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Relationships between current climate and deforestation on *citrus* productivity in Northeastern Pará (Eastern Amazon)

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A B S T R A C T

This study analyzed the temporal and spatial patterns of time series data for Precipitation (PRP) and Maximum Temperature (TMAX) in 37 municipalities proportionally distributed in northeastern Pará (Eastern Amazon) during the period from 1981 to 2018 (37 years). In order to identify the impacts of climate change, environmental data on orange and lime productivity (IBGE), evapotranspiration (ET), and deforestation (PRODES) from the last 15 years were used. The non-parametric approach adopted, specifically the Mann-Kendall test (MK), was applied along with the delta variation analysis in two distinct periods: 1989-2003 and 2004-2018, totaling 15 years. These analyses were conducted to estimate annual and seasonal trends, as well as to detect variations through the use of heatmaps and boxplots. To compose the study of climate change, Principal Component Analysis (PCA) was applied to environmental variables, and Principal Component Regression (PCR) was used to test the hypothesis. The results revealed a growing positive trend in annual and seasonal time series data for TMAX over 37 years, with the most significant trends occurring during the dry season. Regarding PRP, the results showed significant variations in various regions, both positive and negative. At annual and seasonal scales, areas such as R5 in northeastern Pará exhibited positive trends, while negative trends in decreased PRP were observed in the coastal areas of Pará (R1). Based on the results of PCA and PCR, it was possible to establish an association between deforestation data and higher maximum temperatures. Additionally, lime productivity showed a correlation with PRP and ET, while PRP and ET were considered limiting factors for lime productivity.

Keywords: PCA, Precipitation, Productivity, Maximum Temperature, Tren, Variability.

Relações entre o clima atual e o desmatamento na produtividade de *citrus* no Nordeste do Pará (Amazônia Oriental)

R E S U M O

Este estudo analisou os padrões temporais e espaciais das séries temporais de Precipitação (PRP) e Temperatura máxima (TMAX) de 37 municípios proporcionalmente distribuídos no nordeste do Pará (Amazônia Oriental), no período de 1981 a 2018 (37 anos). Para identificar os impactos das mudanças climáticas, foram utilizados dados ambientais de produtividade de laranja e limão (IBGE), evapotranspiração (ET) e desmatamento (PRODES) dos últimos 15 anos. A abordagem não paramétrica adotada, especificamente o teste de Mann-Kendall (MK), foi aplicada juntamente com a análise da variação delta em dois períodos distintos: 1989-2003 e 2004-2018, totalizando 15 anos. Essas análises foram realizadas para estimar as tendências anuais e sazonais, além de detectar variações por meio do uso de heatmap e boxplots. Para compor o estudo das mudanças climáticas, foi aplicada a Análise de Componentes Principais (PCA) às variáveis ambientais e, para testar a hipótese, foi utilizada a Regressão de Componentes Principais (PCR). Os resultados obtidos revelaram uma tendência positiva crescente nas séries temporais anuais e sazonais de TMAX ao longo de 37 anos, sendo mais significativas durante a estação seca. Em relação à PRP, os resultados mostraram variações significativas em diversas regiões, tanto positivas quanto negativas. Nas escalas anuais e

sazonais, áreas como a R5, no nordeste do Pará, apresentaram tendências positivas, enquanto tendências negativas de diminuição da PRP foram observadas nas áreas costeiras do Pará (R1). Com base nos resultados da PCA e PCR, foi possível estabelecer a associação entre os dados de desmatamento e temperaturas máximas mais elevadas. Além disso, a produtividade da laranja mostrou correlação com PRP e ET, enquanto PRP e ET foram considerados fatores limitantes para a produtividade do limão.
Palavras-chave: PCA, Desmatamento, Precipitação, Produtividade, Temperatura Máxima; Tendência, Variabilidade.

Introduction

Climate is one of the main factors influencing agriculture productivity worldwide. Climate change, characterized by the rise in global average temperature, alterations in precipitation patterns, and extreme weather events, poses a serious threat to global food security (IPCC, 2021). Fruit crops, in particular, are highly sensitive to these changes due to their dependence on specific climatic conditions for growth and development (FAO, 2022; USDA, 2022; Carneiro, 2018).

The eastern Amazon, with its vast forest cover and rich biodiversity, is particularly vulnerable to the impacts of climate change (Marengo; Souza Junior, 2018). Uncontrolled deforestation, driven by activities such as agricultural frontier expansion and illegal logging, further exacerbates the challenges for regional agriculture (Sierra et al., 2022; Alves et al., 2017). Loss of native vegetation alters local climate patterns, affecting water availability and the frequency of extreme weather events (Espinoza et al., 2019; Leite-Filho; Costa; Fu, 2020).

In addition, deforestation in the eastern Amazon alters the local energy balance and affects precipitation patterns and air temperature (Nobre et al., 2016). Deforested areas have lower evapotranspiration, resulting in less rainfall and higher temperatures (Davidson et al., 2012). In addition, loss of vegetation contributes to desertification and soil erosion, degrading soil quality and reducing fertility, thereby exacerbating social problems (Fearnside, 2005; Neto et al., 2020).

In the context of the Eastern Amazon, citrus cultivation emerges as an economically important activity, with the potential to contribute to regional development and income generation (Amar, 2019; Araújo; Nicolella, 2018). The state of Pará, with its favorable climatic conditions and fertile soil, stands out as a citrus production hub in the region (ADEPARÁ, 2017). However, the sustainability of citrus cultivation in Pará is at risk due to the increasing impacts of climate change and deforestation.

It is crucial to highlight the complexity of the relationship between climate, deforestation, and citrus productivity, influenced by various factors. Inadequate agricultural practices, such as excessive use of fertilizers and pesticides, can affect productivity (Baccarin, 2016). Natural climate variability, including phenomena like El Niño and La Niña, also plays a significant role (Marengo et al., 2008). Given this complexity, further research is essential for a thorough understanding of the relationships between climate, deforestation, and citrus productivity in Northeast Pará. Such research will contribute to the development of more effective management strategies, considering the challenges posed by climate change and deforestation.

Citrus production also faces socio-economic challenges. Despite its economic importance, many citrus producers in Pará are smallholder farmers who struggle to access markets and receive fair prices for their fruit. In addition, lack of access to modern agricultural technologies and sustainable management practices can limit the productivity and sustainability of citrus cultivation (Carneiro, 2018).

Therefore, it is essential to develop strategies to adapt citrus cultivation to climate change and promote sustainable agricultural practices (Altieri et al., 2015). This may include introducing climate-resilient citrus varieties, implementing efficient water and soil management practices, and strengthening farmers' capacity through training and access to resources. In addition, public policies can play an important role in promoting the sustainability of citrus agriculture, such as encouraging forest conservation and supporting smallholder farmers (Mase; Gramig; Prokopy, 2017).

However, the State of Pará has a humid tropical climate, with high temperatures and abundant rainfall during the rainy season. However, the spatial distribution of rainfall varies considerably, with wetter areas in the north and drier areas in the south. Air temperature also shows regional variations, with hotter areas in the interior and cooler areas along the coast.

The spatial and temporal distribution of precipitation and air temperature in the eastern Amazon is influenced by several large-scale systems, such as the Intertropical Convergence Zone (ITCZ), the South Atlantic Convergence Zone (SACZ) and the Lines of Instability (LI). The dynamics of these systems shape the climatic gradient of the region, with the rainy season concentrated between December and May and the dry season dominating the second half of the year (Souza; Rocha, 2014; Sodré et al., 2015; Azevedo et al., 2017). Studies have identified two large-scale climate scenarios that modulate the Amazonian climate: the "favorable," associated with La Niña, and the "unfavorable," linked to El Niño. The "favorable" scenario presents negative anomalies in sea surface temperature (SST) in the Pacific and positive anomalies in the South Atlantic, while the "unfavorable" exhibits the opposite pattern. This dynamic generates changes in atmospheric circulation and tropical convection patterns, impacting the intensity of the ITCZ and, consequently, precipitation distribution over the region (Souza; Kayano; Ambrizzi, 2005).

In this context, climate gradients become important indicators that are widely discussed in the scientific-political arena of global climate change (IPCC, 2021). Many observational studies have focused on detecting long-term trends and identifying increases/decreases in extreme events on different time scales (Moreira; Cunha; Costa, 2021; Moreira et al., 2020). In addition, the application of the nonparametric Mann-Kendall (MK) test has been common in hydrological (Santos et al., 2020) and climatological (Soares; Nóbrega; Galvíncio, 2018) data series. These studies, together with analyses of the impact of climate anomalies, deforestation, and agricultural productivity (Souza; Rocha, 2014; Souza et al., 2017; Ferreira; Souza; Oliveira, 2020), contribute to a more comprehensive understanding of regional climate dynamics.

Principal component analysis (PCA), a powerful statistical tool for dimensionality reduction, is used in this study to identify the main climate patterns affecting citrus production in the eastern Amazon. By transforming a large set of climatic variables into a smaller set of principal components, PCA allows for a better understanding of the impacts of climate change and deforestation on agricultural production. These valuable insights can be used to develop adaptation strategies to climate change in citrus cultivation in the Eastern Amazon, as seen in various other studies (Mesquita et al., 2020; Sarhadi et al., 2017; Bakalian, 2010).

This study presents an exploratory analysis of factors influencing climate, fruit productivity (orange - *Citrus sinensis* and lime - *Citrus latifolia*), and deforestation rates in the Eastern Amazon. The main objectives were: (i) To reassess the understanding of the monthly, seasonal, and interannual distribution of precipitation and maximum temperature; (ii) To detect and evaluate the spatial pattern of precipitation and maximum temperature, as well as their climatic trends, using the MK test; (iii) To determine the annual and seasonal climate variation (delta); and (iv) To verify the environmental impact on citrus productivity, taking into account the period from 2004 to 2018, considering deforestation as one of the influencing factors.

Materials and methods

Study area

The study area focused on the eastern Amazon, specifically the northeastern part of the state of Pará, which is composed of two mesoregions: the Metropolitan Region of Belém (MRB) and the Northeastern Region of Pará (NP) (Figure 1). 37 municipalities were selected to represent climatic and environmental similarities, such as deforestation rates measured by the Amazon Deforestation Monitoring Project (PRODES) of the National Institute for Space Research (INPE) (available at: http://www. obt. inpe.br)/OBT/subjects/programs/amazonia/prodes) and fruit productivity of orange (Citrus sinensis) and 'Tahiti' sour lime (Citrus latifolia), known as “lemon” (IBGE, 2020), which resulted in 5 uniform clusters across the state, as shown in the figure below.

The spatial and temporal variability of regional rainfall in Pará is caused by the formation of clouds, mainly of the convective, *cumulus*, and *cumulonimbus* types, primarily on the coast of Pará, with penetration towards the continent, on the Belém-Thailand axis as well as towards the Northeast and Marajó Island, due to oceanic atmospheric dynamics associated with large-scale climate systems (ITCZ and SACZ) and mesoscale ILs. These are responsible for the distribution of average monthly and annual rainfall in the Eastern Amazon, with the wettest period defined as the months from December to May (with maximum rainfall in March) and the least rainy as the months from June to November (with minimum rainfall in October), with the transition months being April and November (Souza; Rocha, 2014; Souza et al., 2017).

According to the Köppen scale, Pará's climate is type "A", with three climatic subtypes (Af, Am and Aw), designated for tropical climates with high rainfall and average minimum temperatures of 18 °C. The annual rainfall (PRP) in the northeastern region of Pará ranges from 2,250 mm/year to 3,000 mm/year. In the rainy period from December to May, the daily average of (PRP of 11.2 mm/day) with high humidity (86%) and lower temperatures (minimum of 24ºC and maximum of 31.7ºC), while the period from June to November is marked by the typically less rainy or dry regime (PRP of 3 mm/day) with lower humidity (79.7%) and higher temperatures (minimum of 24.3ºC and maximum of 33.1ºC), according to (Dias et al., 2019).

Data

The Precipitation data consist of monthly averages available on a grid selected along the region that includes the 37 largest producing municipalities in the State of Pará (Figure 1). The resolution is 5 km, corresponding to the geographic coverage from 50ºS to 50ºN, for the period from January 1981 to December 2018 (37 years). These data were obtained from the Climate Hazards Infrared Precipitation with Stations (CHIRPS) group. According to Funk et al. (2015) this series is formed from several sources of information such as, The Climate Hazards Group's Precipitation Climatology (CHPClim); National Oceanic and Atmospheric Administration (NOAA) quasi-global geostationary geostationary satellite observations with Thermal Infrared (TIR) spectroscopy; Climate Prediction Center (CPC); National Climatic Climate Data Center (NCDC); NOAA's Coupled Forecast System, version 2 (CFSv2) and observational data from weather stations, available at (ftp://ftp.chg.ucsb.edu/pub/org/chg/products/CHIRPS-2.0/).

Monthly air temperature data from the CRU Version 2.1 ensemble (Fick; Hijmans, 2017) were also used in this study to measure the association with extreme precipitation events related to *Citrus* productivity. Thus, the points of maximum temperature grid in the region of crop productivity were extracted during the time period (1981 to 2018). More information on the original data can be found at (https://www.worldclim.org/data/index.html).

The agricultural data corresponding to the citrus crops (orange and lime) consist in productivity (in t/ha) were obtained from the Municipal Agricultural Research (PAM) database of (IBGE), with emphasis on the municipalities mentioned in (Figure 1), data available from 2004 to 2018 (fifteen years).

Other data were 1) deforestation, PRODES offered by the National Space Research Institute (INPE) and 2) evapotranspiration (ET) offered by the eight-day (Running; Mu; Zhao, 2019) for 500 meters (https://developers.google.com/earth-engine/datasets/catalog/MODIS_006_MOD16A2). From 2004 to 2018, when the measurement date followed the annual scale.

Methodological approach

A brief description of the analysis procedure is shown in Figure 2. The analyses of the behavior of the climate variables (precipitation - PRP and maximum temperature - TMAX) were selected at a grid point in the series of monthly averages, corresponding to the period from 1981 to 2018, mediated in the 37 municipalities of northeastern Pará (previous figure). Then, seasonal averages were calculated, during the months of summer from December to February (DJF), fall from March to May (MAM), winter from June to August (JJA) and spring from September to November (SON). The results of the images had application of the software package heatmap (R Core Team, 2017).

In addition, the annual variability (PRP and TMAX) was analyzed using Tukey's (1977) boxplot technique. This graphing tool provided five measures of the data: mean, first and third quartiles, minimum and maximum (PRP and TMAX), and possible outliers (deviating values in the data series).

Then, to investigate the positive/negative or increasing/decreasing trends of climate gradients, the non-parametric Mann-Kendall (K or MK) test (Mann, 1945; Kendall, 1948) was applied to the time series data (PRP and TMAX) at seasonal and annual scales (Santos et al., 2020; Soares et al., 2018), with a significance coefficient of 95% ($p<0.05$) (Souza et al., 2017) and $| Z | > 1.96$ (Liang et al, 2014; Ding et al., 2018).

The variation (delta) or difference was also analyzed, where the average of each annual and seasonal period of PRP and TMAX was calculated, with a 15-year average of the following intervals: (1989 to 2003) and (2004 to 2018). The values obtained were used for the assessment of climate change in recent years, calculation information in Table 1 (Souza; Rocha, 2014; Dias et al., 2021).

Finally, principal component analysis (PCA) was applied. PCA is a holistic approach to determine the dynamics of all variables in a system under observation (Gorgoglione et al., 2019). It aims to reduce dimensionality and reveal patterns. It separates the important variables into complex combinations. Thus, the main factors were separated to compare the predictive variables (PRP, TMAX, ET and DEFORESTATION) and the dependent variables (PROD of CItrus). It was necessary to use the Principal Components Regression (PCA) to test the hypothesis that an increase in TMAX and Deforestation will decrease the productivity of citrus. The package FactorMineR (Lê; Josse; Russon, 2008) was used in the continuous objects.

Results and discussion

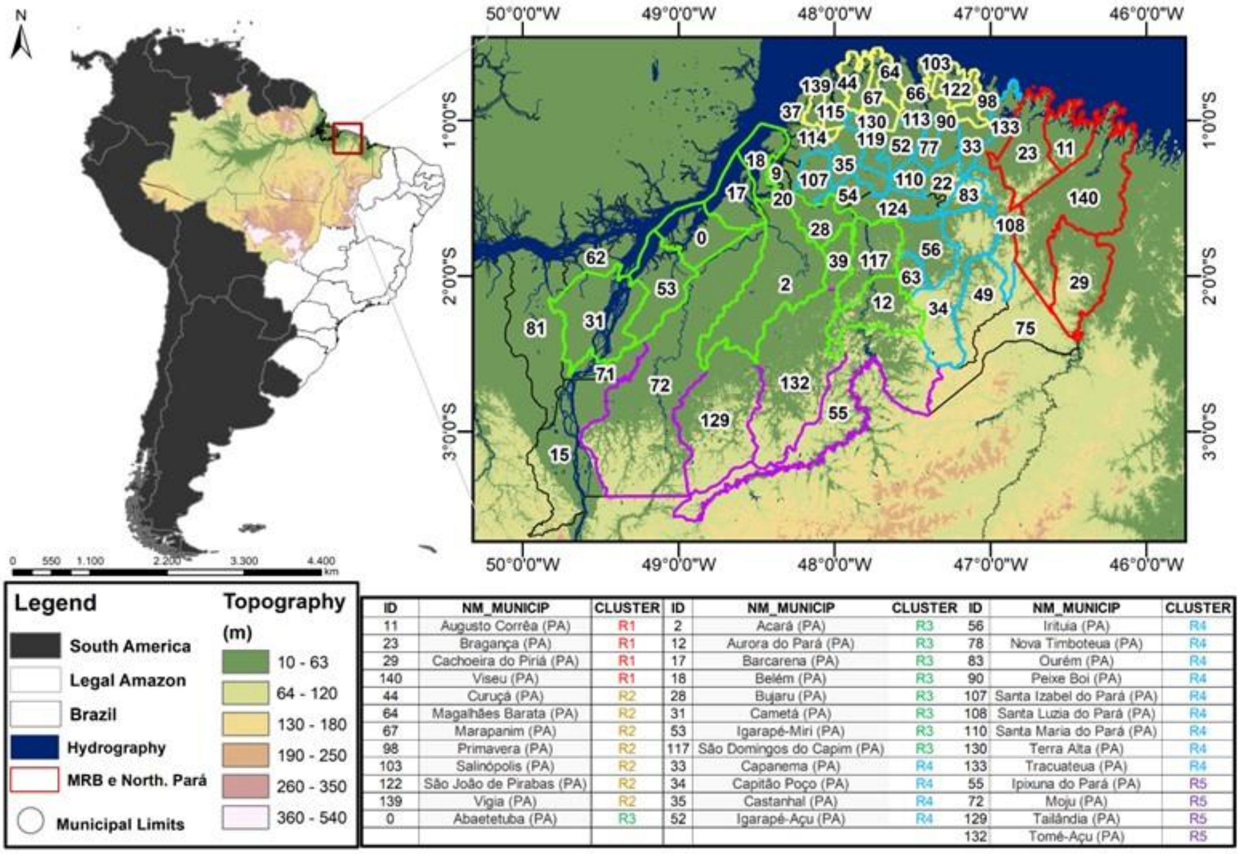
Monthly climatology over northeast Pará

Monthly climatological rainfall in northeastern Pará for the period 1981 to 2018 is shown in the (Figure 3). Using the k-means clustering method, it was possible to identify five regions based on their environmental similarities. These regions have different rainfall regimes over the years. Previous studies have also identified regions with different precipitation regimes in the eastern Amazon, including three regions in the state of Pará and four regions in the northern region (Azevedo et al., 2017; Menezes; Fernandes; Rocha, 2015; Santos, Lucio; Silva, 2015).

The months with the highest precipitation (above 400 mm - in shades of dark blue) occur in February, March and April, with the highest incidence in regions R2 and R4, with a temporal shift to region R5 during the months of January to April. On the other hand, the months with the lowest precipitation (less than 200 mm - in dark red) are September, October and November in regions R1, R2 and R4, in R5 and R3 they occur in July, August and September (Menezes; Fernandes; Rocha, 2015; Souza et al., 2016; Souza et al., 2017; Azevedo et al., 2017).

This rainfall regime can be caused by the action of meteorological systems, since the ITCZ operates in the tropics, is an integral part of the general circulation of the atmosphere and spreads with bands of cumulonimbus clouds over Pará. This results in higher rainfall during the months of December to May (Figure 3), the rainy season, and lower rainfall during the months of June to November, the dry season. The little rain that does occur is caused by local thermodynamic effects. These include sea breezes and easterly waves caused by trade wind currents. The rains that begin during the dry/rainy transition (June/November) are formed by convective clouds (Bastos et al., 2002; Albuquerque et al., 2010; Souza; Rocha, 2014; Souza et al., 2017).

The (Figure 4) shows the climatology of the maximum temperature (TMAX - °C). There are lower TMAX values (less than 30° C) in the months of February and March. They are located in regions R1, R2 and R4. On the other hand, the highest TMAX values.



ID	NM_MUNICIP	CLUSTER	ID	NM_MUNICIP	CLUSTER	ID	NM_MUNICIP	CLUSTER
11	Augusto Corrêa (PA)	R1	2	Acará (PA)	R3	56	Irituia (PA)	R4
23	Bragança (PA)	R1	12	Aurora do Pará (PA)	R3	78	Nova Timboteua (PA)	R4
29	Cachoeira do Piriá (PA)	R1	17	Barcarena (PA)	R3	83	Ourém (PA)	R4
140	Viseu (PA)	R1	18	Belém (PA)	R3	90	Peixe Boi (PA)	R4
44	Curuçá (PA)	R2	28	Bujaru (PA)	R3	107	Santa Izabel do Pará (PA)	R4
64	Magalhães Barata (PA)	R2	31	Cametá (PA)	R3	108	Santa Luzia do Pará (PA)	R4
67	Marapanim (PA)	R2	53	Igarapé-Miri (PA)	R3	110	Santa Maria do Pará (PA)	R4
98	Primavera (PA)	R2	117	São Domingos do Capim (PA)	R3	130	Terra Alta (PA)	R4
103	Salinópolis (PA)	R2	33	Capanema (PA)	R4	133	Tracuateua (PA)	R4
122	São João de Pirabas (PA)	R2	34	Capitão Poço (PA)	R4	55	Ipixuna do Pará (PA)	R5
139	Vigia (PA)	R2	35	Castanhal (PA)	R4	72	Moju (PA)	R5
0	Abaetetuba (PA)	R3	52	Igarapé-Açu (PA)	R4	129	Tailândia (PA)	R5
						132	Tomé-Açu (PA)	R5

Figure 1. Map of the study area in northeastern Pará, the circles with a black dot indicate the 37 selected municipalities, the colors indicate the 5 uniform clusters.

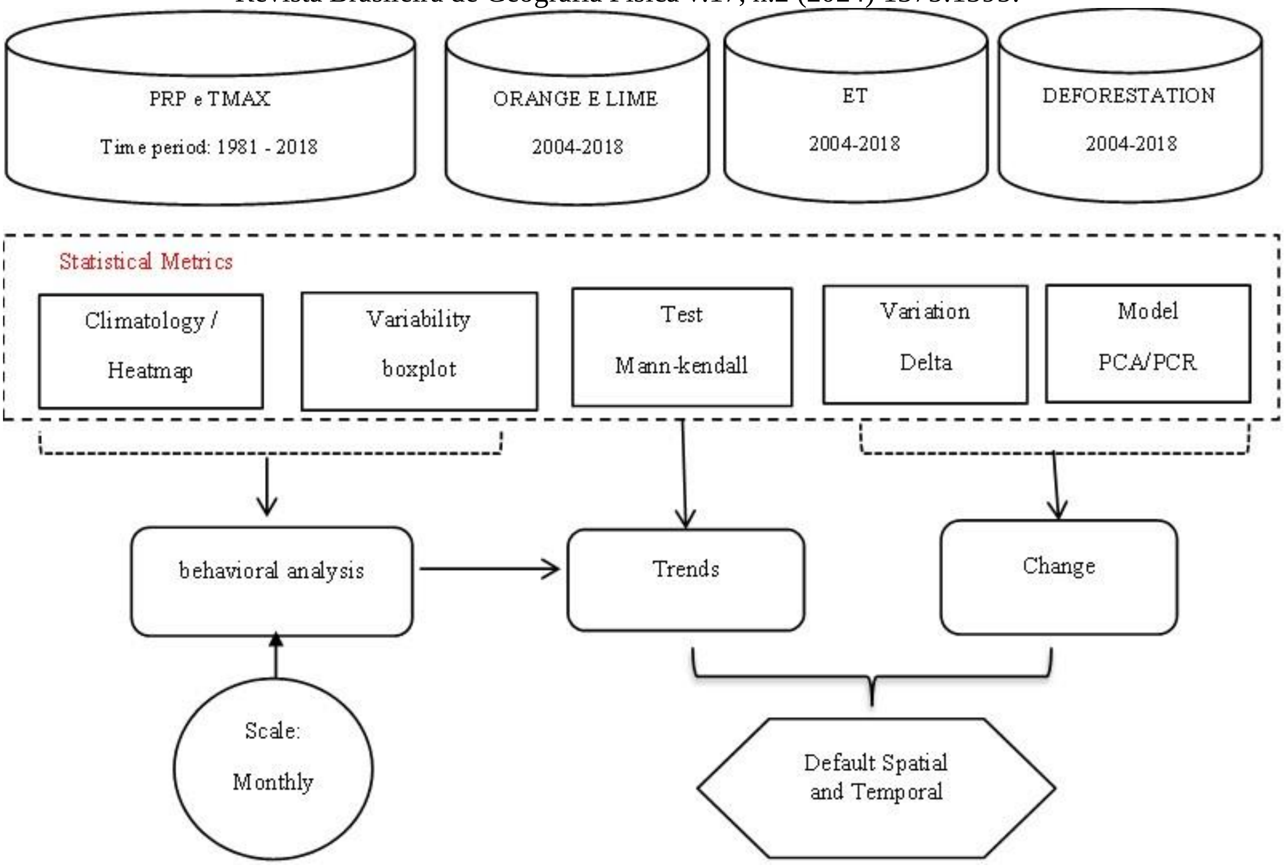


Figure 2. Methodological structure of the research.

Table 1. List of statistical metrics.

Metric	Equation	Description
Variation (Delta)	$\Delta x_n = \frac{\sum_{i=year\ begin}^{j=year\ end} x\ t_f}{n} - \frac{\sum_{i=year\ begin}^{j=year\ end} x\ t_o}{n}$ $\Delta x_{n=15} = \frac{\sum_{2004}^{2018} PRP\ t_f}{15} - \frac{\sum_{1989}^{2003} PRP\ t_o}{15}$ $\Delta x_{n=15} = \frac{\sum_{2004}^{2018} TMAX\ t_f}{15} - \frac{\sum_{1989}^{2003} TMAX\ t_o}{15}$	x = Meteorological Variables; PRP = Precipitation; TMAX = Maximum temperature; t= time on annual and seasonal scale; f= end e 0= begin. n= 15, sample size of 15 years.

(higher than 32° C) are recorded in the months of September, October and November in regions R1, R2 and R4. In regions R3 and R5 they occur in the months August, September and October. These results coincide with the rainy season, since the lowest maximum temperatures occur in the rainy season and the highest in the dry season (Dias et al., 2019).

It is understood that high temperatures are associated with incident solar radiation, where a large part of the energy is converted into latent heat (evapotranspiration) and another part is converted into sensible heat to heat the air (Bastos et al., 2002; Rodrigues et al., 2013). Other factors that can contribute to the increase in temperature are the ocean-atmospheric dynamics mentioned in the previous study, leading to a decrease in convective activity, which reduces the formation of rain clouds, as well as changing land use, deforestation and burning, which affect local biogeophysical effects, etc. (Winckler et al., 2019).

The regions R5 (example of Moju and Tailândia) and R3 (Cametá) present a different behavior during the years, defining the dry regime the months of July to November and the rainy regime the months of December to April. This supports the conclusions of the previous figure, characterized by a low variability of rainfall in the rainy season and a prolonged dry season. In the vicinity, the municipalities of R5 are among the most deforested (PRODES, 2022). According to the authors Lopes et al. (2020) and Pimenta et al. (2018), this is due to expanding agricultural and ranching plantations.

Seasonal climatology over northeastern Pará

In order to study the seasonal climatological aspects of the region, the seasonal averages of PRP and TMAX in the trimester of summer (DJF), autumn (MAM), winter (JJA) and spring (SON) were calculated for the period from 1981 to 2018 (Figure 5).

In the DJF trimester over northeast Pará, near the Marajó coast, average precipitation values of 200 to 400 mm are observed (Figure 5A). Such precipitation values are associated with the ITCZ. This phenomenon has a direct impact on the amount of precipitation that is restricted in these areas (Souza et al., 2014; Ferreira et al., 2020). During this period, TMAX isotherm values of 31°C to 32°C were observed (Dias et al., 2019).

During the autumn (MAM), maximum values of PRP greater than 400 mm are observed in the municipalities located in the northeast of Pará and part of Marajó, confirming the evidence of previous studies (Nobre; Shukla, 1996; Souza; Kayano; Ambrizzi, 2004), in which they explain that the high maximum values of precipitation are due to the action of the ITCZ, which reaches its southernmost position in March, justifying the high precipitation observed in Pará. Thus, isotherms of the TMAX (31 °C to 32 °C) are also observed (Figure 5B).

The trimester (JJA) is characterized by the dry period, the intensity of precipitation is lower in northeastern Pará, especially in the southeastern part, whose precipitation record occurs below 50 mm (unlike the MAM trimester, which shows much higher values). In the coastal sector of Marajó, precipitation oscillates between 150 and 200 mm of rainfall. The TMAX isotherm shows values between 32° and 33°C (Figure 5C). In the spring quarter (SON), the reduction in rainfall continues over much of northeastern Pará, showing values below 100 mm. The exceptions are the municipalities located in the RMB, which show values between 100 and 150 mm. The maximum value of TMAX is 33 °C in R5 (Figure 5D).

This is due to the precession of the Earth's axis, where the descending branch of the Hadley circulation dominates over the Brazilian tropics, inhibiting the formation of convective clouds and depriving the study region of precipitation from large-scale systems (Coelho; Cardoso; Firpo, 2016). However, local convection, lines of instability, and wave disturbances to the east may be responsible for the low precipitation observed in the region (Souza; Ambrizzi, 2003).

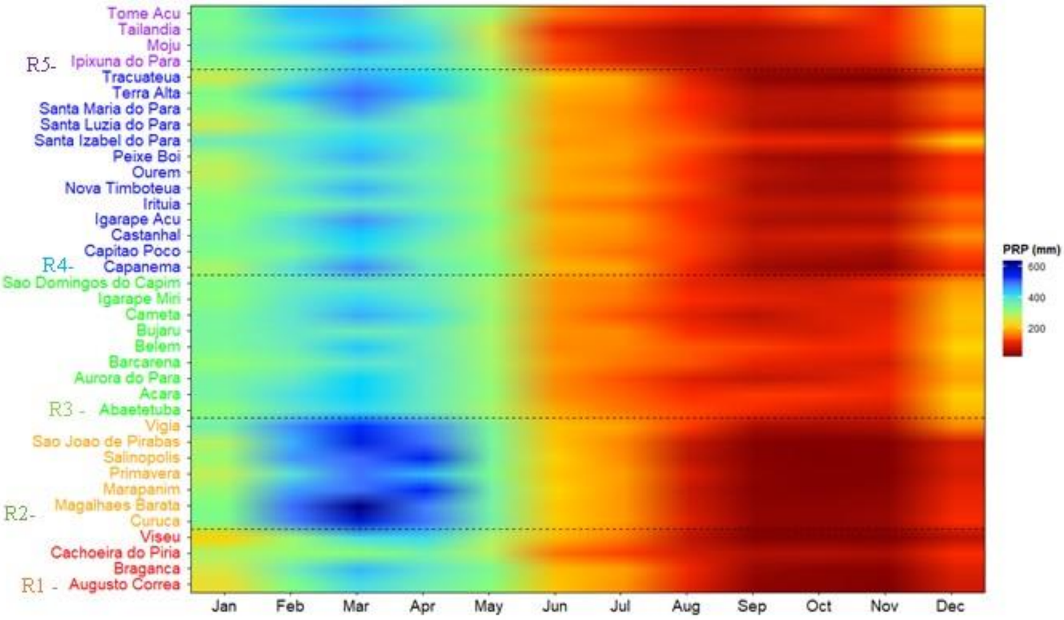


Figure 3. Climatological precipitation (mm/month), average from 1981 to 2018, in the northeast region of Pará.

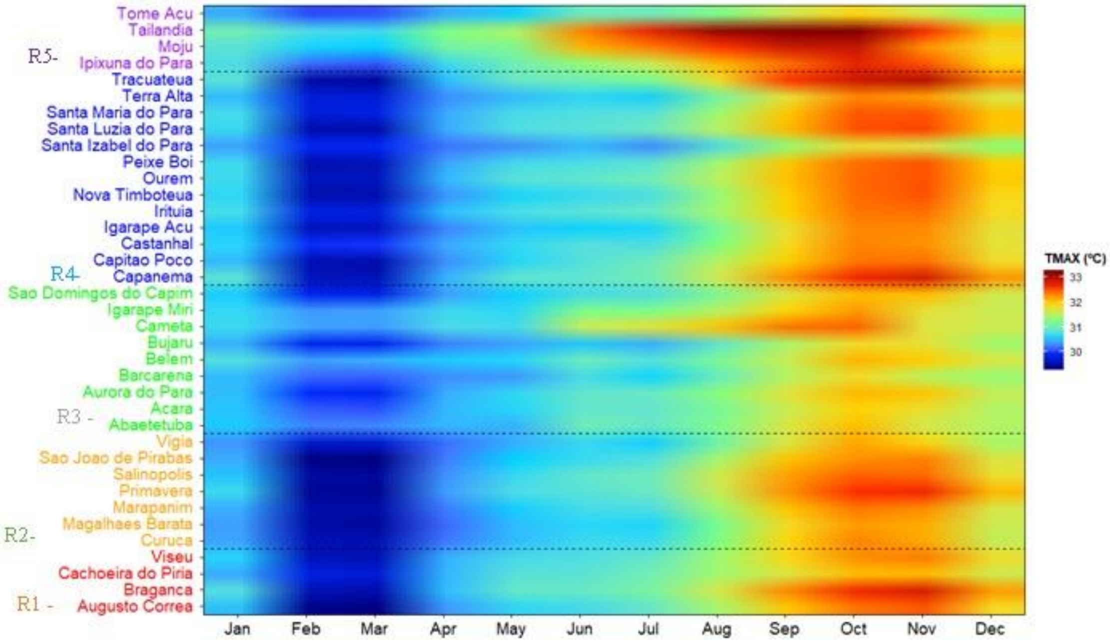


Figure 4. Maximum climatological temperature (°C) (average from 1981 to 2018), in the northeast region of Pará.

Interannual variability of precipitation and temperature

During the period analyzed, the average annual PRP in the northeastern region of Pará varied between 2250 mm/year and 3000 mm/year (Figure 6A). It is important to note the presence of atypical values and standard deviations (Std), which indicate the occurrence of extremely rainy (values above the blue line) and dry (values below the red line) climatic events. The years 1981, 1982, 1983, 1985, 1986, 1987, 1988, 1989, 1992, 1994, 1997, 1999, 2013, 2014 and 2018 stand out.

These extreme values in the PRP series can be explained by relating them to ENSO events. These are physical processes that occur in the tropical equatorial zone of the Pacific Ocean, where surface waters are warm and cold for periods of two to seven years (Kiladis;Diaz, 1989; Trenberth; Hoar, 1997). In this regard, the rainfall rates varied from 2 to 3 years and from 5 to 7 years. It can be observed that the years 82/83 and 97/98 were the years associated with the lowest rates of precipitation. This was due to the strong El Niño event. These years were classified as extremely dry. On the other hand, the years 85/86 and 88/89 were considered to be the wettest years. This pattern has been linked to the La Niña phenomena (Albuquerque et al., 2010; Souza et al., 2015; Tavarez et al., 2018).

The increase in maximum temperature (TMAX) in the northeastern region of Pará has been attributed to several factors, including climatic phenomena, changes in land use and land cover, and an increase in the concentration of greenhouse gases in the atmosphere (Marengo et al., 2013b, Souza; Rocha, 2014; Gomes et al., 2015; Winckler et al., 2019; Gatti et al., 2021). Regression analysis of TMAX values showed that TMAX increases at a rate between 0.223 and 0.772 per year (see Figure 5B and Table 2). This increase can lead to a number of negative impacts on the environment and society, such as droughts, floods, forest fires, and diseases. It is important to take measures to mitigate the increase in TMAX, such as reducing greenhouse gas emissions and protecting forests.

Climate trends in northeastern Pará

In the analysis of the annual aspect of precipitation (upper left panel), significant positive trends were observed, according to the MK test, bringing an increase in precipitation ($p< 0.05$) in several locations in the R3 region in four municipalities: Acará (2), Aurora do Pará (12), Barcarena (17), Igarapé-Miri (53) and in the R5 region Ipixuna do Pará (55) and Tomé-Açu (132). A significant increase ($p<0.20$) in precipitation was also observed in R2 in Santa Maria do Pará (110), in R3 in the municipalities of Bujaru (28) and Cametá (31), in R4 in Terra Alta (130) and in R5 in Tailândia (129) (Figure 7).

In terms of seasonal analysis, during the DJF trimester (upper central panel), a significant positive trend in occurrence ($p<0.05$) was found in the R5 region - municipality of Tomé-Açu (132), and a significant negative trend in the R1 region (municipality of Viseu -140). Significant signs of a negative trend ($p<0.20$) were also observed in the R1 region in Augusto Corrêa (11) and Cachoeira do Piriá (29), and a significant positive trend in the R3 region in Acará (2), Igarapé-miri (53) and Cametá (31). The MAM trimester shows significant positive trends ($p<0.05$) in the R3 region of Acará (2), Barcarena (17) and Igarapé-Miri (53), in the R4 region of Santa Izabel do Pará (107) and in the R5 region of Tomé-Açu (132). Significant positive trends ($p< 0.20$) were also observed in areas R3 in Aurora do Pará (12), Belém (18), Bujaru (28) and Cametá (31); R4 in Ourém (83) and Santa Luzia do Pará (108); R5 in Ipixuna do Pará (55) and Tailândia (129) (upper right panel).

In the JJA trimester (middle bottom panel), a significant positive precipitation trend ($p<0.20$) was observed in the R3 region in the municipalities of Acará (2) and Aurora do Pará (12), in the R5 region in Tomé-Açu (132), and a significant negative precipitation trend in the R1 region in the municipality of Augusto Corrêa (11). And in the SON trimester (lower right panel), significant positive trends ($p<0.20$) in precipitation were observed in the R3 region in Acará (2) and Igarapé-Miri (53), in the R5 region in Tailândia (129) and Tomé-Açu (132).

In general, the MK precipitation trends show a heterogeneous pattern, positive in specific areas in regions R3 and R5, located in the northeast of Pará, and negative in regions R1, R2 and R4, located in the coastal zone of Pará. The results indicate changes in the seasonal aspect, where there was a significant increase in PRP in the dry season at points located in the northeastern mesoregion of Pará, and a tendency for PRP to decrease in the rainy season in the coastal region of Pará. These decreasing/increasing trends may be related to large-scale systems or influenced by ENSO (Santos; Oliveira, 2017; Souza; Rocha, 2014; Souza et al., 2017; Ferreira et al., 2020).

The results of the calculation of the MK test applied to the TMAX series are shown in (Figure 8), annual and seasonal (DJF, MAM, JJA and SON). The annual TMAX (upper left panel) shows significant positive trends ($p <0.05$) in all municipalities. The results are consistent with previous studies showing a global increase in maximum temperatures (IPCC, 2021; Trenberth et al., 2014).

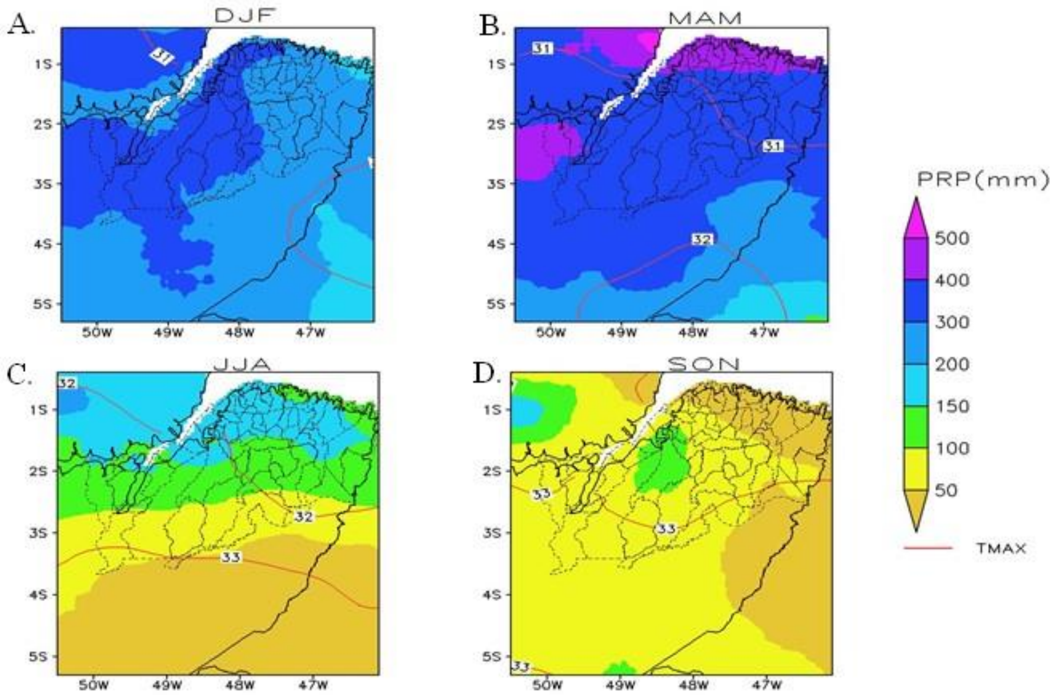
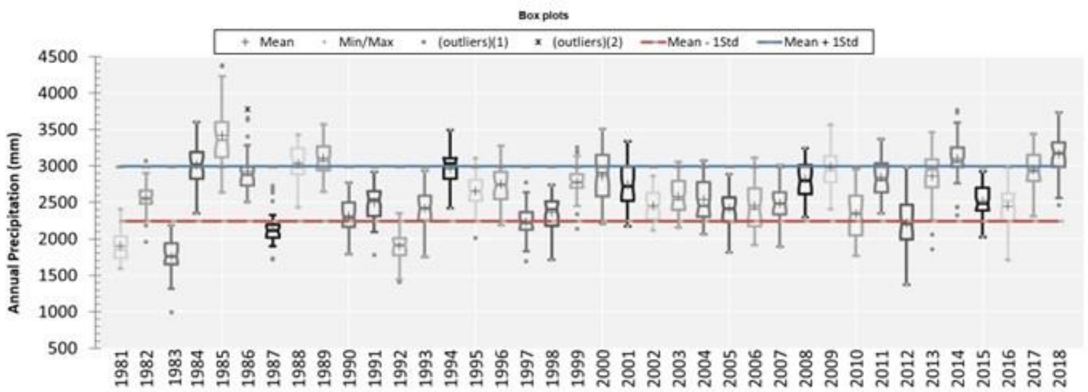


Figure 5. Seasonal climatology (average 1981 to 2018) of PRP and TMAX over northeastern Pará during the seasons: summer (A) DJF, autumn (B) MAM, winter (C) JJA and spring (D) SON. The color scales indicate the magnitude of PRP in mm and TMAX in °C.

A. Precipitation (mm)



B. Maximum temperature (°C)

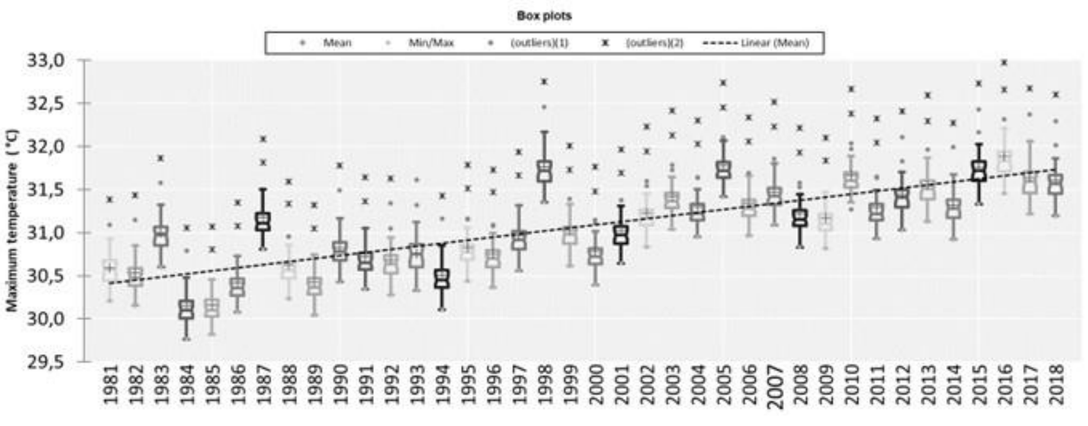


Figure 6. Annual variability (1981/2018) of (A) precipitation - PRP (mm) and of (B) Maximum temperature - TMAX over northeastern Pará.

Table 2 - TMAX Linear Regression Coefficients

Source	Value	Standard error	t	Pr > |t|	Lower limit (95%)	Upper limit (95%)	p-values
Intercept	0,238	0,245	0,971	0,338	-0,259	0,735	°
Minimum	0,772	0,074	10,449	**<0,0001**	0,622	0,922	***
Maximum	0,223	0,067	3,345	**0,002**	0,088	0,359	**

*Significance level: 0 < *** < 0.001 < ** < 0.01 < * < 0.05 < . < 0.1 < ° < 1*

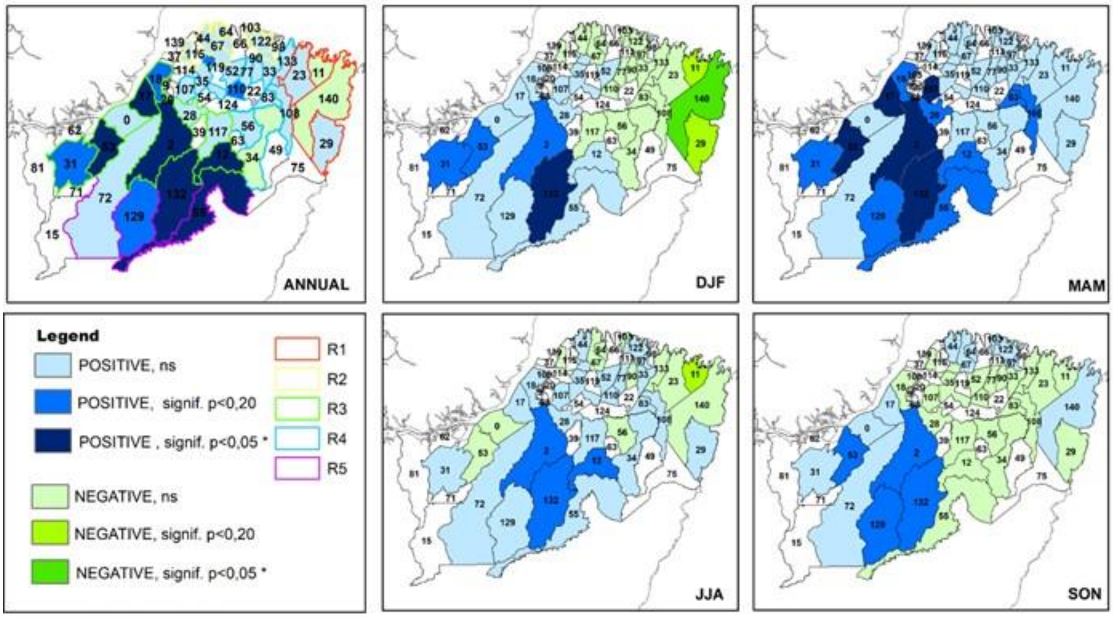


Figure 7. Mann-Kendall test (MK) in the precipitation data series - PRP (mm), in the annual and seasonal scales (DJF, MAM, JJA and SON). The color scales indicate the signs of the MK test, with the value of 95% confidence levels for | Z | > 1.96 (p <0.05*) Liang et al., 2014; Ding et al., 2018).

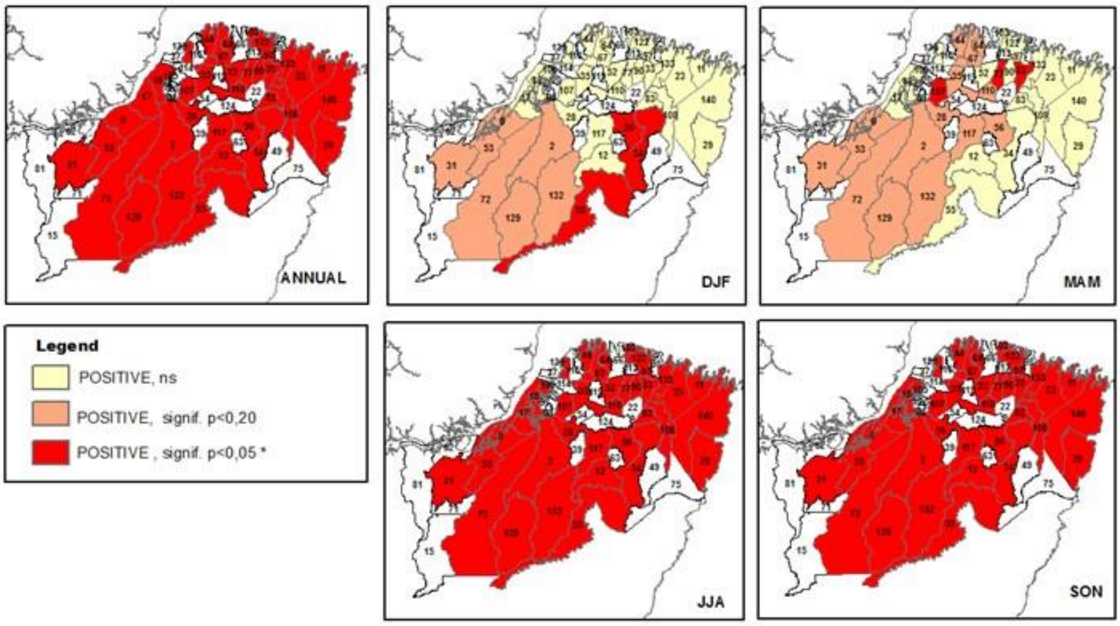


Figure 8. Mann-Kendall test (MK) on the maximum temperature data series - TMAX (°C), on the annual and seasonal scales (DJF, MAM, JJA and SON). The color scales indicate the signs of the MK test, with the value of 95% confidence levels for | Z | > 1.96 (p<0.05*) (Liang et al., 2014; Ding et al., 2018).

In the wet season, DJF trimester (upper central panel), significant positive trends ($p<0.05$) of increasing (warming) TMAX were found in region R4 in Capitão Poço (34) and Irituia (56), region R5 in Ipixuna do Pará (55) and significant positive trends ($p<0.20$) of TMAX over region R3-Abaetetuba (0), Acará (2), Cametá (31) and Igarapé-miri (53), region R5-Moju (72), Tailândia (129) and Tomé-Açu (132).

In the MAM trimester (upper right panel), significant positive trends ($p<0.05$) were recorded in region R4 in Capanema (33), Nova Timboteua (77) and Santa Izabel do Pará (107); the other significant positive trends ($p<0.20$) were recorded in regions R2 in Curuçá (44), Maghães Barata (64) and Abaetetuba (67): R2 in Curuçá (44), Magalhães Barata (64) and Marapanim (67), in region R3 in Abaetetuba (0), Acará (2), Bujaru (28), Cametá (31), Igarapé-miri (53) and São domingos do Capim (117); in region R4 in Castanhal (35), Irituia (56), Santa Maria do Pará (110), Terra Alta (130) and; R5 in Moju (72), Tailândia (129) and Tomé-Açu (132).

During the dry period, in the JJA and SON trimesters, the significant trends ($p<0.05$) were positive throughout the study region (panels: bottom center and bottom right).

The results show a systematic increase in the maximum temperature trend signal in northeastern Pará. This increase in TMAX could lead to a more severe drought, which could harm agriculture and fishing. It can also increase the risk of forest fires, which can destroy property and cause damage to human health (Nobre; Sellers; Shukla, 1991; Dias; Ribeiro; Nunes, 2007; Sampaio et al., 2007; Liesenfeld; Vieira; Miranda, 2016; Marengo et al., 2018; Oliveira et al., 2020). This situation can also affect the hydrological and carbon cycles, contributing to the occurrence of El Niño and La Niña events (Jiménez-Muñoz et al., 2016; Almeida et al., 2017).

Climate change over the past 15 years

In Figure 9 (upper left panel), corresponding to the difference between the period (1989 to 2003) and (2004 to 2018) for the annual scale of the PRP series, we see a positive precipitation value, with growth of more than 150 mm (in shades of dark blue) in some areas of regions R3 and R4 of Northeast Pará, on the other hand, the coastal regions of Pará, in region R1 - Augusto Corrêa (11), Bragança (23) and Viseu (140), region R2 - Primavera (97) and region R4 - Capanema (33) and Peixe Boi (90), which show a decrease in precipitation of 70 mm (negative value in light green). These results are consistent with the MK test, which shows a downward trend on an annual scale for these locations.

For the rainy season, in the DJF trimester (center panel), the PRP variation shows a positive value (above 70 mm - in blue shades) in much of northeastern Pará. The negative PRP value (less than 150 mm - in shades of light green) is highlighted in the regions: R1 in Augusto Corrêa (11), Bragança (23), Cachoeira do Piriá (29) and Viseu (140); in region R2 in Curuçá (44), Magalhães Barata (64), Primavera (97), Salinópolis (103) and São João de Pirabas (122); in the R4 region, in Capanema (33), Capitão Poço (34), Nova Timboteua (77), Ourém (83), Peixe Boi (90), Santa Luzia do Pará (108) and Tracuateua (133). This fluctuation of increasing and decreasing PRP during this quarter can be explained by the formation and inhibition of convective clouds associated with large-scale weather systems. In this context, the MAM quarter (upper right panel), marked by the maximum rainfall caused by the ITCZ, showed a positive variation of PRP in all municipalities, except Cametá (31), which showed a negative sign of decreasing PRP.

In contrast, in the dry regime, JJA (lower middle panel) and SON (lower right panel) show negative PRP values (below 70 mm - in light green tones) in most of the region, but the results show positive PRP values (increase up to 70 mm - in light blue tones) at certain locations in northeastern Pará and the coastal strip of Pará.

The results of the PRP variation show that over the last 15 years the rainfall regime has undergone changes in the annual and seasonal aspects, especially the seasonal aspect. We would highlight the coastal region of Pará (regions R1, R2 and R4) and the DJF rainfall regime. These show negative PRP values, indicating little formation of convective rain clouds. In contrast, there is an increase in precipitation during the SON dry season. This means that convective activity tends towards the formation of rain clouds. Therefore, the decrease/increase in PRP in the wet/dry regime is an indication of a reduction/increase in annual variability, as in (Ferreira; Souza; Oliveira, 2020).

The TMAX shows positive variations in the last 15 years for the annual scale (Figure 10, top left panel). This shows a temperature increase of more than 0.5 °C in practically the whole study region.

In the rainy season, the DJF (top center panel) and MAM (top right panel) trimesters show positive values with an increase of 0.5 °C and up to 0.4 °C, respectively (in shades of orange). Despite the weather systems in operation during this period, an increase in TMAX in the region is visible. On the other hand, the dry periods of JJA (middle background panel) and SON (right background panel) show a higher value of temperature variation with maximum values of 0.6 °C and 0.9 °C (in shades of dark red).

Therefore, the analysis of the variation of TMAX proves that the region has experienced a considered increase in maximum temperature in recent times (15 years) and several factors can influence the growth, natural and anthropic factors, mentioned in this investigation.

Environmental impact ratio for the last 15 years

Figure 11 shows the distribution of orange PROD data (A), lime (B), deforestation rate (C) and ET (D) during the 15-year period (2004 to 2018) (C). As a complement to the study of climate change observed in this research, it is asked which climate variables (PRP, TMAX and ET) associated with the environmental issue (deforestation) influence the decline in citrus productivity. The PCA and the PCR have been used to test this hypothesis (Figure 12).

In (Figure 11A), it is clearly observed that the highest orange PROD (t/ha in red) is concentrated in the R4 region. The top 10 producing municipalities are: Terra Alta (130), Capitão Poço (34), Irituia (56), Ourém (83), Santa Izabel do Pará (107), Ipixuna do Pará (55), Igarapé-Açu and Peixe-Boi (90), excluding Barcarena (17) and Aurora do Pará (12), located in the R3 region (IBGE,2020). On the other hand (Figure 11B), the top ten lime productivities (t/ha in shades of red and yellow) are: Ourém (83), Capitão Poço (34), Irituia (56) and Santa Izabel do Pará (107) in the R4 region, with the exception of Tailandia (129) in R5 and Acará (2), Bujaru (28) and Cametá (31) in the R3 region. This increase could be related to several factors (area, rootstocks, irrigation, fertilization, pest and disease control and spraying, etc.).

It is observed that according to deforestation rate (km2) (Figure 11C), the highest deforestation municipalities are concentrated in regions R1, R4 and R5. These are the regions that are adjacent to the arc of deforestation. According to Fearnside & Graça (2009), the frontier is characterized by dynamic agricultural and livestock activities, as well as the expansion of areas of socio-economic development (Sathler; Adamo; Lima, 2018).

In contrast, ET rates (Figure 11D) show the 10 lowest ET values in the municipalities of Cachoeira do Piriá (29), Augusto Corra (11), and Viseu (140) in Region R1, Tracuateua (133), Ourém (83), Peixe-Boi (90), Terra Alta (130), and Igarapé-Açu (52) in Region R4, and Tailândia (129) in Region R5. Consequently, parts of these municipalities show medium and high deforestation rates (Figure 11D). This confirms the result of the PRP reduction (Figure 9, upper left panels), especially in the municipality of Viseu (140).

On the basis of this geospatial knowledge and on the basis of the parameters of climate variation the results of the environmental variables affecting citrus productivity are shown in (Figure 12). The PCA result shows that the sum of the first three principal components of the PCA explains 72.5% of the total variation. Dimension 1 is the only one that explains the environmental variables affecting citrus productivity. In this case, ET was the most related variable (r=0.78). It was followed by PRP (r=0.74). On the other hand, TMAX (r=0.57) was followed by deforestation (-0.49). Thus, PCR models indicate that positive values of PC1 (environmental variables x citrus productivity) represent localities with more PRP and ET, while negative values indicate localities with higher TMAX and deforestation. Thus, PCR models indicate that positive values of PC1 (environmental variables x citrus productivity) represent localities with more PRP and ET, while negative values indicate localities with higher TMAX and deforestation.

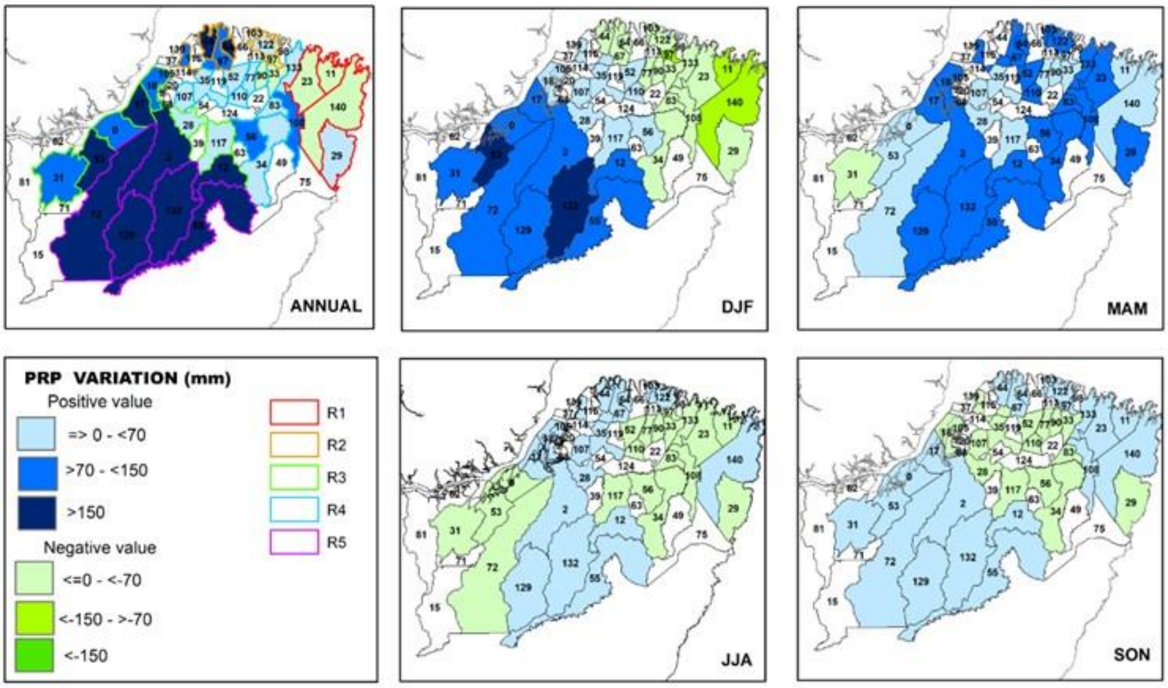


Figure 9. Variation in the last 15 years, averages in the decades (1989 to 2003) and (2004 to 2018) in the precipitation data series - PRP, for annual and seasonal scale. The color scales indicate the delta variation values.

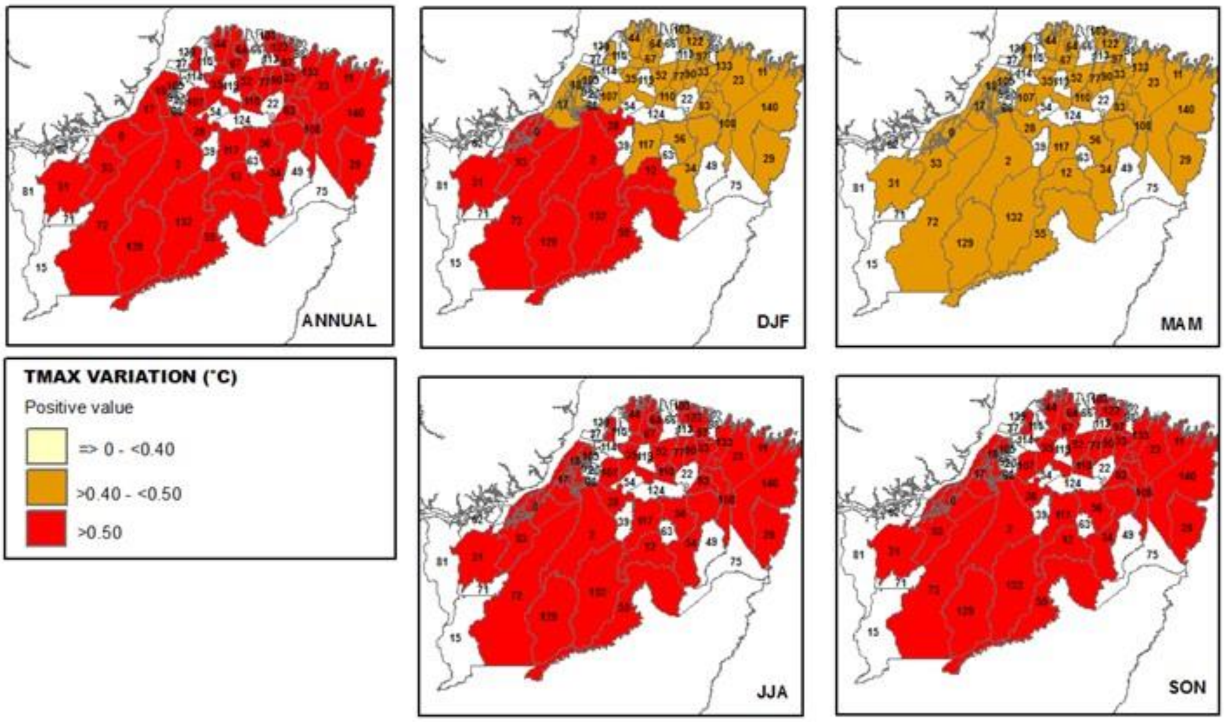


Figure 10. Variation in the last 15 years, averages of the decades (1989 to 2003) and (2004 to 2018) in the maximum temperature data series - TMAX, annual and seasonal scale. The color scales indicate the delta variation values.

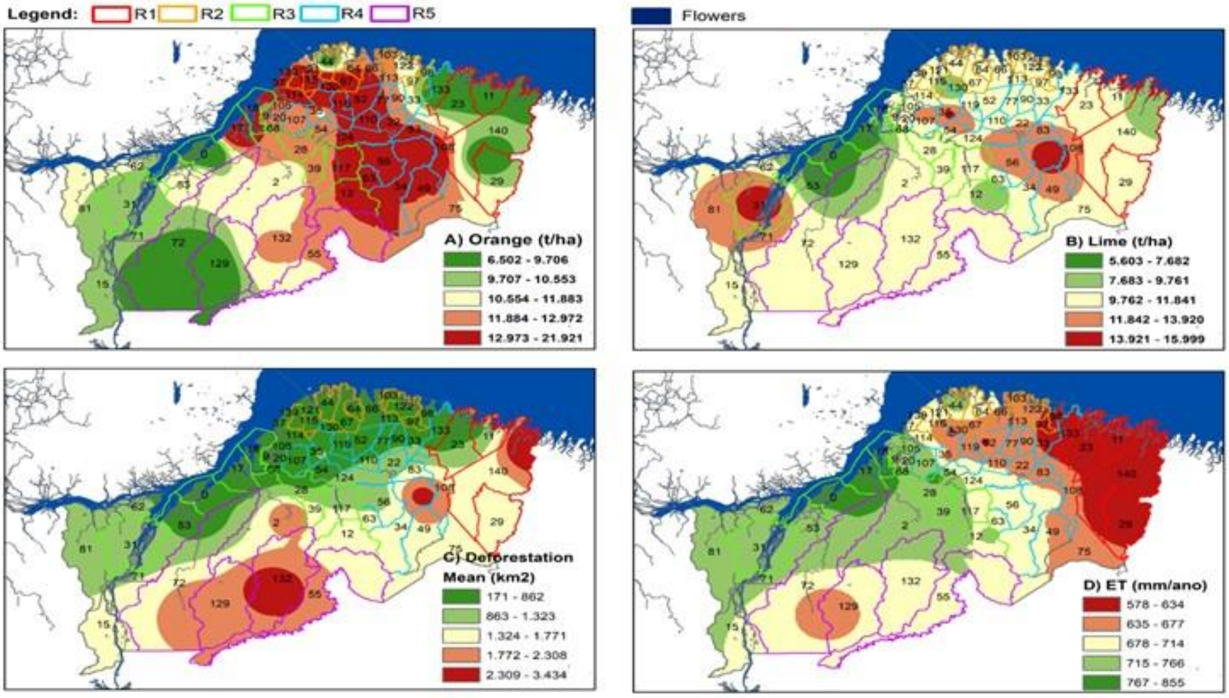


Figure 11. Spatial distribution of orange (A), "lemon" (B), deforestation rate (C), and ET (D) productivity over a 15-year period (2004 to 2018).

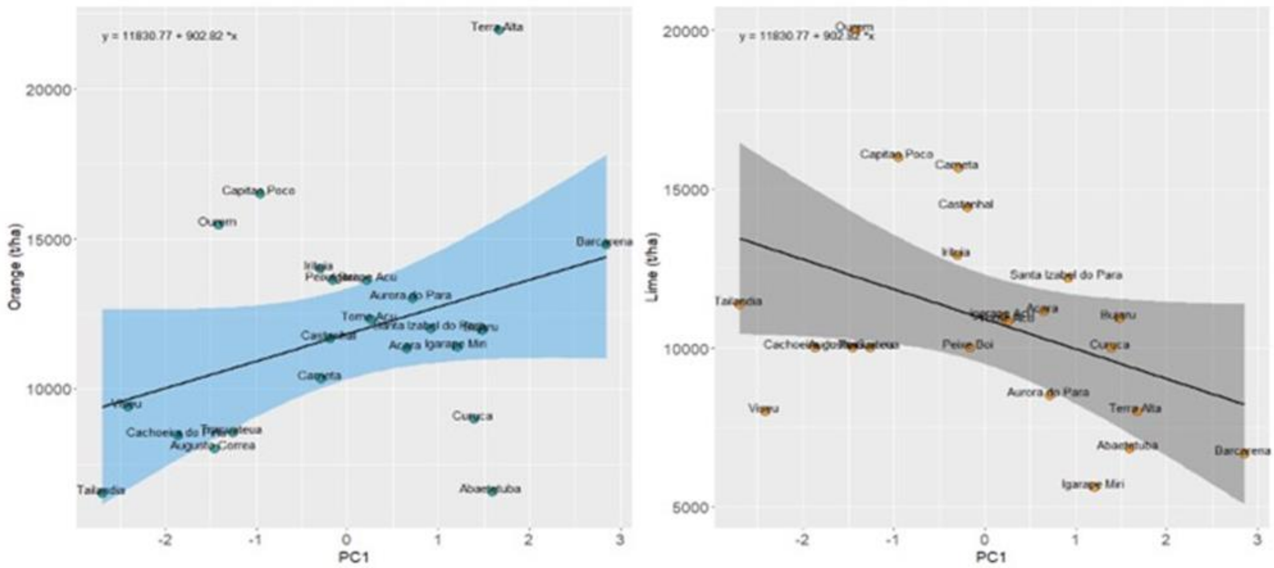


Figure 12. Linear regression model (PCR) showing the relationship of environmental variables in Axis 1 (PRP, TMAX, ET and Deforestation) and citrus productivity in Axis 2 (orange and lime), where Moran's Index :0.014, adjusted R2 is 77%, AIC Orange: 395.68 and AIC lime: 392.78.

Based on this geospatial knowledge and the climate variation parameters, the results of the environmental variables that influence citrus PROD are shown in (Figure 20). The PCA result shows that the sum of the first three principal components of the PCA explains 72.5% of the total variation. Dimension 1 is the one that best explains the environmental variables affecting citrus productivity, with ET being the most closely related variable (r=0.78), followed by PRP (r=0.74). On the other hand, TMAX (r=-0.57) is followed by deforestation (r=-0.49). Therefore, the PCR models indicate that positive values of PC1 (environmental variables x citrus PROD) represent locations with higher PRP and ET, while negative values indicate locations with higher TMAX and deforestation.

It is important to note that orange production is not irrigated in the region in question (ADEPARÁ, 2017), which makes the dependence on rainfall (PRP) and evapotranspiration (ET) even more important in determining citrus productivity. Water availability is a critical factor for the development of citrus plants, and the lack of irrigation makes these crops particularly sensitive to rainfall variability (Silva Junior et al., 2023).

The decrease in "lemon" productivity associated with the increase in rainfall can be explained by the fact that these rains occurred at an inappropriate time for growing this fruit. In tropical and subtropical regions, where many lemon trees are grown, there is a well-defined rainy season and a dry season. Lemon trees generally prefer a rainfall regime that includes a rainy period to provide sufficient water for growth and a dry period to stimulate fruiting. The lack of an adequate dry period can lead to excess moisture in the soil, which can impair root development and cause problems such as the proliferation of fungal diseases (Hardy, 2004).

Increased precipitation during the fruiting season of lemon trees can cause problems such as dilution of juice, fruit cracking, and increased susceptibility to disease. In addition, excess moisture can hinder pollination and proper fruit formation, according to Shafqat et al. (2021).

Therefore, the decrease in lemon production in response to increased rainfall may be related to the fact that these rains occur during a critical period for the growth and fruiting cycle of citrus trees, negatively affecting the ideal conditions for growing this crop. It is important to note that the specific period in which these rains occur may vary depending on the geographical location but is generally related to the rainy season in the region in question. However, it is important to consider the results of the recent study by Silva Junior et al. (2023), which analyzed the dynamics of energy and water in "lemon" production in the Eastern Amazon. The study found that 63% of the available energy was consumed by latent heat during the wettest period, while 60% was consumed during the less wet period. The water consumption of the lemon during the experiment was 1599 mm, with a daily average of 3.70 mm day -1, while the average value of the crop coefficient (Kc) was 1.41. These results allow the design of appropriate water supply protocols for the crop in the main citrus hub of the Amazon region.

Conclusions

1. It identifies wettest and driest periods, covering 1981-2018. Wet season is between December and May and dry season is between June and November.
2. The high temporal and spatial variability of precipitation in the region is evident. Regions R1, R2 and R4 had lower seasonal precipitation values, which resulted in a significant negative trend ($Z<-1.96$, $p<0.05$) and delta ($\Delta<150$ mm). Municipalities in regions R3 and R5 had significant positive trends in precipitation ($Z>1.96$, $p<0.05$) and ($\Delta>150$ mm).
3. The trends of TMAX showed a strong increasing dominance in the annual time series and the seasonal time series. Most of the statistically significant trends were observed in the dry season ($Z > 1.96$, p value < 0.05). In addition, an increasing magnitude ($\Delta > 0.50$) was observed in most municipalities over the 15 years.
4. PCA shows that the sum of the first three principal components explains 72.5% of the total variance of the original data. Dimension 1 is the only one that explains the environmental variables that have an impact on citrus productivity. In this case, ET was the most related variable (r = 0.78), followed by PRP (r = 0.74). Conversely, TMAX (r=-0.57) was followed by deforestation (r=-0.49).
5. It is evident that the region with the highest citrus PROD is concentrated in the R4 region, and the deforested areas are also grouped between R5 and R1. However, some orange producing municipalities are negatively influenced by the deforestation and TMAX parameters. These show a positive relationship with PRP (increase) and ET. With regard to "lemon" PROD, the behavior is different, with some locations tending to decrease with PRP and ET, despite the increase in TMAX and deforestation.

6. Therefore, the PCR model showed that increased deforestation and TMAX can affect citrus productivity. This supports studies on climate change and its impact on fruit productivity in Pará. Furthermore, the model is acceptable because it does not show autocorrelation through the accuracy indices (Moran's index: 0.014; adjusted R2 is 77%; orange AIC: 395.68 and "lemon" AIC: 392.78).

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