ISSN: 2447-3359

REVISTA DE GEOCIÊNCIAS DO NORDESTE

*Northeast Geosciences Journal*

v. 11, nº 1 (2025)

https://doi.org/10.21680/2447-3359.2025v11n1ID36618

# Land use and occupation dynamics and its effect on temperature and precipitation in the Caatinga biome (Seasonally Dry Tropical Forest) - Brazil

# *Dinâmica do uso e ocupação da terra e seu efeito na temperatura e na precipitação no bioma Caatinga (Floresta Tropical Sazonamente Seca) - Brasil*

**Alessandro de Paula[1]; Luiz Fernando Silva Magnago[2]; Cristiano Tagliaferre[3]**

[1] UESB, Department of Agricultural Engineering and Soils, Vitória da Conquista/BA, Brazil. Email: apaula@uesb.edu.br
**ORCID:** https://orcid.org/0000-0003-3676-3846

[2] UFSB, Training Center for Agroforestry Sciences, Itabuna/BA, Brazil. Email: luiz.magnago@ufsb.edu.br
**ORCID:** https://orcid.org/orcid.org/0000-0001-6335-754X

[3] UESB, Department of Agricultural Engineering and Soils, Vitória da Conquista/BA, Brazil. Email: tagliaferre@uesb.edu.br
**ORCID:** https://orcid.org/0000-0003-4776-473X

**Abstract:** The objective of this work was to evaluate the influence of land use and occupation dynamics in the Caatinga biome on precipitation and temperature. The Google Earth Engine platform was used to determine the temperature, precipitation, number of days without rain and of the areas occupied by the classes. Precipitation variability was assessed by the Rainfall Anomaly Index. Trend analyzes were performed using the Mann-Kendall test. Pearson's Correlation Coefficient was calculated between climate variables and land use and land cover classes. The land use and occupation dynamics between 1991 and 2020 demonstrated an advance in anthropized areas. The number of consecutive days without rain, which between 1981 and 1990 had its highest value in September, was observed in October in subsequent decades. An upward trend was observed for temperature between 1991 and 2020. It was not possible to establish a relationship between land use and occupation and precipitation. The reduction in the area occupied by larger formations (forest and savanna) increases the temperature in the region. The change in land use and occupation did not affect precipitation in the region, but had a direct impact on air temperature.

**Keywords:** Climate change; Steppe-savanna; Semi-arid.

**Resumo:** O objetivo deste trabalho foi avaliar a existência de influência da dinâmica do uso e ocupação da terra na Caatinga sobre a precipitação e temperatura. Para a determinação da temperatura, precipitação, número de dias sem chuva e áreas das classes, foi utilizada a plataforma Google Earth Engine. A precipitação foi avaliada pelo Índice de Anomalia de Chuva. As análises de tendência foram realizadas pelo teste de Mann-Kendall. Foi calculado o Coeficiente de Correlação de Pearson entre as variáveis climáticas e as classes de uso e cobertura da terra. A dinâmica do uso e ocupação da terra entre 1991 e 2020 demonstrou um avanço das áreas antropizadas. O número de dias consecutivos sem chuva, que entre 1981 e 1990 tinha seu maior valor em setembro, nas décadas posteriores foi observado em outubro. Para a temperatura foi observada uma tendência de aumento entre 1991 e 2020. Não foi possível estabelecer uma relação entre o uso e ocupação da terra e a precipitação. A redução da área ocupada pelas formações de maior porte (florestal e savânica) aumenta a temperatura na região. A mudança do uso e ocupação da terra não afetou a precipitação na região, mas teve impacto direto na temperatura do ar.

**Palavras-chave:** Mudanças climáticas; Savana-estépica; Semiárido.

Recebido: 11/06/2024; Aceito: 15/10/2024; Publicado: 17/01/2025.

## 1. Introduction

The major topic of current global discussions is climate change caused by industrialization and changes in land use and coverage (MIRZABAEV *et al*., 2022). Within this context, replacing natural areas for developing human activities is one of the main points to be observed. Advanced human activities can be devastating for any biome if it is not based on the rational use of natural resources, in addition to being preceded by planning and supported by environmental legislation. However, depending on the characteristics of the biome, this process can be even more damaging.

The Caatinga is among the unique biomes in the world, which makes it extremely fragile to human impacts solely due to this characteristic (FREIRE *et al*., 2018; SOUZA; ARTIGAS; LIMA, 2015). Furthermore, its vulnerability comes from its singularities, such as drought (predominant in the Northeast region of Brazil), combined with poor rainfall distribution (SILVA *et al*., 2017), and high population density (IBGE, 2013). Approximately 57% of the semi-arid area of the Brazilian Northeast is severely degraded due to its intensive use (MARENGO; TORRES; ALVES, 2017). The effects of degradation and/or desertification can already be observed in 62% of its area (OLIVEIRA *et al.*, 2018).

When compared to humid biomes, the Caatinga is generally associated with low floristic richness and reduced productive capacity, mainly due to the deciduousness of its leaves in the dry season. However, this is one of the areas with the greatest richness among seasonally dry tropical forests (QUEIROZ *et al*., 2018). At least 3,347 species (526 endemic) are known in the Caatinga, distributed in 962 genera (29 endemic) and 153 families (FERNANDES; CARDOSO; QUEIROZ, 2020). Another relevant fact is the species/area ratio observed, which was almost twice as high ($4.0 \times 10^{-3}$ species/km$^2$) when compared to the Amazon rainforest ($2.5 \times 10^{-3}$ species/km$^2$).

Another issue that deserves to be highlighted is its potential for providing ecosystem services. Its biodiversity of native species has several uses, whether for food, homogeneous planting for wood production or medicinal purposes, such as: angico - *Anadenanthera colubrina* (Vell.) Brenan (SILVA; AGUIAR; FREITAS, 2020); umbu - *Spondias tuberosa* Arruda (DIAS *et al*., 2019); and imburana-de-cambão - *Commiphora leptophloeos* (Mart.) J.B.Gillett (MEDEIROS *et al.*, 2022).

The importance of the Caatinga biome is also related to its maintenance of the populations that live in the region and use its natural resources for subsistence and as a means of production (ALBUQUERQUE *et al*., 2017; CUNHA *et al*., 2018; MARENGO; TORRES; ALVES, 2017). However, this use is not always done with adequate management, so the effects of the predatory use of the Caatinga can not only interfere in conservation of the biome, but also in climate variables, with a relevant emphasis on temperature and precipitation. Projections of climate change would cause, among other changes, multi-year drought events above the historical average by 2050 in arid areas of the world. The indication for Brazil is an increase in the frequency, intensity, average duration of drought events (it would increase by 30 months), and in the magnitude of drought, with events that could last up to seven years (JENKINS and WARREN, 2015).

There is an effort by the scientific community to understand the effects of land use and coverage dynamics on climate variables, generally in specific sites in the Brazilian semi-arid region (CUNHA; ALVALÁ; OLIVEIRA, 2013; MARIANO *et al.*, 2018; OLIVEIRA JÚNIOR; PEREIRA; SILVA, 2022; RITO *et al.*, 2017; SOUSA JÚNIOR *et al.*, 2022). Another focus has been given to the relationship between the effect of climate change on dry forests (ALLEN *et al.*, 2017; COSTA *et al.*, 2020b; HASNAT, 2022; ROTENBERG and YAKIR, 2010; SANTOS *et al.*, 2014).

Other factors and positions should be taken into account when analyzing the relationship between climate and land use and land cover. Several authors consider that the variability observed in rainfall in Northeastern Brazil occurs in part due to the action of El Niño and La Niña, while other drought events are attributed to an abnormally northern position of the Intertropical Convergence Zone (ITCZ) (CUNHA *et al.*, 2018; HASTENRATH, 2006; MARENGO; TORRES; ALVES, 2017; SILVA *et al.*, 2017; SPARACINO; ARGIBAY; ESPINDOLA, 2021). Another relevant factor is that the greatest contribution to precipitation comes from evaporation from the oceans, since continental evaporation is responsible for approximately 14% of the total (LIMA, 2008).

Therefore, understanding the influence that changes in land use and land cover in large areas, such as the Caatinga biome, have on climate variables is essential for human activities to be environmentally sustainable and carried out within the carrying capacity of ecosystems. In view of the above, the objective of this study was to evaluate how the land use and occupation dynamics in the Caatinga biome influence precipitation and temperature. To this end, the existence of a tendency for increased or decreased precipitation and temperature was analyzed and a correlation was established with the areas of the main land use and land cover classes in the Caatinga.

## 2. Method

The study covered the entire Caatinga domain area, which was delimited according to IBGE (2004). The biome occupies an area of 844,453 km$^2$, equivalent to 9.9% of the national territory (MAPA and SFB, 2019), being present in a large part of the Northeast and north of Minas Gerais (Figure 1).

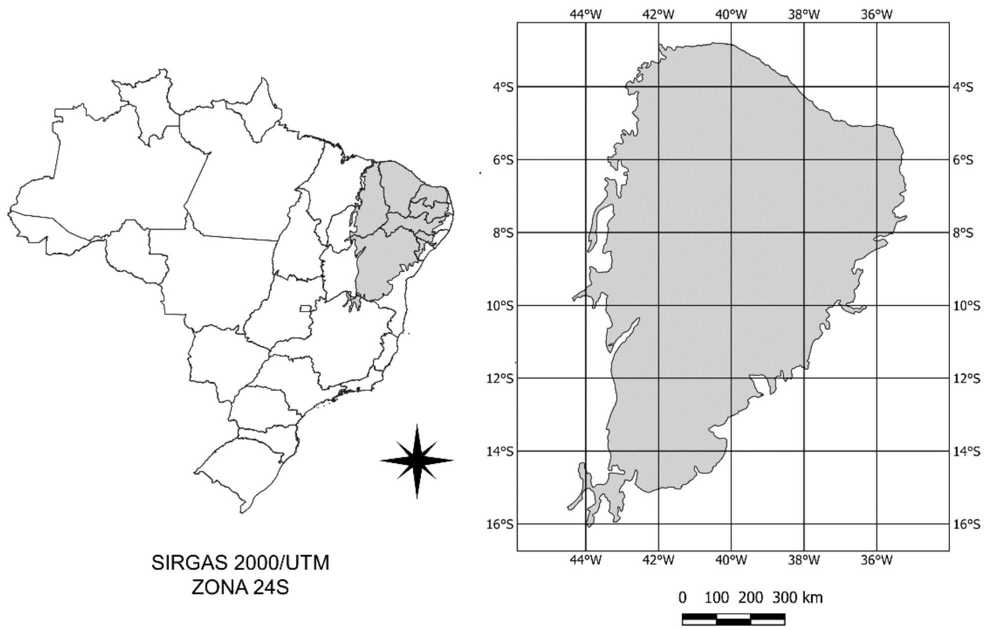



*Figure 1 – Location map of the Caatinga biome, Brazil.*
*Source: Authors (2024).*

The climate classification for most of the biome is hot semi-arid (BSh) according to the Koppen climate classification, with high temperatures, scarcity and irregular distribution of rainfall, with its highest concentration in the summer. The plant types which predominate in the region are Savannah-Steppe (Caatinga) and Savannah (Cerrado), with their respective subgroups (forested, wooded, park and grassy-woody). The term Savannah-Steppe was created by Trochain in 1955, who described a physiognomy formed by trees, shrubs and herbs, without the predominance of trees. The concept of Savannah was introduced by Fernández de Oviedo y Valdes (1851-1855), defining it as xerophytic vegetation, which occurs in different types of climate and in leached soils with the presence of aluminum (IBGE, 2012).

The Google Earth Engine platform was used to determine the mean, maximum and minimum temperature (°C) variables of the air near the surface (2 m) (MUÑOZ-SABATER, 2021), total annual precipitation, rainy and dry seasons (mm), number of days without rain (DWR) (< 1 mm) and the number of consecutive days without rain (CDWR) (FUNK *et al*., 2015), in addition to image processing.

The MapBiomas Project – Collection 7 of the Annual Series of Land Cover and Use Maps of Brazil (SOUZA JÚNIOR *et al*., 2020) was used to determine the forest fragmentation dynamics. The areas occupied by the following classes were calculated from 1991 to 2020: forest formation, savanna formation, grassland formation, pasture, mosaic of uses, urbanized area, other crops and other perennial crops.

The Rainfall Anomaly Index (RAI) (VAN ROOY, 1965), adapted by Freitas (2005), was adopted to analyze precipitation variability:

$$RAI = 3\left[\left(\frac{N-\bar{N}}{\bar{M}-\bar{N}}\right)\right], \text{ for positive anomalies}$$

$$RAI = -3\left[\left(\frac{N-\bar{N}}{\bar{X}-\bar{N}}\right)\right], \text{ for negative anomalies}$$

In which:

- $N$ = annual precipitation (mm);

- $\overline{N}$ = mean precipitation for the period (mm);
- $\overline{M}$ = mean of the 10 highest rainfalls of the period (mm);
- $\bar{X}$ = mean of the 10 lowest rainfalls of the period (mm);
- positive anomalies are precipitation (mm) above average; and
- negative anomalies are precipitation (mm) below average.

Intensity classes were determined according to Table 1.

*Table 1 – Rainfall Anomaly Index (RAI) Intensity Classes).*

| RAI | Intensity class |
|---|---|
| ≥ 4 | Extremely rainy |
| = 2 and < 4 | Very rainy |
| > 0 and < 2 | Rainy |
| 0 | Neutral |
| < 0 and > -2 | Dry |
| ≤ -2 and > -4 | Very dry |
| ≤ -4 | Extremely dry |

*Source: Araújo; Moraes Neto; Sousa (2009).*

The Mann-Kendall test ($\alpha = 0.05$) was used to analyze the trend in total precipitation, DWR, CDWR and temperature (mean, maximum and minimum), which, according to Bombardi and Carvalho (2017), is a method considered robust because it is non-parametric and therefore does not depend on a normal distribution.

In order to assess the existence of trends prior to the period from 1991 to 2020, the previous decade (1981-1990) was also analyzed for DWR and CDWR, and data from 1961 to 1990 for air temperature. The test was performed using the Past 4.02 software (HAMMER; HARPER; RYAN, 2001).

Pearson's Linear Correlation Coefficient (r) was calculated using the "metan" add-on (OLIVOTO and LÚCIO, 2020) of the R software (R CORE TEAM, 2021), between the climate variables and the land use and land cover classes that showed a significant trend according to the Mann-Kendall test ($\alpha = 0.05$).

## 3. Results and discussion

The results showed changes in land use and land cover for the biome between 1991 and 2020 (Figures 2 and 3), with an increase in the pasture areas (4.1%), urbanized area (0.3%), other temporary crop (1.5%) and other perennial crop classes in 2020 (0.5%). This growth was reflected by a reduction of the forest formation (0.1%) and savannah areas (3.8%). The only natural formation which had an increase in its occupied area was the grassland (0.3%).

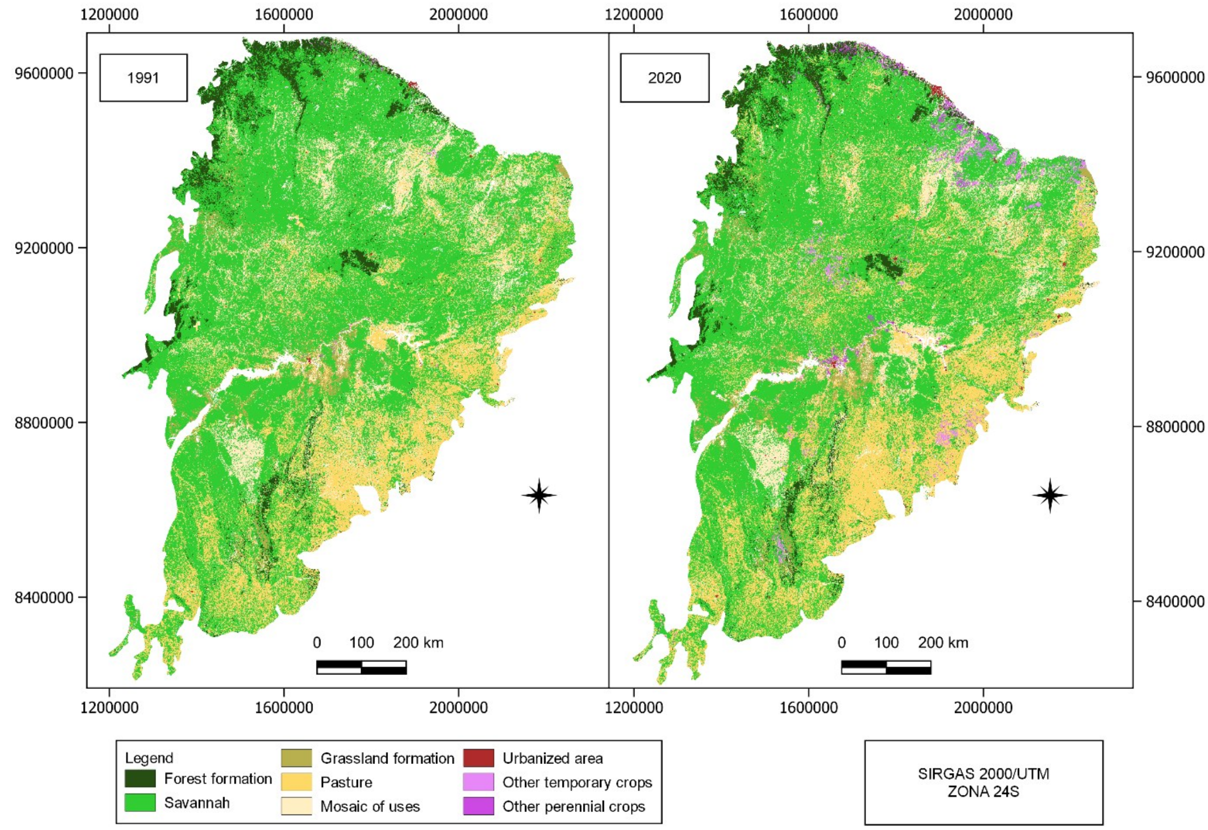



*Figure 2 – Land use and occupation classification in 1991 and 2020 for the Caatinga biome, Brazil. Source: Authors (2024).*

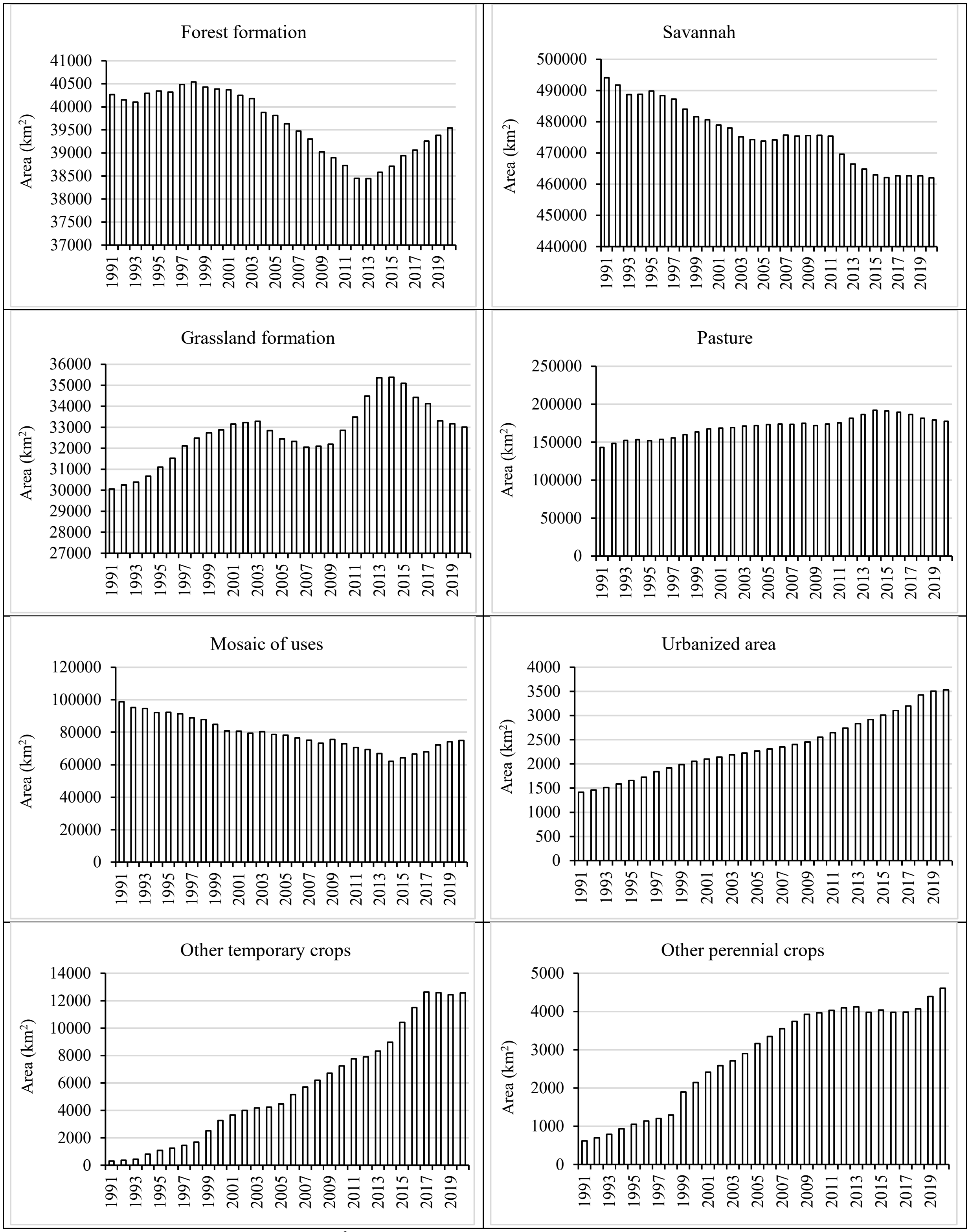



*Figure 3 – Area (km$^2$) by class from 1991 to 2020 for the Caatinga biome, Brazil.*
*Source: Authors (2024).*

The areas affected by anthropogenic activity (pasture, mosaic of uses, urbanized areas, other temporary crops and other perennial crops) which represented 28.9% in 1991 (244,200 $km^2$), and occupied 32.4% in 2020 (273,229 $km^2$).

The mean annual air temperature was 25.6°C, with a maximum average of 27.0°C in November. The rainy season occurred between November and May, concentrating approximately 80% of the annual precipitation (Figure 4). The dry season occurred between June and October, with precipitation below 40 mm. The month with the highest average total precipitation for the period was March with 138.7 mm, with September being the driest month with 7.2 mm..

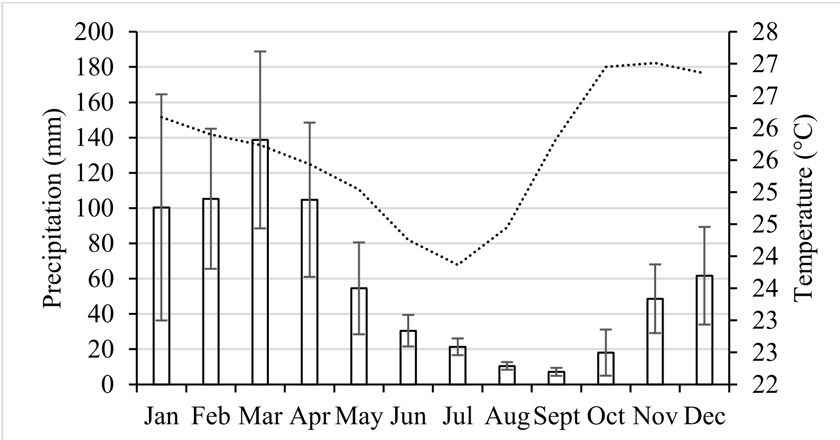



*Figure 4 – Average monthly precipitation and temperature from 1991 to 2020 for the Caatinga biome, Brazil. The error bar represents the standard deviation*
*Source: Authors (2024).*

When analyzing the data seasonally, it was noted that the first and second quarters concentrated the highest percentages of precipitation, with 49.1 and 27.0%, respectively. The third quarter had the lowest precipitation, with only 5.6%, and the fourth quarter showed a recovery, with 18.3%.

The mean annual precipitation in the period was 701.6 mm with a standard deviation of 130.1 mm. The highest precipitation was 963.8 in 2009 and the lowest was in 2012 (406.9 mm). It should also be noted that the total precipitation in 2004, 2008, 2009 and 2020 was above the upper limit of the standard deviation, and these values were therefore considered anomalous due to the large volumes. Four other years were below the lower limit of the standard deviation (1993, 1998, 2012 and 2015); in this case, anomalous due to the low precipitation presented (Figure 5). The averages found in relation to the rainy and dry periods were 606.8 mm and 87.8 mm, with standard deviations of 125.6 and 19.7 mm, respectively.

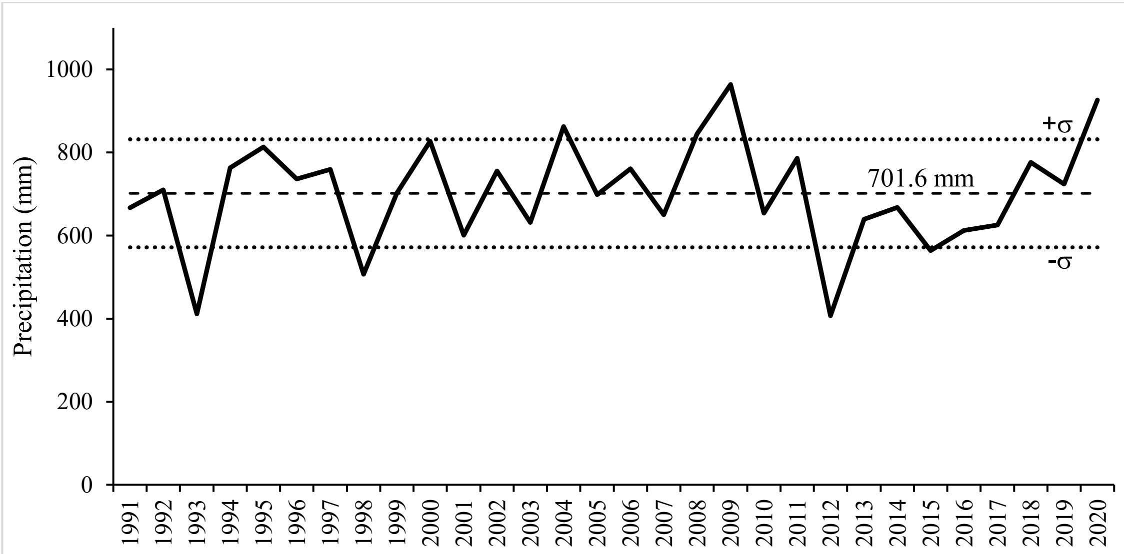



*Figure 5 – Precipitation from 1991 to 2020 for the Caatinga biome, Brazil, in which: solid line = total precipitation, dashed line = mean precipitation, +σ = positive standard deviation, and -σ = negative standard deviation.*
*Source: Authors (2023).*

Figure 6 shows that the RAI was positive in 15 years, negative in 14 and neutral in one. When analyzing the intensity class (Table 1), two years were classified as extremely rainy, four as very rainy, nine as rainy, one as neutral, eight as dry, three as very dry and three as extremely dry. A period with consecutive negative RAIs can be observed between 2012 and 2017.

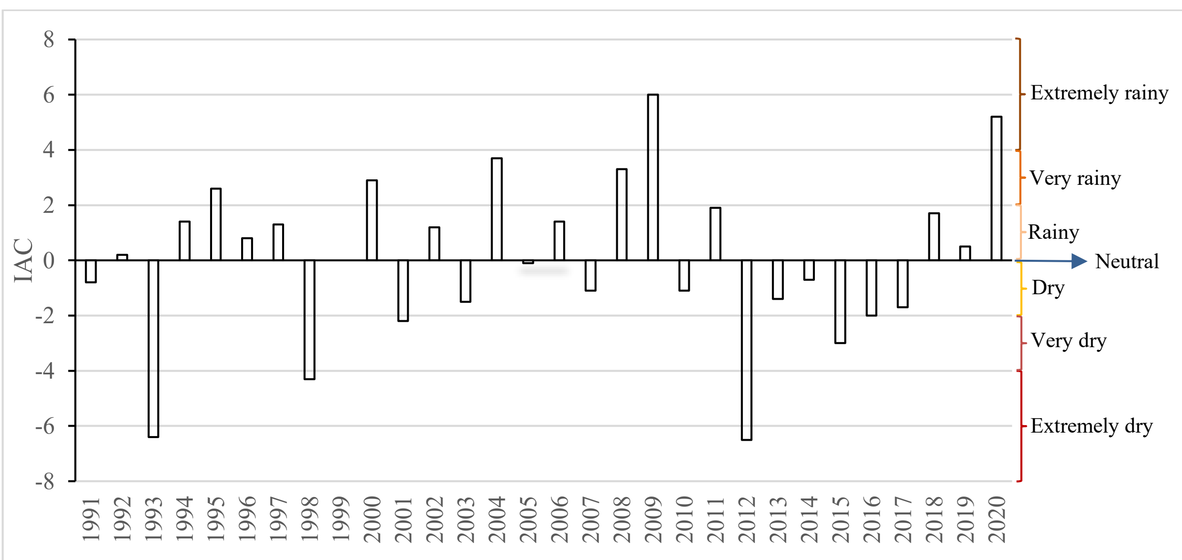



*Figure 6 – Rainfall Anomaly Index (RAI) for the annual total precipitation series from 1991 to 2020 for the Caatinga biome, Brazil.*
*Source: Authors (2024).*

The DWR per year was 208.8 ± 18.1, with no difference in monthly data between the decades analyzed. When checking the CDWR, it is clear that the highest average value in the decade 1981 to 1990 occurred in September (38.3 days). However, there was a shift in the following decades, with the highest values being observed in October. It is worth highlighting a gradual change between 1991 and 2000 with very similar values, in which 40.1 consecutive days without rain were found in September and 41.8 days in October (Figure 7).

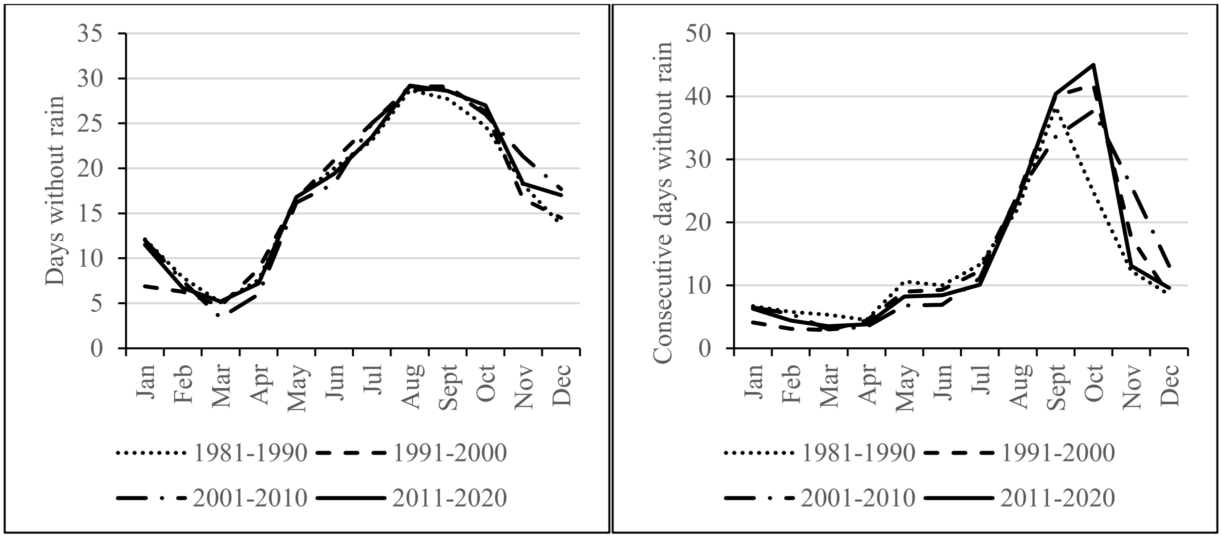



*Figure 7 – Number of days without rain and number of consecutive days without rain (< 1 mm) for the monthly total precipitation series from 1981 to 2020 for the Caatinga biome, Brazil.*
*Source: Authors (2024).*

In Table 2, it is possible to see that there is no statistically significant trend for precipitation (annual total, rainy period and dry period), DWR and CDWR.

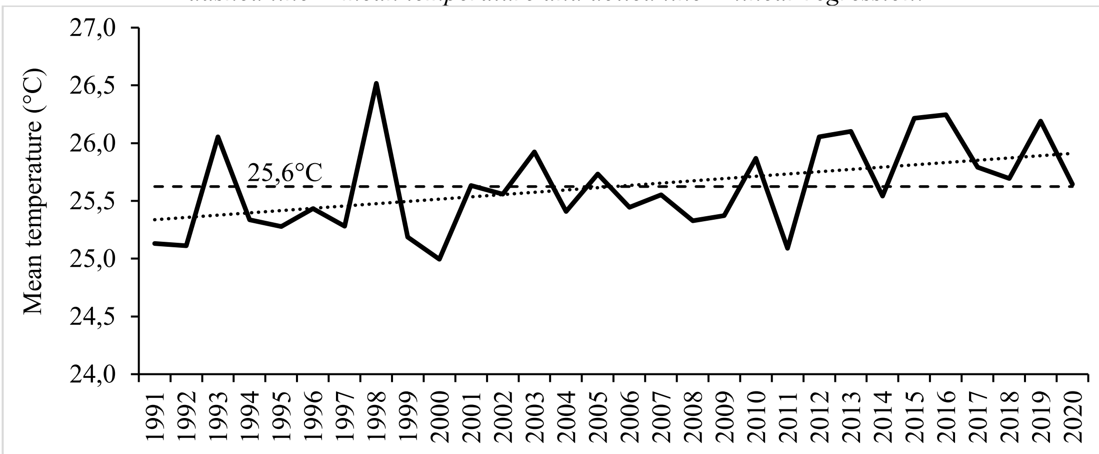
*Table 2 – Analysis of the trend of total annual precipitation, rainy season (November to May), dry season (June to October) and temperature (°C), by the Mann-Kendall test (α = 0.05), for the Caatinga biome, Brazil. Z-value of the Mann-Kendall test.*

| Variables | | Period | Z | p |
|---|---|---|---|---|
| Total precipitation (mm) | annual | 1991 – 2020 | 0.0714 | 0.9431 |
| | rainy | | 0.2498 | 0.8028 |
| | dry | | 0.1784 | 0.8584 |
| No. of days without rain (< 1 mm) | | 1991 – 2020 | 0.0179 | 0.9858 |
| No. of consecutive days without rain (< 1 mm) | | | 0.3750 | 0.7077 |
| Temperature (°C) | mean | 1961 – 1990 | 0.8921 | 0.3724 |
| | maximum | | 0.8207 | 0.4118 |
| | minimum | | 0.7850 | 0.4325 |
| | mean | 1991 – 2020 | 2.319 | 0.0204* |
| | maximum | | 31.273 | 0.0018* |
| | minimum | | 21.076 | 0.0351* |

*Source: Authors (2024).*

The values found regarding the annual mean, maximum and minimum temperatures were 25.6°C, 26.5°C and 25.0°C, respectively. The mean annual temperature in 14 years (46.7%) was higher than the mean for the analyzed period (Figure 8). The lowest mean temperatures were mostly (62.5%) found between 1991 and 2005.

*Figure 8 – Mean annual temperature from 1990 to 2020 for the Caatinga biome, Brazil, where: solid line = temperature, dashed line = mean temperature and dotted line = linear regression.*




*Source: Authors (2024).*

An upward trend of 0.6°C in mean temperature, 0.7°C in maximum temperature and 0.4°C in minimum temperature was observed in the period from 1991 to 2020 (Table 2). Thus, data from the period from 1961 to 1990 were also analyzed in order to verify whether this trend already existed previously, and no statistically significant trend was found.

Figure 9 shows the correlations between temperature and land use and occupation classes. A negative correlation is observed when analyzing the relationship between temperatures (mean, maximum and minimum), forest formation and savanna formation, meaning that the increase in the areas of these natural physiognomies is associated with a reduction in temperature. It is worth noting that the correlation did not present statistical significance for mean and minimum temperature and forest formation. The opposite was observed for grassland formation, a natural physiognomy with a predominance of herbaceous species, where the larger occupied area resulted in a higher mean, maximum and minimum temperature. There was also no statistical significance for the minimum temperature.

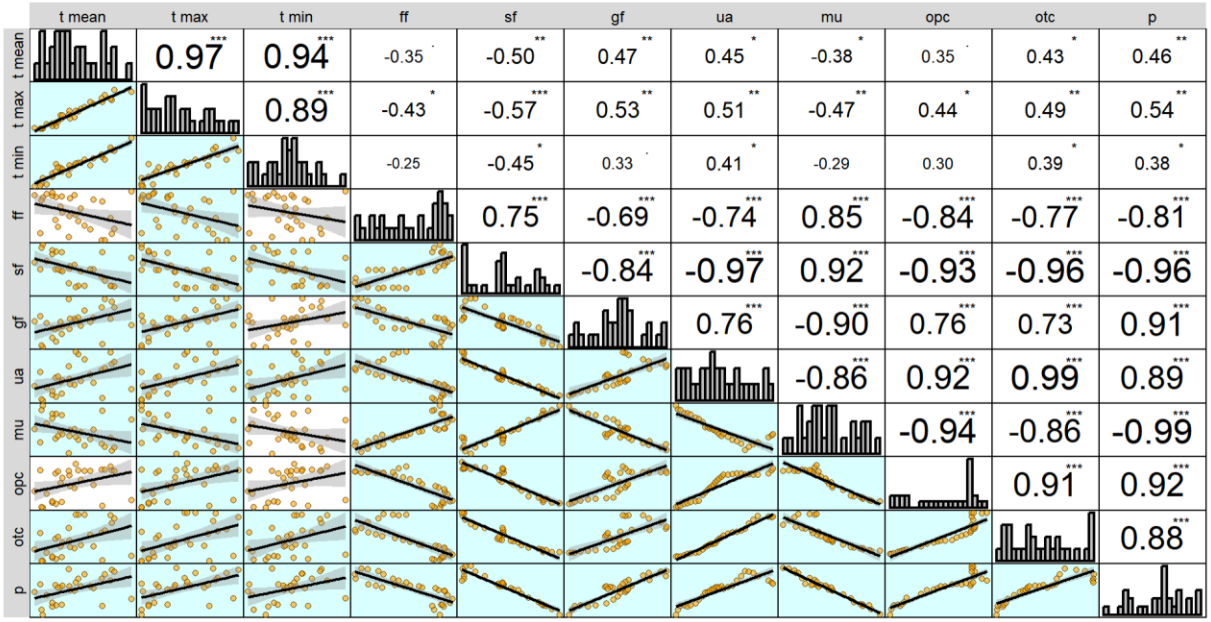



*Figure 9 – Pearson's® Linear Correlation between temperature and land use and land cover classes in the period 1991 to 2020 for the Caatinga biome, Brazil, being: t mean – mean temperature, t max – maximum temperature, t min – minimum temperature, ff – forest formation, sf – savanna formation, gf - grassland formation, ua - urbanized area, mu - mosaic of uses, opc - other perennial crops, otc - other temporary crops, p - pasture, * - statistical significance at 95% probability, ** - statistical significance at 99% probability, and *** - statistical significance at 99.9% probability. Source: Authors (2024).*

Anthropogenic areas, as well as grassland formations, also have a positive correlation, in which the increase in their area is correlated with higher temperatures. No significance was observed with the minimum temperature (Figure 9). This can be verified for both the urbanized area class and for the agricultural classes, such as other perennial crops, other temporary crops and pasture. The mean and minimum temperatures and other perennial crops did not present statistical significance. The exception was the mosaic of uses, which had a negative correlation. This class is defined as "areas of agricultural use where it was not possible to distinguish between pasture and agriculture" or "urban vegetation areas, including cultivated vegetation and natural forest and non-forest vegetation", and it is not possible to determine the characteristics that could explain this behavior, such as its size and density.

This study indicates that changes in land use and coverage in Caatinga should be understood as a concern for the adequate management of this biome (FERNANDES *et al.*, 2015; SILVA *et al.*, 2013; SOUSA JÚNIOR *et al.*, 2022), with the reduction of native forest cover being one of the most important changes in this biome. This reduction was more associated with the advance of agriculture and livestock farming in different Caatinga areas over time (1991-2020) (ALBUQUERQUE *et al.*, 2017; BARBOSA; ANDRADE; ALMEIDA, 2009; COELHO *et al.*, 2014; FERNANDES *et al.*, 2015; SILVA *et al.*, 2009; SOUSA JÚNIOR *et al.*, 2022; SOUSA *et al.*, 2008).

A large oscillation in annual precipitation was observed during the analyzed period, with most events occurring within the standard deviation, indicating few extreme events. However, a drought period was observed between 2012 and 2017. This can be considered the most severe drought in decades, as it had significant impacts on agriculture, industrial production, and the availability of drinking water in wells in rural homes, reducing the level of reservoirs (BRITO *et al.*, 2018; MARENGO; TORRES; ALVES, 2017). In turn, this period negatively affected Caatinga vegetation productivity, as observed through the study of the normalized difference vegetation index (NDVI) (BARBOSA *et al.*, 2019). The existence of these long drought periods can be very critical for plant physiology (SANTOS *et al.*, 2014), which even for Caatinga species (that are mostly adapted to go through severe drought periods) could not withstand. As an example of adaptation, we can mention the greater capacity of deciduous species that have low-density wood (< 0.5 g $cm^{-3}$) to store water in trunks (up to 250% of dry weight) than those with high density (≥ 0.5 g $cm^{-3}$) (LIMA *et al.*, 2012).

Among the extremely dry events (Figure 6), those of 1993 and 1998 are related to the occurrence of El Niño, unlike 2012, when the event was not observed (CUNHA *et al*., 2018). According to the authors, the drought in the latter case was caused by the migration to the north of the ITCZ.

The finding of the lack of a trend for precipitation, DWR and CDWR demonstrates an absence of a relationship between these variables and the reduced native vegetation area. This statement is in agreement with authors who consider that the variation in annual precipitation in the Northeast is mainly related to atmospheric and oceanic characteristics, such as the existence of events such as El Niño, La Niña and ITCZ (RODRIGUES and MCPHADEN, 2014; SPARACINO; ARGIBAY; ESPINDOLA, 2021).

On the other hand, the trend of increasing average temperatures in the period for Northeast Brazil has already been reported by other authors (COSTA *et al*., 2020a; MARENGO and BERNASCONI, 2015; MARENGO; TORRES; ALVES, 2017). Marengo and Bernasconi (2015) also projected an increase in temperature for the Brazilian semi-arid region of 2°C by 2040 compared to the period from 1961 to 1990, constituting a result close to that found in the present study (1.6°C).

The negative correlation between temperatures (average, maximum and minimum) and forest and savanna formations can be explained by the fact that these are physiognomies of greater size (larger basal area per hectare of forest), and therefore have a greater capacity for shading and reducing thermal amplitude. In constrast is the grassland formation, which, due to the predominance of low vegetation, does not have a high shading capacity. Thus, the larger area occupied by this physiognomy can naturally result in a higher temperature. The results observed corroborate those obtained by Gotardo *et al*. (2019), who found a mean daily air temperature which was 9.5% lower in areas with the presence of a forest canopy compared to open areas (without the presence of a canopy and covered by grasses).

## 4. Final considerations

The land use and occupation dynamics in the Caatinga between 1991 and 2020 demonstrated an increase in anthropized areas and a consequent reduction in natural plant areas.

The number of consecutive days without rain shifted from September between 1981 and 1990, to October in subsequent decades. Precipitation (annual, rainy season and dry season) showed no tendency to change.

The mean, maximum and minimum temperature showed no tendency to change between 1961 and 1990, but an increasing tendency was observed between 1991 and 2020.

Negative correlations were observed between the size of the area of the largest physiognomies (forest and savanna) and the temperature, meaning that the reduction in the area occupied by these formations increases the temperature of the environment. The opposite behavior was observed for anthropic areas, where their increase raises the temperature. Given the above, it can be concluded that changes in land use and occupation do not directly affect precipitation in the Caatinga, but have a significant impact on the increase in temperature in this biome.

## Acknowledgements

To the Postgraduate Program in Biosystems for the opportunity, to the Research Support Foundation of the State of Bahia for the scholarship of the first author (Linked Project: 3477/2021, Grant Term: BOL0420/2022).

L. F. S. Magnago was supported by the Research Productivity Grant of the *Conselho Nacional de Desenvolvimento Científico e Tecnológico* (*CNPq*) - Level 2 (307984/2022-2).

## References

ALBUQUERQUE, U. P.; ARAÚJO, E. L.; CASTRO, C. C.; ALVES, R. R. N. People and natural resources in the Caatinga. In: SILVA, J.M.C., LEAL, I.R., TABARELLI, M. **Caatinga.** Cham: Springer International Publishing, 2017. p. 303-333.

ALLEN, K.; DUPUY, J. M.; GEI, M. G.; HULSHOF, C.; MEDVIGY, D.; PIZANO, C.; SALGADO-NEGRET, B.; SMITH, C. M.; TRIERWEILER, A.; VAN BLOEM, S. J.; WARING, B. G.; XU, X.; POWERS, J. S. Will seasonally dry tropical forests be sensitive or resistant to future changes in rainfall regimes? **Environmental Research Letters**, v. 12, n. 2, p. 1-15, 2017.

ARAÚJO, L. E.; MORAES NETO, J. M.; SOUSA, F. A. S. Classificação da precipitação anual e da quadra chuvosa da bacia do rio Paraíba utilizando Índice de Anomalia de Chuva (IAC). **Revista Ambiente e Água**, v. 4, n. 3, p. 93-110, 2009.

BARBOSA, H. A.; KUMAR, T. V. L.; PAREDES, F.; ELLIOTT, S.; AYUGA, J.G. Assessment of Caatinga response to drought using Meteosat-SEVIRI Normalized Difference Vegetation Index (2008–2016). **ISPRS Journal of Photogrammetry and Remote Sensing**, v. 148, p. 235-252, 2019.

BARBOSA, Í. S.; ANDRADE, L. A.; ALMEIDA, J. A. P. Evolução da cobertura vegetal e uso agrícola do solo no município de Lagoa Seca, PB. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 13, n. 5, p. 615-622, 2009.

BOMBARDI, R. J.; CARVALHO, L. M. V. Práticas simples em análises climatológicas: Uma revisão. **Revista Brasileira de Meteorologia**, v. 32, n. 3, p. 311-320, 2017.

BRITO, S. S. B.; CUNHA, A. P. M. A.; CUNNINGHAM, C. C.; ALVALÁ, R. C.; MARENGO, J. A.; CARVALHO, M. A. Frequency, duration and severity of drought in the Semiarid Northeast Brazil region. **International Journal of Climatology**, v. 38, n. 2, p. 517–529, 2018.

COELHO, V. H. R.; MONTENEGRO, S. M. G. L.; ALMEIDA, C. N.; LIMA, E. R. V.; RIBEIRO NETO, A.; MOURA, G. S. S. Dinâmica do uso e ocupação do solo em uma bacia hidrográfica do semiárido brasileiro. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 18, n. 1, p. 64-72, 2014.

COSTA, R. L.; BAPTISTA, G. M. M.; GOMES, H. B.; SILVA, F. D. S.; ROCHA JÚNIOR, R. L.; SALVADOR, M. A.; HERDIES, D. L. Analysis of climate extremes indices over Northeast Brazil from 1961 to 2014. **Weather and Climate Extremes**, v. 28, p. 1-21, 2020a.

COSTA, R. L.; GOMES, H. B.; SILVA, F. D. S.; BAPTISTA, G. M. M.; ROCHA JÚNIOR, R. L.; HERDIES, D. L.; SILVA, V. P. R. Climate change scenarios for the northeast region of brazil through the statistical downscaling technique. **Revista Brasileira de Meteorologia**, v. 35, n. Special Issue, p. 785-801, 2020b.

CUNHA, A. P. M. A.; ALVALÁ, R. C. S.; OLIVEIRA, G. S. Impactos das mudanças de cobertura vegetal nos processos de superfície na região semiárida do Brasil. **Revista Brasileira de Meteorologia**, v. 28, n. 2, p. 139-152, 2013.

CUNHA, A. P. M. A.; TOMASELLA, J.; RIBEIRO-NETO, G. G.; BROWN, M.; GARCIA, S. R.; BRITO, S. B.; CARVALHO, M. A. Changes in the spatial-temporal patterns of droughts in the Brazilian Northeast. **Atmospheric Science Letters**, v. 19, n. 10, p. 1-8, 2018.

DIAS, J. L.; MAZZUTTI, S.; SOUZA, J. A. L.; FERREIRA, S. R. S.; SOARES, L. A. L.; STRAGEVITCH, L.; DANIELSKI, L. Extraction of umbu (Spondias tuberosa) seed oil using CO2, ultrasound and conventional methods: evaluations of composition profiles and antioxidant activities. **The Journal of Supercritical Fluids**, v. 145, p. 10-18, 2019.

FERNANDES, M. F.; CARDOSO, D.; QUEIROZ, L. P. An updated plant checklist of the Brazilian Caatinga seasonally dry forests and woodlands reveals high species richness and endemism. **Journal of Arid Environments**, v. 174, p. 1-8, 2020.

FERNANDES, M. R. M.; MATRICARDI, E. A. T.; ALMEIDA, A. Q.; FERNANDES, M. M. Mudanças do uso e de cobertura da terra na região semiárida de Sergipe. **Floresta e Ambiente**, v. 22, n. 4, p. 472-482, 2015.

FREIRE, N. C. F.; MOURA, D. C.; SILVA, J. B.; MOURA, A. S.; MELO, J. I. M.; PACHECO, A. P. **Atlas das caatingas: o único bioma exclusivamente brasileiro.** Recife: Fundação Joaquim Nabuco, Editora Massangana, 2018. p.200: il.

FREITAS, M. A. S. Um sistema de suporte à decisão para o monitoramento de secas meteorológicas em regiões semi-áridas. **Revista Tecnologia**, v. Suplemento, p. 84-95, 2005.

FUNK, C.; PETERSON, P.; LANDSFELD, M.; PEDREROS, D.; VERDIN, J.; SHUKLA, S.; HUSAK, G.; ROWLAND, J.; HARRISON, L.; HOELL, A.; MICHAELSEN, J. The climate hazards infrared precipitation with stations - a new environmental record for monitoring extremes. **Scientific Data**, v. 2, n. 1, p. 1-21, 2015.

GOTARDO, R.; PINHEIRO, A.; PIAZZA, G. A.; KAUFMANN, V.; TORRES, E. Comparação entre variáveis microclimáticas de local aberto e florestal em um bioma da Mata Atlântica, sul do Brasil. **Ciencia Florestal**, v. 29, n. 3, p. 1415-1427, 2019.

HAMMER, Ø.; HARPER, D. A. T.; RYAN, P. D. PAST: Paleontological Statistics software package for education and data analysis. **Paleontologia Eletronica**, v. 4, n. 1, p. 1-9, 2001.

HASNAT, G. N. T. Climate change effects, adaptation, and mitigation techniques in tropical dry forests. In: KHOSROW-POUR, M. **Research Anthology on Environmental and Societal Impacts of Climate Change**. Pennsylvania: IGI Global, 2022. cap. 3, p. 42–64.

HASTENRATH, S. Circulation and teleconnection mechanisms of Northeast Brazil droughts. **Progress in Oceanography**, v. 70, n. 2-4, p. 407-415, 2006.

IBGE - INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. **Atlas do censo demográfico 2010**. Rio de Janeiro: IBGE, 2013. 160 p.

IBGE - INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. **Manual técnico da vegetação brasileira.** Rio de Janeiro: IBGE, 2012. 271 p.

IBGE - INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. **Mapa de biomas do Brasil. Escala 1:5.000.** Rio de Janeiro: IBGE, 2004.

JENKINS, K.; WARREN, R. Quantifying the impact of climate change on drought regimes using the Standardised Precipitation Index. **Theoretical and Applied Climatology**, v. 120, n. 1-2, p. 41-54, 2015.

LIMA, A. L. A.; SAMPAIO, E. V. S. B., CASTRO, C. C.; RODAL, M. J. N.; ANTONINO, A. C. D.; MELO, A. L. Do the phenology and functional stem attributes of woody species allow for the identification of functional groups in the semiarid region of Brazil? **Trees - Structure and Function**, v. 26, n. 5, p. 1605-1616, 2012.

LIMA, W. P. **Hidrologia florestal aplicada ao manejo de bacias hidrográficas.** Piracicaba: Escola Superior de Agricultura Luiz de Queiroz, 2008. 253 p.

MAPA - MINISTÉRIO DA AGRICULTURA, PECUÁRIA E ABASTECIMENTO; SFB - SERVIÇO FLORESTAL BRASILEIRO. **Florestas do Brasil em resumo: 2019.** Brasília: MAPA/SFB, 2019. 207 p.

MARENGO, J. A.; BERNASCONI, M. Regional differences in aridity/drought conditions over Northeast Brazil: present state and future projections. **Climatic Change**, v. 129, n. 1-2, p. 103–115, 2015.

MARENGO, J. A.; TORRES, R. R.; ALVES, L. M. Drought in Northeast Brazil-past, present, and future. **Theoretical and Applied Climatology**, v. 129, n. 3-4, p. 1189-1200, 2017.

MARIANO, D. A.; SANTOS, C. A. C.; WARDLOW, B. D.; ANDERSON, M. C.; SCHILTMEYER, A. V.; TADESSE, T.; SVOBODA, M. D. Use of remote sensing indicators to assess effects of drought and human-induced land degradation on ecosystem health in Northeastern Brazil. **Remote Sensing of Environment**, v. 213, p. 129-143, 2018.

MEDEIROS, W. P.; PAULA, A.; BARRETO-GARCIA, P. A. B.; LEMOS, O. L. Population structure, diametric distribution and use of *Commiphora leptophloeos* (Mart.) J.B.Gillett in arboreal Caatinga. **Revista Ceres**, v. 69, n. 1, p. 62-69, 2022.

MIRZABAEV, A.; STRINGER, L. C.; BENJAMINSEN, T. A.; GONZALEZ, P.; HARRIS, R.; JAFARI, M.; STEVENS, N.; TIRADO, C. M.; ZAKIELDEEN, S. 2022: Cross-Chapter Paper 3: Deserts, Semiarid Areas and Desertification. In: PÖRTNER, H.-O.; ROBERTS, D. C.; TIGNOR, M.; POLOCZANSKA, E. S.; MINTENBECK, K.; ALEGRÍA, A.; CRAIG, M.; LANGSDORF, S.; LÖSCHKE, S.; MÖLLER, V.; OKEM, A.; RAMA, B. **Climate Change 2022:**

**Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change**. Cambridge and New York: Cambridge University Press, 2022. p. 2195-2231.

MUÑOZ-SABATER, J.; DUTRA, E.; AGUSTÍ-PANAREDA, A.; ALBERGEL, C.; ARDUINI, G.; BALSAMO, G.; BOUSSETTA, S.; CHOULGA, M.; HARRIGAN, S.; HERSBACH, H.; MARTENS, B.; MIRALLES, D. G.; PILES, M.; RODRÍGUEZ-FERNÁNDEZ, N. J.; ZSOTER, E.; BUONTEMPO, C.; THÉPAUt, J. N. ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. **Earth System Science Data**, v. 13, n. 9, p. 4349-4383, 2021.

OLIVEIRA JÚNIOR, I.; PEREIRA, A. J.; SILVA, B.-C. M. N. Uso e cobertura da terra no trópico semiárido: da apropriação ambiental às feições da desertificação. **Caderno de Geografia**, v. 32, n. 69, p. 619-648, 2022.

OLIVEIRA, F. C. S.; MENEZES, L. S., OLIVEIRA, R. R.; BENTO-SILVA, J. S. Considerações sobre unidades de conservação na Caatinga. In: SANTOS, C. A. B.; ANDRADE, W. M.; SILVA, J. S. B. **Sustentabilidade do Bioma Caatinga**. Paulo Afonso: SABEH, 2018. p. 14-32.

OLIVOTO, T.; LÚCIO, A. D. C. Metan: An R package for multi-environment trial analysis. **Methods in Ecology and Evolution**, v. 11, n. 6, p. 783-789, 2020.

QUEIROZ, L. P.; CARDOSO, D.; FERNANDES, M. F.; MORO, M. F. Diversity and evolution of flowering plants of the Caatinga Domain. In: SILVA, J. M. C.; LEAL, I. R.; TABARELLI, M. **Caatinga the largest tropical dry forest region in South America**. Gewerbestrasse: Springer International Publishing, 2018. p. 23-64.

R CORE TEAM. **R: A language and environment for statistical computing**. Vienna, Austria. R Foundation for Statistical Computing, 2021. Disponível em: <https://www.R-project.org/>. Acesso em: 5 mar. 2023

RITO, K. F.; ARROYO-RODRÍGUEZ, V.; QUEIROZ, R. T.; LEAL, I. R.; TABARELLI, M. Precipitation mediates the effect of human disturbance on the Brazilian Caatinga vegetation. **Journal of Ecology**, v. 105, n. 3, p. 828-838, 2017.

RODRIGUES, R. R.; MCPHADEN, M. J. Why did the 2011-2012 la Niña cause a severe drought in the Brazilian Northeast? **Geophysical Research Letters**, v. 41, n. 3, p. 1012-1018, 2014.

ROTENBERG, E.; YAKIR, D. Contribution of Semi-Arid Forests to the climate system. **New Series**, v. 22, n. 5964, p. 451-454, 2010.

SANTOS, M. G.; OLIVEIRA, M. T.; FIGUEIREDO, K. V.; FALCÃO, H. M.; ARRUDA, E. C. P.; ALMEIDA-CORTEZ, J.; SAMPAIO, E. V. S. B.; OMETTO, J. P. H. B.; MENEZES, R. S. C.; OLIVEIRA, A. F. M.; POMPELLI, M. F.; ANTONINO, A. C. D. Caatinga, the Brazilian dry tropical forest: can it tolerate climate changes? **Theoretical and Experimental Plant Physiology**, v. 26, n. 1, p. 83-99, 2014.

SILVA, A. P. N.; MOURA, G. B. A.; GIONGO, P. R.; SILVA, A. Dinâmica espaço-temporal da vegetação no semiárido de Pernambuco. **Revista Caatinga**, v. 22, n. 4, p. 195-205, 2009.

SILVA, A. R.; SANTOS, T. S.; QUEIROZ, D. É.; GUSMÃO, M. O.; SILVA, T. G. F. Variações no índice de anomalia de chuva no semiárido. **Journal of Environmental Analysis and Progress**, v. 2, n. 4, p. 377-384, 2017.

SILVA, E. A.; FERREIRA, R. L. C.; SILVA, J. A. A.; SÁ, I. B.; DUARTE, S. M. A. Dinâmica do uso e cobertura da terra do município de Floresta, PE. **Floresta**, v. 43, n. 4, p. 611-620, 2013.

SILVA, E. L. G. S.; AGUIAR, H. T. V.; FREITAS, R. F. Estudo fitoquímico, atividade antioxidante e tóxica da casca da *Anadenanthera colubrina* (Vell.) Brenan. **Biodiversidade**, v. 19, n. 2, p. 97-106, 2020.

SILVA, E. L. G. S.; AGUIAR, H. T. V.; FREITAS, R. F. Estudo fitoquímico, atividade antioxidante e tóxica da casca da *Anadenanthera colubrina* (Vell.) Brenan. **Biodiversidade**, v. 19, n. 2, 2020.

SOUSA JÚNIOR, V. P.; SPARACINO, J.; ESPINDOLA, G. M.; ASSIS, R. J. S. Land-use and land-cover dynamics in the Brazilian Caatinga Dry Tropical Forest. **Conservation**, v. 2, n. 4, p. 739-752, 2022.

SOUSA, R. F.; BARBOSA, M. P.; SOUSA JÚNIOR, S. P.; NERY, A. R.; LIMA, A. N. Estudo da evolução espaço-temporal da cobertura vegetal do município de Boa Vista-PB, utilizando geoprocessamento. **Revista Caatinga**, v. 21, n. 3, p. 22-30, 2008.

SOUZA, B. I.; ARTIGAS, R. C.; LIMA, E. R. V. **Caatinga e desertificação**. Mercator (Fortaleza), v. 14, p. 131-150, 2015.

SOUZA JÚNIOR, C. M.; SHIMBO, J. Z.; ROSA, M. R.; PARENTE, L. L.; ALENCAR, A. A.; RUDORFF, B. F. T.; HASENACK, H.; MATSUMOTO, M.; FERREIRA, L. G.; SOUZA-FILHO, P. W. M.; OLIVEIRA, S. W.; ROCHA, W. F.; FONSECA, A. V.; MARQUES, C. B.; DINIZ, C. G.; COSTA, D.; MONTEIRO, D.; ROSA, E. R.; VÉLEZ-MARTIN, E.; WEBER, E. J.; LENTI, F. E. B.; PATERNOST, F. F.; PAREYN, F. G. C.; SIQUEIRA, J. V.; VIERA, J. L.; FERREIRA NETO, L. C.; SARAIVA, M. M.; SALES, M. H.; SALGADO, M. P. G.; VASCONCELOS, R.; GALANO, S.; MESQUITA, V. V.; AZEVEDO, T. Reconstructing three decades of land use and land cover changes in Brazilian biomes with Landsat archive and Earth Engine. **Remote Sensing**, v. 12, n. 2735, p. 1-27, 2020.

SPARACINO, J.; ARGIBAY, D. S.; ESPINDOLA, G. Long-term (35 years) rainy and dry season characterization in semiarid northeastern Brazil. **Revista Brasileira de Meteorologia**, v. 36, n. 3, p. 377-391, 2021.

VAN ROOY, M. P. A rainfall anomaly index independent of time and space. **Notos**, v. 14, n. 43, p. 6, 1965.