SPATIAL DISTRIBUTION OF LOCAL CLIMATE ZONES AND POPULATION IN BRAZILIAN CAPITALS

Bruno Vargas Adorno[1], *Hugo Vilela Lemos Ferreira*[2], *Hoi Kay So*[3], *Silvana Amaral*[4]

[1,4] Graduate Program in Remote Sensing (PGSER), Coordination of Teaching, Research and Extension (COEPE), and [4]Earth Observation and Geoinformatics Division (DIOTG)National Institute for Space Research (INPE), São José dos Campos 12227-010, Brazil, {bruno.adorno, silvana.amaral}@inpe.br. [2]Graduate Program in Physical Geography of the University of São Paulo (USP), São Paulo, 05508-000, Brazil, hugovilelalemos@usp.br. [3]Department of Forest Resources Management, Faculty of Forestry, University of British Columbia, Vancouver, V6T 1Z4, Canada, hoikay22@student.ubc.ca

ABSTRACT

The Local Climate Zones (LCZs) have become a key urban classification system for studying urban heat. However, its suitability for cities in the Global South and association with other urban applications, such as population density, remain underexplored. This study assesses the applicability of the LCZ classification in the context of Brazilian capitals and its relationship to population distribution. Using the LCZ Generator, we classified LCZs for all Brazilian capitals, then we integrated IBGE population grid data and census tract boundaries to analyze the association between LCZs, population density. Despite the overall accuracy ranging from 50% to 72%, we identified key urban patterns, such as the concentration of populations in precarious zones (LCZ 7) and in compact (LCZ 1-3) and open (LCZ 1-6 and 9) neighborhoods. These insights contribute to a better understanding of how urban population distributions in Brazil are being associated with each LCZ.

Keywords **–** Population density, building density, remote sensing, urbanization.

1. INTRODUCTION

The Local Climate Zone (LCZ) classification [1] was designed to enhance understanding of urban heat islands within cities, beyond the urban-rural dichotomy. The LCZ system has gained widespread attention from researchers studying heat-related challenges, including thermal discomfort and heat stress, because of increasing urbanization. However, new applications of LCZ to understand its association with population distribution are emerging [2].

In recent years, remote sensing scientists have developed the World Urban Database and Access Portal Tools (WUDAPT) and the LCZ generator to facilitate the mapping and sharing of LCZ maps worldwide [3,4]. These initiatives align with global efforts to promote sustainable cities and address climate change [5]. Despite its international aspirations, the LCZ system was originally developed in the Global North, raising questions about its applicability in diverse urban settings [6]. Thus, more studies are needed to assess the LCZ scheme's suitability for different cities in the Global South.

This study aims to investigate the applicability of the LCZ classification in Brazilian capitals. It also analyzes whether the LCZ classification is suitable for population studies, aiming to contribute to the growing literature focused on mapping LCZ for population-related challenges [2,7].

2. MATERIAL AND METHODS

For this study, we selected contiguous urban areas of Brazilian capitals, as defined by the Brazilian Institute of Geography and Statistics (IBGE) [8]. Around 25% of Brazilian population lives in these capitals [9]. The IBGE also classifies urban areas into High Building Density and Low Building Density [8].

For data collection, we used Google Earth to gather reference samples for LCZ classification and downloaded the 2021 census tract boundaries [8] and latest IBGE population grid available [10]. The population grid is based on the 2010 census, while the 2021 tracts include attributes for high and low building density categories. The data processing for our analysis followed three main steps, as illustrated in Figure 1.

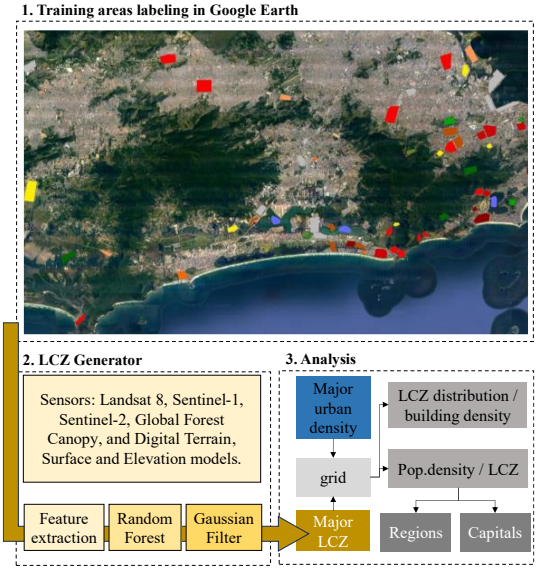


Figure 1: Workflow to analyse the relationship of LCZ classes and Population data in Brazil.

First, we collected 4,085 training areas (TAs) in Google Earth following WUDAPT guidelines [3,11]. We had few or no samples for LCZ 1, 2, 10, E, and F in some cities, due to variations in urban development and the size of these zones within the landscape. Additionally, certain LCZs, such as LCZ 4, did not fully align with descriptions in [1], as high-rise buildings seldom coexist with abundant vegetation in Brazilian capitals. Similarly, in the North Region, LCZ 7 often included lightweight housing on both paved and vegetated surfaces, but rarely on unpaved surfaces. Despite these nuances, we kept these areas classified as LCZ 4 or 7, for consistency in this initial study. Balancing the number of TAs across cities was also challenging due to the varying urban morphologies. For most cities, we sampled over 150 TAs. In smaller capitals like Vitória, Boa Vista, and Aracaju we sampled less than 100 TAs.

We mapped 27 cities, prioritizing collecting representative samples over the high-quality refinement of each TA. While ensuring high-quality TA that meet recommended criteria can improve classification accuracy [12], this process was too time-consuming. Nonetheless, Ferreira, who contributed to this study, has studied LCZ in Brazil and assessed these areas in the last five years [13].

In the second step, we uploaded the TAs into the LCZ Generator (November 2022, software version 1.5.0) for automated quality control, ensuring proper size and spectral similarity within classes [4]. The LCZ Generator uses 33 Earth Observation features at 100 m resolution, including inputs from Landsat 8, Sentinel-1, Sentinel-2, and terrain data. A random forest algorithm runs 25 times using a 70/30 training/testing split, producing confidence intervals for accuracy metrics (Overall, Producer's, and User's accuracies). The LCZ Generator also applies a Gaussian filter to reduce noise and eliminate isolated pixels that are unlikely to represent an LCZ [4].

Finally, in the third step, we analyzed the data by aggregating the major LCZ classes and major urban building density categories within each population grid cell. Pivot table analysis revealed the distribution of LCZs across building density categories and population density within each LCZ, with further breakdowns by Brazilian geographical regions and capitals.

3. RESULTS

3.1. Classification assessment

The map results for Brazilian capitals (Figure 2) reveal the diverse urban morphologies across the country, even within standard LCZ classes. A key observation is the variation in the distribution of LCZ 3 (compact low-rise buildings) and LCZ 6 (open low-rise buildings surrounded by vegetation), which appear in most capitals but exhibit different spatial patterns. In the north and in the midwest, LCZ 3 is typically located in the city center, with LCZ 6 and 9 (sparser buildings) towards the outskirts. Along the northeastern coast, LCZ 3 is dominant near the sea, while less dense and natural areas are further inland. In the Southeast, LCZ 3 prevails, with small clusters of LCZ 1, 4, and 6. The South shows distinct patterns, with Curitiba dominated by LCZ 6, Florianópolis by LCZ 3 and 6, and Porto Alegre by LCZ 3.

LCZ 7 (informal housing) is less common but noticeable in cities like Belém, Macapá, Campo Grande, and São Paulo. LCZ 8 is also less frequent but was found in cities like São Paulo, Curitiba, Goiânia, whereas LCZ 10 is found in Vitória. Vegetated areas (LCZ A, B, C, D) and water bodies (LCZ G) are primarily located on the outskirts of most capitals.

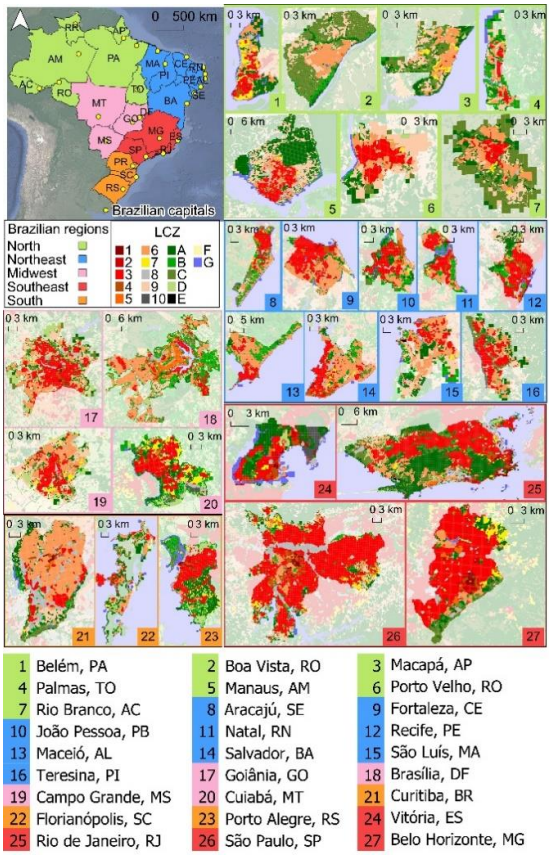


Figure 2: LCZ classification in Brazilian capitals.

Regarding classification accuracy, LCZ 3 had the highest built-up class accuracy across most capitals (generally above 60%). Natural classes (LCZ A and G) achieved nearly 100% accuracy. For classes mixing permeable and impermeable surfaces (LCZ 4-6, 9), the producer's accuracies were mostly below 50%, with some reaching 50-70%. Global accuracies ranged from 50% to 72%.

3.2. Building density analysis

We calculated the relative occurrence of each LCZ class within high and low-building-density areas (Figure 3). Our results reflect a reasonable alignment between LCZ and IBGE classes, at the national scale. The relative LCZ occurrence in high building density areas is close to

100% for LCZ 1-4, and around 80% for LCZ 5-8. A peak in LCZ 9 (sparse building zones) showed a 40% higher frequency in low building density areas compared to other built-up classes, while LCZ 10 (industrial zones) was predominantly found in high building density areas. As for vegetated classes, approximately 65% of LCZ A-D areas were found in low building density areas, whereas paved soil (LCZ E), bare soil (LCZ F), and water (LCZ G) were almost equally distributed between both density categories.

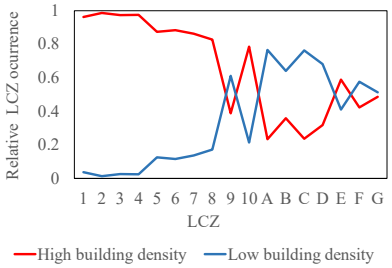


Figure 3: LCZ classes distribution in IBGE categories of high and low building density areas.

3.3. Population density analysis

Overall, we observed that the dominant built-up LCZ types in Brazilian capitals are LCZ 3 and LCZ 6 (82% of the total population distribution) (Figure 4). High-rise buildings (LCZ 1 and 4) are home to a relatively small portion of the population (6.9%) and only occupies 2% of the study area.

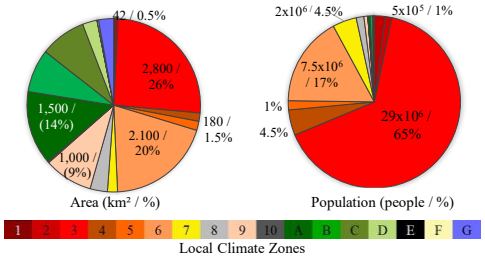


Figure 4: Area and population by LCZ in Brazilian capitals.

When examining absolute population density across Brazilian regions (Figure 5a), although LCZ 1 and 4 cover limited areas and populations, they are among the most densely populated LCZs, except in the north, where LCZ 1 was not identified. LCZ 7, which is more prevalent in the southeast, northeast, and north regions, also exhibits high population density, but this becomes more apparent when we normalize population density by region (Figure 5b). After normalization, LCZ 7 shows relatively greater population density in the north and northeast than in the southeast.

Looking at the population density in individual capitals (Figure 6), LCZ 1-6 frequently show densities exceeding 1,600 people per km², while natural LCZ types consistently show densities lower than 523 people per km². A few exceptions stand out: Teresina had very low densities (below 27 people per km²) in LCZ 2, 5, and 7, and Porto Alegre shows a high population density in LCZ E (Paved zones). Upon further investigation in Teresina, LCZ 2 and 5 represent only a single misclassified cell without population, while LCZ 7 is mapped in peripheral zones, likely indicating new expansion areas since the population grid is based on the 2010 Census. In Porto Alegre, the high population density in LCZ E resulted from a border issue between LCZ E and LCZ 3 (compact built-up areas), causing a misclassification when the major class was attributed to the grid cell.

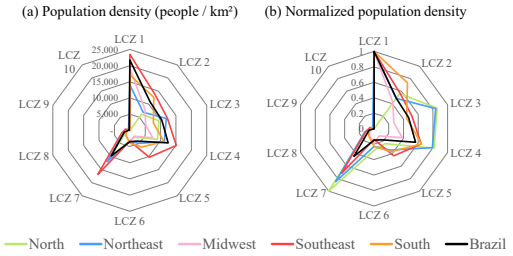


Figure 5: (a) Absolute and (b) normalized population density by LCZ in each Brazilian region. Brazil values refer to an average for all regions.

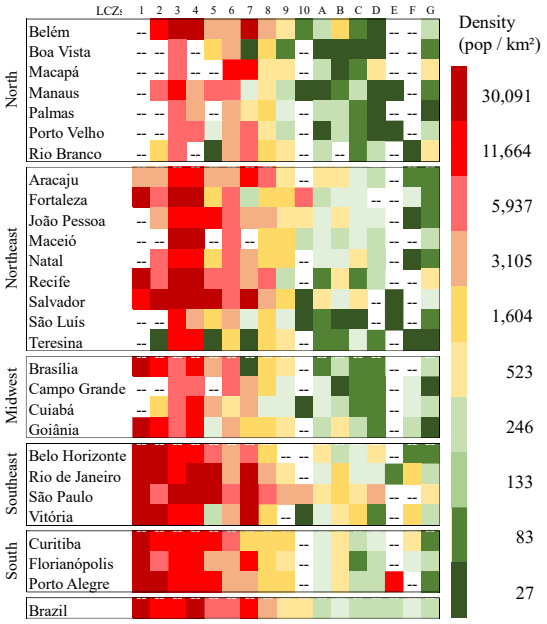


Figure 6: Decile classification of population density by LCZ in Brazilian capitals. The last line represents the average for Brazil. The value indicated in the legend is the maximum for each class.

Overall there is a decrease in population density from compact LCZs (1, 2, and 3) to more vegetated or sparsely built LCZs (4, 5, 6, 8, and 9). LCZ 7, however, stands out with extremely high population densities (11,664 to 30,091 people per km²) corresponding to or slum-like zones such as Terra Firme in Belém, Favela da Rocinha in Rio de Janeiro, Paraisópolis in São Paulo, and Complexo da Penha in Vitória.

4. DISCUSSION

The WUDAPT and LCZ Generator [4,7] have been

relevant for urban climate research. LCZ mapping has become more worldwide accessible, facilitating cross-field studies and scientific advancements. Scaling and comparing results across different contexts are major advantages of using LCZ generator. However, as noted elsewhere [2, 12], generating high-quality LCZ maps is not simple. Users must evaluate training areas and perform multiple classification rounds to eliminate non-representative TA samples. As limitation, the LCZ Generator does not allow the manipulation of input features beyond those offered by [4]. Despite these challenges, the LCZ Generator remains a valuable starting point for non-experts and resource-limited countries, offering an accessible tool for urban planning.

A new trend in LCZ mapping involves integrating remote sensing with GIS-based approaches, incorporating more input features than just satellite imagery. In Brazil, socioeconomic information from census data could distinguish LCZ 7 (informal housings in dense, and low-rise zone) from LCZ 3, based also on very dense and low-rise buildings. We believe that including socioeconomic data could enhance classification accuracy for such classes.

We also found that LCZ subclasses should be considered for Brazilian capitals, particularly concerning LCZ 7 and LCZ 4. Researchers focusing on specific regions or metropolitan areas should explore local characteristics that influence LCZ classification. To do so, LCZ subclasses that are climate-relevant and representative of a particular study area could be created such as LCZ 3_7, which would be predominantly LCZ 3 with some LCZ 7 characteristics [1,7].

Finally, we explored the suitability of LCZ classification for population studies by relating it to the IBGE census tract and the population grid. Despite moderate to low accuracy for some LCZ classes, the classification aligned with expectations for population and building density (e.g. most population living in very dense and low-rise buildings LCZ 3,), while revealed distinct characteristics in certain capitals (e.g., high density of people in informal housings associated with LCZ 7.

5. CONCLUSIONS

We investigated the suitability of standard LCZ classification for population studies in a Global South country. To the best of our knowledge, this is the first LCZ map published for all Brazilian capitals.

By associating population distribution data with the LCZ classification using LCZ Generator, we confirmed that, despite its overall moderate accuracy, it is well-suited for analyzing general aspects of urban landscapes. This includes identifying concentrations of people living in slums (LCZ 7) and in compact (LCZ 3) neighborhoods. This provides valuable understandings about the spatial distribution of populations in Brazil's urban environments.

6. REFERENCES

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