Mapping socio-environmental vulnerability to the desertification process in the northeastern region of Brazil: The case of the Cabrobó nucleus

Mapeando a vulnerabilidade socioambiental ao processo de desertificação na região Nordeste do Brasil: o caso do núcleo Cabrobó

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Abstract

Desertification generally has adverse environmental, social, and economic consequences. However, areas lacking adequate social and infrastructural conditions face greater challenges in addressing the risks associated with desertification. Research evaluating the socio-environmental implications of the desertification process remains limited. In Brazil, the Cabrobó desertification nucleus is characterised by significant economic activities such as irrigated fruit farming and fish farming. Although this region has been the subject of several studies addressing the physical and natural impacts of desertification, investigations focusing on socio-environmental aspects, particularly vulnerability, are still scarce. Vulnerability mapping is a crucial tool for informing and improving public policy, particularly when it is based on census sector data. This study aimed to develop vulnerability maps of the desertification risk for the Cabrobó desertification nucleus. The analysis utilised census sector data from five municipalities: Cabrobó, Belém do São Francisco, Carnaubeira da Penha, Itacu-

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ruba, and Floresta, based on the 2010 census, the last provided by the Brazilian Institute of Geography and Statistics (IBGE). It was not possible to use more recent census sector data, as such data are currently unavailable. Social variables and environmental variables were included in the analysis. Indices were generated using Exploratory Factor Analysis and subsequently visualised on maps. The results revealed varying levels of vulnerability across census sectors, with social and rural socio-environmental vulnerabilities being particularly high. Strengthened collaboration between government and society is essential for improving regional conditions. The findings of this study may support the development of targeted social assistance policies for residents of the region.

Keywords: Socio-environmental vulnerability. Cabrobó desertification nucleus. Census sectors. Exploratory factor analysis. Public policies.

Resumo

A desertificação tem consequências ambientais, sociais e econômicas adversas. No entanto, áreas sem condições sociais e infraestruturais adequadas enfrentam maiores desafios para lidar com os riscos associados à desertificação. Pesquisas que avaliam as consequências socioambientais do processo de desertificação permanecem limitadas. No Brasil, o núcleo de desertificação Cabrobó é caracterizado por atividades econômicas significativas, como fruticultura irrigada e piscicultura. Embora esta região tenha sido objeto de diversos estudos abordando os impactos físicos e naturais da desertificação, investigações centradas em aspectos socioambientais – particularmente a vulnerabilidade – ainda são escassas. O mapeamento de vulnerabilidades é uma ferramenta crucial para informar e aprimorar políticas públicas, principalmente quando baseado em dados censitários. Este estudo teve como objetivo desenvolver mapas de vulnerabilidade do risco à desertificação para o núcleo de desertificação Cabrobó. A análise utilizou dados censitários de cinco municípios: Cabrobó, Belém do São Francisco, Carnaubeira da Penha, Itacuruba e Floresta, com base no censo de 2010 fornecido pelo Instituto Brasileiro de Geografia e Estatística (IBGE). Não foi possível utilizar dados mais recentes dos setores censitários, uma vez que estes não estão disponíveis no momento. Variáveis sociais e ambientais foram incluídas na análise. Os índices foram gerados por meio da Análise Fatorial Exploratória e posteriormente representados através de mapas. Os resultados revelaram níveis variados de vulnerabilidade entre os setores censitários, com vulnerabilidades socioambientais rurais particularmente elevadas. O fortalecimento da colaboração entre governo e sociedade é essencial para a melhoria das condições regionais. Os resultados deste estudo podem subsidiar o desenvolvimento de políticas de assistência social direcionadas aos moradores da região.

Palavras-chave: Vulnerabilidade socioambiental. Núcleo de desertificação de Cabrobó. Setores censitários. Análise fatorial exploratória. Políticas públicas.

1. Introduction

Land degradation affects the well-being of approximately 3 billion people and results in the loss of ecosystem services equivalent to around 10% of the annual global Gross Domestic Product (GDP) worldwide (UNCCD, 2019). In regions undergoing desertification, the impacts are diverse and often linked to socio-economic challenges, including, in the most severe cases, the intensification of migration processes (Hermans & McLeman, 2021). Desertification is defined as land degradation occurring in

arid, semi-arid, and dry sub-humid areas, and has been recognised as a critical global issue addressed within the framework of the Sustainable Development Goals (Sterk & Stoorvogel, 2020). Between the 1980s and 2000s, critical desertification hotspots expanded by approximately 9.2% in dryland areas, affecting nearly 500 million people by 2015, particularly in South and East Asia and in regions surrounding the Sahara, including North Africa and the Middle East (IPCC, 2022).

In Brazil, approximately 1,143,491 km^2 are considered susceptible to desertification, distributed across four nuclei: Gilbués (PI), Irauçuba (CE), Seridó (RN) and Cabrobó (PE) (Bezerra et al., 2020). In the state of Pernambuco, the Cabrobó desertification nucleus comprises five municipalities: Belém do São Francisco, Cabrobó, Carnaubeira da Penha, Floresta, and Itacuruba. Numerous studies focusing on the spatio-temporal dynamics of desertification processes in the Brazilian Northeast can be found in the literature (da Silva et al., 2024; Ferreira et al., 2017; Moura et al., 2022; Tomasella et al., 2018).

However, research specifically addressing socio-environmental vulnerability within this context remains limited. According to Vieira et al. (2020), vulnerability encompasses the social and environmental conditions that influence a population's capacity to face, resist, and recover from environmental risks such as desertification, including land degradation. These conditions shape the level of risk, distinguishing vulnerabilities from the direct impacts of desertification. Vieira et al. (2020) also highlighted that the spatial distribution of vulnerability is influenced by political and social structures. Nonetheless, studies that assess vulnerability at the census sector scale or that distinguish between urban and rural contexts remain absent in the region.

Socio-environmental vulnerability can be defined as the economic, social, cultural, and environmental conditions of a population that influence their capacity to withstand, respond to, and recover from risk or environmental degradation in their habitual place of residence (Cartier et al., 2009). Vulnerability is the outcome of specific spatial socioeconomic, demographic, cultural, and institutional contexts, making its assessment particularly sensitive to local conditions and cultural dimensions (Kuhlicke et al., 2011; Mendes et al., 2011). This concept is structured around two main components: criticality and support capacity (Freitas & Cunha, 2013; Mendes et al., 2011). The former refers to the set of conditions that disrupt the system and the resources available to a community to cope with or respond to disasters or catastrophes. The latter relates to the territorial infrastructure that enables communities to react effectively to such events.

Therefore, this study seeks to address the following questions: Do census sectors within the same municipality exhibit significant variation in socio-environmental vulnerability? Does the disaggregation of data – between urban and rural areas or between social and environmental dimensions – reveal notable differences in vulnerability across census sectors? If such differences exist, do they hold significance that permits their utilisation in the formulation and implementation of public policies at the municipal level, aimed at reducing vulnerability and, consequently, minimising the extent of losses experienced by the population during major risk events? This research is guided by the hypothesis that vulnerability is generally very high across all municipalities within the Cabrobó desertification nucleus. It is further hypothe-

sised that social vulnerability is more relevant than environmental vulnerability, and that rural sectors are more vulnerable than urban ones. The main objective of this study is to construct and evaluate socio-environmental vulnerability cartography for the Cabrobó desertification nucleus – representing, to the best of our knowledge, the first such effort in the scientific literature focused on this region.

2. Materials and methods

2.1. Study area

The study was conducted across the entire Cabrobó desertification nucleus (Figure 1), located in the state of Pernambuco, Brazil. This nucleus comprises five municipalities: Belém do São Francisco (8º 45' 28''S; 38º 57' 52''W); Cabrobó (8º 30' 43''S; 39º 18' 24''W), Carnaubeira da Penha (8º 19' 20''S; 38º 44' 39''W), Floresta (8º 36' 2''S; 38º 34' 5''W), and Itacuruba (8º 50' 2''S; 38º 42' 14''W). The geographic coordinates represent the central point of the municipal headquarters. The municipalities are situated within the semi-arid zone of the Caatinga biome, with an economy primarily based on agriculture, pasture, and fish farming (da Silva et al., 2023). According to governmental data provided by the Institute for Society, Population, and Nature (https://ispn.org.br), the region is also home to various indigenous populations, including the Atikum, Truká, and Fulni-ô peoples, among others.

The municipalities and their respective land areas and population are as follows: Belém do São Francisco – 1,830.8 km^2 with a population of 20,164; Cabrobó – 1,657.7 km^2 and 30,775 inhabitants; Carnaubeira da Penha – 1,004.7 km^2 and 11,775 inhabitants; Floresta – 3,644.2 km^2 and 29,209 inhabitants; and Itacuruba 430 km^2 with a population of 4,368 (IBGE, 2010).

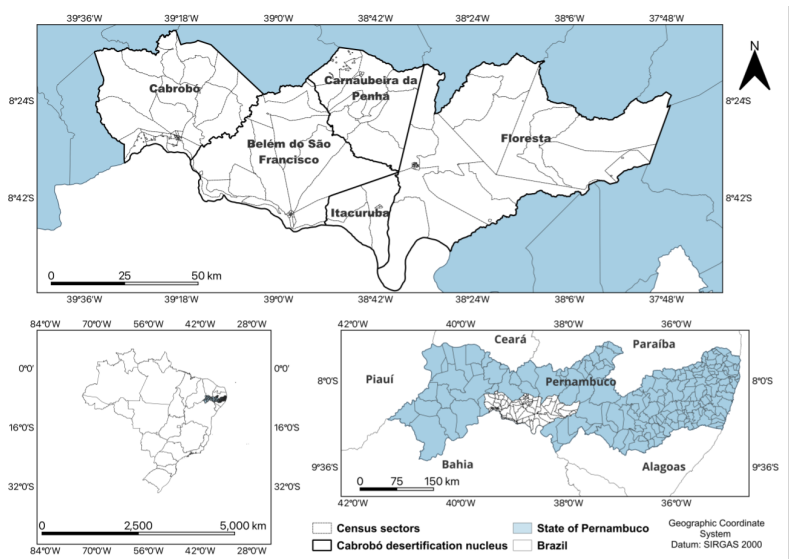

Figure 1. Location of the municipalities comprising the Cabrobó desertification nucleus in the state of Pernambuco, Brazil.

2.2. Methodology

Socio-environmental vulnerability was assessed using demographic data from the Brazilian Institute of Geography and Statistics website[1], based on the 2010 census. The most recent census (2022) could not be used as data at the census sector level are not yet available.

Exploratory Factorial Analysis (EFA) was employed as the statistical technique to construct the vulnerability indexes for the study area. This method is widely recognised as appropriate for such purposes, and the analytical procedure adopted follows the approach described by Cutter (2003); Mendes et al. (2011), Cunha et al. (2011), and Costa et al. (2024).

The dataset comprised 180 census sectors, with 118 located in rural areas and 62 in urban areas (Figure 2). A total of 89 variables were initially obtained for each census sector, encompassing both social dimensions (e.g., age, education level, number of residents per household) and environmental dimensions (e.g., waste collection, public lighting, and sewage infrastructure). These variables were selected following criteria similar to those adopted by Zucherato (2018).

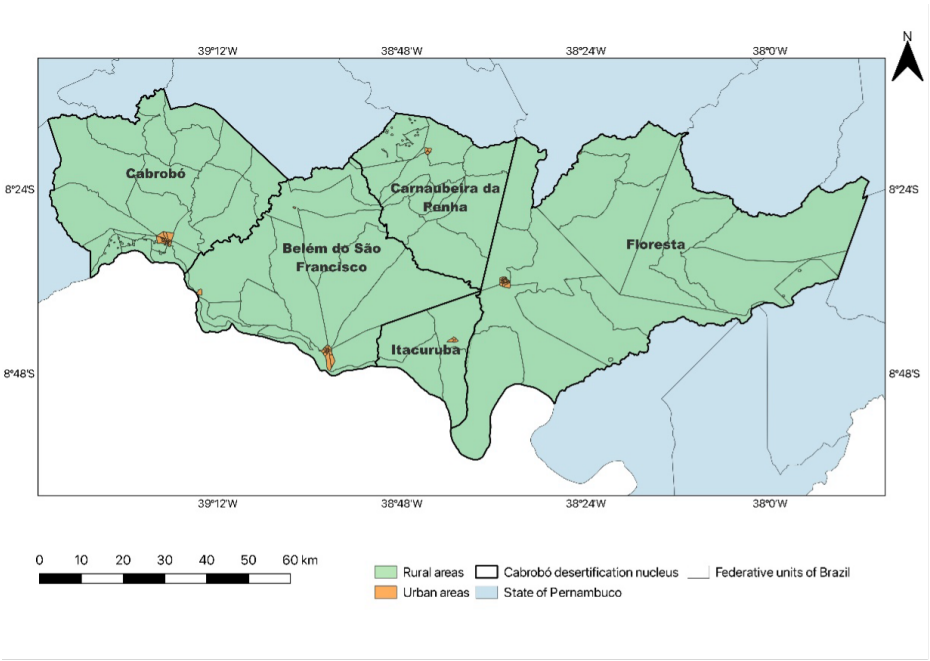

Figure 2. Census sectors identified both rural and urban areas within the Cabrobó desertification nucleus.

In order to reduce multicollinearity and improve interpretability, a variable reduction process was conducted: among pairs of variables with Pearson correlation coefficients greater than 0.8, only the most representative variables were retained (Kyriazos & Poga, 2023). The set of variables used to construct the vulnerability is presented in Table1 (Appendix).

[1] https://www.ibge.gov.br/estatisticas/downloads-estatisticas.html

The reduction process was conducted in successive stages. Initially, the dataset comprising 89 variables was reduced to 69 through Pearson correlation analysis. Subsequently, the socio-environmental vulnerability analysis was performed. These 69 variables were first grouped into social and environmental subcategories, resulting in 46 social and 23 environmental variables, which were used to generate the respective social and environmental vulnerability maps. In addition, the 69 variables were divided into rural and urban subsets to assess socio-environmental vulnerability in both contexts.

The number of components retained was determined so that the cumulative explained variance reached a minimum of 70% (Cunha et al., 2011; Costa et al., 2024). All statistical analyses, including EFA, were performed using the R programming language, which ensured flexibility in data processing and reproducibility of results.

The adequacy of the EFA was assessed using the communality index, with values above 0.6 considered acceptable. The cartographic outputs were generated according to the following structure (vulnerability index):

$$V_x = F_1 \times \mathrm{Var}(F_1) \pm F_2 \times \mathrm{Var}(F_2) \pm F_3 \times \mathrm{Var}(F_3) \ldots \quad (1)$$

where Vx represents the vulnerability calculated for each group within each census sector (final vulnerability index); F refers to the score of each territorial unit for the factors resulting from the EFA (F1,F2); Var (F) denoted the percentage of variance explained by each factor; and $\pm$ indicates the direction of the relationship (a positive direction represents increased vulnerability, while a negative direction represents a decrease in vulnerability).

The final cartographic maps were produced using QGIS version 3.16. The classification process was performed using the natural breaks method, which is based on the natural grouping inherent in the data. This method groups similar values together, resulting in the formation of distinct classes.

3. Results

Considering that the calculation process essentially allows for the derivation of relative values, that is, values which compare levels of vulnerability only within this specific territorial unit, the corresponding vulnerability cartographic maps are presented in this section, revealing distinct results for each group. The socio-environmental data revealed a predominance of areas with moderate and high levels of vulnerability (Figure 3). Rural areas clearly reflect higher levels of vulnerability than urban areas. However, the municipalities of Cabrobó and Carnaubeira da Penha exhibited multiple census sectors classified as having very high vulnerability. Notably, Carnaubeira da Penha was the only municipality to display census sectors with a representative proportion of low vulnerability. Belém do São Francisco was the only municipality in which no census sectors were classified as having a representative level of very high vulnerability.

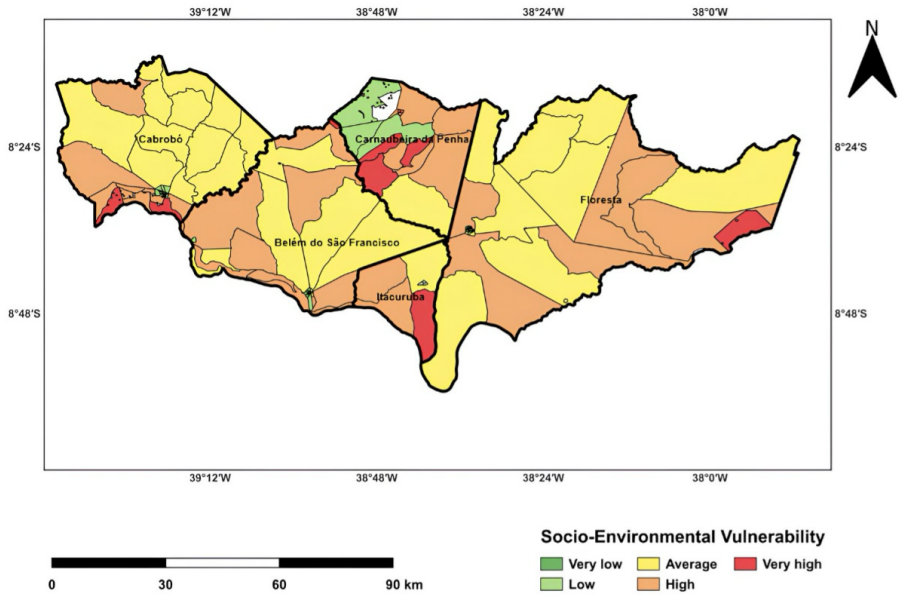

Figure 3. Socio-environmental vulnerability cartography based on demographic data for the municipalities within the Cabrobó desertification nucleus, Pernambuco, Brazil.

The social vulnerability cartography (Figure 4) generally revealed census sectors ranging from very low to moderate levels of vulnerability. Cabrobó was the only municipality that presented areas with high vulnerability and more than one census sector classified as very highly vulnerable. It is also noteworthy that the municipality of Floresta reported a census sector with very high vulnerability. Although very low vulnerability was not widely observed across the census sectors, Cabrobó stood out for having at least a few sectors with a representative level of very low vulnerability, particularly in the urban centre, due to its generally better infrastructure. Itacuruba was the only municipality in which moderate vulnerability predominated.

The environmental vulnerability analysis (Figure 5) revealed a predominance of very high vulnerability, particularly in the municipalities of Belém do São Francisco and Carnaubeira da Penha. Environmental vulnerability was generally lower in urban census sectors compared to rural areas, due to factors such as building characteristics and better access to water and electricity, for example. Cabrobó, Floresta, and Itacuruba also presented census sectors with low vulnerability. However, these latter municipalities also exhibited notable census sectors with moderate and high levels of vulnerability.

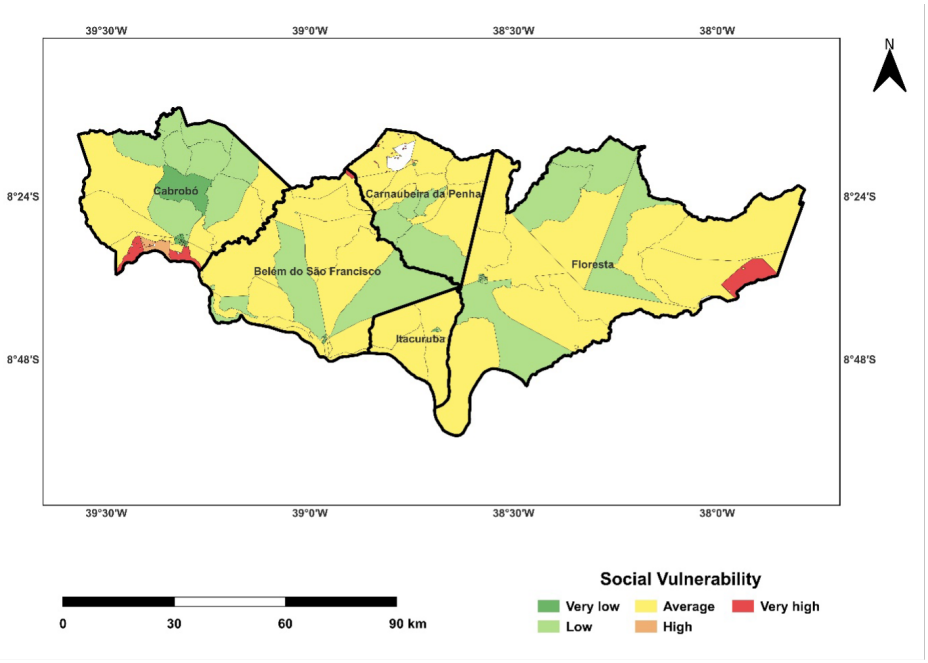

Figure 4. Social vulnerability cartography based on demographic data for the municipalities within the Cabrobó desertification nucleus, Pernambuco, Brazil.

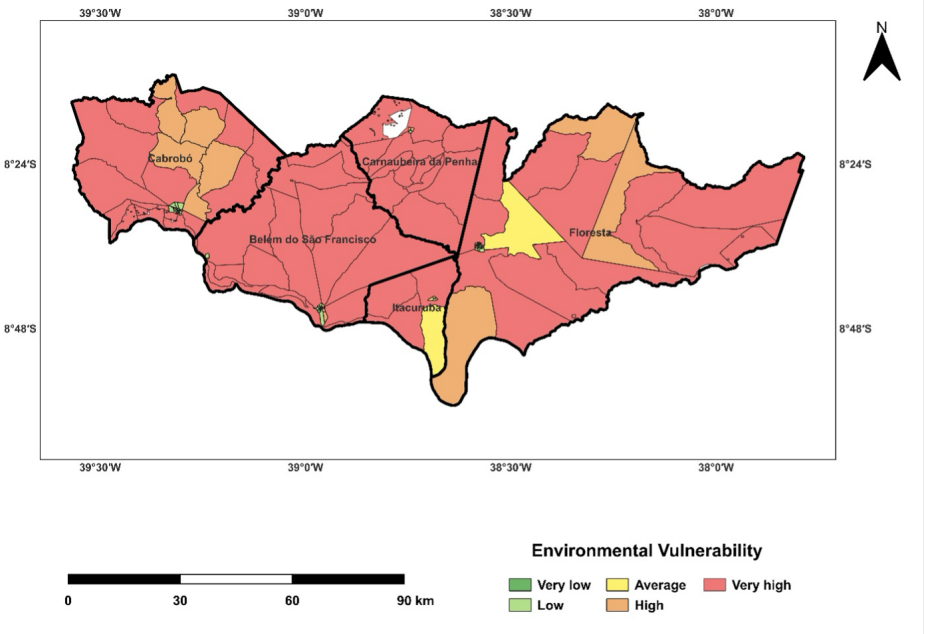

Figure 5. Environmental vulnerability cartography based on demographic data for the municipalities within the Cabrobó desertification nucleus, Pernambuco, Brazil.

The rural socio-environmental vulnerability analysis (Figure 6) highlighted areas of very high vulnerability in the municipalities of Cabrobó, Itacuruba, and Floresta.

Nevertheless, Cabrobó and Floresta predominantly exhibited very low to low vulnerability. Itacuruba was the only municipality that did not report any census sectors with very low vulnerability. Carnaubeira da Penha and Cabrobó were the only municipalities to present census sectors with high vulnerability. All municipalities showed the presence of census sectors classified as having moderate vulnerability.

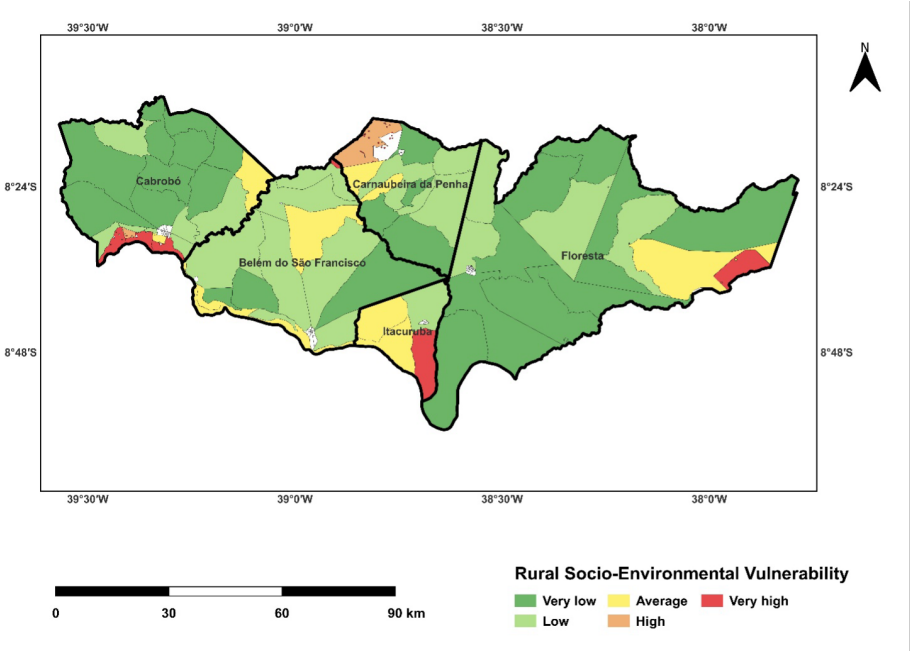

Figure 6. Rural socio-environmental vulnerability cartography based on demographic data for the municipalities within the Cabrobó desertification nucleus, Pernambuco, Brazil.

The urban socio-environmental vulnerability analysis (Figure 7) revealed that Itacuruba was the only municipality in which all census sectors exhibited low vulnerability. Floresta and Carnaubeira da Penha presented census sectors with high vulnerability, with the latter also displaying at least one sector classified as having very high vulnerability, similar to Belém do São Francisco. Cabrobó was the only municipality that exhibited census sectors, with varying levels of vulnerability, ranging from very low to moderate.

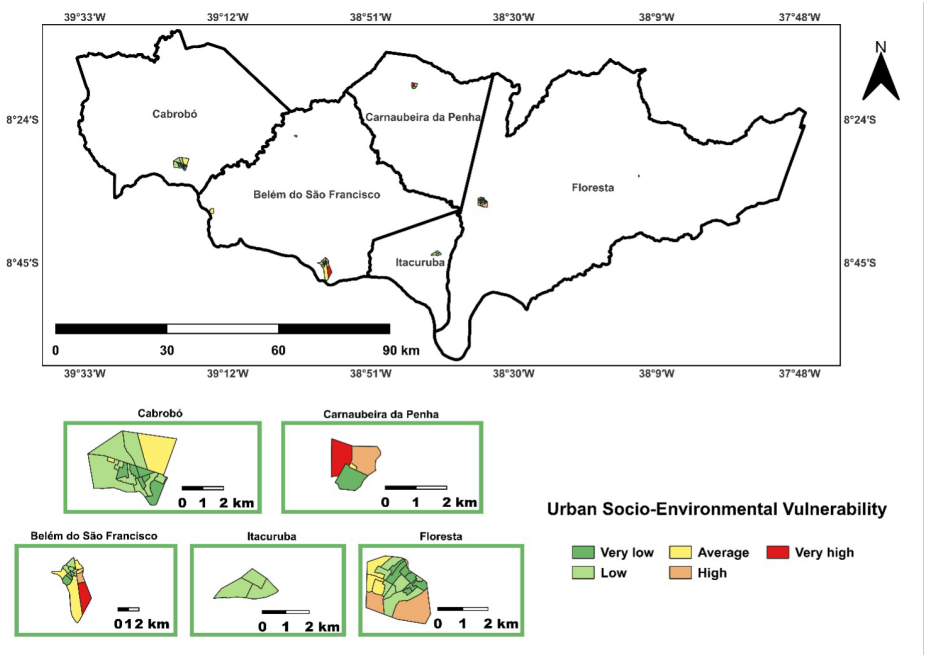

Figure 7. Urban socio-environmental vulnerability cartography based on demographic data for the municipalities within the Cabrobó desertification nucleus, Pernambuco, Brazil.

4. Discussion

The results are consistent with expectations and can be used to guide public policies aimed at reducing vulnerability. The results demonstrated a clear differentiation when the data were disaggregated into rural-urban and socio-environmental categories. It is therefore evident that social parameters, which primarily influence vulnerability. Notably, rural areas, which usually lack adequate infrastructure, also include census sectors with very high levels of vulnerability, which can be such as are commonly associated with structural shortcomings, for example, the absence of public lighting and limited access to safe water supply.

This aspect cannot be attributed solely to physical characteristics or land degradation, since the study area is strongly influenced by an agricultural-based economy. As highlighted by Vieira et al. (2020), the primary drivers of vulnerability are closely linked to dependence on public policies and the degree of collaboration between government and society. A study conducted in the Brazilian semi-arid region further demonstrated that increases in population income were not identified as the main factor contributing to improvements in social well-being. Instead, the findings underscore the necessity for diversified public policies, particularly through economic diversification and the enhancement of the agricultural GDP (Sathler, 2021). The distinction between urban and rural areas, characterised by markedly different population sizes and levels of infrastructure, plays a significant role in shaping vulnerability and must be taken into account in any analysis.

Regarding the agricultural sector within the desertification nucleus, no clear association was identified between this economic activity and improvements in social

vulnerability. This pattern was particularly evident in the southern region of the Cabrobó municipality, where high and very high levels of vulnerability were reported in the socio-environmental, social, and rural socio-environmental maps. This area has been characterised by a strong agricultural influence, particularly related to irrigated fruit cultivation since the mid-1985s, which has expanded significantly in recent years (da Silva et al., 2023). Although this study relied on 2010 data, the region also has a long-standing historical connection to this economic activity, with production ongoing since the 1940s (Chaves et al., 2004).

This study reveals differences when compared to other desertification-affected regions. Research conducted in Iraq has demonstrated that high levels of social vulnerability, characterised by poverty and limited infrastructure, intensify the risk of desertification and related impacts. As a result, population migration has emerged as a significant consequence in these high-risk settings (Al-Obaidi et al., 2022). In Brazil, specific studies examining the association between desertification and migration remain limited. However, data from IBGE indicate a 48% increase in return migration to the semi-arid region (Oliveira et al., 2019). This trend may be associated with the National Action Program to Combat Desertification and Mitigate the Effects of Drought (PAN-Brazil), which aims to promote sustainable development in the region and address poverty and inequality (MMA, 2004). In this context, populations already facing high levels of vulnerability due to poverty, limited infrastructure, and dependence on public policies tend to experience more impacts from desertification processes. The influence of this programme explains the relatively low levels of out-migration.

An important aspect that warrants attention is the presence of indigenous communities in the region, many of whom reside in census sectors classified as highly or very highly vulnerable. This classification likely reflects the structural fragilities which have historically been faced by these populations (from the 1500s), such as limited access to basic infrastructure and public services, rather than their presence being a direct cause of vulnerability. Although this study was unable to map the distribution of indigenous populations within each census sector, it is reasonable to assume that these groups experience significant socio-environmental vulnerability, which may have contributed to the elevated social vulnerability observed in the cartographic analysis.

Several variables used in the construction of the vulnerability index are particularly relevant in this context, including low levels of education among household heads, limited access to basic sanitation and water supply, precarious housing conditions, and reduced income levels. These factors tend to disproportionately affect indigenous communities, given their historical exclusion from public policies and limited access to infrastructure. Thus, the presence of indigenous populations in certain sectors may be indirectly associated with higher vulnerability scores due to these structural disadvantages (Chakraborty et al., 2021).

Political and regulatory frameworks are essential instruments in combating desertification. However, it is necessary for regions to develop specific policies that incorporate forecasting mechanisms and operate across multiple scales – national, regional, and local – while addressing the particularities of each area (You et al.,

2021). This approach can support the formulation of new public policies, particularly those aimed at reducing social vulnerability at the level of each individual census sectors. Such policies should prioritise rural areas across all municipalities as a starting point for intervention. According to IBGE data, the rural population is predominantly classified as extremely poor and faces significant limitations in access to education (De Oliveira et al., 2025). Furthermore, it is essential to develop public policies based on respect towards the values of indigenous traditional communities that reside in the desertification nucleus, since these communities share in the preservation of our common culture (Pereira Truká et al., 2024).

5. Conclusion

The use of IBGE data enabled the construction of vulnerability maps for the Cabrobó desertification nucleus at the census sectors. However, the absence of sector-level data from the 2022 census limited the inclusion of a temporal dimension, which could have revealed trends in vulnerability over the past decade. Nevertheless, the results revealed variation in vulnerability, particularly when the data were disaggregated into distinct categories (socio-environmental, social, environmental, rural socio-environmental, and urban socio-environmental). The hypothesis that rural areas exhibit greater vulnerability than urban areas was confirmed. Environmental vulnerability was generally higher than social vulnerability, but social vulnerability exhibited greater heterogeneity.

The results indicate that land degradation and other physical factors do not have an intrinsic relationship with vulnerability, although more vulnerable populations are disproportionately affected by the impacts of land degradation. Instead, vulnerability appears to be more strongly influenced by the need for improvements in public policies and greater integration between governmental institutions and society. For this reason, Brazilian public policies – such as the PAN programme – may contribute to reducing vulnerability in the region.

The cartographic outputs presented in this study may support governmental programmes in the formulation of public policies that consider the specific characteristics of each census sector. Additionally, they serve as an important tool for identifying areas that require urgent interventions. It is recommended that similar cartographic analyses be developed for other desertification nuclei, alongside further research focused on the relationship between desertification and migration, specifically within the Brazilian context.

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References

Al-Obaidi, J. R., Yahya Allawi, M., Salim Al-Taie, B., Alobaidi, K. H., Al-Khayri, J. M., Abdullah, S., & Ahmad-Kamil, E. I. (2022). The environmental, economic, and social development impact of desertification in Iraq: A review on desertification control measures and mitigation strategies. *Environmental Monitoring and Assessment*, *194*(6), 440. https://doi.org/10.1007/s10661-022-10102-y

Bezerra, F. G. S., Aguiar, A. P. D., Alvalá, R. C. S., Giarolla, A., Bezerra, K. R. A., Lima, P. V. P. S., do Nascimento, F. R., & Arai, E. (2020). Analysis of areas undergoing desertification, using EVI2 multi-temporal data based on MODIS imagery as indicator. *Ecological Indicators*, *117*, 106579. https://doi.org/10.1016/j.ecolind.2020.106579

Cartier, R., Barcellos, C., Hübner, C., & Porto, M. F. (2009). Vulnerabilidade social e risco ambiental: Uma abordagem metodológica para avaliação de injustiça ambiental. *Cadernos de Saúde Pública*, *25*(12), 2695–2704. https://doi.org/10.1590/S0102-311X2009001200016

Chakraborty, L., Thistlethwaite, J., Minano, A., Henstra, D., & Scott, D. (2021). Leveraging hazard, exposure, and social vulnerability data to assess flood risk to indigenous communities in Canada. *International Journal of Disaster Risk Science*, *12*(6), 821–838. https://doi.org/10.1007/s13753-021-00383-1

Chaves, L. H. G., Tito, G. A., Chaves, I. B., Luna, J. G., & Silva, P. C. M. (2004). Propriedades químicas do solo aluvial da Ilha de Assunção – Cabrobó (Pernambuco). *Revista Brasileira de Ciência do Solo*, *28*(3), 431–437. https://doi.org/10.1590/S0100-06832004000300004

Costa, M., Zacharias, A. A., Cunha, L., & dos Santos, M. (2024). O estudo das vulnerabilidades sociais e ambientais aos riscos hidrogeomorfológicos no município de Rio Claro (Rio de Janeiro, Brasil). *Territorium*, *31*(N.º Especial), 123–135. https://doi.org/10.14195/1647-7723_31-extra1_9

Cunha, L., Mendes, J. M., Tavares, A., & Freiria, S. (2011). Construção de modelos de avaliação de vulnerabilidade social a riscos naturais e tecnológicos: O desafio das escalas. In N. Santos & L. Cunha (Eds.), *Trunfos de uma geografia activa: Desenvolvimento local, ambiente, ordenamento e tecnologia* (pp. 627–637). Imprensa da Universidade de Coimbra. https://doi.org/10.14195/978-989-26-0244-8_71

Cutter, S. L. (2003). The vulnerability of science and the science of vulnerability. *Annals of the Association of American Geographers*, *93*(1), 1–12. https://doi.org/10.1111/1467-8306.93101

da Silva, B. F., dos Santos Rodrigues, R. Z., Heiskanen, J., Abera, T. A., Gasparetto, S. C., Biase, A. G., Ballester, M. V. R., de Moura, Y. M., de Stefano Piedade, S. M., de Oliveira Silva, A. K., & de Camargo, P. B. (2023). Evaluating the temporal patterns of land use and precipitation under desertification in the semi-arid region of Brazil. *Ecological Informatics*, *77*, 102192. https://doi.org/10.1016/j.ecoinf.2023.102192

da Silva, J. L. P., da Silva Junior, F. B., de Souza Santos, J. P. A., dos Santos Almeida, A. C., da Silva, T. G. F., Oliveira-Júnior, J. F., Araújo Júnior, G. D. N., Scheibel, C. H., da Silva, J. L. B., de Lima, J. L. M. P., & da Silva, M. V. (2024). Semi-arid to arid scenario shift: Is the Cabrobó desertification nucleus becoming arid? *Remote Sensing*, *16*(15), 2834. https://doi.org/10.3390/rs16152834

de Oliveira, F. R., Cecílio, R. A., & Zanetti, S. S. (2025). Socioenvironmental vulnerability of rural communities in Espírito Santo, Brazil. *Sustainability*, *17*(9), 4054. https://doi.org/10.3390/su17094054

Ferreira, T. R., Pace, F. T. D., Silva, B. B., & Delgado, J. R. (2017). Identification of desertification-sensitive areas in the Brazilian northeast through vegetation indices. *Engenharia Agrícola*, *37*(6), 1190–1202. https://doi.org/10.1590/1809-4430-eng.agric.v37n6p1190-1202/2017

Freitas, M. I. C., & Cunha, L. (2013). Cartografia da vulnerabilidade socioambiental: Convergências e divergências a partir de algumas experiências em Portugal e no Brasil. *URBE – Revista Brasileira de Gestão Urbana*, *5*(449), 15. https://doi.org/10.7213/urbe.7783

Hermans, K., & McLeman, R. (2021). Climate change, drought, land degradation and migration: Exploring the linkages. *Current Opinion in Environmental Sustainability*, *50*, 236–244. https://doi.org/10.1016/j.cosust.2021.04.013

IBGE. (2010). Downloads estatísticas.

IPCC. (2022). *Climate change and land: IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* (1st ed.). Cambridge University Press. https://www.ipcc.ch/srccl/

Kuhlicke, C., Scolobig, A., Tapsell, S., Steinführer, A., & De Marchi, B. (2011). Contextualizing social vulnerability: Findings from case studies across Europe. *Natural Hazards*, *58*(2), 789–810. https://doi.org/10.1007/s11069-011-9751-6

Kyriazos, T., & Poga, M. (2023). Dealing with multicollinearity in factor analysis: The problem, detections, and solutions. *Open Journal of Statistics*, *13*(3), 404–424. https://doi.org/10.4236/ojs.2023.133020

Mendes, J. M., Tavares, A. O., Cunha, L., & Freiria, S. (2011). A vulnerabilidade social aos perigos naturais e tecnológicos em Portugal. *Revista Crítica de Ciências Sociais*, *93*, 95–128. https://doi.org/10.4000/rccs.90

MMA. (2004). National action program to combat desertification and mitigate the effects of drought PAN-Brazil.

Moura, M. M., Walter, L. S., Lins, T. R. S., Araújo, E. C. G., da Cunha Neto, E. M., Santana, G. M., Brasil, I. S., & Silva, T. C. (2022). Temporal analysis of desertification vulnerability in northeast Brazil using Google Earth engine. *Transactions in GIS*, *26*(4), 2041–2055. https://doi.org/10.1111/tgis.12926

Oliveira, H. C. G., Costa, J. V., & Ojima, R. (2019). Return migration to the Brazilian semi-arid Northern region. *Mercator*, *19*(10), 1–13. https://doi.org/10.4215/rm2019.e18023

Pereira Truká, A. L. S., Florêncio, R. R., & Santos, C. A. B. (2024). Truká: Identidade, cultura e resistência na Ilha da Assunção. *Cadernos Cajuína*, *9*(6), e249601. https://doi.org/10.52641/cadcajv9i6.682

Sathler, D. (2021). Understanding human development, poverty and water scarcity patterns in the Brazilian semi-arid through cluster analysis. *Environmental Science & Policy*, *125*, 167–178. https://doi.org/10.1016/j.envsci.2021.09.004

Sterk, G., & Stoorvogel, J. J. (2020). Desertification–scientific versus political realities. *Land*, *9*(5), 156. https://doi.org/10.3390/land9050156

Tomasella, J., Silva Pinto Vieira, R. M., Barbosa, A. A., Rodriguez, D. A., Oliveira Santana, M. D., & Sestini, M. F. (2018). Desertification trends in the northeast of Brazil over the period 2000–2016. *International Journal of Applied Earth Observation and Geoinformation*, *73*, 197–206. https://doi.org/10.1016/j.jag.2018.06.012

UNCCD. (2019). Land degradation neutrality for biodiversity conservation: How healthy land safeguards nature.

Vieira, R. M. S. P., Sestini, M. F., Tomasella, J., Marchezini, V., Pereira, G. R., Barbosa, A. A., Santos, F. C., Rodriguez, D. A., do Nascimento, F. R., Santana, M. O., Barreto Campello, F. C., & Ometto, J. P. H. B. (2020). Characterizing spatio-temporal patterns of social vulnerability to droughts, degradation and desertification in the Brazilian northeast. *Environmental and Sustainability Indicators*, *5*, 100016. https://doi.org/10.1016/j.indic.2019.100016

You, Y., Zhou, N., & Wang, Y. (2021). Comparative study of desertification control policies and regulations in representative countries of the belt and road initiative. *Global Ecology and Conservation*, *27*, e01577. https://doi.org/10.1016/j.gecco.2021.e01577

Zucherato, B. (2018). *Cartografia da vulnerabilidade socioambiental no Brasil e Portugal: Estudo comparativo entre Campos do Jordão e a Guarda* [Doctoral dissertation, Universidade Estadual Paulista (UNESP)] [Tese de Doutorado em Geografia, Programa de Pós-Graduação em Geografia – IGCE]. https://repositorio.unesp.br/handle/11449/154915

Appendix A

Table 1. Final set of variables used in the construction of the vulnerability index and its corresponding maps

Nº	Variable	Category
1	Residents in permanent private households	socio-environmental, social
2	Average monthly nominal income of heads of permanent private households (with or without income)	socio-environmental, social, rural socio-environmental, urban social environmental
3	Permanent private households	socio-environmental, social, rural social-environmental, urban social environmental
4	Permanent private households in terraced houses or gated communities	socio-environmental, social
5	Permanent private households that are fully owned and paid off	socio-environmental, social, rural social-environmental, urban social environmental
6	Permanent private households supplied with water from the public mains	socio-environmental, environmental, rural social-environmental, urban social environmental
7	Permanent private households supplied with well or spring water on the property	socio-environmental, environmental
8	Permanent private households supplied with rainwater stored in cisterns	socio-environmental, environmental
9	Permanent private households with a toilet or bathroom for exclusive use of the residents	socio-environmental, environmental, rural social-environmental, urban social environmental
10	Permanent private households with an exclusive-use toilet or bathroom and a septic tank sewage system	socio-environmental, environmental
11	Permanent private households without an exclusive-use toilet or bathroom	socio-environmental, environmental, rural social-environmental, urban social environmental
12	Permanent private households with 4 bathrooms for exclusive use of the residents	socio-environmental, environmental
13	Permanent private households with 5 bathrooms for exclusive use of the residents	socio-environmental, environmental
14	Permanent private households with electricity supply	socio-environmental, environmental, rural social-environmental, urban social environmental
15	Permanent private households with 1 resident	socio-environmental, social, rural social-environmental, urban social environmental

Nº	Variable	Category
16	Permanent private households with 6 residents	socio-environmental, social
17	Permanent private households with 7 residents	socio-environmental, social
18	Permanent private households with 8 residents	socio-environmental, social
19	Permanent private households with 9 residents	socio-environmental, social
20	Permanent private households with 10 or more residents	socio-environmental, social, rural social-environmental, urban social environmental
21	Permanent private households without any male resident	socio-environmental, social, rural social-environmental, urban social environmental
22	Permanent private households with a male head and one additional resident	socio-environmental, social, rural social-environmental, urban social environmental
23	Permanent private households with a female head and one additional resident	socio-environmental, social, rural social-environmental, urban social environmental
24	Permanent private houses with exclusive-use toilet or bathroom and public sewage or stormwater drainage	socio-environmental, environmental
25	Terraced houses or gated community households with electricity supply	socio-environmental, environmental
26	Apartments with water supply from the public mains	socio-environmental, environmental
27	Apartments with 4 or more bathrooms for exclusive use of the residents	socio-environmental, environmental
28	Permanent private households with rubbish collection and water supply from the public mains	socio-environmental, environmental, rural social-environmental, urban social environmental
29	Permanent private households with rubbish collection and a bathroom	socio-environmental, environmental
30	Residents in permanent private households	socio-environmental, social, rural social-environmental, urban social environmental
31	Female household heads	socio-environmental, social, rural social-environmental, urban social environmental
32	Female household heads aged 10	socio-environmental, social
33	Female household heads aged 11	socio-environmental, social, rural social-environmental, urban social environmental
34	Literate female household heads	socio-environmental, social

Nº	Variable	Category
35	Literate female household heads aged 10 to 14	socio-environmental
36	Household heads	socio-environmental, social, rural social-environmental, urban social environmental
37	Household heads aged 10	socio-environmental, social
38	Household heads aged 11	socio-environmental, social, rural social-environmental, urban social environmental
39	Literate household heads	socio-environmental, social, rural social-environmental, urban social environmental
40	Literate household heads aged 10 to 14	socio-environmental, social
41	Literate individuals aged 5 or over	socio-environmental, social, rural social-environmental, urban social environmental
42	Residents	socio-environmental, social, rural social-environmental, urban social environmental
43	Residents of white ethnicity or race	socio-environmental, social, rural social-environmental, urban social environmental
44	Residents of black ethnicity or race	socio-environmental, social
45	Residents of mixed ethnicity or race (pardo)	socio-environmental, social, rural socio-environmental, urban social environmental
46	Indigenous residents	socio-environmental, social, rural social-environmental, urban social environmental
47	Opposite-sex partners aged 10	socio-environmental, social
48	Opposite-sex partners aged 11	socio-environmental, social
49	Children aged 10 or under without birth registration	socio-environmental, social
50	Children aged 10 or under who did not know whether they had birth registration (including those with no declaration)	socio-environmental, social
51	Residents in private and collective households	socio-environmental, social, rural social-environmental, urban social environmental
52	Children of the household head and their partner, in private households	socio-environmental, social, rural social-environmental, urban social environmental

Nº	Variable	Category
53	Children only of the household head, in private households	socio-environmental, social
54	Stepchildren in private households	socio-environmental, social
55	Boarders in private households	socio-environmental, social
56	Domestic workers in private households	socio-environmental, social
57	Individuals in collective households	socio-environmental, social, rural social-environmental, urban social environmental
58	People aged 65	socio-environmental, social, rural social-environmental, urban social environmental
59	People aged 100 or over	socio-environmental, social
60	Total of improvised private households	socio-environmental, social, rural social-environmental, urban social environmental
61	Private households with per capita monthly income above 10 minimum wages	socio-environmental, social
62	Fully owned private households – Street identified	socio-environmental, environmental
63	Fully owned private households – Public lighting available	socio-environmental, environmental
64	Fully owned private households – Pavement available	socio-environmental, environmental
65	Fully owned private households – Storm drains available	socio-environmental, environmental
66	Fully owned private households – Wheelchair ramp available	socio-environmental, environmental
67	Fully owned private households – Open sewage present	socio-environmental, environmental
68	Fully owned private households – Rubbish accumulation on streets	socio-environmental, environmental
69	Private households with public water supply – Street identified	socio-environmental, environmental

Source: IBGE (2010). Available in
https://www.ibge.gov.br/estatisticas/downloads-estatisticas.html