018			
Rocky Outcrop	6.00	Not observed	0.0
Apicum	-1036.00	NoData	7.0
Annual and Perennial Culture	-13778	Other Non-Vegetated Area	124.0
Forest Formation	-58.00	Other Non-Forest Formation	95.0
Urban infrastructure	60061.00	Pasture	-807.0
Mangrove	209.00	Beach and Dune	-59088.0
Mining	-584.00	River, Lake and Ocean	1467.0
Agriculture and Pasture Mosaic	13383.00		

Figure 4 - (a) Graphical analysis of gains and losses in land use and occupation between 2014 and 2018; (b) Graphical analysis of net changes in land use and occupation between 2014 and 2018

As expected, the results for the analysis of changes in land use and occupation confirm that Urban Infrastructure is the class with the greatest changes over the years, presenting an area gain of 60219.0 hectares (ha), approximately 75,23%, and a total net change of 60061.0 (ha). It is important to note that the Mosaic class of Agriculture and pasture underwent significant changes, with a gain of 17.09%, in contrast with annual Culture and Perennial class that had a loss of 17.21%. This result suggests a possible substitution of one class for another, once changes were observed in the same period. The other classes of land use and occupation have not undergone significant changes over the years, remaining practically with the same distribution settings, as seen in the change analysis.

SPATIAL AND TEMPORAL DISTRIBUTION OF THE EARTH'S SURFACE TEMPERATURE

The seasonal estimate of the Earth's surface temperature from year 2014 to 2018 in Rio de Janeiro city is shown in Figure 5.

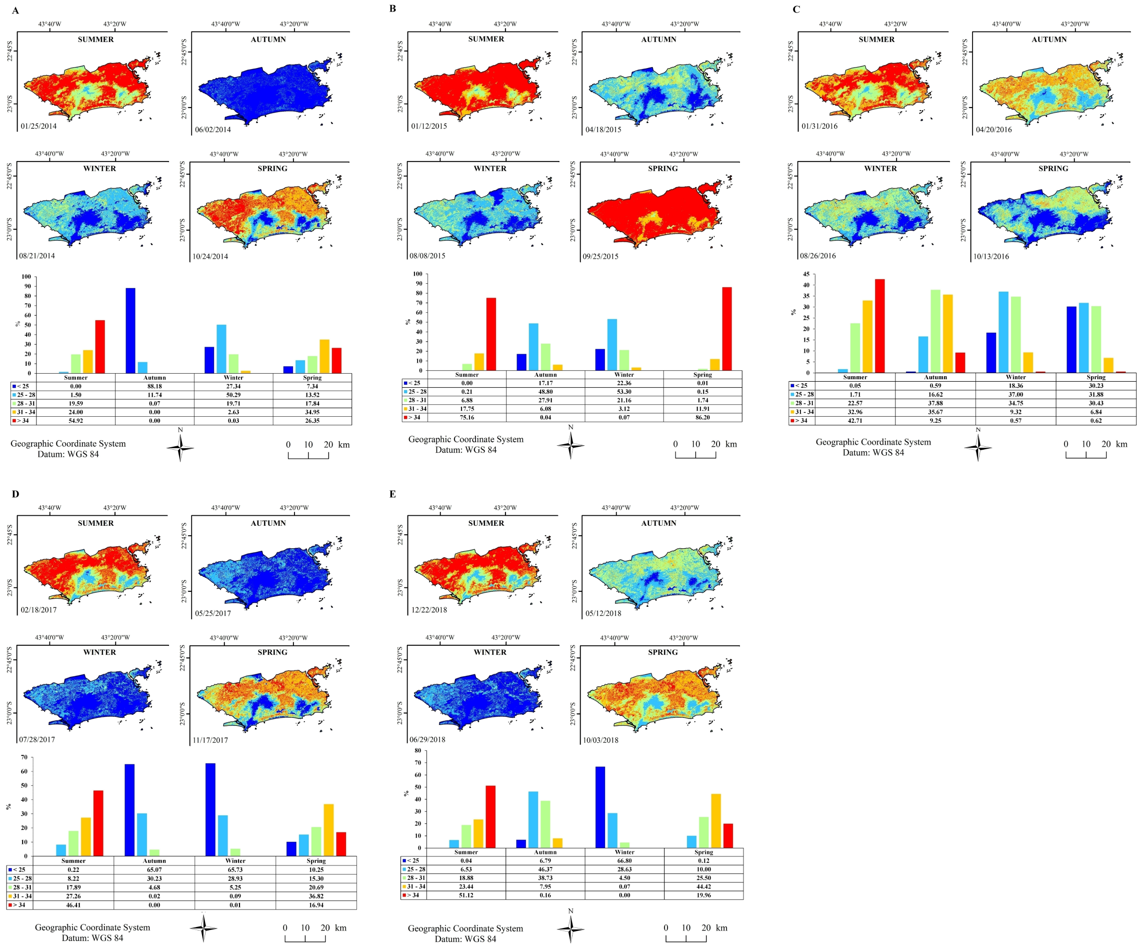


Figure 5 - (a)Distribution of the Earth's surface temperature for the year 2014; (b) Distribution of the Earth's Surface Temperature for the year 2015; (c) Distribution of Earth's Surface Temperature for the year 2016; (d) Distribution of Earth's Surface Temperature for the year 2017; (e) Distribution of Earth's Surface Temperature for the year 2018

In 2014, during summer period, 55% of the area was found with temperatures above 34 ºC. In some of these places, temperatures have even exceeded 40 ºC. These high temperatures correspond exactly to the most urbanized areas. On the other hand, South Zone regions near to Tijuca Forest, showed milder temperatures for the hottest period of the year (summer), with temperatures ranging from 28 ºC to 31 ºC, what confirms the effect of vegetation in reducing temperatures. The same behavior was noticed in the areas surrounding Pedra Branca State Park.

For the autumn day, milder temperatures were recorded, with a total of 88.18% of the area with temperatures below 25 ºC. This pattern remained similar during winter, with a record of pleasant temperatures for the whole city and some points of higher temperatures in the West and North of the city, whose temperatures were in the range of 28 ºC to 31 ºC. During spring, fluctuations in temperature could be observed, with a predominance of temperatures between 31 ºC and 34 ºC in the North, West and Center areas, which are very densely populated regions with significant urban occupation. It is important to note that in this same period, the regions close to Tijuca Forest and Pedra Branca State Park had temperatures below 25 ºC, confirming, once again, the decrease of temperature around nearby forests.

In 2015 the spatial distribution of temperature made the predominance of high temperatures during summer and spring periods very evident, temperatures prevailed above 34 ºC comprising approximately 75.16%. and 86.20%, respectively. This pattern of variation can be explained by the fact that in 2015 Brazil was affected by El Niño-Oscilação Sul phenomenon (ENOS) with strong intensity (INPE, 2019). The phenomenon is associated with abnormal conditions of surface waters warming in the

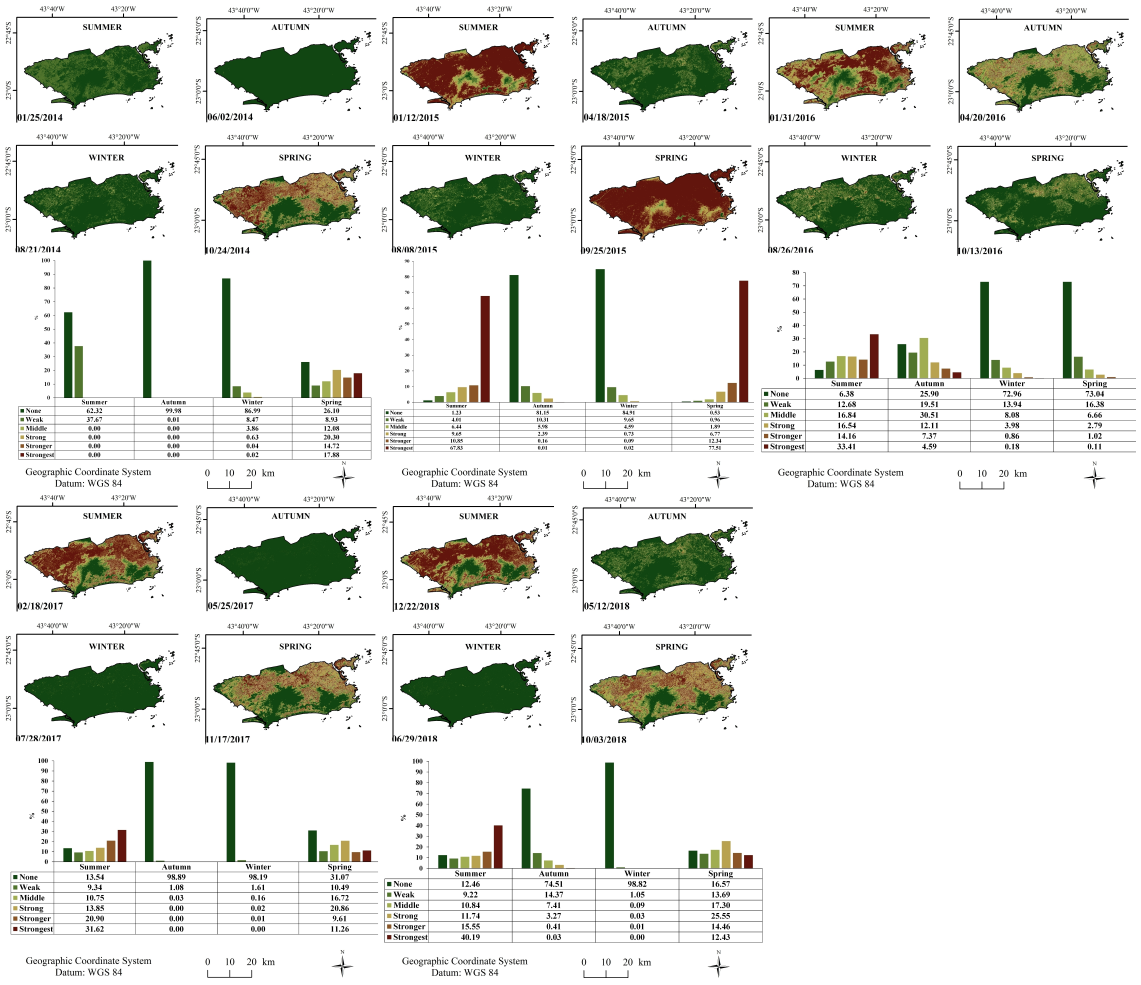
Tropical Pacific Ocean, which can affect the regional and global climate. Its impacts in Brazil are quite diversified, in some areas it produces extreme droughts, while in others, it considerably raises temperatures (SANTOS, et al., 2011).

Regarding the year 2016, there was a pattern of increased temperatures in the autumn and winter seasons compared to previous years and a decrease in temperature during spring. Temperature images for 2017 reveal the presence of high temperatures (34 ºC) only in some parts of the city during summer period.

It is possible to observe among the analyzed years that the values of surface temperature distribution were higher in summer and in densely urbanized areas.

ECOLOGICAL ASSESSMENT OF URBAN HEAT ISLANDS USING THE THERMAL FIELD VARIATION INDEX

Through the calculation of thermal field variation index, it was possible to analyze the intensity and areas of the worst classifications regarding the presence of heat islands. The results for all analyzed years and seasons are shown in Figure 6.



	Summer	Autumn	Winter	Spring
None	62.32	99.98	86.99	26.10
Weak	37.67	0.01	8.47	8.93
Middle	0.00	0.00	3.86	12.08
Strong	0.00	0.00	0.63	20.30
Stronger	0.00	0.00	0.04	14.72
Strongest	0.00	0.00	0.02	17.88

	Summer	Autumn	Winter	Spring
None	1.23	81.15	84.91	0.53
Weak	4.01	10.31	9.65	0.96
Middle	6.44	5.98	4.59	1.89
Strong	9.65	2.39	0.73	6.77
Stronger	10.85	0.16	0.09	12.34
Strongest	67.83	0.01	0.02	77.51

	Summer	Autumn	Winter	Spring
None	6.38	25.90	72.96	73.04
Weak	12.68	19.51	13.94	16.38
Middle	16.84	30.51	8.08	6.66
Strong	16.54	12.11	3.98	2.79
Stronger	14.16	7.37	0.86	1.02
Strongest	33.41	4.59	0.18	0.11

	Summer	Autumn	Winter	Spring
None	13.54	98.89	98.19	31.07
Weak	9.34	1.08	1.61	10.49
Middle	10.75	0.03	0.16	16.72
Strong	13.85	0.00	0.02	20.86
Stronger	20.90	0.00	0.01	9.61
Strongest	31.62	0.00	0.00	11.26

	Summer	Autumn	Winter	Spring
None	12.46	74.51	98.82	16.57
Weak	9.22	14.37	1.05	13.69
Middle	10.84	7.41	0.09	17.30
Strong	11.74	3.27	0.03	25.55
Stronger	15.55	0.41	0.01	14.46
Strongest	40.19	0.03	0.00	12.43

Figure 6 - (a) Thermal field variation index for the year 2014; (b)Thermal field variation index for the year 2015; (c)Thermal field variation index for the year 2016; (d)Thermal field variation index for the year 2017; (e)Thermal field variation index for the year 2018

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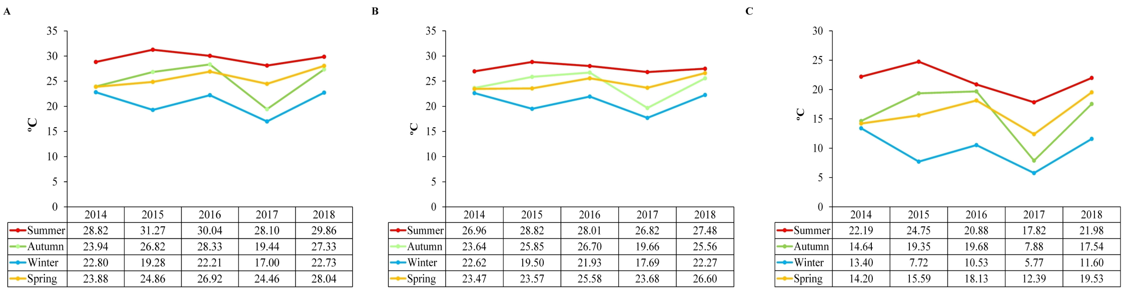
It should be noted that, according to results of ecological assessment, the most urbanized areas, especially during the hottest seasons (summer and spring) in all years, present a “Very strong” intensity heat islands phenomenon, being ecologically classified as terrible. In the autumn and winter periods, the presence of this phenomenon was not identified, obtaining the “None” classification in practically every year in these seasons, except for 2015 with a record of “Medium” intensity.

ANALYSIS OF URBAN THERMAL COMFORT

The estimated results for the city of Rio de Janeiro concerning the ITU, IDT and TEV - index along with proposed comfort levels are shown in Figure 7.



A

	2014	2015	2016	2017	2018
Summer	28.82	31.27	30.04	28.10	29.86
Autumn	23.94	26.82	28.33	19.44	27.33
Winter	22.80	19.28	22.21	17.00	22.73
Spring	23.88	24.86	26.92	24.46	28.04

B

	2014	2015	2016	2017	2018
Summer	26.96	28.82	28.01	26.82	27.48
Autumn	23.64	25.85	26.70	19.66	25.56
Winter	22.62	19.50	21.93	17.69	22.27
Spring	23.47	23.57	25.58	23.68	26.60

C

	2014	2015	2016	2017	2018
Summer	22.19	24.75	20.88	17.82	21.98
Autumn	14.64	19.35	19.68	7.88	17.54
Winter	13.40	7.72	10.53	5.77	11.60
Spring	14.20	15.59	18.13	12.39	19.53

Figure 7 - (a)Graph representing the feeling of thermal comfort from 2014 to 2018, according to the ITU index; (b) Graph representing the feeling of thermal comfort from 2014 to 2018, according to the IDT index; (c) Graph representing the feeling of thermal comfort from 2014 to 2018, according to the TEV index

Following the classification criteria adopted by Nóbrega and Lemos (2011), in the summer season for all studied years, the city is in extreme level of discomfort, reaching temperatures above 26 ºC. From the point of view of urban thermal comfort, these results raise concern about the quality of life of the population.

In (Figure 8-B), it is possible to observe the results found for the thermal discomfort index – IDT. During summer, there is a dominance of “Uncomfortable” and “Very uncomfortable” days for all analyzed years. However, it is noted that, in general, days classified as "comfortable" and "partially comfortable" stand out in the city.

The effective temperature index as a function of wind presented controversial results (Figure 8-C). In the summer season of 2014, the classification for the city was "Comfortable", and for all other seasons the days were classified as "Slightly cold". In 2015, summer was classified as “Comfortable”, autumn as “Slightly cool” and spring as “Little cold”. In 2016, the summer and autumn seasons were classified as “Light fresh”, and the spring “Little cold”. In 2017, it followed a cooling pattern for all seasons, ranging from “Cold” to “Little cold”. In 2018 the classification went from “Slightly cold” to “Slightly cool”.

PEARSON'S CORRELATION ANALYSIS

Seeking to understand the relationship between urbanization and vegetation, analyzes of correlation concerning Normalized Difference Vegetation Index (NDVI), Improved Vegetation Index (EVI), as well index of constructed area (NDBI), were done with terrestrial surface temperature, for every year in each studied season. Figure 8 shows the correlation results for the entire study period (2014-2018).

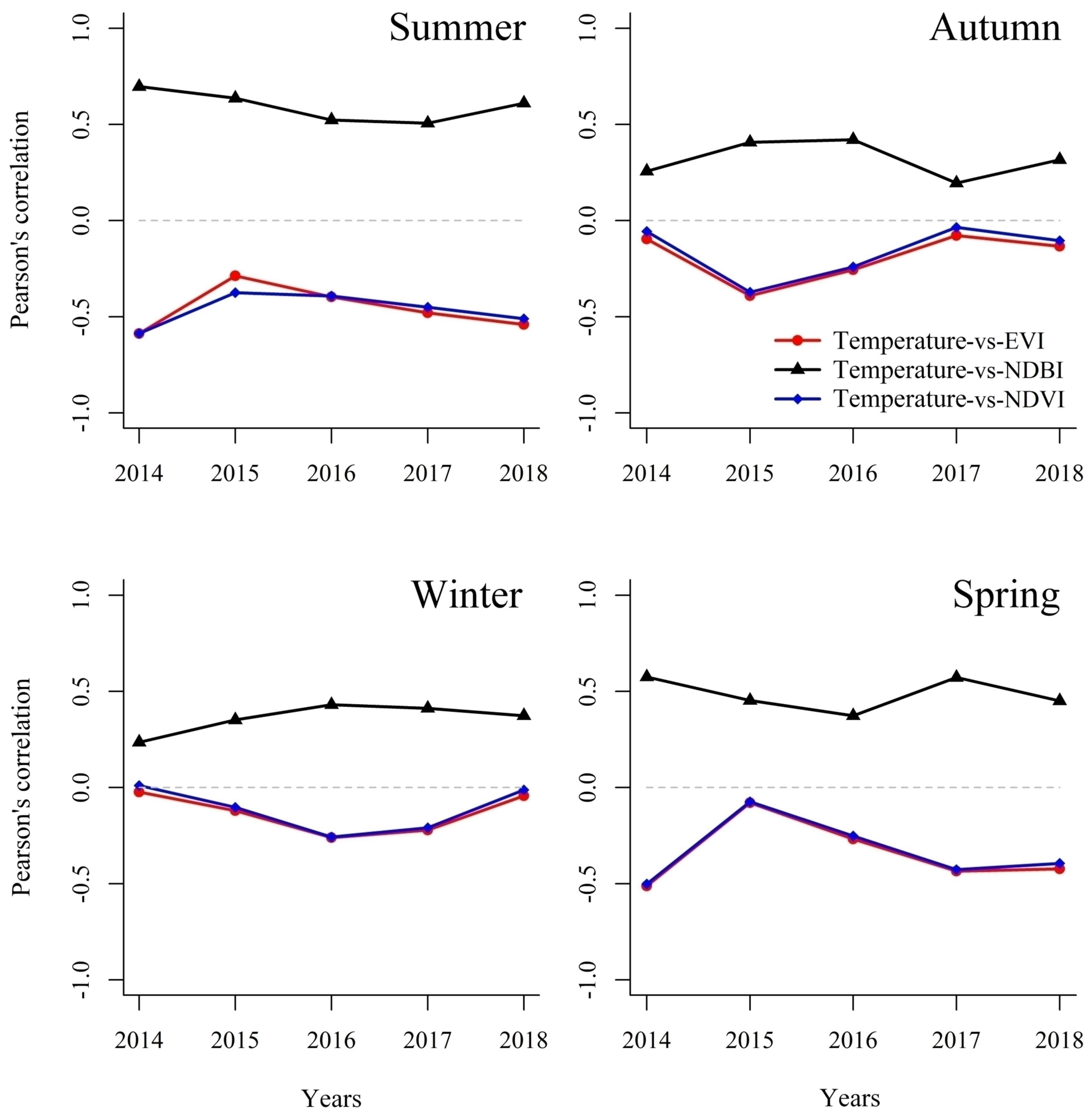


Figure 8 - Pearson's correlation between Temperature and EVI, NDBI, as well NDVI index for the analyzed years (2014-2018)

It was verified a negative correlation between surface temperature and improved vegetation index (EVI) for all studied years. These results show that the areas with the highest percentage of vegetation tend to have lower temperatures.

The same pattern of negative correlation coefficient occurred for all years when comparing NDVI and temperature variables, which means that, as the percentage of vegetation increases, the temperature tends to show a decrease, what shows, once again, the role of vegetation in mitigating temperature.

On the other hand, when it comes to the relationship between built-up areas and temperature, the influence of urban environments in increasing temperature was evident, since positive correlations were found for all years between temperature and NDBI.

In order to verify the influence of EVI, NDVI and NDBI indices on the formation of the urban landscape, a correlation analysis between these indices with each other was carried out. In figure 9 it is possible to see the correlations between the indexes (EVI, NDVI and NDBI).

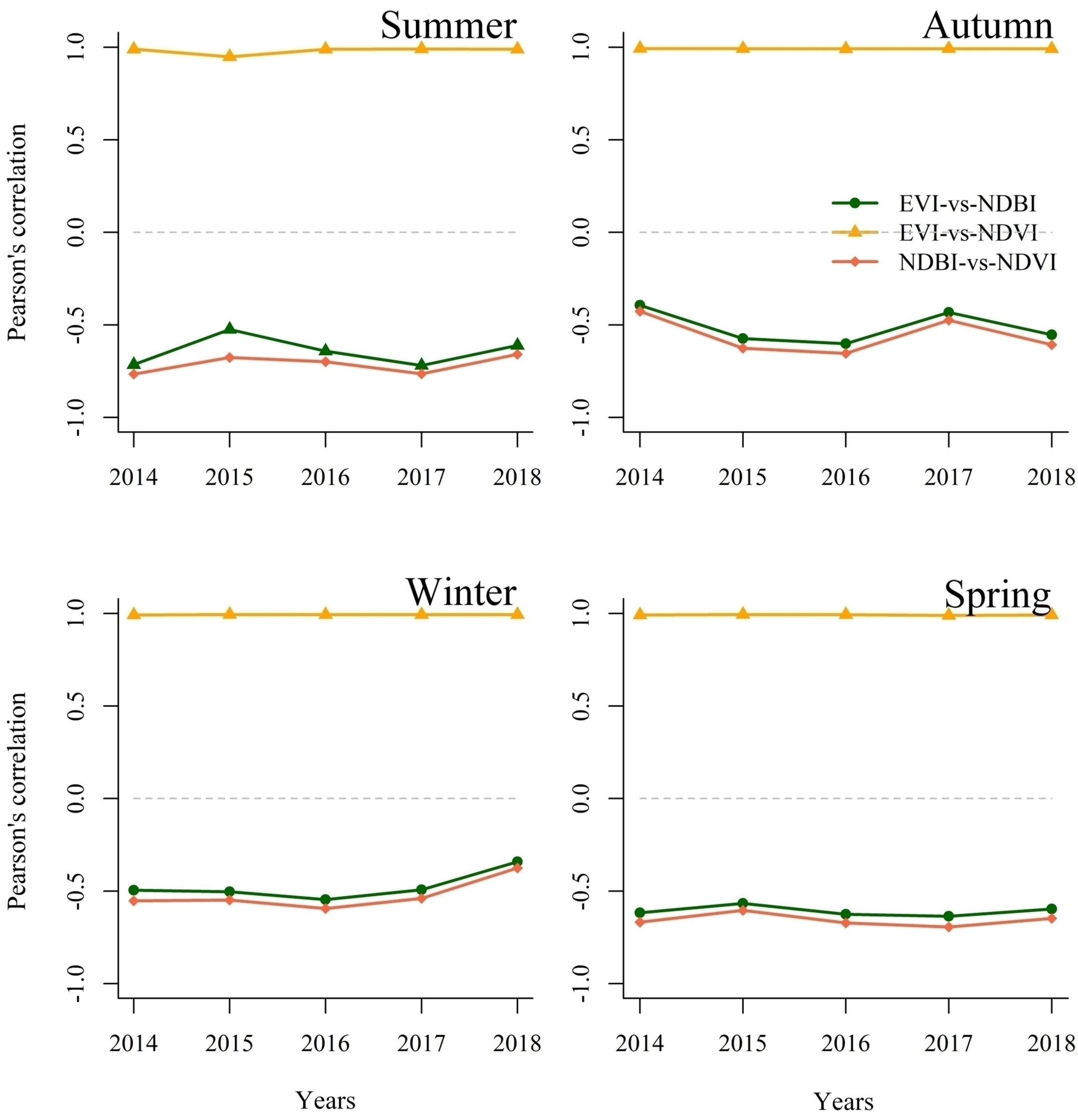


Figure 9 - Pearson's correlation between EVI, NDBI and NDVI indices for the analyzed years (2014-2018)

Very strong negative correlations were found between NDBI and the vegetation indices (NDVI and EVI) in practically every year, confirming the relationship that as one variable increases the other decreases, that is, the direct influence that urban growth acts in suppressing urban vegetation.

DISCUSSION

ASSESSMENT OF CHANGES IN LAND USE AND OCCUPATION

Although the pattern of land use and occupation over the five studied years presents a diversification of classes, the Urban Infrastructure and Forest Formation classes predominate in the city, with the other classes having much lower occupancy proportions as could be observed. However, together these classes are important to urban ecology, once Forest Formation, Apicum, Mangrove, pasture and Other Non-Forest Formation correspond to 47.38% of the urban green areas.

The city has an expressive percentage of urban green areas, approximately, 98.33 m² per inhabitant, a value that is well above the 15m2/inhabitant recommended by the Sociedade Brasileira de Arborização Urbana (Brazilian Society of Urban Afforestation) (SBAU, 1996). The values of green area underscore the importance of maintaining and preserving these areas, especially the conservation units present in the city.

Green areas are of great importance to urban ecology, providing several benefits. The research of Kim, Gu and Kim, (2018), which focused on investigating the effectiveness of strategies to mitigate the effects of heat islands, pointed out the benefits regarding the use of green roofs, for example, to minimize the effects of heat islands in buildings. Furthermore, they found that increases in green cover rates, whether in grass or trees, were effective in attenuating the overall temperature.

SPATIAL AND TEMPORAL DISTRIBUTION OF THE EARTH'S SURFACE TEMPERATURE

Based on the 20 images of spatial and temporal distribution of the Earth's surface temperature from 2014 to 2018, it can be noticed the presence of heat island phenomenon in the city of Rio do Janeiro, Brazil. It is possible to observe that the city's heat islands behave in proportion to the type of land use and occupation and in accordance to seasonal climatic variations.

In general, it was possible to observe that the hottest and largely influenced areas by the phenomenon of heat islands are mainly located in the most urbanized areas of the city that have less vegetation. This same pattern was found by Jain et al., (2019), in which urban areas with a good proportion of vegetation, had lower temperatures compared to the densely built areas of the city.

The spatial pattern of the heat islands in the city reflects the different nature of its constituent and aggravating factors. The formation of this phenomenon in the vicinity of dense residential and commercial areas, together with air pollution induced by traffic and, consequently, the release of dangerous environmental pollutants are the most important factors that threaten the health of residents and considerably increase the risk of many diseases, specially respiratory and cardiovascular ones (BOKAIE et al., 2016).

Consequently, the mitigation of the effects must be based on the adoption of strategic urban regeneration actions, seeking to replace the surfaces constructed with traditional materials by a greener infrastructure (reflective and green roofs, for instance). In addition, urban projects must be reformulated to avoid concentrations of tall buildings that favor the creation of microclimates, which capture heat during sunny hours (JATO-ESPINO, 2019).

The results found by Dimoudi and Nikolopoulou (2003), confirm that the greater the proportion of green area to area built in the urban environment, the greater the reduction of air temperature. The authors Albuquerque and Lopes (2016), analyzed the city of Teresina, Piauí State, by comparing wooded places and regions with lower proportions of vegetation. As a result, lower temperature values were found in points with vegetation (more vegetated neighborhoods), while in more urbanized neighborhoods with less vegetation, significant thermal rigor was found. These results are in line with the pattern found for the city of Rio de Janeiro, reinforcing the importance of vegetation in the urban environment.

The city suburb has heavily populated and uncomfortable areas, with little or no trees, poor housing and inadequate sanitation, such as slums. Thus, many of the suburban areas recorded high temperature values (LUCENA et al., 2013).

Although being highly wooded areas, some neighborhoods in the South Zone, such as Jardim Botânico, presented an expressive domain of high temperatures. This result can be justified due to the fact that cooling can be considerably reduced or even lost during periods of extreme dry summer, when the soil dries up and evapotranspiration decreases as consequence. In the future, due to global climate change, this effect is likely to be even more pronounced and occur for a longer period (GILL et al., 2013).

It is worth noting the percentages found for Lagoa neighborhood, with much milder temperatures compared to other surrounding neighborhoods. In addition to vegetation, water bodies also function as islands of freshness, taking into account that much of the absorbed radiation is used for evaporation. In addition, the winds that circulate in these areas move and cool the adjacent areas (MENEZES; MENDES, 2017).

ECOLOGICAL ASSESSMENT OF URBAN HEAT ISLANDS

The results of NDVI and EVI indexes reveal that the distribution of vegetation in the city is quite homogeneous, mainly concentrated in the areas occupied by Tijuca National Park and Pedra Branca State Park, with small points of vegetation spread throughout the rest of the city. In addition, areas in the North and Center zones have very low vegetation. The NDBI index confirms the significant urban density in the city.

Santos et al., (2017) also employed the UTFVI index to analyze heat islands in Vila Velha city (ES state). In their research, areas with great urban density were classified as “terrible”, while areas in the vicinity of vegetation, such as parks and nature reserves, obtained an “excellent” classification, what corroborates the results found for Rio de Janeiro city.

For Pinheiro and Souza (2017), public management has a preponderant role in the sustainable development of cities, considering that several environmental impacts, as verified and confirmed in this research, may arise due to disordered or poorly planned changes in the environment.

ANALYSIS OF URBAN THERMAL COMFORT

According Souza and Nery (2012), studies concerning the consequences of urban heat islands have emphasized and demonstrated the need for knowledge about the problem of thermal comfort, since thermal sensation perceived by the individual is closely related to issues such as: public health; profitability at work; energy consumption, thus, subjectsinherent in quality of life.

The reflexes of increases in number of buildings and asphalt surfaces, outcomes from the growing urbanization in recent years, have direct consequences on thermal sensation perceived by the population. Climate alteration due to anthropic actions on the surface, lead to thermal discomfort, especially in warmer periods (SOUZA; SILVA, 2017).

Among all analyzed comfort indexes, “TEV” was the one with the greatest presence of thermally pleasant days, however, a tendency towards cooling is observed for this index, which is often not consistent with the situation of real thermal comfort. In low wind situations the index tends to maximize the cooling by wind, generating an error in the actual result of the observed thermal comfort (GOBO et al., 2017).

The results of the “TEV” index did not show any unpleasant thermal sensation to heat in any year or season, in contrast to the results from the other indices for the same study period. Although each index classifies the comfort sensation in different ranges, such a discrepancy suggests that for the study area, under analyzed conditions, TEV application was not suitable.

Comparing the indices, in general, it appears that the classification ranges adopted by the indices somewhat restrict the understanding of the real thermal sensation that is perceived. Thus, among application limitations for Rio de Janeiro city, the Effective Temperature Index as a function of wind - TEV was the one that presented the most unsatisfactory results, not so much matching the perceived real thermal sensation. More satisfactory classification ranges for the city were obtained through Temperature and Humidity Index - ITU and Thermal Discomfort Index - IDT.

STATISTICAL ANALYSIS: PEARSON CORRELATION

The negative correlation coefficients between temperature and vegetation indexes indicate the positive impact that green areas have on temperature, showing that they are capable of weakening the effect of urban heat islands (SANTAMOURIS, 2013). They can be explained by the fact that vegetation cover reduces surface and air temperature, providing shade and evapotranspiration (SHIRANI-BIDABADI et al., 2019).

The negative correlation therefore confirm the important role of vegetation in mitigating the effects of urban heat islands. In fact, several studies (Li et al., 2012; Myint et al., 2013; Zhou et al.,

2014) indicate that green areas function as mitigation islands, a pattern often confirmed by the negative correlations between temperature and vegetation indexes. Dwivedi and khire (2018) confirm that the increase in urbanization is the main cause that leads to the reduction of green areas, and, therefore, the increase in temperature.

Although the relationship magnitudes have not been so strong in some periods, the direction is revealing. The positive relationship between temperature and NDBI for example, reveals the impact of accumulated heat and impermeable surface areas on the surface temperature, while the negative relationship between temperature and vegetation indexes indicate the cooling effect by green areas (ALFRAIHAT; MULUGETA; GALA, 2016).

Alfraihat, Mulugeta and Gala (2016), when analyzing the intensity of heat islands in the city of Chicago-USA, also found a high negative correlation (-0.90) between NDBI and NDVI, indicating the decrease in vegetation cover as the existing land use and occupation is replaced by built-up areas.

CONCLUSION

The pattern of change in land use and occupation, especially in large urban centers, such as the city of Rio de Janeiro, directly contributed to the formation of heat islands and its spatial configuration, being closely related to thermal classification.

Significant temperature variations were found, mainly in areas with less vegetative vigor, with correlation coefficients (negative) between temperature and vegetation indexes showing the positive influence that green areas have on the attenuation of temperature. The positive correlation coefficients between temperature and built-up areas (NDBI) indicate the strong influence in temperature increase due to changes in land use and occupation for urbanization purposes.

Studies related to urban thermal comfort are important to assist in planning and management of the urban space, contributing to the development of pleasant environments for the population concerning their thermal aspect.

The employed methodology has the potential to be applied for the behavioral study of urban heat islands in other cities around the world.

ACKNOWLEDGMENT

The authors would like to thank the United States Geological Survey (USGS), the Rio Alerta System of the City of Rio de Janeiro, the National Institute of Meteorology and the Annual Mapping of Land Cover and Use in Brazil - MAPBIOMAS, for providing the necessary data for the development of this work. We also thank the Graduate Program in Forest Sciences at the Federal University of Espírito Santo for the academic and scientific incentive and the research group Geotechnology Applied to the Global Environment (GAGEN). This work was carried out with the support of the Coordination for the Improvement of Higher Education Personnel - Brazil (CAPES) - Financing Code 001.

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Costa, G.A. - The author elaborated the entire text.
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