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Relationship between the average annual temperature and the area of Amazonian humid forest in the departments of Peru, 2013-2021

Maria De Los Angeles Guzman Cuba[a], Eliana Rosmeri Navarro Rojas[a*] and Dante Manuel García Jimenez[a]

[a]*Universidad Continental, Peru*
[b]*Altoandina National Autonomous University of Tarma (UNAAT), Peru*
[c]*San Luis Gonzaga National University (UNICA), Peru*
[d]*Continental University (UC), Peru*
[e]*Peruvian University Los Andes (UPLA), Peru*

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The present study analyzed the relationship between the average annual temperature and the area of Amazonian forest in the departments of Peru during the period 2013-2021, using a panel data model with random effects. The data used come from the National Institute of Statistics and Informatics (INEI) and include the average annual temperature in degrees Celsius and the area of Amazonian rainforest in thousands of hectares, both disaggregated by department. Additionally, CO2 emissions resulting from the loss of tree cover, measured in megatons (Mt) of carbon dioxide equivalent (CO_2e), were considered as a control variable. The results revealed a positive and statistically significant relationship between the area of Amazonian forest and the average annual temperature, denoting that an increase of one thousand hectares in the extension of the forest corresponds to an increase of 0.0004 °C in temperature. In this sense, the finding contradicts the climate-regulating role played by forests, however, this is attributed to the influence of unobserved confounding variables that are linked to both forest area and temperature.

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1. Introduction

The Amazon, the largest tropical rainforest ecosystem on the planet, stretches across eight South American nations and is of vital importance for global biodiversity, providing habitat for thousands of plant and animal species. While previous efforts have been made to conserve it, deforestation rates have increased recently, highlighting the urgent need for international and local action to protect this essential ecosystem (Butler, 2024). The processes of slash-and-burn forests lead to the release of carbon, thus contributing to global warming and altering local microclimates, with a decrease in humidity and an increase in temperatures (Houghton, 2018). Leite-Filho et al. (2020) found that with every 10% increase in deforestation, the start of the rainy season is delayed by about 0.4 days, the end is brought forward by about 1.0 days, and the total duration is reduced by about 0.9 days. In addition, they observed that the onset of rains is significantly influenced by large-scale climatic factors, with a predictive model explaining 69% of the year-on-year variability. In addition, the loss of forest cover reduces the forest's capacity to act as a carbon sink, exacerbating the problem of climate change, aggravated by the expansion of agricultural and livestock activities, which cause even more widespread deforestation (Daniel & Yap, 2020). Similarly, climate changes could accelerate tree mortality, affecting both carbon capture and storage in tropical forests, which, in turn, could influence regional temperature and environmental conditions of the forest ecosystem (Aleixo et al., 2019). In the case of the Pantanal, a large Brazilian wetland, Bergier et al. (2018) analyzed precipitation data from 1926 to 2016, revealing a positive trend in the average rate of rainy days per season, also underlining how Amazon deforestation can impact water security and the preservation of

* Corresponding author
E-mail address 72569155@continental.edu.pe (E.R. Navarro Rojas)

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ecosystem services. Likewise, in Latin America, during the La Niña phenomenon, there was an increase in rainfall and an impact on evapotranspiration in the rainiest months, while in El Niño the opposite occurred, with a reduction in rainfall during the less rainy months. These changes in precipitation and evapotranspiration influence humidity and ambient temperature. Variations in these conditions can directly affect the dynamics and extent of the Amazon rainforest, modifying vegetation and potentially altering the regional microclimate (Melo et al., 2019). This is considered relevant, because, since the 2000s, more than three-quarters of the forest is losing resilience, especially in areas with less rainfall and close to human activities. This is related to changes in the length of the dry season and an increase in the frequency of droughts, pushing the Amazon towards a critical point of irreversible degradation (Boulton et al., 2022). By reducing forest cover, logging decreases the ability of forests to regulate temperature and the hydrological cycle, thereby altering rainfall and raising local temperatures, highlighting the critical relationship between deforestation and climate changes observed in the region (Hobley et al., 2017). That is why it is considered necessary to strengthen public policies on environmental care.

A clear example of this is the soy moratorium, which was in force between 2006 and 2016 in Brazil, and proved to be effective in almost eliminating deforestation in the Amazon by prohibiting the commercialization of soy from newly deforested areas. This initiative stressed that economic development can coexist with environmental conservation, supporting the expansion of agricultural production without further deforestation (de Area et al., 2020). However, recent government policies in Brazil reduce environmental controls and eliminate crucial records, such as the Rural Environmental Registry. On the other hand, Almeida et al. (2017) evaluated the variability of rainfall and temperatures in the Brazilian Legal Amazon between 1973 and 2013. To do this, they analyzed 47 stations and found an average increase in annual temperatures of about 0.04 °C per year, observing increases in annual and wet-season rainfall in some places, contrasting with decreases during the dry season in others. According to Aleixo et al. (2019), extreme weather events have an impact on the structure and dynamics of these forest ecosystems, in which the increase in tree mortality could lead to a decrease in forest cover. Carbon and water cycles are also altered, as trees play a crucial role in carbon sequestration and regulation of the forest microclimate. Similarly, in the central Amazon, Branco and Marenco (2017) stated that tree species sensitive to mild drought conditions are significantly affected by an extension and greater severity of the dry season, a possible scenario due to climate change, as well as they found that there is a positive growth trend associated with the increase in monthly precipitation and minimum relative humidity in some of the species studied. Likewise Kitayama et al. (2021) stressed that, if the average annual temperature increases due to factors such as climate change or deforestation, it could alter forest growth and regeneration patterns, including leaf phenology (e.g., budding and falling). These phenological changes could, in turn, affect the structure and function of the forest, including its ability to store carbon, regulate the microclimate, and maintain biodiversity. In addition, when comparing forested and deforested areas, Ventura et al. (2018) highlighted that deforestation significantly affects evapotranspiration, which has direct implications on temperature and environmental humidity. The reduction in evapotranspiration in deforested areas could lead to an increase in local temperature, due to the lower availability of moisture to cool the air during the evapotranspiration process. In this way, the loss of forest area could influence the average annual temperature in the Amazon, affecting the climate and environmental conditions of the humid forest. In this case, Wongchuig et al. (2022) analyzed hydroclimatic changes in the Southern Amazon from 1981 to 2018, directly linking deforestation to drier conditions. The Bolivian Amazon, with a forest reduction of 40-50%, shows a decrease in precipitation and actual evapotranspiration, and an increase in potential evapotranspiration, evidencing an environment increasingly limited by water. With respect to the Peruvian Amazon, a vast expanse of biodiversity and a crucial carbon sink, it faces unprecedented pressures due to environmental and human changes. Zevallos and Lavado-Casimiro (2022) project that, although 82% of biomes will remain stable by 2065, significant changes in humidity will especially affect glaciers and swamps, the most vulnerable with losses of more than 50% of their area.

Similarly, Vicente-Serrano et al. (2018) investigated changes in maximum and minimum temperatures in Peru from 1964 to 2014, highlighting a general warming trend in surface air temperature with significant seasonal and spatial variations. Maximum temperatures increased especially during the austral summer, while minimum temperatures showed the greatest increase in the austral winter. In addition, the warming of maximum temperatures was more pronounced in areas of high elevation. On the other hand Rojas et al. (2021) developed in Peru a predictive model evaluated with forest loss data in near real-time for the year 2020. The most influential variables were distance to agricultural land and distance to roads, providing about 80% of the information needed for predictions. The model demonstrated high efficacy, registering 73.2% of early warnings in 2020 in categories of high or very high risk of deforestation. National protected areas showed a very high risk of less than 1%, but buffer zones were considerably more vulnerable, with 15% of forest cover in this risk category. Despite the efforts and financial resources dedicated annually to protect these areas, a significant loss of 114,463 hectares was recorded within protected areas and 782,781 hectares in buffer zones from 2001 to 2019 (Cotrina et al., 2021). The objective of this research is to analyze the relationship between the average annual temperature and the surface of Amazonian rainforest in the departments of Peru during the period 2013-2021.

2. Theoretical bases

Amazonian forests are important in regulating the hydrological cycle, absorbing carbon, and mitigating climate change (Spracklen et al., 2018). In fact, deforestation alters these ecological and climatic processes, modifying the physical characteristics of the earth's surface, such as its albedo, evapotranspiration, and roughness, which in turn disturbs the flows of energy and water between forests and the atmosphere (Bonan, 2008). As a result, forest cover loss tends to increase surface temperature, reduce evapotranspiration, and alter precipitation patterns, although the magnitude of these changes and the possible existence of tipping points remain uncertain (Lejeune et al., 2015). In addition, the climate impacts of deforestation are highly dependent on land uses that follow the loss of forest cover (Silvério et al., 2015). Forest transition theory outlines a conceptual framework for understanding the dynamics of forest cover change over time (Mather, 1992). According to this theory, places experience forest transitions when forest cover declines cease and recoveries begin, either due to economic development that creates non-farm jobs and takes farmers off the land, or because of the scarcity of forest products that leads to planting trees in some fields, dynamics that allow carbon to be sequestered and soil to be conserved (Rudel et al., 2005). On the other hand, Gaia hypothesis, proposed by Lovelock and Margulis (1974), suggests that the Earth functions as a self-regulating system in which the biosphere, including forests, plays a critical role in regulating the climate. Amazon forests are a key component of this system, as they store large amounts of carbon, regulate hydrological cycles, and affect atmospheric circulation patterns (Nobre et al., 2016). In addition, the theory of the albedo effect of Charney et al. (1975) suggests that the removal of forest cover can increase the reflectivity of the land surface, which in turn can alter the energy balance and atmospheric circulation patterns. Likewise, Makarieva y Gorshkov (2007) propose that Amazonian forests play a crucial role in generating precipitation through evapotranspiration and the creation of atmospheric pressure gradients. Van der Werf et al. (2009) point out that deforestation contributes to global climate change by releasing the carbon stored in biomass and forest soils, second only to the burning of fossil fuels.

3. Methodology

The present research employs a quantitative approach with a non-experimental and longitudinal panel data design. The data used come from the National Institute of Statistics and Informatics (INEI) and include the average annual temperature in degrees Celsius and the area of Amazonian rainforest in thousands of hectares, both disaggregated by department for the period 2013-2021. In addition, CO2 emissions resulting from the loss of tree cover, measured in megatons (Mt) of carbon dioxide equivalent $(CO)_2e$). The departments studied are: Amazonas, Ayacucho, Cajamarca, Cusco, Huancavelica, Huánuco, Junín, La Libertad, Loreto, Madre de Dios, Pasco, Piura, Puno, San Martín, and Ucayali. For the analysis of the data, a panel data model is used, whose estimator is determined based on the results of a series of statistical tests. First, the Breusch-Pagan test is applied to determine whether there is unobserved heterogeneity between departments and, therefore, whether a random-effects model is preferable to a pooled data model. An F-test is then performed to assess whether a fixed-effect model is more suitable than a pooled data model. Finally, the Hausman test is carried out to determine whether the fixed-effect or random-effects estimator is more consistent. The dashboard data model is specified as follows:

$$TPA_{it} = \beta_0 + \beta_1 SBA_{it} + \beta_2 ECO2_{it} + u_{it}$$

where: is the average annual temperature in department *i* in year *t*; $TPA_{it}SBA_{it}$is the area of Amazonian forest in department *i* in year *t*; $ECO2_{it}$ is the CO2 emissions from tree cover losses in department *i* in year *t*; and u_{it} is the error term. After the estimation of the model, the assumptions of autocorrelation and heteroskedasticity are verified, which, in the presence of fixed effects, have the Wooldridge test for first-order autocorrelation defined, and the modified Wald test, while, with random effects, only the tests for autocorrelation are defined, and in this case, the Sosa-Escudero and Bera test is used.

4. Results

In the first instance, Table 2 presents the descriptive statistics of the study variables disaggregated into three levels: general, between groups and within groups. The average annual temperature variable has a general average of 17.9389 °C, with a standard deviation of 6.662. There is evidence of variability between departments, with a minimum of 5,455 and a maximum of 27,367 °C. On the other hand, the variability within departments over time is lower, with a standard deviation of 0.532. Regarding the variable area of Amazonian forest, the general average is 4571.82 thousand hectares (should it be 4571.82 Ha?), with a standard deviation of 8619.511. Likewise, the variability between departments ranges from a minimum of 17,351 to a maximum of 35076,930 thousand hectares (should it be 35076.93 Ha?), and within departments over time is lower, with a standard deviation of 38,887. Finally, with respect to the control variable (CO2 emissions due to tree cover losses), the general average is 7.43705 Mt of CO_2e, with a standard deviation of 9.228, a variability between departments ranging from a minimum of 0.087 to a maximum of 31.763 Mt of CO_2e, whereas, the variability within departments over time is reflected in a standard deviation of 2.442.

Table 1
Descriptive statistics

Variable		Stocking	Standard deviation	Minimal	Maximum	Remarks
Average annual temperature	General	17.9389	6.662	5.000	27.633	N= 135
	Between groups		6.848	5.455	27.367	n= 15
	Within the groups		0.532	15.258	19.601	T= 9
Amazon forest area	General	4571.82	8619.511	17.014	35199.610	N= 135
	Between groups		8888.845	17.351	35076.930	n= 15
	Within the groups		38.887	4429.369	4699.177	T= 9
CO2 emissions from tree cover losses	General	7.43705	9.228	0.024	42.273	N= 135
	Between groups		9.177	0.087	31.763	n= 15
	Within the groups		2.442	-2.790	17.947	T= 9

Note. Prepared by the author with Stata 16.

Subsequently, Table 2 presents the results of the statistical tests carried out to choose the most appropriate estimator in the panel data model. First, the Breusch-Pagan test is applied, whose significance level of 0.000 indicates that the null hypothesis of absence of unobserved heterogeneity should be rejected, therefore, a random-effects model should be used and not a pooled data model, since this model allows controlling for unobserved heterogeneity between departments. On the other hand, the F-test is carried out to assess whether a fixed-effect model is more suitable than a pooled data model, obtaining a significance level of 0.000 indicating that the null hypothesis that fixed effects are equal to zero should be rejected, and therefore a fixed-effect model is preferable to a pooled data model. Finally, the Hausman test with a significance level of 0.3039 indicates that the null hypothesis cannot be rejected. Therefore, random-effects estimation is the most appropriate for data analysis.

Table 2

Tests for estimator choice

Test	Statistical	Level of significance
Breusch-Pagan	513.29	0.000
Exhibit F	826.88	0.000
Hausman's Test	2.38	0.3039

Note. Prepared by the author with Stata 16.

Then, the model is estimated through random effects, and its results are presented in Table 3. The estimated coefficients suggest that there is a positive and statistically significant relationship between the area of Amazon forest and the average annual temperature, i.e., an increase of one thousand hectares in the area of Amazon forest is associated with an increase of 0.0004 °C in the average annual temperature, keeping CO2 emissions constant due to tree cover losses. The result is contrary to expectations, given the ecosystem services provided by forests, such as climate regulation and carbon sequestration, whose explanation lies in the presence of unobserved confounding factors that are correlated with both the area of the Amazon forest and the average annual temperature. Thus, other variables have effects that generate an increase in local temperature that is not completely captured by the CO2 emissions included in the model. In relation to CO2 emissions due to tree cover losses, the coefficient is not statistically significant. The R-square "within" is 0.000, indicating that the model does not explain any part of the variability of the annual average temperature within departments over time, while the R-square "between" is 0.2652, i.e., the model explains 26.52% of the variability of the annual average temperature between departments. Finally, the "overall" R-square is 0.2635, denoting that the model explains 26.35% of the total variability of the annual average temperature, considering both the variations within the departments over time and the differences between the departments. However, the estimated model is subjected to diagnostic tests to verify compliance with the fundamental assumptions of the panel data models.

Table 3

Panel data model estimated by random effects

Average annual temperature	Coefficient
Amazon forest area	0.0004**
	(0.0002)
CO2 emissions from tree cover losses	0.0084
	(0.0200)
Constant	16.1202***
	(1.7132)
R-Square	
Within groups	0.0000
Between groups	0.2652
Global	0.2635
Number of observations	135
Number of groups	15
Observations by group	9
Wald chi2(3)	4.97
Prob > chi2	0.0833

Note. **Indicates significance at 5% and *** indicates significance at 1%. Standard errors are presented in parentheses.

Table 4 presents the results of the Sosa-Escudero and Bera Test, a test designed to detect the presence of autocorrelation in panel data models estimated by random effects, observing a p-value of 0.097, which is higher than the threshold of 5%, therefore, the null hypothesis of the absence of serial correlation in the model residuals cannot be rejected.

Table 4

Sosa-Escudero and Bera test for autocorrelation

Test	Statistical	P value
Serial Correlation	2.76	0.097
Random Effects		
Two tails	368.56	0.000
A queue	19.2	0.000
Joint Testing	516.05	0.000

Note. Prepared by the author with Stata 16.

5. Discussion

The research, through a panel data model estimated by random effects, found a positive and statistically significant relationship between the area of Amazon forest and the average annual temperature in the departments of Peru during the period 2013-2021. Specifically, the coefficient of 0.0004 indicates that an increase of 1,000 hectares in the area of Amazonian forest is associated with an increase of 0.0004 degrees Celsius in the average annual temperature, keeping CO_2 emissions constant due to tree cover losses. The result, contrary to what is expected, indicates that a set of unobserved confounding variables that are linked to both forest area and temperature have an influence on the relationship. Namely, the model does not account for the effect of other factors that contribute to the increase in local temperature. Previous literature identifies how deforestation in the Amazon can significantly alter hydrological and climatic cycles at local and regional scales. Such is the case of the study of Leite-Filho et al. (2020), who found that deforestation modifies the timing and duration of the rainy season, while, Almeida et al. (2017) showed a sustained increase in annual temperatures in the Brazilian Legal Amazon over four decades, with differentiated patterns in rainfall depending on location and season. In addition, changes in the area of Amazon forest can influence the forest's ability to absorb carbon and regulate the microclimate of localities (Hobley et al., 2017). Likewise Aleixo et al. (2019) suggest that variations in forest extent could affect tree mortality and alter carbon and water cycles. On the other hand Ventura et al. (2018) pointed out that deforestation, and the consequent changes in forest area, has a significant impact on evapotranspiration, with direct implications on temperature and environmental humidity. However, the study presents limitations in the availability of statistical information in the environmental sector at the level of the Departments of Peru, with incomplete time series that lead to unbalanced panels, as well as the impossibility of including other control variables in the model.

6. Conclusion

The research concludes that the relationship between the area of the Amazon forest and the average annual temperature, asserting that an increase in the extension of the Amazon forest corresponds to a slight increase in temperature in the period studied, even controlling for CO_2 emissions derived from the loss of tree cover. The finding differs from the climate-regulating role played by forests, denoting the complexity of the dynamics between the area of Amazonian forest and climatic variations in the various departments of Peru. In this sense, there are other unobserved variables that are influencing the temperature of the regions in the period studied that are not incorporated into the model. In future research, the incorporation of additional variables, such as changes in land use and precipitation and evapotranspiration patterns, is explicit in order to achieve a more comprehensive understanding of the impacts of variations in the area of Amazonian forest on the climate of the Departments of Peru.

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