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Application of remote sensing for climatic vulnerability analysis of the urban area of Lages/SC through the use of radiometric index and surface temperature

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A B S T R A C T

The growth of cities caused by the increase in population and human activities directly resulted in an increase in air temperature in the urban area, which can lead to changes in microclimatic patterns and consequently impact on the quality of life of the population. To mitigate these effects, the need for climate studies in urban areas becomes essential, as it is a measure that can guide public managers to make effective decisions aimed at the pursuit of sustainable urban planning. The objective of the present study was, through remote sensing, to verify possible alterations in the microclimatic patterns of the mountainous region of Santa Catarina, in the long term, through the analysis of data referring to the Normalized Difference Vegetation Index (NDVI) and Land Surface Temperature (LST). These data were obtained through the use of orbital images from the LANDSAT satellite (centered in 1997, 2009 and 2021) together with the processing carried out by the QGIS software. The results obtained from the NDVI show that there is a significant increase in the exposed soil class of 16.88% (Winter) and 11.63% (Summer) over the analyzed period (1997-2021). The LST also showed a significant increase for both winter and summer, especially the average temperature. Therefore, the results of this study demonstrate the importance of the contribution of Remote Sensing, as a tool that allows the monitoring and spatial analysis of long decades, which can serve as subsidies for public managers to act effectively in their communities, in the issue of urban planning.

Keywords: Microclimate, Normalized Difference Vegetation Index, Land Surface Temperature, Urban planning.

Aplicação do sensoriamento remoto para análise de vulnerabilidade climática da área urbana de Lages/SC através do uso de índice radiométrico e da temperatura da superfície

R E S U M O

O crescimento das cidades causado pelo aumento da população e das atividades antropicas afetam diretamente o aumento da temperatura do ar na área urbana, o que pode levar a mudanças nos padrões microclimáticos e consequente impacto na qualidade de vida da população. Para mitigar esses efeitos, torna-se essencial a necessidade de estudos climáticos em áreas urbanas, pois é uma medida que pode orientar os gestores públicos a tomar decisões efetivas visando a busca de um planejamento urbano sustentável. O objetivo do presente estudo foi, por meio de sensoriamento remoto, verificar possíveis alterações nos padrões microclimáticos da região serrana de Santa Catarina, em longo prazo, por meio da análise de dados referentes aos Índice de Vegetação por Diferença Normalizada (NDVI) e Temperatura da Superfície Terrestre (TST). Esses dados foram obtidos através do uso de imagens orbitais do satélite LANDSAT (centrado em 1997, 2009 e 2021) juntamente com o processamento realizado pelo software QGIS. Os resultados obtidos do NDVI, mostram que há um aumento significativo da classe solo exposto de 16,88% (Inverno) e 11,63% (Verão) ao longo do período analisado (1997-2021). A TST também apresentou um aumento significativo tanto para o inverno quanto para o verão, especialmente a temperatura média. Portanto, os resultados deste estudo demonstram a importância da contribuição do Sensoriamento Remoto, como ferramenta que permite o monitoramento e a análise espacial de longas décadas, que podem servir de subsídios para que os gestores públicos atuem efetivamente em suas comunidades, na questão do planejamento urbano.

Palavras-chave: Microclima, Índice de Vegetação por Diferença Normalizada, Temperatura da Superfície Terrestre, Planejamento Urbano.

Introduction

The growing and inadequate urban expansion observed in recent years is a global problem, since the absence of planning norms promotes significant changes in land use and occupation and changes in climate conditions (Lima et al. 2021; Chegury et al., 2022). According to the United Nations (UN), more than half of the world's population lives in urban areas, a percentage that will increase to 70% or more by 2050, in Brazil this contingent reaches 85.6% according to the IBGE (Monteiro, 2022).

Interest in urban climate studies has increased not only because the majority of the population lives in cities, but also because of the degradation process of these environments and their effects on quality of life (Martelli and Delbim, 2022) such as the increase in diseases related to air quality (Vassari-Pereira et al., 2023). The replacement of vegetation cover by built environments in large cities changes weather patterns, leading to an increase in air temperature and a decrease in relative humidity. Artificial environments generally have characteristics on their surface such as impermeability and a high capacity to emit heat. From a climatic point of view, it is notable that the transformation of formerly green areas by these environments implies changes in the radiation balance, since there will be an increase in absorbed radiation (Silva et al., 2021; Chegury et al., 2022)., such as in asphalt (low reflection – lower albedo), promoting phenomena such as urban heat islands, the result of the difference in temperature between an urban center and its surroundings.

According to research carried out in recent years, major changes in the rainfall regime and an increase in air temperature have been occurring in several regions of the Earth's surface, including an increase in ocean temperatures (Song et al., 2022; Muniz et al., 2022; Bruno et al., 2022; Lourenço et al., 2020). An important variable to be analyzed in this process is the Land Surface Temperature (LST), since it highlights the processes of dependence on the soil/atmosphere interface and acts on local climates, given that thermal variations on the surface can contribute with the acceleration of the evaporation process, changing the physical state of the water and increasing the amount of vapor sent to the atmosphere (Pires, 2015). In this sense, it is of great importance to reliably estimate the LST, as it has become an essential method for evaluating the exchange of water and surface energy with the atmosphere, which can have an impact on improving people's quality of life (Hidalgo-Garía, 2021).

Recently, several researches have been focused on the correlation between Land Surface Temperature (LST) and the Normalized Difference Vegetation Index (NDVI) (Stuani et al., 2021; Nguyen et al., 2022; Silveira et al., 2023), as the presence of natural vegetation cover greatly influenced the distribution of LST. The NDVI-LST ratio is controlled by various factors such as dense vegetation, sand dunes, bodies of water, dry soil, surface of exposed rock, swamp, building materials, etc. In urban areas, the high value of LST is generated mainly in the area with lowest vegetation intensity. Therefore, most thermal remote sensing methods use the normalized difference vegetation index NDVI as the significant indicator of LST (Guha and Govil, 2021).

In the pursuit of quality of life, priority should be given to the benefits of vegetation in the urban environment with its ecosystem services. It is important to highlight that vegetation promotes environmental comfort in cities, as it qualifies circulation spaces, contrasting with intense urbanization in order to reduce the temperature of the environment.

Currently, the difference in temperature trend between urban and rural regions and the difference in LST trend in relation to urban density variations are investigated using remote sensing (Moradi and Darand, 2022). For example, in a study carried out by Silva et al. (2021) for the city of Marabá in Pará, using the Remote Sensing, an average variation in maximum temperatures was observed, where heat islands had an increase in formation, while whereas vegetated areas decreased by 43.86%, thus confirming the role of vegetation in regulating surface temperature and the premise that impermeable areas or areas with exposed soil are more prone to the formation of urban heat islands.

In this way, Remote Sensing is one of the main tools for monitoring and estimating various meteorological and environmental phenomena, providing support for territorial planning and management (Oliveira et al., 2021). Through information generated by satellites, which capture and record the energy reflected or emitted by the surface, it is possible to obtain images and data of the Earth's surface, in addition to allowing its manipulation through different methodologies, which makes it possible to generate results according to the need (Lombardo et al., 2022). Landsat was one of the first operational observation systems of the Earth's surface in recent decades and presents a long record of historical images at multispectral and thermal wavelengths. According to the United States Geological Survey (USGS, 2021), the missions began in 1972, with the launch of Landsat 1 and continue to this day with the Landsat 9 satellite.

From the climatic point of view, studies on the LST and the NDVI are some of the possibilities that geotechnologies encompass. The LST is related to the remote detection of radiation emitted by the surface (Silva et al., 2021), whereas the NDVI represents the link between the index and the fraction of active photosynthetic radiation absorbed and intercepted.

Due to environmental changes, the use of NDVI in environmental studies is well established, being widely used to classify vegetation cover as a form of subsidy to define land use capacity (Rodrigues et al., 2022). Combined with data observed from meteorological stations, this type of study covers the analysis of several parameters that can be used to characterize the presence of climate change at a regional level. Studies that aim to address the issues mentioned are of great importance in communities, as they are linked to the urban planning of these locations, serving as a subsidy for the creation of solutions that seek to mitigate the climate impacts caused by human activities. Furthermore, the results may be indicative of the use of remote sensing tools in conjunction with data from meteorological stations to corroborate the analysis of possible climate changes.

Several investigations were carried out in order to analyze the spatial behavior of LST and thermal radiation based on NDVI, using different methodologies (Maroni et al., 2021; Mokarram et al., 2023; Santos et al., 2023; Silveira et al., 2023). The negative correlation between the LST and the normalized difference vegetation index (NDVI) indicates that the presence of vegetation can help reduce urban heat island effects, while the positive correlation between the LST and the cumulative normalized difference index (NDBI) indicates that urbanization can worsen the effects of heat islands. To identify the potential occurrence of a heat island, researchers used an integrated method of remote sensing techniques and geographic information system (GIS). The processing result showed the urban heat island potential in Depok Sub-district, Ngemplak Sub-district, Kalasan Sub-district and part of Mlati Sub-district with intensity ranging between 2 – 6 °C during the period 2014 to 2019 (Dewantoro et al., 2021). In another study, data obtained through remote sensing from the Global Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER GDEM) model and the Moderate-Resolution Imaging Spectroradiometer (MODIS) sensor were used. Initially, different state-of-the-art algorithms were employed, but a convolutional neural network (CNN) model was chosen based on its accuracy. This model was developed using as input parameters the TST values of the last 19 years, combined with elevation, road density (RD) and Enhanced Vegetation Index (EVI), in order to analyze and predict the behavior of the LST. It was found that the forecast error for most of the district remained within 0.1 K of the observed values. Therefore, the CNN model developed proved to be essential for the analysis and prediction of land surface temperature (LST) and, consequently, for evaluating the effect of the urban heat island in any location (Khalil et al., 2021).

This data is important for accurately predicting urban heat flows, planning cities and understanding the links between the thermal responses of urban environments and energy needs. Furthermore, the result provides a method to analyze nonlinear dynamic climate models and identify a path to sustainability (Kimothi et al., 2023). By using remote sensing techniques, we can comprehensively and effectively analyze the relationships between urbanization and radiometric indices.

In this context, the study aims to identify urban patterns in the city of Lages/SC, during summer and winter, through the analysis, over the years, of surface temperature and NDVI, as well as finding a relationship between them. Through the use of images from Landsat 5 and Landsat 8 satellites, to obtain the indexes, it will be possible to relate both the remote sensing area and climatology, using historical data, from orbital images and meteorological stations.

Therefore, the hypotheses are related to the type of interaction between the indices, where the climatological characteristics of each season will directly interfere with the soil cover, modifying the NDVI, and thus, inversely influencing the surface temperature.

Material and methods

Characterization of the study area

The focus of this study comprises the urban area of the municipality of Lages, which is located in the Planalto Serrano region of the State of Santa Catarina, with south latitude at 27°49' and west longitude at 50°40' (Figure 1), forming part of of the Caveiras River basin (Cardoso et al., 2003). Lages is 930 m above sea level and has a total area of 2651.4 km² and an urban area of 49.26 km² (IBGE, 2019), making it the municipality with the largest territorial area in the state of Santa Catarina (Schier et al., 2019). The population is approximately 158 thousand inhabitants, with 97.11% residing in urban areas and only 2.89% residing in rural areas (Xavier et al., 2019).

According to the Köppen-Geiger classification, the municipality of Lages has a humid temperate Cfb climate and mild summer, with well-distributed rainfall throughout the year (Lemos et al., 2021), with an average annual air temperature of 14 °C and average annual precipitation of 1441 mm (Nunes and Nunes, 2018).

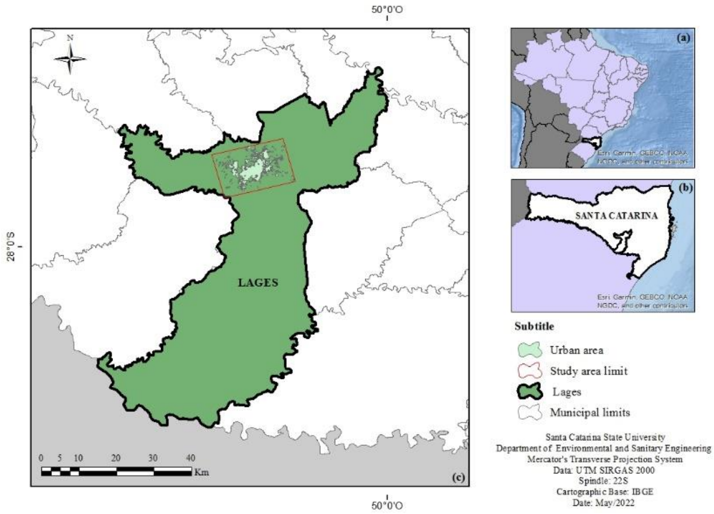


Figure 1. Location of Santa Catarina in southern Brazil (a). Location of the municipality of Lages in the state of Santa Catarina (b). Location of the urban area of the municipality of Lages (c).

Application of Remote Sensing tools

Landsat 8 and 5 images were obtained by the American Geological Survey (USGS), with resolutions of 30, 100 and 120 m. The Landsat 5 products used refer to the years 1997 and 2009. For Landsat 8, the images refer to the year 2021, as shown in Table 1. These dates were chosen due to the lower cloud cover in the images, occurring in the winter and summer period, with clearer weather conditions and in order to maintain a periodicity of 12 in 12 years between each time cut.

Table 1. Information about metadata of Landsat series satellite images and their dates and acquisition.

Satellite	Resolution	Date
Landsat 5 TM	30 m and 120 m	01/06/1997
		07/01/1997
		01/07/2009
		07/18/2009
Landsat 8 OLI- TIRS	30 m and 100 m	08/04/2021
		12/26/2021

The Normalized Difference Vegetation Index (NDVI) matrices used in the study were obtained by processing bands 3 and 4 of the Landsat 5 satellite and from bands 4 and 5 of the Landsat 8 satellite, OLI sensor.

The Land Surface Temperature (LST) was estimated through the images of the thermal bands, in order to visualize the possible increases in the temperature of each area, over the years. Therefore, band 6 of the Thematic Mapper (TM) sensor of the Landsat 5 satellite and band 10 of the satellite TIRS sensor of Landsat 8 were used.

Image processing

The elaboration of the TST and NDVI maps occurred through the processing and treatment of data and metadata of the QGIS 3.4.15 software. First, the orbital images were imported into the QGIS database, where they were projected to coordinates SIRGAS 2000 UTM, time zone 22S. Subsequently, the indexes were calculated using the RS&GIS complement. The flowchart in Figure 2 demonstrates the process carried out to obtain the products.

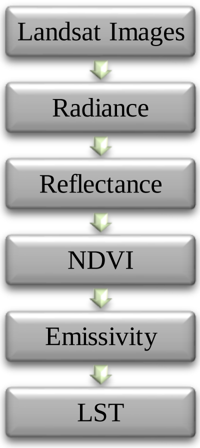


Figure 2. LST and NDVI definition process using plugin.

Obtaining the Normalized Difference Vegetation Index (NDVI)

The NDVI is an index used to verify vegetation density and composition and is widely used to analyze changes in land use and land cover (Filho et al., 2021). It is calculated by the ratio between the red and near infrared spectral bands, according to Equation 1:

$$NDVI = \frac{NIR - R}{(NIR + R)} \quad (1)$$

where, NDVI = Normalized Difference Vegetation Index; NIR = Near infrared band; R = Red band.

Index values range from -1 to +1, with areas with more vegetation approaching the value +1, while negative values close to -1 indicate the presence of areas without vegetation or bodies of water.

Thus, to analyze the NDVI values, the methodology by Filho et al. (2021) was used. Table 2 shows the four classes used in the study.

According to the classification, the negative values correspond to the body of water, presence of clouds and exposed soil; the thin vegetation corresponds to the area of agriculture and pasture; and areas considered to have healthy and dense vegetation are areas of native forests (Filho et al., 2021).

Table 2. Land use classes according to the NDVI.

Thematic Classes	NDVI range
Rivers, rocks and clouds	< 0
Exposed Soil	0 – 0.3
Sparse vegetation	0.3 – 0.6
Dense vegetation	> 0.6

Obtaining Land Surface Temperature (LST)

To calculate the LST, it is first necessary to transform the digital numbers of each pixel into brightness. Thus, two equations were used, one for Landsat 5 (Equation 2) and the other for Landsat 8 (Equation 3), according to Medeiros et al. (2020).

$$L\lambda = \left(\frac{Lmax - Lmin}{DNmax}\right) * DN + Lmin \quad (2)$$

where, Lλ = Spectral brightness at the top of the atmosphere (TOA) (W/m2*srad*μm); Lmax and Lmin = Calibration constants for each band; DNmax = Maximum value of the digital number (DNmax = 255); DN = Digital number of each pixel.

$$L\lambda = ML * Qcal + AL \quad (3)$$

where, Lλ = Spectral brightness at the top of the atmosphere (TOA) (W/m2*srad*μm); ML = Band-specific multiplicative factor; AL = Band-specific additive factor; Qcal = Pixel-calibrated quantized value (DN).

After determining the Brightness Temperature (TOA), the spectral brightness obtained was converted into Kelvin temperature according to Equation 4:

$$T_B = \left(\frac{K_2}{\left(\frac{K_1}{L_\lambda}\right) + 1}\right) \quad (4)$$

where, T_B = Surface temperature (K), $L\lambda$ = Spectral brightness at the top of the atmosphere (TOA) (W/m2*srad*µm); K_1 = Band-specific thermal conversion constant; K_2 = Band-specific thermal conversion constant.

Finally, the conversion of units was carried out transforming the Land Surface Temperature values, which were in Kelvin, to Celsius, through Equation 5:

$$LST = T_B - 273.15 \quad (5)$$

The constants used for the calculations were all taken from the metadata of each image, represented in Table 3.

Table 3. Constants used to convert images to brightness and surface temperature.

Landsat 5	Landsat 8
Band = 6	Band = 10
Lmax = 15.303	ML = 3.342e-04
Lmin = 1.2378	AL = 0.1000
K1 = 607.76	K1 = 774.89
K2 = 1260.56	K2 = 1321.08

Statistical Validation of Maps

To validate the RS data, the classification accuracy of the NDVI maps was carried out as a way of checking whether the results obtained are close to reality, for which the AcATaMa add-on was used in QGIS. The tool allowed the generation of 99 random points proportional to the size of the study area, using the statistical method of stratified random sampling, to be verified and analyzed by comparing the points with the help of the Google Satellite image. After verification, an error matrix was generated, through which the Total Accuracy of the classification was calculated (Lima et al., 2019; Janko, 2019; Machado et al., 2022). Table 4 shows the degree of agreement of the thematic classification, as described by Machado et al. (2022).

Table 4. Degree of Agreement of thematic classification

Values	Agreement
0.0 – 0.20	Bad
0.21 – 0.40	Reasonable
0.41 – 0.60	Good
0.61 – 0.80	Very Good
0.81 – 1.0	Excellent

Climate Analysis - Meteorological Data

For this study, daily data of maximum, average and minimum air temperature provided by the National Institute of Meteorology – INMET and EPAGRI/CIRAM were analyzed. Data from weather stations in Lages (230, 231, 1028) were used, both located at the same coordinates, latitude, -27°81' longitude -50°33' and altitude of 952.7 m, but with installations in different periods. The data used were from January 1, 1960 to December 31, 2021.

Based on daily, annual, seasonal series (Summer – DJF; Autumn – MAM; Winter – JJA; Spring – SON) and monthly data were calculated for further statistical analysis. It says: DJF – December/January/February, MAM – March/April/May, JJA – June/July/August and SON – September/October/November, according to the norms determined by the World Meteorological Organization - WMO.

Results and discussion

Vegetation Index Analysis (NDVI)

The results obtained from mapping the Vegetation Index (NDVI) for the urban area of the municipality of Lages, in the winter and summer period, centered on the years 1997, 2009 and 2021, are represented by figures 3 and 4. Values less than 0 (< 0) are represented by blue color (rivers, rocks and clouds) and values greater than 0.6 (> 0.6) are represented by green color (presence of dense vegetation).

For the winter NDVI (Figure 3), the results show the occurrence of changes in vegetation cover between the years studied. According to Table 5, the exposed soil class corresponded to 31.46 km² in 1997, reaching 34.66 km² in 2021, representing an increase in coverage of this class of 3.2 km², that is, in the last 24 years the urbanized area increased by 9.18% which corresponds to the exposed soil.

With regard to dense vegetation, in 1997 it comprised 17.58 km², with a gradual increase of 43.44 km² in 2009, reaching 61.85 km² in 2021, representing an increase of 13.93% in this class between 1997 and 2021.

The sparse vegetation associated with pasture areas and other crops, predominated in relation to the other classes, a gradual decrease of the class can be seen over the years, which may be related to its replacement by exposed soil. These values are representative of urban buildings, public roads and exposed soil. Rural areas or areas further away from urban areas had higher NDVI values, particularly in areas with arboreal vegetation, grasses and agricultural crops.

The results of the study carried out by Silva et al. (2021) on the temporal variation of the NDVI of the Itanhaém River Basin in São Paulo, indicated that in both the studied periods of 2013 and 2020, there was a predominance of the NDVI class between 0.3 - 0.4, which corresponds to the area sparse vegetation. One-off reductions in the NDVI were also observed, related to the expansionof the urban area.

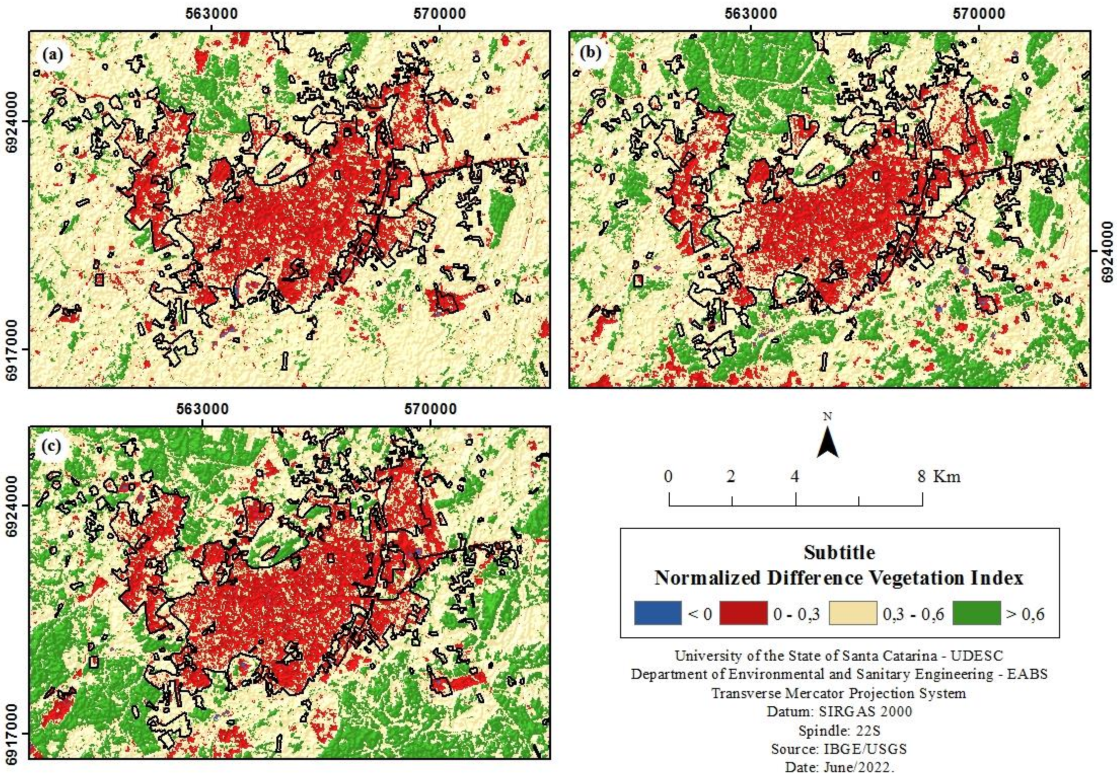


Figure 3. Thematic map of the variation of the Vegetation Index by Normalized Difference (NDVI) from 1997 to 2021 in the urban area of Lages/SC in the winter period: (a) 07/01/1997, (b) 07/18/2009 and (c) 08/04/2021.

Table 5. Proportion of area by type of vegetation over the period analyzed for the winter period.

Classes	1997		2009		2021		1997-2021
	km²	%	km²	%	km²	%	%
River, rocks and clouds (< 0)	0.22	0.11	0.39	0.19	0.45	0.22	2.01
Exposed soil (0 – 0.3)	31.46	15.32	30.66	14.93	34.66	16.88	9.18
Sparse vegetation (0.3 – 0.6)	156.12	76.02	130.88	63.73	108.41	52.79	6.8
Dense vegetation (> 06)	17.58	8.56	43.44	21.15	61.85	30.12	13.93

The map in Figure 4 shows the NDVI variation in the summer period of the years 1997, 2009 and 2021. As shown in Table 6, the exposed soil class shows a gradual increase over the years, it can be noted that this class corresponded to 11.46 km² of area in 1997, rising to 23.88 km² in 2021, representing an increase of 6.04% in area between the initial year and the final year.

The dense vegetation class had a significant increase between 1997 and 2009, corresponding to 120.1 km² and 125.18 km², respectively. A reduction of this class is observed for the year 2021, in which it presented 107.44 km², equivalent to a decrease of 6.17% of the area, between 1997 and 2021. It is noticed, again, the predominance of the sparse vegetation class over the years, mainly in the year 2021, where it corresponded to 73.94 km².

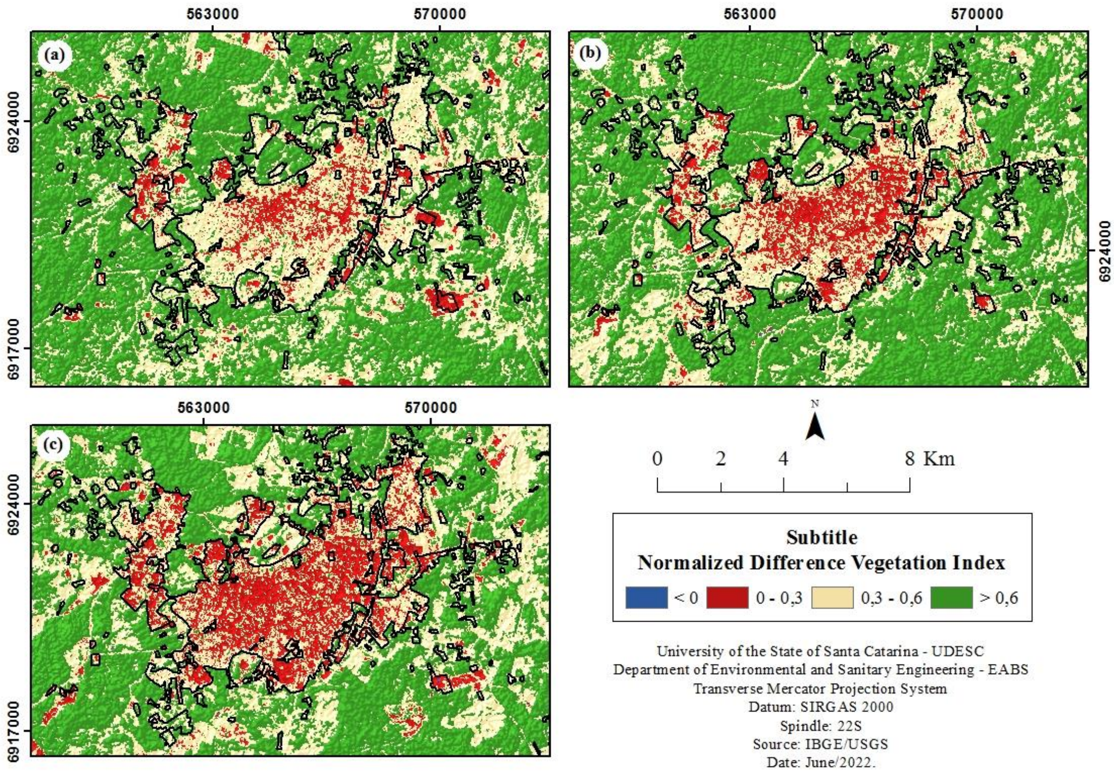


Figure 4. Thematic map of the variation of the Vegetation Index by Normalized Difference (NDVI) from 1997 to 2021 in the urban area of Lages/SC in the summer period: (a) 01/06/1997, (b) 01/07/2009 and (c) 12/26/2021.

Table 6. Proportion of area by type of vegetation over the analyzed period for the summer period.

Classes	1997		2009		2021		1997 - 2021
	km²	%	km²	%	km²	%	%
River, rocks and clouds (< 0)	0.06	0.03	0.08	0.04	0.12	0.06	0.03
Exposed soil (0 – 0.3)	11.46	5.59	14.15	6.89	23.88	11.63	6.04
Sparse vegetation (0.3 – 0.6)	73.72	35.90	65.96	32,12	73.94	36	0.1
Dense vegetation (> 0.6)	120.1	58.48	125.18	60.95	107.44	52.31	6.17

During the summer period, the 0 – 0.3 class, represented by the exposed soil, demonstrates a not so accentuated increase compared to the winter NDVI, where the increase was significant. This demonstrates that there is a strong interaction between the urbanized area and the sparsely vegetated areas, as these areas are representative of pastures and temporary crops around the urban center. In this way, the identification of the urban area can be confused with surrounding pasture areas depending on the period analyzed, a fact that does not occur in the summer (Fialho and Santos, 2021).

A study produced by Barros et al. (2022), who applied the NDVI in a transition area of cerrado and secondary vegetation in the municipality of Vigia in Pará, reports the presence of very thin vegetation cover, with low-sized species associated with exposed soils, in areas of river plains close to the urban area, water bodies, crop and livestock areas, environments where there is intense use of vegetation.

In general, when comparing the NDVI of the two periods (winter-summer), there is a difference in the alteration of vegetation cover. This difference may be related to the influence of the rainy and dry periods analyzed. It is noticed that the winter period presented the highest rates of decrease in the NDVI, with greater intensity in the month of August/2021, considered the driest month of the year for the region. On the other hand, the summer period, mainly the month of January, which is rainier, showed a significant increase in the NDVI in 1997 and 2009, as shown in Figure 4 (a) and (b).

Neto et al. (2019) highlights the influence of the precipitation variable on the development of the vegetation cover, which identified a pattern between the types of vegetation cover, where the NDVI values were higher from February to May (rainy period) and started to decrease significantly from July (dry period).

The increase in NDVI values during the summer may also be related to the dynamics of nature. According to Silva and Trentin (2018), the highest NDVI values of field and pasture areas occur in the summer period, decaying in autumn and reaching the lowest values in the winter period, when plants reduce the photosynthetic rate and have a lower reflectance response.

Among other factors that may interfere with the vegetation index are small-scale agricultural activities in these areas, as well as reforestation for commercial purposes, a reflection of a strong policy of forest exploitation in the 50s and 60s (Schneider, 2017). The decrease in photosynthetic activity detected both in the winter and summer periods in the municipality of Lages is also related to temporary crops due to soil exposure. According to Santos and Aquino (2015), who carried out a study on the agricultural dynamics of the municipality of Castelo do Piauí, they inferred that there was an increase in the area destined for the planting of temporary crops, resulting in a reduction in the protection provided by the vegetation cover and an increase in degradation. confirmed through NDVI data.

As claimed by Lemos et al. (2021), there was an increase in reforestation in Lages, for economic purposes, from 0.18% in 1984 to 5.32% in 2019. The authors also point out the presence of reforestation in areas intended for preservation, as well as the replacement of soil exposed by reforestation and urbanization in the municipality.

Thus, the Normalized Difference Vegetation Index – NDVI can be considered an important indicator of the effects of the advance of land use and occupation classes.

Land Surface Temperature Analysis (LST)

The surface temperature variation for the urban area of Lages in the years 1997, 2009 and 2021 in the winter and summer period are represented in Figures 5 and 7. According to details in Figure 5, it is possible to observe that there is a variation in the surface temperature land in the winter period over the years analyzed.

Figure 6 shows the results regarding temperature over the winter period, in which it is possible to observe an increase in higher temperatures over the years studied.

It can be noticed that in 1997 the surface temperatures were concentrated between 0 – 10 °C, corresponding to 65.1% of the area proportion. In 2009, temperatures between 5 – 10 °C decreased, representing 41.16%, and temperatures between 10 – 20 °C increased in 58.83% of the area. In the year 2021 there was a significant decrease in temperatures < 0 – 10°C, representing only 37.27% of the study area, and a significant increase in temperatures between 10 - 20 °C, and > 20 °C, corresponding to 50.36% and 12.35%, respectively.

According to the NDVI carried out for the winter period, areas with greater vegetation cover had temperatures below < 5 °C, located in the peripheral region of the urban area of Lages. On the other hand, when looking at the center of the urban sprawl, between 2009 and 2021, an increase in temperatures greater than > 20 °C can be seen. This is because, according to Fialho and Santos (2021), these behaviors occur because the waterproofed surface or the exposed soil have a greater thermal capacity, heating rapidly during the period of sun exposure, leading to a consequent rise in surface temperature.

In areas with vegetation cover in parks or other types of green terrain, temperatures are milder, with comparatively higher rates of evapotranspiration, which favors the exchange of latent heat between the surface and the atmosphere, when compared to places with less of vegetation (Pessi et al., 2019; Guilherme et al., 2020).

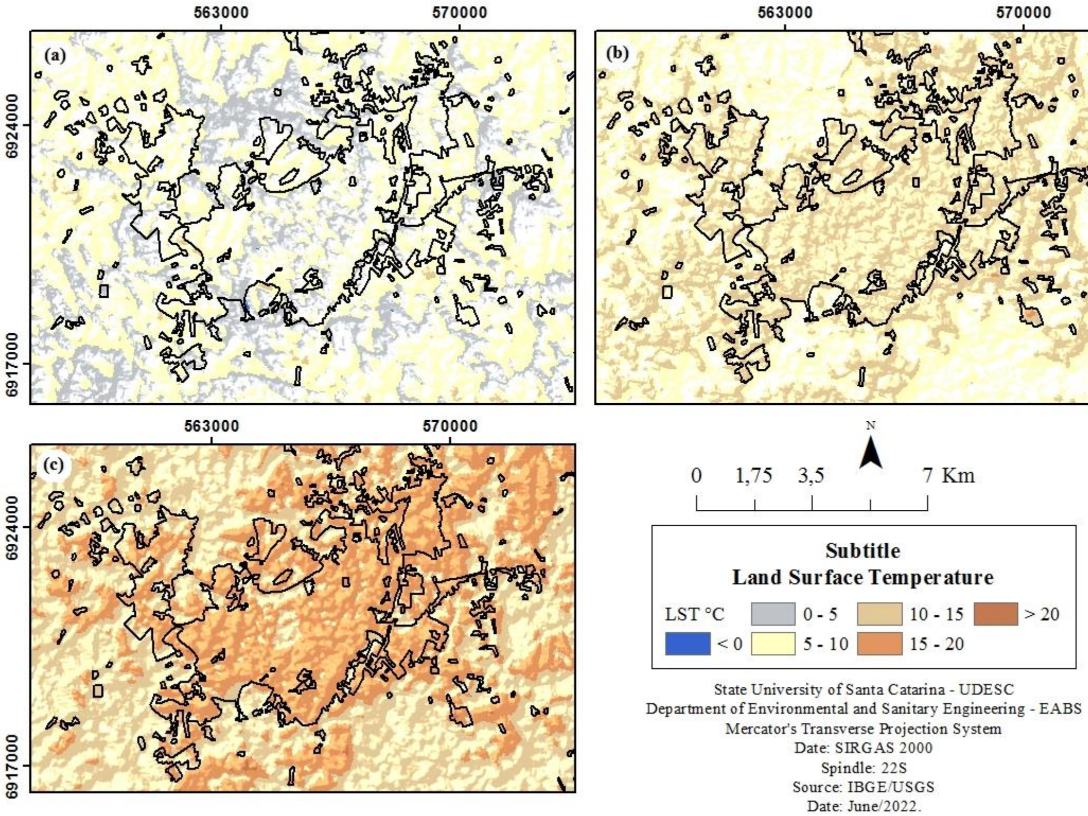


Figure 5. Land Surface Temperature Variation (LST) from 1997 to 2021 in the urban area of Lages/SC in the winter period: (a) 7/1/1997, (b) 7/18/2009 and (c) 08/04/ 2021.

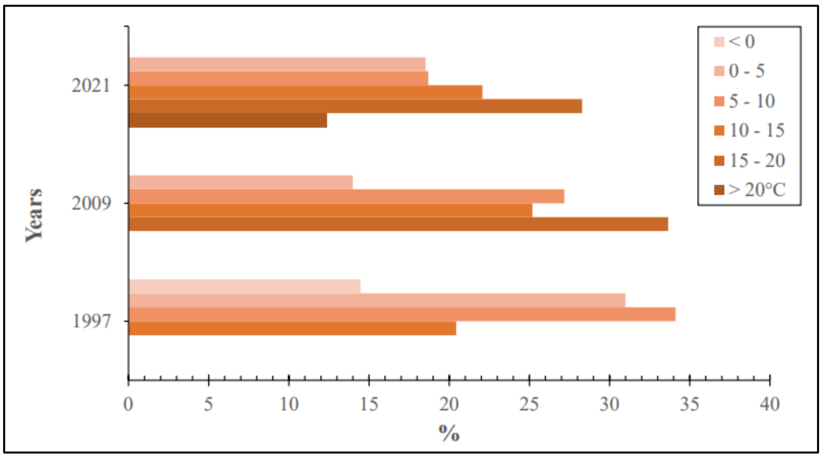


Figure 6. Temperature chart according to the proportion of area over the winter period, for the urban area of Lages/SC.

Figure 7 shows the variation in terrestrial surface temperature for the summer period of 1997, 2009 and 2021. When compared with the winter period (Figure 5), there is an increase in temperature for the summer period. In addition to the increase in temperature, the effect of urbanization is more notable, due to areas of buildings and industrial areas (Pessi et al., 2019).

In Figure 8, it is possible to observe that in 1997 the temperatures were concentrated between 25 - 30 °C, corresponding to 36.98%, followed by temperatures between 20 - 25 °C, representing 29.41% of the area. According to the summer NDVI images, these areas correspond to sparse vegetation, such as crops, pasture and small trees. Temperatures between 30 - 35 °C represent 13.04%, located in the center of the urban area, where temperatures range from 30 - 40 °C.

In 2009, there was an increase in temperatures > 35 °C, representing 11.64%, and the predominance of temperatures between 20 – 30 °C. Comparing with the initial year, 2009 had a small increase in temperatures between 15 - 20 °C, in turn, these temperatures are located in areas with a higher concentration of vegetation cover (Figure 4b), consisting of larger trees.

In 2021, an increase in temperatures between 25 – 35 °C is observed, with a significant increase in temperatures > 35 °C. It is evident that the highest temperatures are found around and in the center of the urban area. It is also possible to notice that there is an increase in the milder temperatures (15 – 20 °C) over time, proportional to the increase in vegetation.

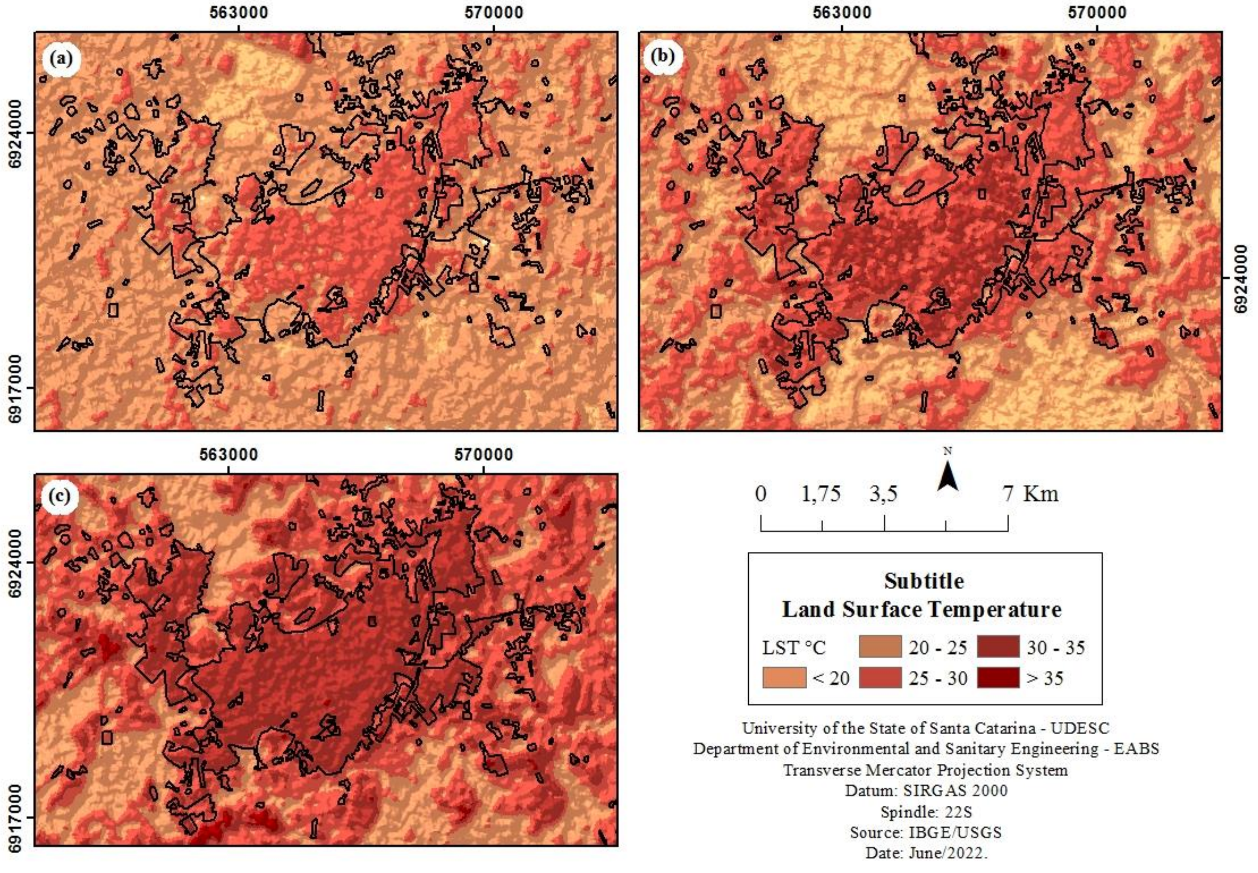


Figure 7. Land Surface Temperature (LST) variation from 1997 to 2021 in the urban area of Lages/SC in the summer period: (a) 01/06/1997, (b) 01/07/2009 and (c) 12/26/ 2021.

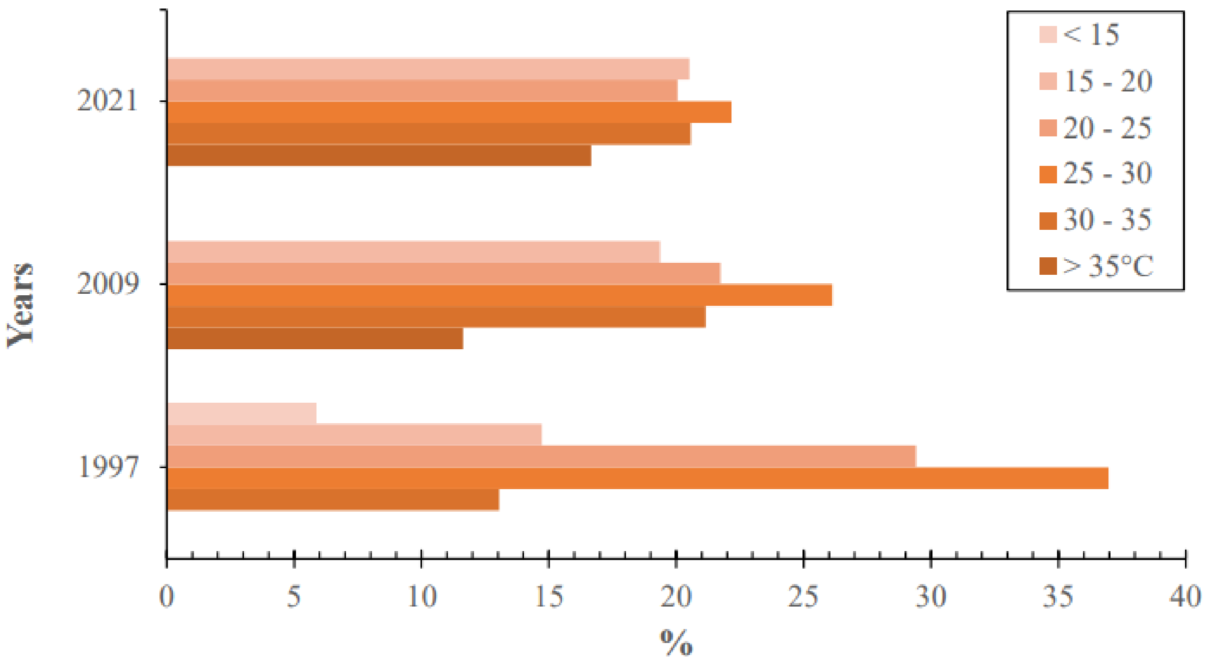


Figure 8. Area proportion temperature graph over the summer period for the urban area of Lages/SC.

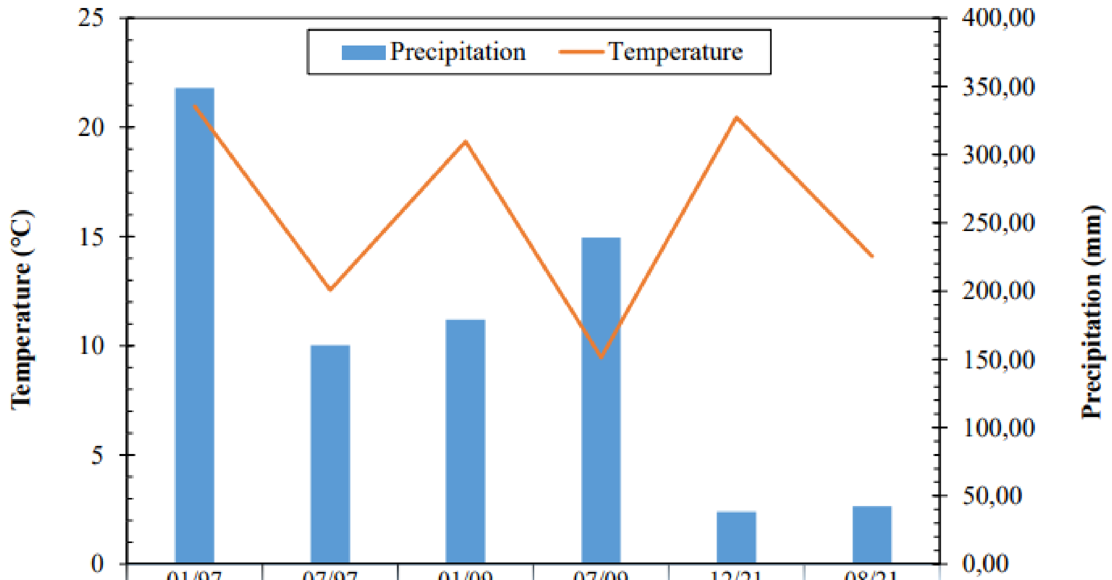
When comparing the data obtained (Figures 3, 4, 5 and 7) it can be verified that for values > 0.6 (dense vegetation) of the NDVI, the LST varied between 0 – 10 °C in winter and between 20 – 25 °C in summer. On the other hand, values between 0 - 0.3 (exposed soil) of the NDVI, provided a LST between 15 - 20 °C in winter and 25 - 35 °C in summer.

Similar results were found by Toffolli et al. (2019) in their study, where the lowest values obtained for LST (15 – 20 ºC) were observed in areas with a concentration of vegetation, areas of temporary culture and places with the presence of watercourses. While the highest values obtained (30 - 35ºC) were evidenced in areas with exposed soil and the existence of the urban zone.

In addition, it should be noted that the areas with the highest LST value are also linked to agricultural areas and degraded pasture areas, where the erosion process begins to produce an unprotected surface. And finally, these environments may present, in some locations, LST higher than the urban área, as also identidfied in the work of Silveira et al. (2023) for the cities of Criciúma and Lages in 2020.

The milder temperatures, detected in the center of the urban area in the winter period, are due to neighborhoods with less agglomeration of houses and with the presence of undergrowth in the other vacant spaces, which is not evident in the summer due to the greater homogenization of spaces built (Santos and Fialho, 2020).

According to Figure 9, referring to temperature and precipitation of each month/year, it is possible to notice that there were no large variations in air temperature for the analyzed periods.



	01/97	07/97	01/09	07/09	12/21	08/21
Precipitation	348,80	160,50	179,10	239,20	38,40	42,40
Temperature	20,96	12,55	19,34	9,46	20,46	14,09

Figure 9. Monthly average air temperature and precipitation values (month/year), referring to images obtained in 1997, 2009 and 2021 (summer and winter).

It is worth noting that July 1997 was a month of very low temperatures, which may have interfered with the temperature of the earth's surface, since the average air temperature was 4.88 °C on the date the images were taken and in the three previous days it was also low temperature. Furthermore, July 1997 and 2009 were periods of intense rainfall for this region, due to the presence of the El Niño phenomenon, which could interfere with reflectance values. According to Fialho and Santos (2021), precipitation causes a cooling effect on the surface, which can influence the results of the Land Surface Temperature (LST).

With regard to the year 2021, it was a year of little rain compared to previous years, in which it had less rainfall in summer (38.40 mm) and winter (42.40 mm), resulting in drier periods and extreme cold, influenced by the La Niña phenomenon. According to Lobato et al. (2022), low rainfall rates for long periods tend to reduce vegetative vigor, increasing evapotranspiration. The increase in evapotranspiration can demonstrate a serious problem, with global warming, soils and vegetation dry more quickly. In addition, more favorable conditions are created for the occurrence of droughts (Pascolini-Campbell et al., 2021).

The long period without precipitation may have favored the condition of exposed surface, poorly developed crops and low vigor vegetation, which consequently favored the identification of high thermal responses in different portions of the territory and mainly in the surroundings and in the center of the urban area.

Statistical Validation of Maps

At this stage, the NDVI images were reclassified to desired values and accuracy calculated based on these images. The overall accuracy results for each image (summer and winter) are detailed in Figure 10.

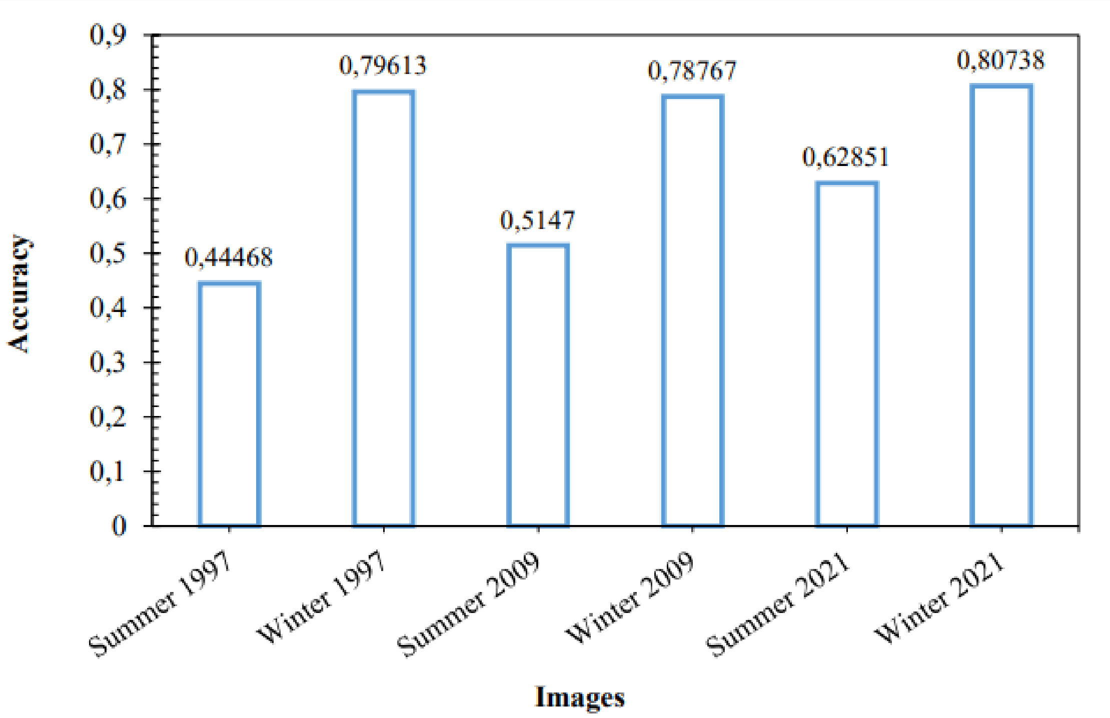


Figure 10. General accuracy values for each section of the NDVI image.

The average overall accuracy value for image classification was 0.6635, qualifying as a "Very Good" classification. According to the graph in Figure 10, summer images obtained the lowest accuracy values when compared to winter images, which obtained accuracy values > 0.75. Only the 1997 and 2009 summer images had results < 0.60, indicating a "Good" classification according to the degree of agreement.

The accuracy and precision values for each NDVI class (winter and summer) are shown in Tables 7 and 8. According to the tables, more than 295 points were analyzed in total. The general accuracy values obtained by Acatama are a direct relationship, that is, 0.5 corresponds to 50% classification accuracy.

Table 7. Degree of accuracy of the NDVI thematic classification for the winter period.

		Exposed Soil	Sparse Vegetation	Dense Vegetation	Total	Accuracy
Winter	**1997**	10	4	1	15	0.67
		5	61	9	75	0.81
		0	1	7	8	0.88
	2009	13	1	1	15	0.87
		7	48	8	63	0.76
		1	3	17	21	0.81
	2021	16	0	1	17	0.94
		8	38	6	52	0.73
		3	1	26	30	0.87
Total		63	157	76	296	
Precision		0.62	0.93	0.61		0.81

Table 8. Degree of accuracy of the NDVI thematic classification for the summer period.

		Exposed Soil	Sparse Vegetation	Dense Vegetation	Total	Accuracy
Summer	**1997**	2	2	2	6	0.33
		17	14	4	35	0.40
		7	23	28	58	0.48
	2009	6	1	0	7	0.86
		16	14	2	32	0.44
		1	28	31	60	0.52
	2021	12	0	0	12	1.00
		13	20	3	36	0.56
		1	20	31	52	0.60
Total		75	122	101	298	
Precision		0.26	0.39	0.89		0.58

The most discrepant values from the average (0.6635) were 0.33, 0.40, 0.48, 0.44, 0.56 and 0.60 for summer images. And the highest accuracy values were 0.81, 0.88, 0.87 and 0.94 for winter images, resulting in an overall average of 0.81. However, only one of the summer ratings received a value of 1.00, which falls under “Excellent”.

A possible explanation for the difference in values between the images with the highest overall accuracy and the lowest overall accuracy is the difference in seasonality, which implies changes in the landscape. It is possible to notice that there is a large amount of sparse vegetation in the winter images, which results in a classification accuracy of 0.93, while in the summer period the dense vegetation is well highlighted, obtaining an accuracy of 0.89. Furthermore, the difference between the temporal cut of the images can interfere with the values, since the landscape of 1997 is no longer the same as that of 2021, meaning that the Google satellite images used to assess accuracy are appropriate for each classified image.

Another possible explanation for the difference in the general accuracy values of the images is associated with the socioeconomic reality of the municipality, which has a high rate of anthropized areas, used for agriculture and pasture, and even for forestry for the extraction of wood. In this way, the large percentage of sparse and dense vegetation found in the proposed NDVI classification is justified. As for the water class, it was not detected in the classification, due to the smaller proportion of area, as well as interference in the reading due to some areas having reflectance similar to that of water (Machado et al., 2022).

Conclusion

The results generated from remote sensing showed the intrinsic relationship between the by Normalized Difference Vegetation Index and the Surface Temperature, as predicted by the hypothesis. It was observed that in the winter season (drier) the NDVI showed the greatest enhancements in the values corresponding to the exposed soil and the lowest values referring to the dense vegetation cover.

On the other hand, the NDVI of the summer season (wettier) showed a higher frequency of vegetation cover values, with the exception of the year 2021, where the month of December had low NDVI due to having low precipitation rates. In agreement with the NDVI, the TST showed mild values in areas with vegetation cover, however, high temperatures were identified in the urban center and close to it. Surface humidification in the summer enabled the development of vegetation, especially undergrowth and crops in the nearby rural surroundings, while the higher solar incidence of the season favored the small increase in temperature over the urban area.

The data obtained also show the influence of some variables on the indexes studied, such as precipitation and seasonality that can interfere with the reflectance of the vegetation and significantly alter the photosynthetic activity, thus modifying the thermal response of the vegetation cover. In addition to these, other factors, such as surface shading by buildings and irregular relief, can interfere with surface temperature averages, as well as air temperature and atmospheric phenomena that can affect the climate response of a given region.

The urbanization process and the implications for temperature in the city are evident. In these urbanized areas, the formation of heat islands can be observed, which may be related to the absence of vegetation, which affect the population, causing physical wear and discomfort. The NDVI also showed that the vegetation cover areas are almost all temporary, due to the strong activity of silviculture and reforestation existing in the municipality.

Areas of vegetation are essential, as they ease the strong temperatures in urban centers. In this way, it is important to implement environmental systems such as parks, gardens and lakes, which are fundamental for the quality of urban space in various aspects (thermal comfort, drainage, recreation, etc.), in which adequate territorial planning, as well as, the implementation of public policies for the preservation and restoration of degraded areas must be prioritized in the municipality.

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