sociedade
& natureza

DOI: 10.14393/SN-v37-2025-73957
Received: June 11, 2024 | Accepted: October 30, 2024 | Published: January 10, 2025

Papers

Thornthwaite Moisture Index for the Triângulo Mineiro, Brazilian Cerrado Region, Under Climate Change

João Alberto Fischer Filho[1]
Giovani Bonício Rosa[2]
Júlia Cristina Amâncio Vieira[3]
Daniela Fernanda da Silva Fuzzo[4]

Keywords
IPCC
Water deficit
Water surplus
Climate zones

Abstract

Climate change represents one of the main challenges of the 21st century for planning and sustainable development. However, little is known about how climate change can affect a region's climate zones. The objective was to evaluate probable changes in climatic zones using the Thornthwaite climate classification (1948). Historical series between 1981 and 2021 of rainfall and air temperature were used. The water balance was calculated from Thornthwaite and Mather. Thornthwaite's humidity index (1948) was used to classify localities according to their level of humidity and the scenarios RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 to analyze projections for the 21st century (period 2081–2100). The current characterization, with historical data, of the region's climate presented air temperature, rainfall and average potential evapotranspiration, respectively, of 22.4ºC, 1,318.8 mm and 1,123.74 mm, in addition to a water surplus of 391.04 mm and water deficit of 195.04 mm. The region currently has five climate indices, with a prevalence of more humid classes (B1, B2 and B3), corresponding to 62% of the territory. The results derived from the projections indicate reductions in climate classes and an increase in the area occupied by drier climates. For example, the percentage of area occupied by class C1 (dry subhumid) would increase from the current 8.4% to 69.68% in the RCP 8.5 scenario. The study of these change projections is important since profound consequences for the hydrology, ecology and social area of the region will take place, potentially harming agriculture, the region's main economic activity.

[1] Universidade do Estado de Minas Gerais - UEMG, Frutal, MG, Brazil. joao.fischer@uemg.br
[2] Universidade do Estado de Minas Gerais - UEMG, Frutal, MG, Brazil. giovanirosa0410@gmail.com
[3] Universidade do Estado de Minas Gerais - UEMG, Frutal, MG, Brazil. julia.amancio.521@gmail.com
[4] Universidade do Estado de Minas Gerais - UEMG, Frutal, MG, Brazil. daniela.fuzzo@uemg.br

INTRODUCTION

Delimiting the climate of a region makes it possible to establish some indicators of the physical environment's potential for a given location. Thus, when using tools that aim to study climate impacts on the development of human activities, especially agriculture, more assertive responses in agricultural production are likely to be obtained.

Climatic classification aims to identify, in a large area or region, zones with relatively homogeneous climatic and biogeographical characteristics. This classification is necessary to establish strategies aimed at the most appropriate management of natural resources (Bieniek *et al.*, 2012). To characterize the climate of a region, climate classification systems (CCS) are used.

Among the CCS, the one proposed by Thornthwaite (1948) stands out, which is considered the most important in studies of agriculture, ecology and water resources precisely because it uses climatological water balance (CWB) in its methodology. In this classification, the plant is considered the physical means by which it is possible to transport water from the soil to the atmosphere (Rolim *et al.*, 2007), thus presenting greater sensitivity in defining climatic limits, as it detects small spatial variations with greater efficiency (Li *et al.*, 2022). This makes this system more advantageous, which justifies its use in the present study.

Climate change is largely caused by human actions, and affects humanity, as well as animals, plants and ecosystems (Wheeler; von Braun, 2013; Talchabhadel; Karki, 2019). In the last century, global temperature has increased by 1°C (± 0.2°C), and according to the Intergovernmental Panel on Climate Change (IPCC, 2023), forecasts for 2100 indicate increases between 1.5°C and 6°C. It is evident that changes in the current climate can alter the entire water classification of a region, impacting ecosystems and, consequently, economic activities (Shen *et al.*, 2018; Thayer *et al.*, 2020).

It is presumed that the acceleration of climate change will have major implications for climatic zones and may cause significant zonal changes (Mahlstein *et al.*, 2013). Consequently, studies on the impact of climate projections on the climatic and hydrological behavior of regions are essential to minimize damage to various economic activities, such as agriculture (Michalak, 2020).

In order to study future climate projections, the so-called RCPs (Representative Concentration Pathways) can be used, which are trajectories of greenhouse gas and aerosol concentrations in the Earth's atmosphere. They are used in climate modeling studies to explore different emission scenarios and understand how different levels of greenhouse gases can affect the global climate (Pulkkinen *et al.*, 2024). These different scenarios are useful for understanding the consequences of climate change mitigation policies and for planning adaptation measures.

Several studies aim to characterize the climate of a region and adopt climate change scenarios (Montes-Veja *et al.*, 2023; Elguindi *et al.*, 2014; Yang *et al.*, 2016). A recent study by Martins *et al.* (2018) aimed to carry out the current climate classification and future projections for the state of Minas Gerais, Brazil. However, for the Triângulo Mineiro region, the authors used data from only three surface meteorological stations, which tends to reduce the quality of information and make its spatialization difficult. Therefore, new studies that adopt new acquisition methodologies and a greater volume of data are crucial to obtain more accurate and current information.

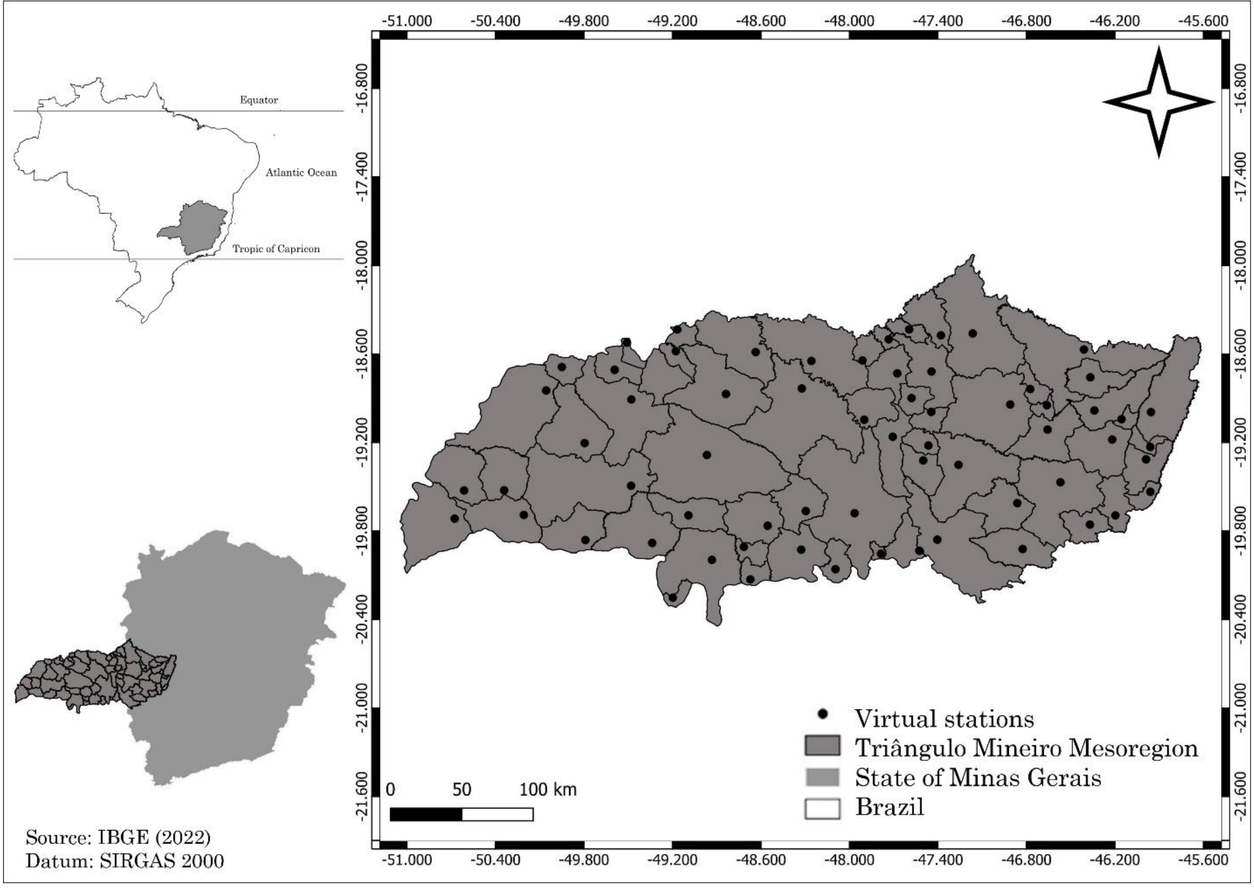
Based on this, the objective was to climatically characterize the Triângulo Mineiro region, in the Brazilian Cerrado, using the Thornthwaite moisture index, for the current and future climate change scenarios.

MATERIALS AND METHODS

Study region

The study was carried out in the Triângulo Mineiro mesoregion, Brazil, which is predominantly characterized as a Cerrado biome. The region comprises 66 municipalities and covers an area of 90,545 km², with an average altitude of 769 m (Figure 1). This region stands out in agriculture, with agribusiness being one of the predominant activities in the region due to the suitability of the soils and favorable climatic conditions (Araújo; Araújo Sobrinho, 2020).

Figure 1 - Location map of the Triângulo Mineiro region, Brazil



Source: IBGE (2022)
Datum: SIRGAS 2000

Source: The authors (2023).

The region's climate is classified as Aw according to the Köppen classification, characterized as tropical with alternating wet and dry seasons, and Semi-dry Tropical of South-Central Brazil (Tr*scb) according to the Novais and Machado (2023), whit an average annual rainfall of 1374 mm and an average annual temperature of 24.7°C (Fuzzo *et al.*, 2024).

Meteorological data

The NASA Power system (Stackhouse *et al.*, 2015) was developed to provide meteorological information for direct use in architecture, power generation and agrometeorology. It compiles information from multiple direct data sources and those derived from gridded data systems. For example, real-time daily data for temperature and relative humidity are obtained from the Global Model and Assimilation Office (GEOS-4) system, and rainfall data are obtained from the Global Precipitation Climate Project (Maldonado Júnior *et al.*, 2019).

Data between 1981 and 2021 was retrieved, via http requests. The data used were total daily rainfall (mm) and average, minimum and maximum daily temperatures (°C). Virtual stations (Figure 1) were used for all 66 municipalities in the Triângulo Mineiro region, Brazil.

Climatological water balance

The climatological water balance was calculated according to Thornthwaite and Mather (1955). Soil water storage (STR), water deficit (DEF) and water surplus (SUR) of the soil-plant-atmosphere system were estimated.

To determine potential evapotranspiration, the equation proposed by Thornthwaite (1948) was used (Equations, 1, 2, 3, 4 and 5), which presents good accuracy in estimating PET for the region (Rosa *et al.*, 2023).

$$\mathrm{PET} = \mathrm{ETp} \times \mathrm{Cor} \tag{1}$$

$$\mathrm{Cor} = \left(\frac{\mathrm{ND}}{30}\right) \times \left(\frac{\mathrm{N}}{12}\right) \tag{2}$$

$$\mathrm{I} = (0{,}2 \times \mathrm{Tn})^{1{,}514} \tag{3}$$

$$\mathrm{ETp} = -415{,}85 + 23{,}24 \times \mathrm{T} - 0{,}43 \times \mathrm{T}^2,\ \text{for T} \geq 26{,}5°\mathrm{C} \tag{4}$$

$$\mathrm{ETp} = 16 \times \left(10 \times \frac{\mathrm{T}}{\mathrm{I}}\right),\ \text{for } 0°\mathrm{C} \leq \mathrm{T} \leq 26{,}5°\mathrm{C} \tag{5}$$

In which:

PET – potential evapotranspiration (mm day^{-1});
T – average air temperature (°C);
ND – number of days;
N – photoperiod (hours);
Tn – average monthly temperature (°C);
I – monthly heat index (°C).

The calculated water balance uses the available water capacity (AWC) of 100 mm, which is the value that represents the characteristics of the soils in the region (Latossolo) and the used value in studies for soil moisture (Novais *et al.*, 2018; Lorençone *et al.*, 2022).

Moisture indices

The moisture indices proposed by Thornthwaite (1948) became popular among the scientific community and are a widely accepted climate classifier and were therefore adopted to characterize the places studied as humid and dry. The calculations of aridity, water and humidity indices were determined according to Equations 6, 7 and 8.

$$I_w = \frac{\mathrm{SUR}}{\mathrm{PET}} \times 100 \qquad (6)$$

$$I_a = \frac{\mathrm{DEF}}{\mathrm{PET}} \times 100 \qquad (7)$$

$$I_m = I_w - 0{,}6 \times I_a \qquad (8)$$

In which:

I_w – water index;
I_a – aridity index;
I_m – moisture index.

To classify the region's climate, Thornthwaite's climate classification (1948) was used based on the moisture index (Table 1), for each city studied.

Table 1 - Climatic classes, based on the moisture index

Climatic types		**Moisture index (I_m)**
Class	**Type**	
A	Perhumid	$100 \leq I_m$
B_4	Humid	$80 \leq I_m < 100$
B_3	Humid	$60 \leq I_m < 80$
B_2	Humid	$40 \leq I_m < 60$
B_1	Humid	$20 \leq I_m < 40$
C_2	Subhumid	$0 \leq I_m < 20$
C_1	Dry subhumid	$-33{,}3 \leq I_m < 0$
D	Semi arid	$-66{,}7 \leq I_m < 33{,}3$
E	Arid	$-100 \leq I_m < -66{,}7$

Source: Thornthwaite (1948). Elaborated by the authors (2023).

Analyses

The representative concentration pathways (RCPs) receive their names according to the levels of radioactive forces, in W/m² (Hartin *et al.*, 2015). In this work, the RCP 2.6, RCP 4.0, RCP 6.0 and RCP 8.5 scenarios were used to analyze projections for the end of the 21st century, between the years 2081 and 2100, using the BCC-CSM2MR global climate model developed in the Beijing Climate Center (BCC), obtained by the WorldClim (2023).

The moisture indices calculated in the various tested scenarios made it possible to generate maps using the interpolation method, with the IDW model (Valjarević *et al.*, 2022), nearest neighbor and resolution of 0.25° (25 km), using the Qgis *software*.

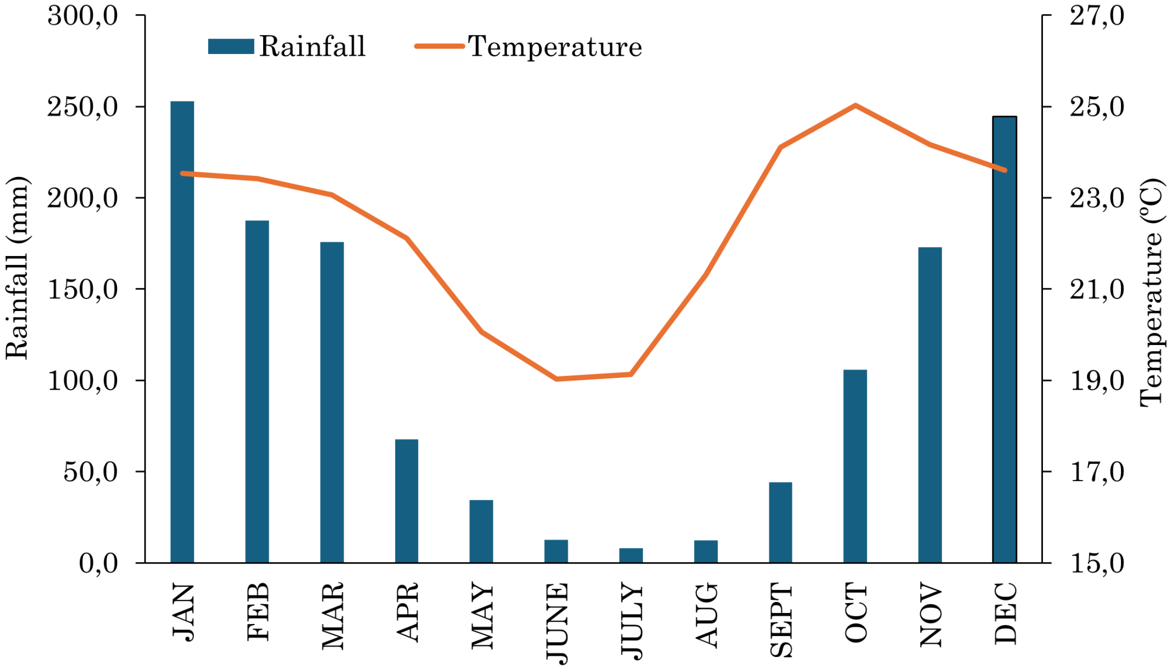
RESULTS AND DISCUSSION

Moisture index for the current scenario

The moisture index proposed by Thornthwaite (1948) is based on the relationship between water availability and evapotranspiration, considering factors such as temperature and rainfall (Souza *et al.*, 2013). Based on this, a current characterization of these factors, with historical data, becomes necessary.

The air temperature in the Triângulo Mineiro region showed a pattern in monthly variation (Figure 2). Monthly air temperature values varied between 16.2 and 28.0°C, with an average annual air temperature of 22.4°C (±1.02°C). High air temperatures in the region occurred between January and March and from September to December, with an average of 23.9°C, with October being the hottest month in the region with 25.0°C. However, the air temperature decreases between April and August, with an average of 20.3°C, July standing out with an average temperature of 19.0 °C.

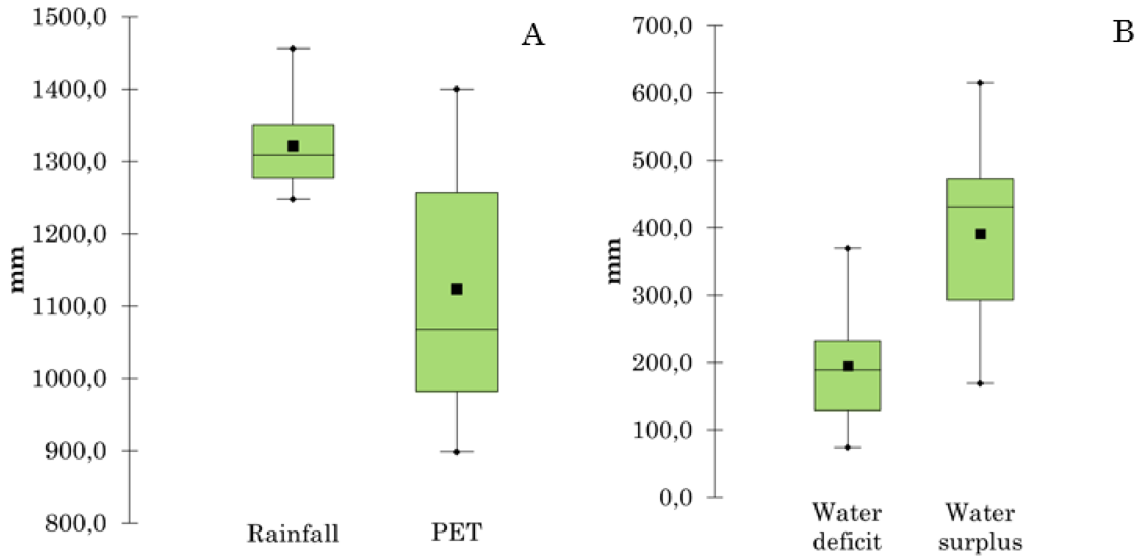
Figure 2 - Monthly air temperature variation (°C) and rainfall (mm) for the Triângulo Mineiro-MG, Brazil



Source: The authors (2023).

The average annual rainfall accumulated in the Triângulo Mineiro was 1,318.8 mm (± 52.0 mm) (Figure 2 and Figure 3A). The annual distribution of precipitation in the region varies between months, with rainfall concentrated in the hottest periods of the year. The lowest rainfall values were observed from May to September. However, rainfall increased from January to March and from November to December, representing 91.6% of the total volume of rainfall for the year in the region.

Figure 3 - Box plot graphs of rainfall and potential evapotranspiration (A), and water deficit and water surplus (B) for the Triângulo Mineiro, Brazil



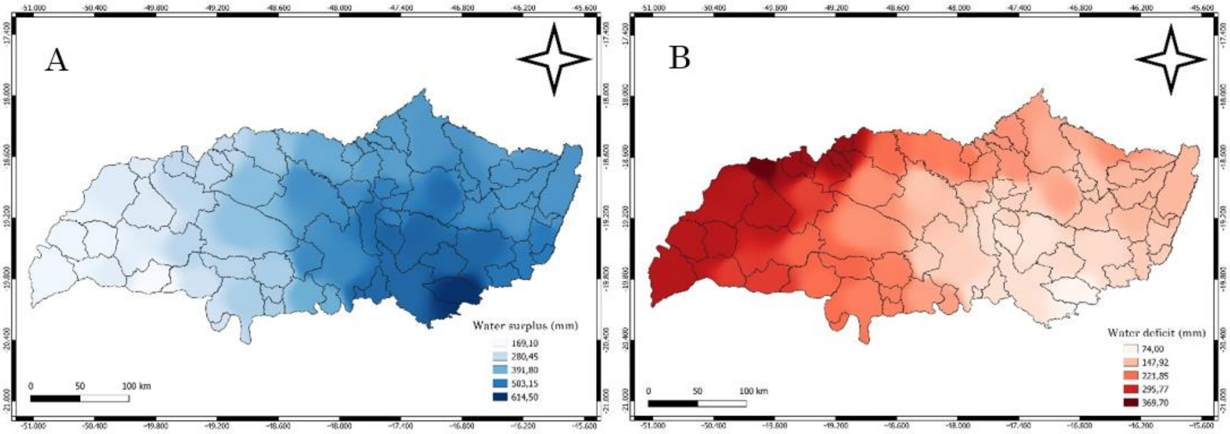
Source: The authors (2023).

According to Sanches *et al.* (2017) the reduction in rainfall and relative humidity in the months of October, together with the increase in temperatures (maximum, average and minimum) are directly related to the permanence of tropical atmospheric systems over the Brazilian continent, that is, atmospheric blocking, which prevents the penetration and advance of polar systems. Corroborating the results, Fuzzo *et al.* (2023) carried out rainfall mapping for the southern region of the Triângulo Mineiro, Brazil, with 20 years of rainfall data, and identified periods of rainy seasons, with emphasis on the month of January, and dry seasons, especially the month of July.

The annual potential evapotranspiration (PET) for the Triângulo Mineiro region is 1,123.74 mm (±149.2 mm) (Figure 3A), with greater dispersion of data in relation to rainfall. The PET determines the demand for water in each region, being widely used in different fields (Xiang *et al.*, 2020), such as hydrology and climatology. Regarding climate characterization, the high PET values present in the region directly interfere with the water balance in the soil, altering the water deficit and surplus in the area (Figure 3B).

The interannual distribution patterns of water surplus (SUR) and water deficit (DEF) in the studied municipalities were similar (Figure 3B). The DEF for the region presented an average of 195.04 mm (± 77.54 mm) and the SUR average of 391.04 mm (± 113.71 mm). Figure 4 shows the spatial distribution of the water deficit and surplus for the Triângulo Mineiro region.

Figure 4 - Spatial distribution of water surplus (A) and deficit (B) for the Triângulo Mineiro region



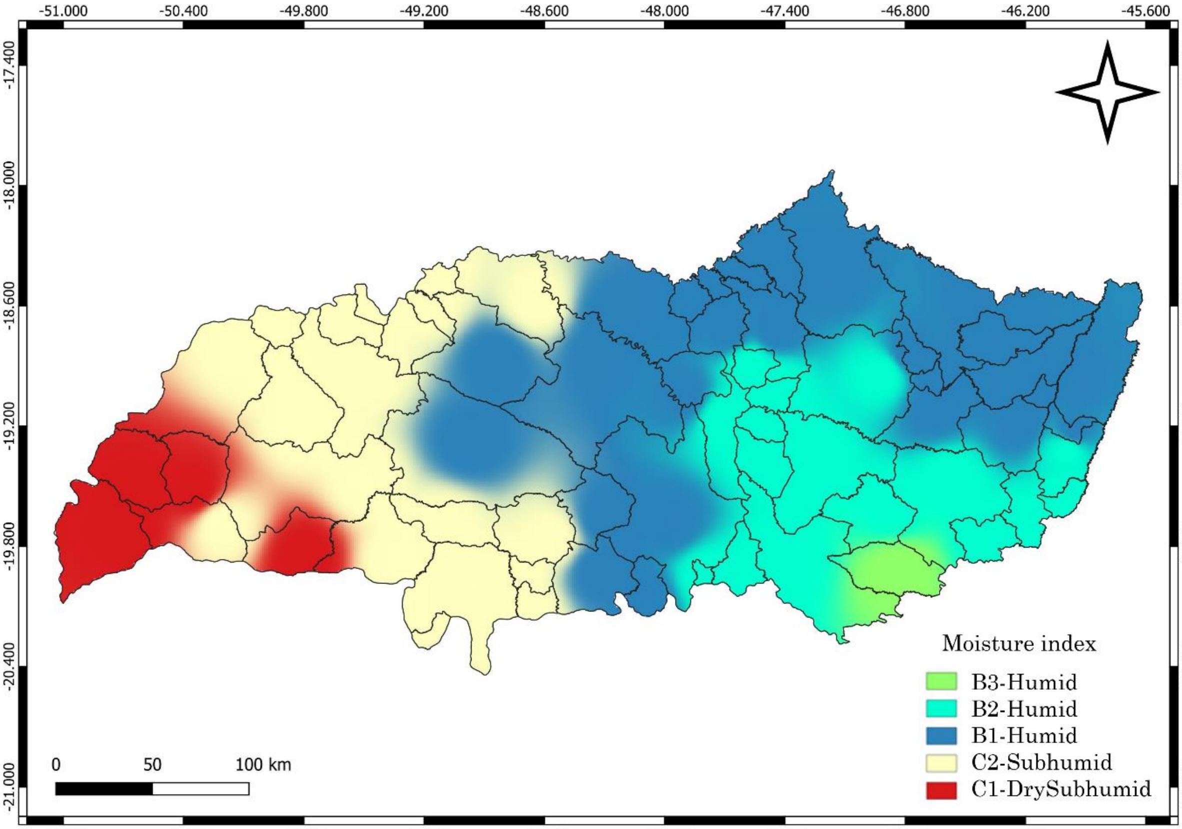
Source: The authors (2023).

The increase in DEF and reduction in EXC in the Triângulo Mineiro region occurred in the western direction (Figure 4). The highest water deficit values were observed as latitude decreased and longitude increased. This region is known as Pontal do Triângulo Mineiro, Brazil, and is characterized by high temperatures and low thermal amplitude (close to 2ºC) (Mello *et al.*, 2007).

The topographic decline towards the Paraná river (at the junction of the Parnaíba and Grande rivers) directly influences the temperature distribution and consequent evapotranspiration in the study area. At the top of the relief located to the east, temperatures are below 19ºC on average throughout the year, while in Pontal, to the west, the altitude is below 400 m and the continentality causes the average annual temperature to rise to 26ºC (Novais *et al.*, 2018). Therefore, such conditions directly affect the climate classification of the region.

According to the humidity index (Iu), the Triângulo Mineiro region presented five types of climates: that is, B1 (humid), B2 (humid), B3 (humid), C2 (subhumid) and C1 (dry subhumid) (Figure 5). The greater number of climatic subtypes is a characteristic of the Thornthwaite classification system due to its greater sensitivity (Phumkokrux; Trivej, 2024).

Figure 5 - Thornthwaite moisture index for the current scenario in the Triângulo Mineiro region, Brazil



Source: The authors (2023).

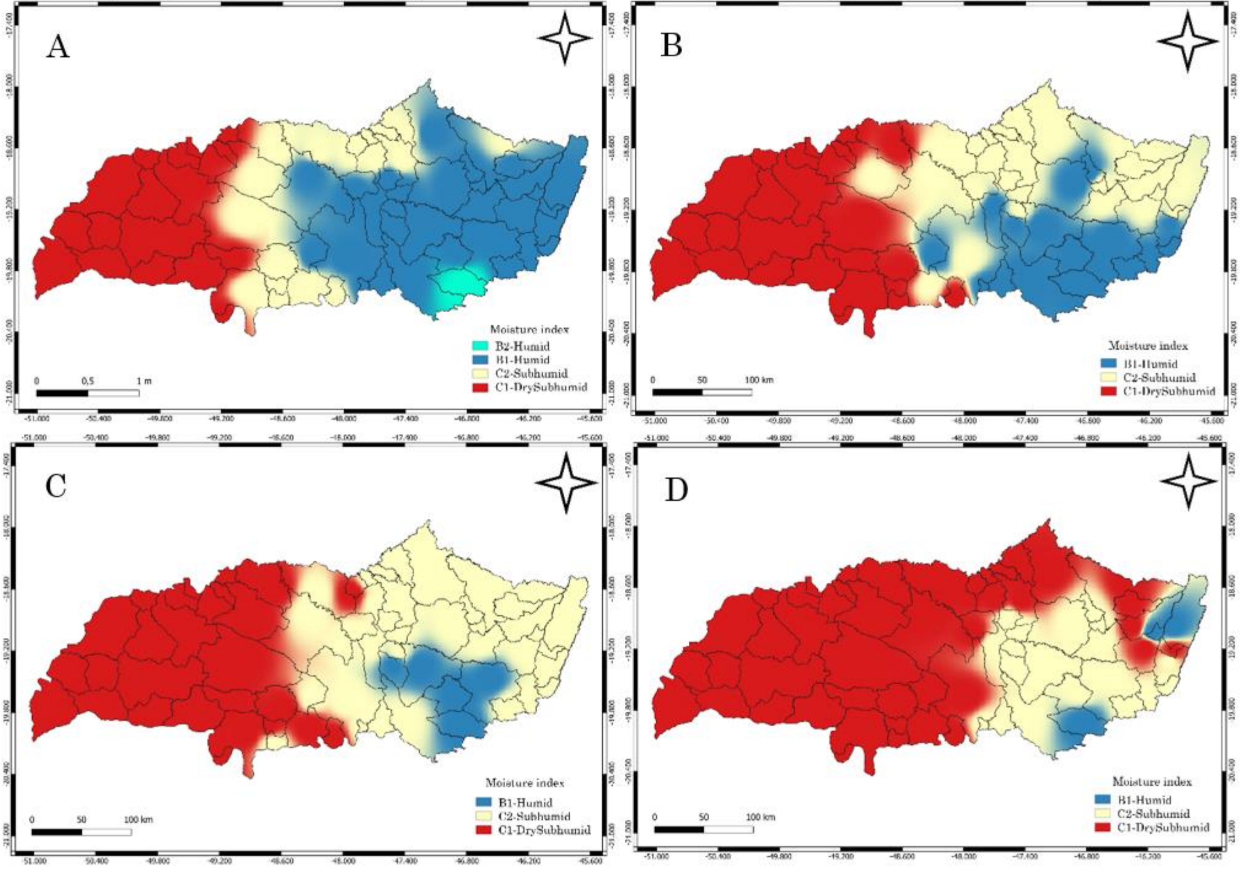
Subtype B1 has the greatest significance in the region, covering 40.70% of the total area, while B3 had the lowest presence, covering only 2.12% of the Triângulo Mineiro region. The B1 subtype is characterized by being present in subtropical climate regions with a humid climate (Karim *et al.*, 2021), characteristic of the study region. In agreement with the results obtained for soil water deficit, subtypes C1 and C2, characterized by being subhumid and dry subhumid, covered a large part of the western region of the Triângulo Mineiro, as previously described.

In a study developed by Lorençone *et al.* (2022), which adopted the moisture index, it was observed that the state of Mato Grosso do Sul presented four types of climates, namely B1 (humid), B2 (humid), B3 (humid) and C2 (subhumid). The authors further report that it was already expected due to the sensitivity of Thornthwaite's classification criteria.

Moisture index for climate change scenarios

In relation to possible climate change scenarios, between the period 2081-2100, the end of the 21st century, there was variation in the distribution of the moisture index in the Triângulo Mineiro region (Figure 6).

Figure 6 - Thornthwaite climatic classification for climate change scenarios in the Triângulo Mineiro region, Brazil. A) RCP 2.6; B) RCP 4.5; C) RCP 6.0 and D) RCP 8.5



Source: The authors (2023).

The main changes in the current scenario (Figure 2), with the different climate scenarios, were the significant reduction of the wetter climate classes and the advancement of the drier subclasses, starting from the first scenario studied (RCP 2.6). Future changes in climate will be characterized by a significant contraction in the humid region and an expansion of the arid/humid transition zones (Ma *et al.*, 2019; Baronetti *et al.*, 2022), like what was observed in the Triângulo Mineiro region.

In work carried out by Sanches *et al.* (2017) on the effect of climate change on the cities of Uberaba (1961-2015) and Capinópolis (1971-2015), located in the study region of this work, the authors suggest that rising temperatures are affecting the decrease in rainfall and causing longer dry seasons. Furthermore, the delay in the rainy season combined with the expansion of cultivation areas, population growth and rising temperatures has severely affected the availability of water resources and worsened water stress.

When analyzing climate change scenarios, a reduction in moisture index classes is observed (Table 2). In the RCP 2.6 scenario, four classes are present, with a substantial reduction in humid subtypes for the region.

Table 2 - Percentage of the Triângulo Mineiro territory for moisture index classes, in current and future climate change scenarios for the period 2081-2100

	B3 Humid	B2 Humid	B1 Humid	C2 Subhumid	C1 Dry subhumid
Current (%)	2,12	20,57	40,70	28,21	8,4
RCP 2.6 (%)	-	2,14	44,14	24,14	29,58
RCP 4.5 (%)	-	-	23,04	36,55	40,42
RCP 6.0 (%)	-	-	9,35	45,29	45,37
RCP 8.5 (%)	-	-	4,46	25,87	69,68

Source: The authors (2023).

The RCP 4.5 and 6.5 scenarios were similar, presenting three classes, with an increase in subhumid classes and a predominance of subtype C1, with values greater than 40.0% of the area (Table 2). Rahimi *et al.* (2019), in a study for Southwest Asia, observed that the changes in moisture indices proposed by Thornthwaite's classification (Thornthwaite, 1948), because of climate changes associated with the RCP 4.5 and RCP 8.5 scenarios, suggest a general trend of drying and warming in most of the region, compared to historical conditions.

For the RCP 8.5 scenario, characterized as one with high levels of greenhouse gases in the atmosphere, there is a great predominance of class C1 – Dry subhumid, with almost 70.0% of the region occupied by this subtype. This highlights a major concern, as the reduction in humidity in the region could directly impact the main economic activity in the region, agriculture, which could lead to a decrease in local agricultural productivity (Srivastava *et al.*, 2018).

Feng *et al.* (2014), in a more in-depth analysis, suggest that changes in precipitation played a slightly more important role in causing changes in climate type during the 20th century. However, projected changes in temperature play an increasingly important role and predominate over changes in climate type as warming becomes more pronounced in the 21st century. In line, Sylla *et al.* (2015) predict that global warming will increase evapotranspiration and the frequency and intensity of extreme climate events in the 21st century, altering soil water storage, which was in fact observed in the projections modeled in the present work.

Given this, the Brazilian Cerrado may be directly affected by climate change, as the biome could face direct consequences in terms of biodiversity, water resources, agriculture and the regional economy. Environmental conservation will be essential to mitigate adverse effects, requiring effective environmental management policies, sustainable agricultural practices and collaborative efforts between governments, local communities and environmental organizations. Furthermore, it is essential to promote public awareness about the importance of implementing measures to reduce greenhouse gas emissions to further minimize the impacts of climate change on this ecosystem.

FINAL CONSIDERATIONS

The predominant climate in the Triângulo Mineiro region, Brazil, is classified as B1 (humid). The Triângulo Mineiro has two well-defined periods throughout the year: a dry period and a rainy period. The five predominant types of climates in the Triângulo Mineiro, according to the Thornthwaite (1948) classification, are B1 (humid), B2 (humid), B3 (humid), C2 (subhumid) and C1 (dry subhumid).

The water characterization of the Triângulo Mineiro showed an average of 398.84 mm year^{-1} of water surplus, 191.08 mm year^{-1} of water deficit and 1,215.4 mm year^{-1} of potential evapotranspiration. The water deficit and potential evapotranspiration increase towards the west, being an important region for the recharge of springs and underground aquifers.

Climate projections show, in all scenarios, a reduction in the area classified as humid in the region (B3, B2, B1). The RCP 8.5 Scenario in 2081-2100 is the most worrying situation of all, as the region could experience drastic changes in its climate.

Based on predicted changes in climate in the study region, it can be concluded that the results can support risk analyses, particularly for agricultural production systems, and encourage scientists and interested parties to develop and evaluate adaptation strategies.

ACKNOWLEDGMENTS

To the Fundação de Amparo à Pesquisa do Estado de Minas Gerais (Fapemig), for the financial support and for granting a scholarship to the second author; Programa de Bolsas de Produtividade em Pesquisa (PQ/UEMG), for granting scholarships to the first and fourth authors; and Programa Institucional de Apoio à Pesquisa (PAPQ/UEMG), for granting a scholarship to the third author.

FUNDING SOURCE

Programa de Bolsas de Produtividade em Pesquisa (PQ/UEMG).

Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG).

REFERENCES

ARAÚJO, D. F. C.; ARAÚJO SOBRINHO, F. L. A dinâmica do setor sucroenergético no Triângulo Mineiro/Alto Paranaíba. **Cerrados**, v. 18, n. 1, p. 248-277, 2020. https://doi.org/10.46551/rc24482692202001

BARONETTI, A.; DUBREUIL, V.; PROVENZALE, A.; FRATIANNI, S. Future droughts in northern Italy: high-resolution projections using EURO-CORDEX and MED-CORDEX ensembles. **Climatic Change**, v. 172, p. 22, 2022. https://doi.org/10.1007/s10584-022-03370-7

BIENIEK, P. A.; BHATT, U. S.; THOMAN, R. L.; ANGELOFF, H.; PARTAIN, J.; PAPINEAU, J.; FRITSCH, F.; HOLLOWAY, E.; WALSH, J. E.; DALY, C.; SHULSKI, M. Climate divisions for Alaska based on objective methods. **Journal of Applied Meteorology and Climatology**, v. 51, p. 1276–1289, 2012. https://doi.org/10.1175/JAMC-D-11-0168.1

ELGUINDI, N.; GRUNDSTEIN, A.; BERNARDES, S.; TURUNCOGLU, U.; FEDDEMA, J. Assessment of CMIP5 global model simulations and climate change projections for the 21 st century using a modified Thornthwaite climate classification. **Climatic change**, v. 122, p. 523-538, 2014. https://doi.org/10.1007/s10584-013-1020-0

FENG, S.; HU, Q.; HUANG, W.; HO, C. H.; LI, R.; TANG, Z. (2014). Projected climate regime shift under future global warming from multi-model, multi-scenario CMIP5 simulations. **Global and Planetary Change**, v. 112, p. 41-52, 2014. https://doi.org/10.1016/j.gloplacha.2013.11.002

FUZZO, D. F. S.; ASSUNÇÃO, F. J. M.; FUZZO, B. E.; FISCHER FILHO, J. A. Tendências e padrões de variação em séries temporais de temperatura do ar e precipitação na microrregião de Frutal – MG. **Revista Brasileira De Geografia Física**, v. 17, n. 3, p. 1977–1991, 2024. https://doi.org/10.26848/rbgf.v17.3.p1977-1991

FUZZO, D. F. S.; FERREIRA DA SILVA, L.; FISCHER FILHO, J. A. Google Earth Engine applied to rainfall mapping in Triângulo Sul Mineiro – Brazil. **Agua Y Territorio Water and Landscape**, v. 23, e7282, 2023. https://doi.org/10.17561/at.23.7282

HARTIN, C. A.; PATEL, P.; SCHWARBER, A.; LINK, R. P.; BOND-LAMBERTY, B. P. A simple object-oriented and open-source model for scientific and policy analyses of the global climate system–Hector v1. 0. **Geoscientific Model Development**, v, 8, n. 4, p. 939-955, 2015. https://doi.org/10.5194/gmd-8-939-2015

IBGE. INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. **Cidades e estados:** Minas Gerais. 2022. Available: https://www.ibge.gov.br/cidades-e-estados/mg.html. Accessed on: May 8, 2024.

IPCC. INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE. Summary for policymakers. IN: LEE, H.; ROMERO, J. (Eds.). **Climate change 2023**: synthesis report: contribution of working groups I, II and III to the sixth assessment report of the Intergovernmental Panel on Climate Change. Geneva: IPCC, 2023. p. 1-34.

KARIM, M. R.; RAHMAN, M. M.; NGUYEN, K.; CAMERON, D.; IQBAL, A.; AHENKORAH, I. Changes in Thornthwaite Moisture Index and reactive soil movements under current and future climate scenarios—A case study. **Energies**, v. 14, n. 20, p. 6760, 2021. https://doi.org/10.3390/en14206760

LI, Y.; QIN, Y.; RONG, P. Evolution of potential evapotranspiration and its sensitivity to climate change based on the Thornthwaite, Hargreaves, and Penman–Monteith equation in environmental sensitive areas of China. **Atmospheric Research**, v. 273, p. 106178, 2022.

https://doi.org/10.1016/j.atmosres.2022.106178

LORENÇONE, J. A.; APARECIDO, L. E. D. O; LORENÇONE, P. A.; LIMA, R. F. D.; TORSONI, G. B. Assessment of climate change using humidity index of Thornthwaite climate classification in Pantanal biome. **Revista Brasileira de Meteorologia**, v. 37, p. 99-119, 2022. https://doi.org/10.1590/0102-7786370075

MA, D.; DENG, H.; YIN, Y.; WU, S.; ZHENG, D. Sensitivity of arid/humid patterns in China to future climate change under a high-emissions scenario. **Journal of Geographical Sciences**, v. 29, p. 29-48, 2019. https://doi.org/10.1007/s11442-019-1582-5

MAHLSTEIN, I.; DANIEL, J. S.; SOLOMON, S. Pace of shifts in climate regions increases with global temperature. **Nature Climate Change**, v. 3, n. 8, p. 739-743, 2013. https://doi.org/10.1038/nclimate1876

MALDONADO JÚNIOR, W.; VALERIANO, T. T. B.; DE SOUZA ROLIM, G. EVAPO: A smartphone application to estimate potential evapotranspiration using cloud gridded meteorological data from NASA-POWER system. **Computers and Electronics in Agriculture**, v. 156, p. 187-192, 2019. https://doi.org/10.1016/j.compag.2018.10.032

MARTINS, F. B.; GONZAGA, G.; DOS SANTOS, D. F.; REBOITA, M. S. Classificação climática de Köppen e de Thornthwaite para Minas Gerais: cenário atual e projeções futuras. **Revista Brasileira de Climatologia**, v. 14, p. 129-156, 2018. https://doi.org/10.5380/abclima.v1i0.60896

MELLO, C. R. D.; SÁ, M. A. C. D.; CURI, N.; MELLO, J. M. D.; VIOLA, M. R.; SILVA, A. M. D. Erosividade mensal e anual da chuva no Estado de Minas Gerais. **Pesquisa Agropecuária Brasileira**, v. 42, p. 537-545, 2007. https://doi.org/10.1590/S0100-204X2007000400012

MICHALAK, D. Adapting to climate change and effective water management in Polish agriculture–At the level of government institutions and farms. **Ecohydrology & Hydrobiology**, v. 20, n. 1, p. 134-141, 2020. https://doi.org/10.1016/j.ecohyd.2019.12.004

MONTES-VEGA, M. J.; GUARDIOLA-ALBERT, C.; RODRÍGUEZ-RODRÍGUEZ, M. Calculation of the SPI, SPEI, and GRDI Indices for Historical Climatic Data from Doñana National Park: Forecasting Climatic Series (2030–2059) Using Two Climatic Scenarios RCP 4.5 and RCP 8.5 by IPCC. **Water**, v. 15, n. 13, p. 2369, 2023. https://doi.org/10.3390/w15132369

NOVAIS, G. T.; BRITO, J. L. S.; SANCHES, F. O. Unidades climáticas do Triângulo Mineiro/Alto Paranaíba. **Revista Brasileira De Climatologia**, v. 23, p. 223-243, 2018. https://doi.org/10.5380/abclima.v23i0.58520

NOVAIS, G. T.; MACHADO, L. A. Os climas do Brasil: segundo a classificação climática de Novais. **Revista Brasileira de Climatologia**, v. 32, p. 1-39, 2023. https://doi.org/10.55761/abclima.v32i19.16163

PHUMKOKRUX, N.; TRIVEJ, P. Investigation of Temperature, Precipitation, Evapotranspiration, and New Thornthwaite Climate Classification in Thailand. **Atmosphere**, v. 15, n. 3, p. 379, 2024. https://doi.org/10.3390/atmos15030379

PULKKINEN, J.; LOUIS, J. N.; DEBUSSCHERE, V.; PONGRÁCZ, E. Near-, medium-and long-term impacts of climate change on the thermal energy consumption of buildings in Finland under RCP climate scenarios. **Energy**, v. 302, p. 131636, 2024. https://doi.org/10.1016/j.energy.2024.131636

RAHIMI, J.; KHALILI, A.; BUTTERBACH-BAHL, K. Projected changes in modified Thornthwaite climate zones over Southwest Asia using a CMIP5 multi-model ensemble. **International Journal of Climatology**, v. 39, n. 12, p. 4575-4594, 2019. https://doi.org/10.1002/joc.6088

ROLIM, G. D. S.; CAMARGO, M. B. P. D.; LANIA, D. G.; MORAES, J. F. L. D. Climatic classification of Köppen and Thornthwaite sistems and their applicability in the determination of agroclimatic zonning for the state of São Paulo, Brazil. **Bragantia**, v. 66, p. 711-720, 2007. https://doi.org/10.1590/S0006-87052007000400022

ROSA, G. B.; SILVA FUZZO, D. F.; FISCHER FILHO, J. A. Modelos de estimativa da evapotranspiração de referência para a região sul do Triângulo Mineiro, Brasil. **Revista Brasileira de Climatologia**, v. 33, p. 81-97, 2023. https://doi.org/10.55761/abclima.v33i19.16965

SANCHES, F. O.; DA SILVA, R. V.; FERREIRA, R. V.; CAMPOS, C. A. A. Climate change in the Triângulo Mineiro region–Brazil. **Revista Brasileira de Climatologia**, v. 21, p. 570-587, 2017. http://doi.org/10.5380/abclima.v21i0.51867

SHEN, M.; CHEN, J.; ZHUAN, M.; CHEN, H.; XU, C. Y.; XIONG, L. Estimating uncertainty and its temporal variation related to global climate models in quantifying climate change impacts on hydrology. **Journal of Hydrology,** v. 556, p. 10-24, 2018. https://doi.org/10.1016/j.jhydrol.2017.11.004

SOUZA, A. P.; MOTA, L. L.; ZAMADEI, T.; MARTIN, C. C.; ALMEIDA, F. T.; PAULINO, J. Classificação climática e balanço hídrico climatológico no estado de Mato Grosso. **Nativa**, v. 1, n. 1, p. 34-43, 2013. https://doi.org/10.14583/2318-7670.v01n01a07

SRIVASTAVA, A. K.; MBOH, C. M.; ZHAO, G.; GAISER, T.; EWERT, F. Climate change impact under alternate realizations of climate scenarios on maize yield and biomass in Ghana. **Agricultural Systems**, v. 159, p. 157-174, 2018. https://doi.org/10.1016/j.agsy.2017.03.011

STACKHOUSE, P. W.; WESTBERG, D.; HOELL, J. M.; CHANDLER, W. S.; ZHANG, T. **Prediction of Worldwide Energy Resource (POWER)-Agroclimatology methodology-(1.0 latitude by 1.0 longitude spatial resolution)**. Hampton: NASA Langely Research Cente. 2015.

SYLLA, M. B.; GIORGI, F.; PAL, J. S.; GIBBA, P.; KEBE, I.; NIKIEMA, M. Projected changes in the annual cycle of high-intensity precipitation events over West Africa for the late twenty-first century. **Journal of Climate**, v. 28, n. 16, p. 6475-6488, 2015. https://doi.org/10.1175/JCLI-D-14-00854.1

TALCHABHADEL, R.; KARKI, R. Assessing climate boundary shifting under climate change scenarios across Nepal. **Environmental monitoring and assessment**, v. 191, p. 1-17, 2019. https://doi.org/10.1007/s10661-019-7644-4

THAYER, A. W.; VARGAS, A.; CASTELLANOS, A. A.; LAFON, C. W.; MCCARL, B. A.; ROELKE, D. L.; WINEMILLER, K. O.; LACHER, T. E. Integrating agriculture and ecosystems to find suitable adaptations to climate change. **Climate**, v. 8, n. 1, p. 10, 2020. https://doi.org/10.3390/cli8010010

THORNTHWAITE, C. W. An approach toward a rational classification of climate. **Geographical Review**, v. 38, n. 1, p. 55-94, 1948. https://doi.org/10.2307/210739

THORNTHWAITE, C. W.; MATHER, J. R. **The water balance**. Centerton: Drexel Institute of Technology, Laboratory of Climatology, 1955.

VALJAREVIĆ, A.; MILANOVIĆ, M.; GULTEPE, I.; FILIPOVIĆ, D.; LUKIĆ, T. Updated Trewartha climate classification with four climate change scenarios. **The Geographical Journal**, v. 188, n. 4, p. 506-517, 2022. https://doi.org/10.1111/geoj.12458

WHEELER, T.; VON BRAUN, J. Climate change impacts on global food security. **Science**, v. 341, p. 508-513, 2013. https://doi.org/10.1126/science.1239402

WORLDCLIM. **Global climate and weather data.** Available: https://www.worldclim.org/data/index.html. Accessed on: Jun. 15, 2023.

XIANG, K.; LI, Y.; HORTON, R.; FENG, H. Similarity and difference of potential evapotranspiration and reference crop evapotranspiration–a review. **Agricultural Water Management**, v. 232, p. 106043, 2020. https://doi.org/10.1016/j.agwat.2020.106043

YANG, H.; LOHMANN, G.; WEI, W.; DIMA, M.; IONITA, M.; LIU, J. Intensification and poleward shift of subtropical western boundary currents in a warming climate. **Journal of Geophysical Research: Oceans**, v. 121, n. 7, p. 4928-4945, 2016. https://doi.org/10.1002/2015JC011513

AUTHORS CONTRIBUTION

João Alberto Fischer Filho: Conceptualization, formal analysis, funding acquisition, investigation and writing.

Giovani Bonício Rosa: Data curation, formal analysis and writing.

Júlia Cristina Amâncio Vieira: Data curation, formal analysis and writing.

Daniela Fernanda da Silva Fuzzo: Formal analysis and writing.