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Research Paper

Trend analysis and change-point detection of temperature and rainfall in southern Peruvian Amazon and its relation to deforestation

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ABSTRACT

The study aimed to identify the change points, tendencies, and trends in climatic parameters (precipitation and temperatures) and to investigate their relationship with deforestation in the southeastern Peruvian Amazon (Tambopata). Rainfall and temperature data for the Puerto Maldonado station from 1970 to 2023 was used. Monthly, seasonal, and annual precipitation as well as temperature (maximum, minimum, and mean) were analyzed for possible trends using nonparametric Mann-Kendal statistic test, while the Pettitt test was employed to detect the abrupt change point in time series. The Spearman's correlation coefficient was used to identify the relationship between deforestation and climate parameters. The results revealed a rise in mean, minimum, and maximum temperatures. Mann Kendall and Sen's slope revealed significant trends in the monthly, seasonal and annual temperatures in the study period. However, in contrast to the temperature variation trend, the monthly, seasonal and annual precipitation did not present a significant trend. Significant positive correlations were obtained between deforestation and temperatures but its association with precipitation was not significant.

Keywords: Change point, climate change, climate variability, deforestation, Tambopata, Madre de Dios.

Aerosol emissions, deforestation and other human activities have increased during the second half of the 20th century, increasing the frequency of extreme events such as increased heat waves, frequent droughts, and flooding, which have affected human populations and the global ecosystem. Likewise, the change generates other severe impacts on the environment such as increased extreme flows, fires, forest loss, water depletion and loss of ecosystem services. In addition, global climate change affects food security, water, health and housing for human populations (Fattah *et al.,* 2024; Swami, 2024; Umeh and Gil-Alana, 2024). Trend studies analyze changes over time in a specific climate variable e.g., temperature, precipitation and drought (Da Silva *et al.,* 2019). The nonparametric Mann-Kendall test is widely used for trend analysis because it is robust to outliers, missing values and can be used for seasonal or cyclic data (Espinoza *et al.,* 2009; Sridhara and Gopakkali, 2021). Likewise, the World Meteorological Organization has used the Mann-Kendall test in climate trend studies (Espinoza *et al.,* 2009; Fattah *et al.,* 2024; Lavado *et al.,* 2012).

Temperature and precipitation are considered the main indicators for investigating global climate change (Lute and Abatzoglou, 2021). Nevertheless, deforestation and fires that occur in the Amazon have potential impacts on land surface temperature and rainfall variability (Reygadas *et al.,* 2023; Silva *et al.,* 2023). In the southeastern Peruvian Amazon (Madre de Dios), agriculture, gold-mining and selective logging cause negative impacts on biodiversity and ecosystem services in forest ecosystems, and they are considered major drivers of deforestation (Lagneaux *et al.,* 2024). Although, gold-mining causes the most severe negative impacts on ecosystems (Pisconte *et al.,* 2024), agriculture drives the highest proportion of deforestation (Alarcón-Aguirre *et al.,* 2023). Therefore, in the current context of global warming and

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biodiversity crisis, deforestation in the Amazon is a major global concern due to its impacts on climate, the natural environment, and the socioeconomic conditions of the most vulnerable populations (Cabral *et al.,* 2024). On the other hand, recent studies have demonstrated how deforestation in the Amazon can drastically affect climatic variables. The surface temperature increases as deforestation progresses (Maillard *et al.,* 2022) but the precipitation tends to decrease (Reygadas *et al.,* 2023). However, little is known about how forest degradation can affect precipitation and temperature at local scales. This is because climate studies have covered large areas and analyzed trends on a global scale, but to understand climate change it is essential to study at the local scale (Restrepo-Coupe *et al.,* 2023). In Madre de Dios, to our knowledge there are limited studies on trends and change points of precipitation and temperature at local and long-term scales. Therefore, considering the impacts of anthropogenic activities on climate variability, it is important to understand the relationship between deforestation, precipitation and temperature.

The objectives of the study were to (i) evaluate temporal trends and magnitude of annual, seasonal and monthly rainfall and temperature during 1970–2023 in the southeastern Peruvian Amazon; (ii) detect an abrupt change point of rainfall and temperatures; and (ii) identify the effects of deforestation on climatic variables.

MATERIALS AND METHODS

Study area

The study area is Puerto Maldonado, which is located in the southwest Peruvian Amazon, Tambopata, Madre de Dios. Madre de Dios is considered Peru's capital of biodiversity due to high levels of cultural and biological diversity within its Amazonian ecosystems (Saatchi *et al.,* 2011). The study area has a seasonal climate, with a marked dry season from June to September, months with less than 100 mm/month (dry-season precipitation) (Restrepo-Coupe *et al.,* 2023). The study area has a tropical, warm, and humid climate. The mean total annual precipitation between 1970 and 2023 was 2257 mm (ranging from 1413 to 3734), and the rainy season is typically between November and April (>250 mm/month). The average annual temperature is 27.7 °C (ranging from 16 and 33.8 °C). However, cold spells in Puerto Maldonado could produce an average minimum temperature drop of 8 ºC.

Data sources

We used the monthly precipitation (mm) and monthly average data of maximum (Tmax), minimum (Tmin) and mean temperatures (Tmean) (ºC) provided by the Peruvian Meteorological and Hydrological Service (SENAMHI) for the Puerto Maldonado meteorological station (12°35'1" S, 69°12'1" W, and 200 m a.s.l.), for a period of 53 years (1970–2023). The deforestation data at the study site between 1985 and 2023 was obtained from MapBiomas Collection 7 (https://amazonia.mapbiomas.org). MapBiomas produces annual land cover/use maps from a pixel-by-pixel classification of the Landsat satellite images using machine learning algorithms on the Google Earth Engine platform.

Trends and change point detection

Monthly, seasonal and annual precipitation and temperature trends were analyzed using the Mann-Kendall (MK) (Kendall, 1975). MK is a non-parametric test, that has no prerequisite conditions for the data to be normally distributed (Swami, 2024; Uwizewe *et al.,* 2024). The change per unit time (slope magnitude) was determined using Sen's slope estimator (Sen, 1968). The non-parametric Pettitt's test was used to detect change points in climate data without any assumption about the distribution of the data (Pettitt, 1979).

The "trend" package of the R software (https://www.r-project.org) was used to detect trends, change points and slope magnitude in the time series of precipitation, Tmax, Tmean and Tmin.

Data analysis

Annual, monthly and seasonal precipitation and temperature data for 54 years (1970-2023) were analyzed. The seasonal variability of precipitation and temperature were analyzed in quarterly groupings: December-January-February (Summer), March-April-May (Autumn), June-July-August (Winter), and September–October November (Spring). Spearman's correlation coefficient was used to analyze the relationship between deforestation and climate variables because the data do not comply with assumptions about the distribution of the data. R software version 4.4.0 and SigmaPlot v15 were used to perform the analysis and figures at a significance level of 0.05.

RESULTS AND DISCUSSION

Precipitation trends

Trends (Sen's slope; $p > 0.05$) and change points were not significant (Pettit's test; $p > 0.05$) in monthly, annual and seasonal precipitation (Table 1) during the study period (1970-2023). Although, precipitation has shown a non-significant decreasing trend in January, February, March, July, August, September and in all seasons of the year. The non-existence of significant trends and change points in annual precipitation found in the present study are consistent with those reported by previous studies (Almeida *et al.,* 2016; Espinoza *et al.,* 2010; Lavado *et al.,* 2012; Sridhara and Gopakkali, 2021). Espinoza *et al.,* (2010) and Almeida *et al.,* (2016) found a non-significant decrease in annual precipitation in the Amazon Basin between 1975-2003, and in the Peruvian Amazon between 1973 and 2013, respectively. In addition, Lavado *et al.,* (2012) found non-significant trends in annual and monthly precipitation in the Amazon Basin between 1965 and 2007. However, the results about seasonal and monthly precipitation trends differ from those reported by previous studies (Espinoza *et al.,* 2009; Lavado *et al.,* 2012). In the Amazon basin, during the 1975–2003 period, Espinoza *et al.,* (2009) observed that the precipitation decreased in winter, spring, January and February, June, July, August, September, October, November and December. Deforestation of tropical forests may cause precipitation reductions (Smith *et al.,* 2023). In the Brazilian Amazon, De Souza *et al.,* (2023) found that annual precipitation decreased due to the loss of forest cover between 1982 and 2020, while Silva *et al.,* (2023) found a decrease in the precipitation volume due to severely increased deforestation between 2001 and 2020.

Table 1: Results of the statistical tests (Mann–Kendall, Pettitt and Sen's slope) for annual, seasonal and monthly precipitation and temperatures over the period 1970–2023.

Period	Mean temperature			Maximum temperature			Minimum temperature			Precipitation		
	Z_S	Pet_u	Q_{med}	Z_S	Pet_u	Q_{med}	Z_S	Pet_u	Q_{med}	Z_S	Pet_u	Q_{med}
Summer	4.25**	2004**	0.026**	3.49**	1997**	0.031**	3.19**	2010**	0.033**	-0.84	1988	nd
Autumn	4.99**	2004**	0.029**	3.28**	1998**	0.025**	3.76**	2010**	0.038**	0.46	1978	nd
Winter	4.95**	2000**	0.046**	3.55**	2000**	0.037***	5.06**	2002**	0.059**	-0.31	1975	nd
Spring	4.99**	2003**	0.041**	3.80**	1996**	0.037*	3.60**	2008**	0.043**	-0.72	2003	nd
Annual	5.68***	2003***	0.036***	4.36***	1997***	0.031***	4.36***	2010***	0.048***	-0.37	1986	nd
Jan	3.72***	2004**	0.023***	3.12**	1997***	0.030***	2.45*	2010**	0.027*	-1.42	1988	nd
Feb	2.91**	2004***	0.022**	2.49*	1997***	0.023*	2.63**	2010***	0.035**	-0.52	1986	nd
Mar	3.58***	2004***	0.024***	2.58**	1998***	0.022**	2.81**	2010**	0.032**	0.01	1984	nd
Apr	4.45***	2004***	0.033***	3.67***	1998***	0.037**	3.46***	2010***	0.037***	0.18	2015	nd
May	4.70***	2000***	0.033***	2.36*	1998***	0.022*	3.50***	2010**	0.042***	1.06	1977	nd
Jun	3.95***	2000***	0.041***	2.10*	2000**	0.026*	4.01***	2003***	0.054***	0.17	1993	nd
Jul	3.88***	2000***	0.052***	2.63**	2000***	0.038**	4.48***	2000***	0.066***	-0.21	1978	nd
Aug	4.98***	1999***	0.058***	4.18***	1998***	0.053***	4.85***	2003***	0.053***	-1.49	1977	nd
Sep	4.95***	2003***	0.054***	3.79***	1996***	0.047***	4.93***	2003***	0.068***	-0.6	1992	nd
Oct	4.39***	2008***	0.039***	3.60***	1997***	0.037***	4.26***	2008***	0.055***	-0.26	1994	nd
Nov	3.54***	2003***	0.025***	2.60**	1994**	0.027**	2.69**	2008***	0.035**	0.63	2013	nd
Dec	4.72***	2003***	0.032***	4.24***	1996***	0.036***	3.26**	2008***	0.034**	0.73	1991	nd

Z_S: Mann-Kendall test. Pet_u: Pettit's test (U) test. Q_{med}: Sen's slope estimator. * p < 0.05; ** p < 0.01; *** p < 0.001. nd = No trend.

Temperature trends

Maximum, minimum, mean temperatures showed a significant rising trend for annual, seasonal and all months (Sen's slope $p < 0.05$; Table 1). The annual mean temperature showed a significant increasing trend (0.036 °C year $^{-1}$), and a change point was estimated in 2003 (Pettit's test, $p < 0.01$). The increase in the seasonal mean temperature was higher in winter (0.046 °C year $^{-1}$) and spring (0.041 °C year $^{-1}$). The change points for the seasonal mean temperature were detected between 2000 and 2004 (Pettit's test $p < 0.01$). Winter was the first season to present a change point (2000), while summer and autumn experienced a change point in 2004 (Pettit's test $p < 0.01$; Table 1). The existence of significant trends and change points in mean annual and seasonal temperature found in the present study are consistent with those reported by previous studies in the Amazon (Lavado *et al.,* 2012; Malhi and Wright, 2004). The slopes of the mean annual and seasonal temperatures were more than four times higher than those reported by previous studies in the Amazon (Lavado *et al.,* 2012; Malhi and Wright, 2004). Despite of the change point varied in more than 20 years, Malhi and Wright (2004) found a change point in 1970, and Lavado *et al.,* (2012) found a change point in 1978.

The annual minimum temperature showed a significant increasing trend (0.048 °C year^{-1}), and a change point was estimated in 2010 (Pettit's test, $p < 0.01$). The increase in the seasonal minimum temperature was higher in autumn (0,059 °C year^{-1}), while in summer (0.038 °C year^{-1}) and spring were the lowest (0.033 °C year^{-1}). The change points for the seasonal minimum temperature were detected between 2002 and 2010 (Pettit's test, $p < 0.01$). Winter was the first season to present a change point (2002), while summer and autumn experienced a change point in 2010 (Pettit's test, $p < 0.01$; Table 1). Our findings are different from the results reported in Lavado *et al.,* (2012), because they did not detect significantly decreasing trends from 1965 to 2007. However, the positive minimum temperature trends reported in the present study are in agreement with studies conducted in the southwestern Brazilian Amazon (Almeida *et al.,* 2016; Marengo and Camargo, 2008). Even though, the slopes of the minimum annual temperature were greater than 1.5 times, between 1.6 and 7 times, those reported by Marengo and Camargo (2008) (0.008 °C year^{-1}) and Almeida *et al.,* (2016) (0.04 °C year^{-1}).

The maximum temperature had a similar pattern and trend to that observed in the mean and minimum temperatures. The annual maximum temperature showed a significant increasing trend (0.031 °C year $^{-1}$), and a change point was estimated in 1997 (Pettit's test $p < 0.01$). The increase in the seasonal maximum temperature was higher in winter and spring (0.037 °C year $^{-1}$), while the lowest was in autumn (0.025 °C/year). The change points for the seasonal maximum temperature were detected between 1996 and 2000 (Pettit's test, $p < 0.01$). Spring was the first season to present a change point (1996), and the last one was winter (2000) (Pettit's test, $p < 0.01$; Table 1). Positive maximum temperature trends reported in the present study are in agreement with studies conducted in the Amazon region (Almeida *et al.,* 2016; Marengo and Camargo, 2008). Although, the rates of seasonal and monthly maximum temperature increases were smaller than those in previous studies, Marengo and Camargo (2008), and Almeida *et al.,* (2016) found a 30% greater increase in annual maximum temperature than in the present study. However, for seasonal maximum temperature our findings were different from the results reported in Marengo and Camargo (2008) because the slope of the annual temperature was two times greater and the increase in the summer was much higher than those found in the present study.

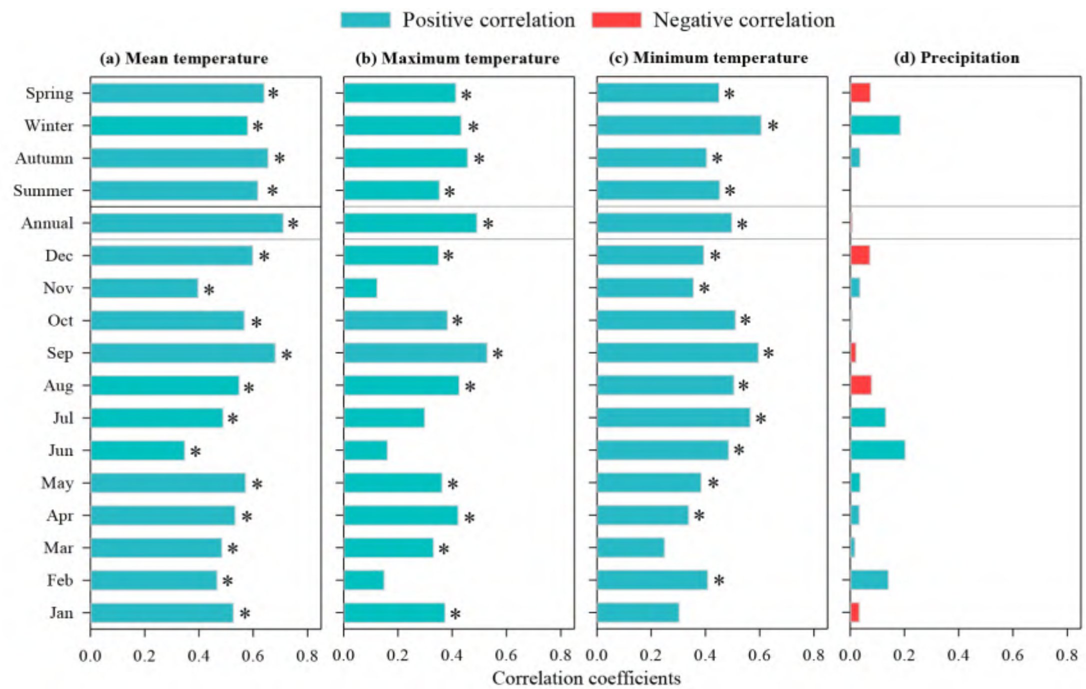

Fig. 1: Results of Spearman's correlation analysis between deforestation and climate variables (temperature and precipitation). Barplots represent the absolute values of Spearman's correlation coefficient. Asterisks represent significant correlations ($p < 0.05$). Red bars mean negative correlations and green bars positive correlations.

Relationships among deforestation, temperature and precipitation

The results showed that deforestation was positively correlated (rho > 0.3; p<0.05) with the seasonal and annual temperatures (Tmin, Tmax and Tmean) (Fig. 1). However, the relationship between deforestation and monthly temperatures varied slightly depending on the month. Deforestation was significantly and positively correlated with the all-month mean temperature (rho > 0.3; $p < 0.05$; Fig. 1a). A positive relationship between deforestation and maximum temperature was found in all months, but only relationships in January, March, April, August, September and December were statistically significant (rho > 0.3; $p < 0.05$; Fig. 1b). Deforestation was significantly and positively correlated with all month's minimum temperatures, except for January and March (rho > 0.3; $p < 0.05$; Fig. 1c). On the other hand, no significant correlation was found between deforestation and all precipitations (monthly, seasonal and annual) ($p > 0.05$; Fig. 1d). These results corroborate and indicate the potential effects of deforestation on surface temperature in the southeastern Peruvian Amazon.

Changes in climatic variables are related to changes in forest cover (Bakr *et al.,* 2024). The result of this study shows a low to moderate positive correlation between deforestation and temperature. These findings are in agreement with studies conducted in the Amazon region (Layza and Gonzales, 2018; Maillard *et al.,* 2022; Mesia, 2015; Silva *et al.,* 2023), who demonstrated that deforestation in the Amazon increases the temperature. In the Peruvian Amazon, Layza and Gonzales (2018) and Mesia (2015) found high variability explained (r^2 > 0.6) by deforestation in temperature increases in the departments of San Martin and Iquitos. This highlights the negative impacts that deforestation may have on temperature and conservation in the Peruvian Amazon region (Layza and Gonzales, 2018). Although it is observed that the southwestern Amazon portion of the Amazon still conserves its native forest (Silva *et al.,* 2023), our study draws the attention to reduce deforestation trends in Madre de Dios and thus reduce its potential negative effects on surface temperature. Therefore, the local society and public authorities need to have and implement public policies (Silva *et al*., 2023) aimed at environmental conservation of Madre de Dios and to try to stop the advances in agriculture, mining and forestry industry. This can be achieved with public policies oriented to territorial planning, promoting forest restoration, monitoring deforestation and climate variables at different scales (Maillard *et al.,* 2022).

In the present study, deforestation was not significantly associated with precipitation, which differs from previous studies (De Souza *et al.,* 2023; Maillard *et al*., 2022; Silva *et al*., 2023). Maillard *et al.,* (2022) reported that deforestation tends to decrease precipitation in the Bolivian Amazon. In the Brazilian Amazon, De Souza *et al.,* (2023) found that annual precipitation decreased (6.6 to 9.9% less) due to the reduction of forest cover between 1982 and 2020 in Mato Grosso, and (Silva *et al.,* 2023) found a reduction in precipitation volume due to a severe increase in deforestation between 2001 and 2020 in Northern Brazil. These differences between our results and previous studies are because deforestation may also shift precipitation patterns (Smith *et al*., 2023). In the study area, an increase in the dry season, decrease precipitation in summer and increase precipitation in the winter season was observed.

CONCLUSIONS

Our study represents the first to provide evidence-based field data about the relationship between deforestation and surface temperatures at the local scale in the southeastern Peruvian Amazon. We found a rise in mean, minimum, and maximum temperatures. Mann Kendall and Sen's slope revealed significant trends in the monthly, seasonal and annual temperatures (mean, minimum, and maximum) in the study period. In contrast to the temperature variation trend, the monthly, seasonal and annual precipitation did not present a significant trend during 1970–2023. On the other hand, the result of this study shows a low to moderate positive correlation between deforestation and temperature. However, deforestation was not significantly associated with precipitation.

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