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Comparison of rainfall patterns and rainfed maize yields in the Pacific region of Nicaragua and the Atlantic region of Colombia, 2007-2023

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RESUMEN

Se analizaron los efectos de la sequía sobre los rendimientos del maíz de temporal en el Atlántico colombiano y en el Pacífico nicaragüense, en el marco de ENOS. Se calculó el índice de precipitación estandarizado (SPI-12m) de 2000 a 2024 y se correlacionó con los rendimientos. En el Pacífico se obtuvo un coeficiente de determinación (R^2) de 0.52 entre rendimientos y SPI; una correlación moderada (R = 0.66) entre rendimientos con valores absolutos y sin correlación tras eliminar la tendencia; y una fuerte correlación (R = 0.80) entre valores de SPI. ENOS afectó los patrones de precipitación de manera diferente. En el Atlántico se registraron más valores del SPI fuera del rango normal (10), 60% de ellos por sequía, en dos ocasiones consecutivas (2001-2002 y 2014-2015). En el Pacífico, 30% de los nueve años con valores fuera del rango normal se debieron a la sequía y 6 a la humedad, comparados con cuatro en el Atlántico. En ambas regiones se registraron ciclos anormalmente húmedos consecutivos entre 2010 y 2011, con mayor intensidad en el Atlántico (1.94 y 1.32 vs. 1.64 y 1.13 en el Pacífico), siendo 2022 un año extremadamente húmedo (2.02 y 2.09). A pesar de una tendencia creciente de rendimientos, la productividad del maíz de temporal fue vulnerable a condiciones climáticas extremas, causadas por sequía en el Pacífico, con las mayores disminuciones en 2009 y 2015 (–0.47 y –0.22), y por lluvias excesivas en el Atlántico en 2021 (–0,42). El Atlántico mostró mayor variabilidad en los rendimientos (var = 0.097 frente a 0.03 en el Pacífico), donde fenómenos prolongados de ENOS tienen un mayor impacto en los patrones de precipitación y rendimientos.

ABSTRACT

The effects of drought on non-irrigated maize yields in the Colombian Atlantic and in the Pacific of Nicaragua were analyzed within the scope of ENSO. The Standardized Precipitation Index (SPI-12m) was calculated for 2000-2024 and correlated with crop yields, resulting in a coefficient of determination (R^2) of 0.52 between yields and SPI in the Pacific, a moderate correlation (R = 0.66) between regional yields (abs values)—although no correlation after removing series trend—, and a strong correlation (R = 0.80) between SPI values. ENSO affected rainfall regional patterns differently. In the Atlantic, more annual SPI values (10) were outside the normal range than in the Pacific, 60% due to drought, occurring twice consecutively (2001-2002 and 2014-2015). In the Pacific, three of the nine years outside the normal range were due to drought, while the other six were due to abnormally wet conditions, compared to four in the Atlantic. In both regions, abnormally wet conditions occurred consecutively from 2010-2011, although with greater intensity in the Atlantic (1.94, 1.32) than in the Pacific (1.64, 1.13), with 2022 being an extremely wet year (2.02 and 2.09). Even with an upward yield trend, rainfed maize productivity was vulnerable to extreme weather conditions, caused by drought in the Pacific, with the greatest decreases in 2009 and 2015 (–0.47 and –0.22), as well as excessive rainfall in the Atlantic in 2021 (–0.42). The Atlantic showed greater variability in yields (var = 0.097 vs. 0.03 for the Pacific), where prolonged ENSO of any intensity has a greater impact on rainfall patterns and yields.

Keywords: Standardized Precipitation Index, ENSO, maize yields, Nicaragua, Colombia.

1. Introduction

According to the UN (2020), climate change (referring to "long-term changes in temperatures and weather patterns") represents one of the most significant challenges for global agriculture (Altieri and Nicholls, 2009). These changes can be natural, such as variations in the solar cycle, or human-induced, such as greenhouse gas emissions, and affect the ability to produce food, our health, housing, safety, and jobs. Climatic factors such as altitude, latitude, prevailing winds, ocean currents, distance from the sea, and relief can accentuate, prevent, modify, or limit the presence and intensity of climatic phenomena, with the populations of small island nations and developing countries being the most vulnerable to their impacts (UN, 2020).

The challenges to global food security posed by climate change affect food production, distribution, and quality. One of the consequences is the reduction in agricultural yields due to the presence of droughts, higher temperatures, and erratic precipitation patterns (Zhu et al., 2022). Droughts are more frequent and prolonged, while rainfall is more intense, negatively affecting essential crops such as wheat, maize, and rice, reducing their productivity (Nelson et al. 2009) and causing rising global concern (Altieri and Nicholls, 2009).

Given that maize is a globally important crop for food security (Shiferaw et al. 2011), it is essential to analyze the effects of climate change on its yields at a regional or subregional scale, as these effects vary (Guajardo-Panes et al. 2018; Zhang et al. 2022; Cruz-González et al. 2024) depending on the geographic and climatic context. While predictions of a 10% reduction in rainfed maize yields by 2055 prevail (Jones and Thornton, 2003), studies in monsoon regions have also shown that the disruption of rainfall patterns, which increases during winter, accompanied by temperature increases, reduces the likelihood of negative impacts on this crop (Senthilnathan et al., 2025).

Therefore, this study aims to assess changes in rainfall patterns across the Pacific region of Nicaragua and the Atlantic region of Colombia, as expressed by drought/humidity levels using the Standardized Precipitation Index (SPI), and their effects on rainfed maize yields. This study adopts a primarily climate-focused approach that incorporates the effects of El Niño Southern Oscillation (ENSO) on the regions and temperature increases over time into the analysis of rainfed maize yield behavior.

2. Study area

2.1 The Pacific region of Nicaragua

The Pacific region of Nicaragua has warm sub-humid climates (Aw0, Aw1, and Aw2), according to Köppen, with average temperatures between 26 and 29 ºC and a bimodal rainfall pattern, with the most pronounced peak occurring from May to June and the second from September to November, resulting in a rainy season that covers 60% of the year (Vargas-Ulate, 2004). Its annual rainfall is among the lowest in Nicaragua, ranging from 1000 to 1800 mm, according to the Instituto Nicaragüense de Estudios Territoriales (Nicaraguan Institute of Territorial Studies) (INETER, 2025).

In the Pacific region of Nicaragua, municipalities in the Central American Dry Corridor, along with parts of Guatemala, El Salvador, and Honduras, experience varying degrees of drought, ranging from mild to severe (González-Figueroa, 2012). This corridor is characterized by high environmental and socioeconomic vulnerability to climate change and is at high risk of meteorological drought due to the combined effects of low precipitation and high evaporation, leading to hydrological drought (van der Zee et al., 2012). The rainfall regime has recorded accumulated rainfall decreases of up to 40%, according to the INETER (2023), while crop losses have reached 50% for maize and 100% for beans (ACF, 2010), showing the vulnerability of food security and the economy to the effects of climate change (Gotlieb et al., 2019). This represents a major challenge for the country's food sovereignty.

However, throughout Nicaragua, maize forms the basis of the national diet and therefore represents food and nutritional security for the population(García-Zeledón and Plata-Suncing, 2015). It accounts for 29% of the dietary energy consumed by its inhabitants (Castillo-Cajina and Bird-Moreno, 2013). The cultural relevance of this crop is also evident in the gastronomic diversity based on maize, with dishes such as *güirila*, *yoltamal*, *tamal*, *tortilla*, and *indio viejo*, as well as beverages such as *tiste*, *chicha de maíz*, *pozol*, and *pinolillo*. Nevertheless, 80% of maize producers nationwide are small farmers who do not have access to irrigation systems, and thus rely directly on rainfall (MIFIC, 2007), in scenarios of low yields of between 2 and 3 t ha^{-1} per cycle (INIDE, 2025).

2.2 The Atlantic region of Colombia

According to the Climatological Atlas of Colombia (IDEAM, 2017), the convergence of various macro- and meso-scale meteorological processes across the country is the main cause of the pronounced diversity of rainfall among its different regions. Annual rainfall exceeds 9000 mm in some extremely humid areas near the Pacific coast. Conversely, the driest regions are in the north-central strip of Colombia, which includes the Caribbean region. The study area for this work, known as the Departamento del Atlántico (Atlantic Department), is located in the southwestern portion of this region.

The average annual rainfall in the Atlantic region ranges from 1000 to 1500 mm, with a bimodal pattern characterized by two dry seasons (December to April and mid-year) and two rainy seasons. The rainy season from September to November is wetter than the mid-year season. The presence of tropical anticyclones, which generate high-pressure systems, is the predominant meteorological factor influencing rainfall patterns in these latitudes (IDEAM, 2017). According to the same source, 92.4% of the Atlantic region's territory has a hot and semi-arid climate, with the remainder classified as arid. Based on the Köppen climate classification, this corresponds to a savanna climate (Aw/As), representing the transition from humid tropical to hot and semi-arid. The average annual temperature of the Atlantic is among the highest in Colombia, ranging from 27 to 30º C, according to the temperature normals for the period 1991-2020 (IDEAM, 2025).

Colombia is considered a country highly vulnerable to climate change due to its physical, geographical, socioeconomic, and biodiversity conditions (DNP, 2012). One of the most concerning physical risks associated with increasing temperatures is the rise in sea level and the change in the coastline along both the Pacific Ocean and the Caribbean coasts, where sea level could increase by up to 90 mm by 2040 (Mendoza, 2016).

Rainfed agriculture is particularly affected by these climatic variations. White maize for human consumption is the grain with the third-largest planted area in Colombia (Carvajal, 2024). Approximately half of this area (more than 57 000 ha) is rainfed and traditionally produced, meaning its production depends largely on climatic conditions. The Atlantic region is a key agricultural area in Colombia with an agricultural frontier of 277 192 ha, making it one of the departments with the largest agricultural area in the country (Minagricultura, 2023). However, it is the region with the lowest production of this grain (Minagricultura, 2021). There, traditional management (non-irrigated) prevails in more than 80% of the area dedicated to growing maize.

The objective is to compare regions in the Intertropical Convergence Zone (ITCZ) that border the Atlantic and Pacific oceans and have different territorial configurations. Given the cultural and nutritional importance of the maize crop, this aims to achieve a deeper understanding of the factors affecting non-irrigated maize yield, as well as the limited local research on the subject in these regions.

3. Materials and methods

3.1 Yields' data

The period with available data on rainfed maize yields in the Pacific region of Nicaragua spans the years 2000 to 2023. Data were available from the statistical yearbooks of the National Institute of Development Information (INIDE, 2025) for the period 2000-2022. The 2023 data were obtained from the 2024 Macroeconomic Statistics Yearbook of the

Central Bank of Nicaragua (BCN, 2024). The annual data available from these sources provide only national values, along with the regional proportions of area and production volume contributed by each region, which serve as the basis for calculating yields for the Pacific region. Recorded values were converted from *quintales por manzana* (qq mz^{-1}) to tons per hectare (t ha^{-1}). For Colombia, the non-irrigated yield information was obtained directly from the Colombian government's agricultural statistics (Agronet, n.d.), which records data at the municipal and departmental levels for the years 2007 to 2023. The trend of the yield series was removed (*Y'*) in order to subsequently correlate them with SPI values (Table I).

Table I. Non-irrigated maize crop yields in the Atlantic region (*Y_A*) and the Pacific region (*Y_P*) in tons per hectare.

Year	Y_A (t ha^{-1})	Y_P (t ha^{-1})	*Y'_A*	*Y'_P*
2007	0.87	2.6	0.090	0.277
2008	0.81	2.53	–0.030	0.153
2009	0.78	2.11	–0.120	–0.321
2010	0.85	2.3	–0.110	–0.185
2011	0.95	2.62	–0.070	0.080
2012	1.18	2.61	0.100	0.016
2013	0.99	2.72	–0.150	0.072
2014	1.03	2.66	–0.169	–0.042
2015	1.09	2.49	–0.169	–0.266
2016	1.41	2.68	0.091	–0.131
2017	1.70	2.94	0.321	0.075
2018	1.46	3.21	0.021	0.291
2019	2.48	3.04	0.981	0.067
2020	1.73	2.86	0.171	–0.168
2021	1.37	3.16	–0.249	0.078
2022	1.30	3.04	–0.379	–0.096
2023	1.41	3.29	–0.329	0.100
SD	0.434	0.325	0.311	0.175
Var	0.188	0.105	0.097	0.030

Y': yield values of the detrended series for each region.

3.2 Climate data

For the calculation of the SPI, the monthly precipitation values utilized were those recorded by meteorological stations that spatially covered the study areas and could provide the longest recorded periods of time, ideally 30 years (Fig. 1). In Nicaragua, precipitation data were only available for the years 2000 to 2024, compiled until 2022 from the Statistical Yearbooks of the National Institute of Development Information (INIDE, 2025). Since precipitation data for 2023 and 2024 have not yet been included in the yearbooks, they were obtained from the monthly climate bulletins for the year, which document this variable at the regional level. In the Pacific region of Nicaragua, data from three meteorological stations were utilized: Chinandega, Managua, and Rivas (Fig. 1b).

In the case of Colombia, climate data were more readily available, and monthly precipitation for the period 1993-2023 was collected from the Information System for the Management of Hydrological and Meteorological Data (DHIME). This information came from seven meteorological stations: Casa de Bombas, Loma Grande, La Pintada, Normal Manatí, Piojó, Campo de la Cruz, and Candelaria (Fig. 1c).

Average annual temperatures were calculated by averaging the monthly values of the meteorological stations listed above. For Nicaragua, it was obtained from the same weather stations from 2000 to 2022. The values for 2023, as with precipitation, were retrieved from the monthly climate bulletins issued by the Nicaraguan Institute of Territorial Studies (INETER, n.d.). The average temperature data for the Atlantic coast of Colombia were also obtained from DHIME (n.d.), using two of the three stations in the region with monthly data available (Normal Manatí and Juan Acosta) from 2000 to 2023.

The few missing precipitation and temperature values were estimated using the historical averages analyzed for the corresponding months. The annual values obtained in the Atlantic region of Colombia were compared with the 1991-2020 temperature and precipitation normals published by IDEAM (2025). In the Pacific region of Nicaragua, the values obtained from the stations were compared with the 1971-2010 climate variability maps from INETER (2025) and were found to be consistent and reliable for use in this research.

3.3 ENSO information

While ENSO is a global phenomenon, the start and end dates of the oscillations vary slightly across regions. The information for the Atlantic region was

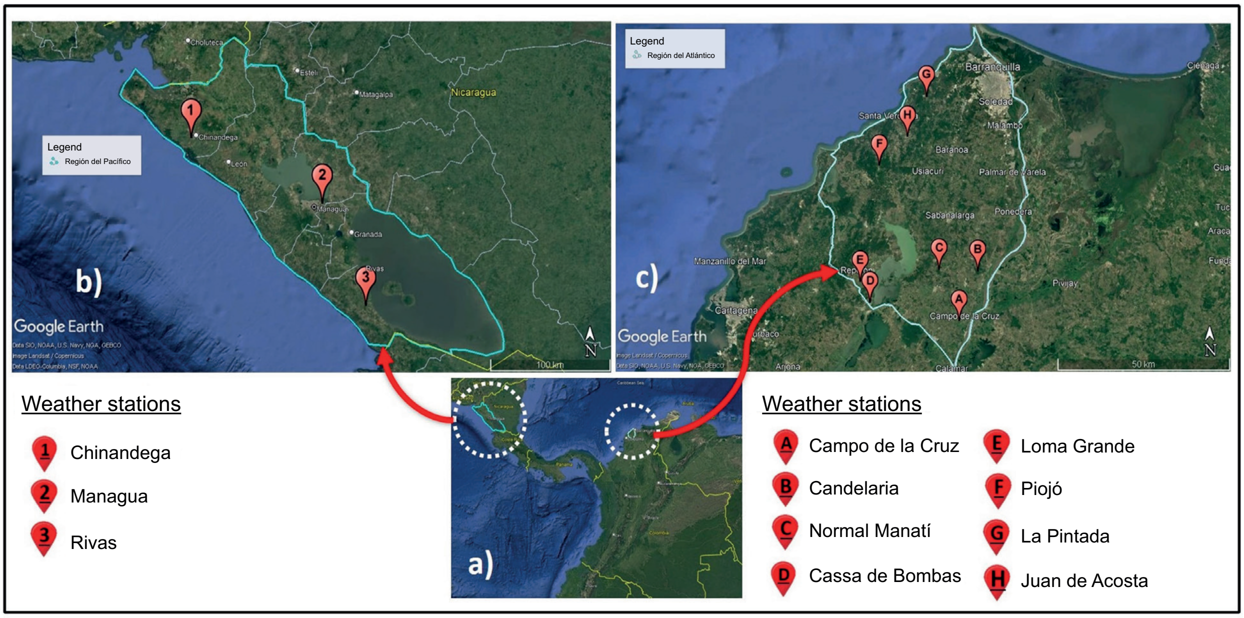

Fig. 1. Study regions and weather stations. (a) Location, (b) Pacific region of Nicaragua, (c) Atlantic region of Colombia.

obtained entirely from the monetary policy report of the Central Bank of Colombia (Caicedo-García and Bonilla-Pérez, 2023). Data for the Pacific region were obtained from various official sources over several years and cross-referenced with the historical cold and warm episodes by season records from the Climate Prediction Center (NOAA, 2025) (Table II).

3.4 SPI calculation method

The SPI proposed by McKee et al. (1993) was chosen for its flexibility in analyzing drought/humidity across different time scales, its ability to compare regions with different climates, and its ease of calculation, since it requires only precipitation data. Precipitation data series were accumulated annually to calculate the 12-month SPI, given the lack of disaggregated agricultural cycle data for Nicaragua. Based on the available climate information, the SPI was calculated for Nicaragua from 2000 to 2024, and for Colombia from 1993 to 2024.

The specific calculation of the SPI was carried out according to the methodology of Mckee et al. (1993) modified by Rathore (2011) of the National Institute of Hydrology in Roorkee, using the theoretical gamma probability distribution function (Eq. [1]), which has two parameters, namely α (shape factor), and β (scale factor). The parameters are estimated using the maximum likelihood estimator (Eqs. [2]-[4]). Finally, the cumulative probability distribution function is defined in Eq. (5).

$$g_x = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha\text{-}1} e^{-X/\beta} \tag{1}$$

$$\alpha = \frac{1}{4A}\left(1 + \sqrt{1 + \frac{4A}{3}}\right) \tag{2}$$

$$\beta = \frac{\bar{x}}{\alpha} \tag{3}$$

$$A = ln(\bar{x}) \text{-} \frac{\sum ln(x)}{n} \tag{4}$$

$$G_x = \int_0^x g_x\, dx = \frac{1}{\beta^{\alpha}\Gamma(\alpha)_0} \int_0^x x^{\alpha-1}\, e^{-x/\beta}\, dx \tag{5}$$

The gamma distribution ranges from 0 to 1, with 1 representing a 100% probability of rain. This index allows drought and humidity conditions to be measured and monitored, providing both an accurate and standardized assessment of climate conditions. It was calculated for the average annual precipitation of all stations.

Table II. ENSO episodes in the study areas from 1998 to 2024

Pacific region			Atlantic region		
Periods	Episode	Intensity	Periods	Episode	Intensity
Oct 98-Jun 99	Niña	Moderate	Jul 98-Feb 01	Niña	Moderate
Jun 02-Mar 03	Niño	Moderate	Jun 02-Feb 03	Niño	Moderate
Oct 04-Mar 05	Niño	Weak	Jul 04-Feb 05	Niño	Weak
Sep 05-Mar 06	Niña	Weak	Nov 05-Mar 06	Niña	Weak
Jun 06-May 07	Niño	Weak	Sep 06-Jan 07	Niño	Weak
Aug 07-Mar 08	Niña	Moderate	Jun 07-Jun 08	Niña	Moderate
			Nov 08-Mar 09	Niña	
Jun 09-Mar 10	Niño	Moderate	Jul 09-Mar 10	Niño	Strong
Jun 10-May 11	Niña	Strong	Jun 10-May 11	Niña	Strong
Jan 12-Jun 12	Niña	Strong	Jul 11-Apr 12	Niña	Strong
Jul 14-Apr 16	Niño	Very strong	Oct 14-Apr 16	Niño	Very strong
			Aug 16-Dec 16	Niña	Moderate
Sep 17-Feb 18	Niña	Moderate	Oct 17-Apr 18	Niña	Moderate
			Sep 18-Jun 19	Niño	Moderate
Nov 20-Apr 2021	Niña	Strong	Aug 20-May 21	Niña	Strong
Aug 22-Oct 22	Niña	Strong	Aug 21-Jan 23	Niña	Very strong
Dec 23-May 24	Niño	Strong			

Coefficients α and β were calculated for each region. All assessments were performed in a Google spreadsheet (https://docs.google.com/spreadsheets/). SPI values range from 3 to –3, according to the classification presented in Table III.

Table III. Drought/humidity conditions according to the Standard Precipitation Index (SPI).

SPI values	Condition
2 and more	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
−0.99 to 0.99	Near normal
−1.0 to −1.49	Moderately dry
−1.5 to −1.99	Very dry
−2 and less	Extremely dry

Source: McKee et al. (1993).

3.5 Correlation methods

Parametric statistics of Pearson correlation and polynomial regression models were implemented, as the normality of the distribution of SPI data and non-irrigated maize yields (*Y* and *Y'*) was verified through the Shapiro-Wilk (W) and Lilliefors (L) tests. To assess the correlation between regional yields, Pearson's correlation coefficient (Eq. 6) was used for the period with data available for both regions (2007-2023) to determine whether the direction and magnitude of changes were similar across the study areas. The time series of yields for each region was used with absolute values (*Y*) to observe the long-term pattern, along with detrended values (*Y'*), to understand the cycles within the data. This statistic was also used to correlate the regions' SPI values over the period 2000-2024.

$$r = \frac{\sum (x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum (x_i - \overline{x})^2}\sqrt{(y_i - \overline{y})^2}} \tag{6}$$

Furthermore, a regression model was implemented to determine whether *Y'* depends statistically on drought-humidity conditions (SPI), ultimately finding the best fit function.

The t- and F-tests were used for correlation and regression, respectively, to verify the validity of the results using the critical values and their non-randomness. All statistical analyses were performed using the free software PAST4.13 (Hammer et al., 2001).

4. Results

4.1 SPI-12m results

SPI values for the Atlantic region of Colombia were calculated from 1993 to 2024, with a maximum value of 2.48 in 1997 (extremely wet) and a minimum value of –1.81 in 2015 (very dry) (Fig. 2). With precipitation data from 2000 to 2024, the Pacific region of Nicaragua had the lowest SPI values in 2015, the same as in the Atlantic (–1.81), making it the driest year in both regions. Other years when drought conditions fell outside the near-normal range in the Atlantic were 2002, 2009, and 2012, with values of –1.61, –1.01, and –1.47, respectively. The first was classified as very dry, and the last two as moderately dry. Similarly, these three years also recorded negative values for the Pacific region of Nicaragua (with –0.48, –1.11, and –0.73). However, only 2009 fell outside of the near-normal range, reaching a moderately dry condition (see the supplementary material at https://www.revistascca.unam.mx/atm/SupplementaryMaterial/53527-Azuara-SupMat.xlsx).

Regarding humidity, the years 2010, 2011, 2022, and 2024 recorded SPI values outside the near-normal range, with 1.94, 1.32, 2.02, and 1.01 in the Atlantic region, respectively, and 1.64, 1.13, 2.09, and 1.54 in Nicaragua. For both regions, 2022 was classified as extremely wet and 2010 as moderately wet. In the Pacific region, 2005 and 2007 were also classified as moderately wet, with SPIs of 1.06 and 1.31, respectively. In the Atlantic region, the rainfall regime fell outside the near-normal SPI range in 40% of the years recorded, compared to 22% in the Pacific region.

4.2. Results of the normality tests

The results of the normality test of variables are given in Table IV. The normality of the *Y* data was confirmed by the Lilliefors (L) test for both regions.

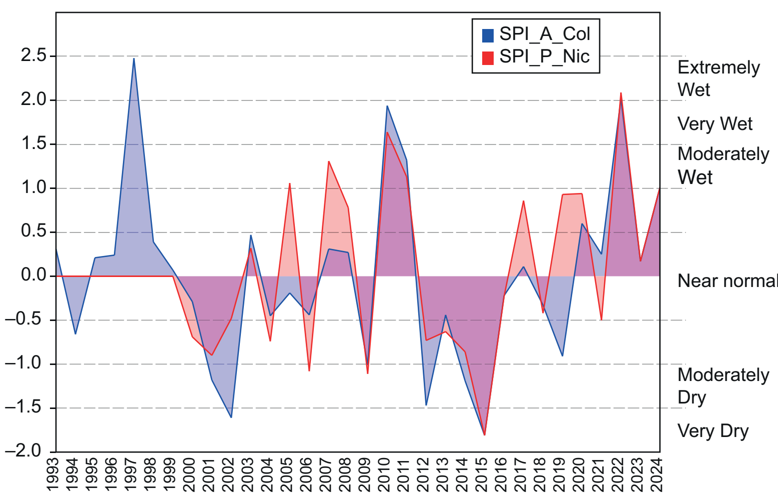

Fig. 2. Values of the 12-month Standardized Precipitation Index.

Table IV. Normality tests for annual Standard Precipitation Index (SPI) and yields.

Type of test	*Y_A*	*Y_P*	*Y'_A*	*Y'_P*	SPI_*A*	SPI_*P*
N	17	17	17	17	25	25
Shapiro-Wilk W	0.880	0.969	0.822	0.957	0.966	0.925
p(normal) > 0.05	**0.031**	0.798	**0.004**	0.576	0.544	0.066
Lilliefors L	0.133	0.146	0.197	0.178	0.095	0.197
p(normal) > 0.05	0.579	0.432	0.075	0.157	0.813	**0.014**

Characters in bold highlight p-values where the normal distribution was not confirmed.

The normal distribution of the yields from the Pacific region was also confirmed using the Shapiro-Wilk test (W). The SPI values were confirmed as normally distributed by the W test in both regions; those obtained in the Atlantic were also normal according to the L test.

Regarding rainfed maize yields, a long-term increasing trend was observed in both study areas, as shown in Figure 3, which also shows *Y'* values. In the Atlantic region of Colombia (Fig. 3a), yields of 0.87 t ha^{-1} were obtained in 2007, and the year 2023 ended with yields of 1.41 t ha^{-1}. In the Pacific region of Nicaragua (Fig. 3b), with higher values, yields were 2.6 t ha^{-1} in the first year of the series and 3.29 t ha^{-1} towards 2023.

The negative variations of *Y'* for the Atlantic were more significant in the later years of the period 2020-2023, despite an anomalous increase in 2019. In the Pacific, the largest decreases were observed in 2009-2010, even greater than those recorded during the longer drought of 2014-2015, and the largest increase was in 2018.

4.3 Mean annual air temperature (MAAT)

The yearly average temperatures in each region are shown in Figure 4. The average temperature for the period 1993-2023 was 27.94 ºC in Colombia (Fig. 4a) and 27.38 ºC in Nicaragua over the period 2000-2024 (Fig. 4b).

Increasing temperature trends were observed in both regions. In Colombia, the 5-year moving average was 27.45 ºC in the first five-year period, while in the last five-year period, it was 0.76 ºC higher. In Nicaragua, the moving average of the first five years of the period was 27.23 ºC, and for the last five-year period, it was 0.3 ºC higher. The regional anomalies showed that, in line with the increasing temperature trend, the Atlantic region remained consistently above average, a trend that has not reversed since 2012. In the Pacific region, 2017-2018 and 2022 registered below-average temperatures.

4.4. Statistical results

Figure 5 presents the results of correlations, along with model regression-variate correlations. Univariate correlations indicated a strong correlation between the SPI values of the regions (0.80) (Fig. 5a) and a moderate to strong correlation (0.66) between regional *Y* values (Fig. 5b). No correlation was found between the *Y'* values. The relationship between the SPI and yields was analyzed for *Y'* to determine how changes in inter-annual cycles relate to drought/humidity conditions. In the Pacific region, a moderate dependence ($R^2 = 0.52$) was observed using a 4th-order polynomial regression, with the values fitted to the model (Fig. 5c).

The validity of the correlations was confirmed using the hypothesis t-test. The SPI index obtained $|t| > CV$ (6.3415 > 2.0106), for $\alpha = 0.025$, while *Y* recorded $|t| > CV$ (3.3779 > 2.0369) for $\alpha = 0.05$, as shown in Table V.

The validity of the relationship between the SPI and *Y'* variables for the period 2000-2023 was confirmed using Fisher's exact test, where F > CV

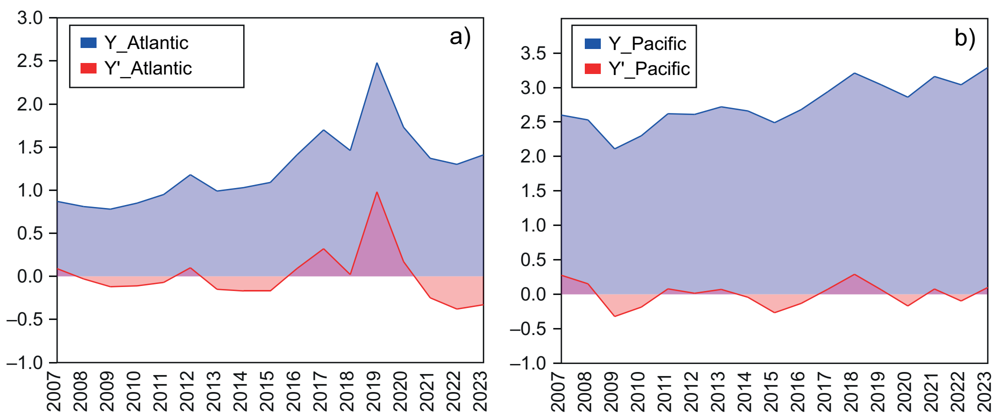

Fig. 3. Changes in yields (*Y*) and detrended yields (*Y'*) series for the period 2007-2023: (a) Atlantic of Colombia, (b) Pacific of Nicaragua.

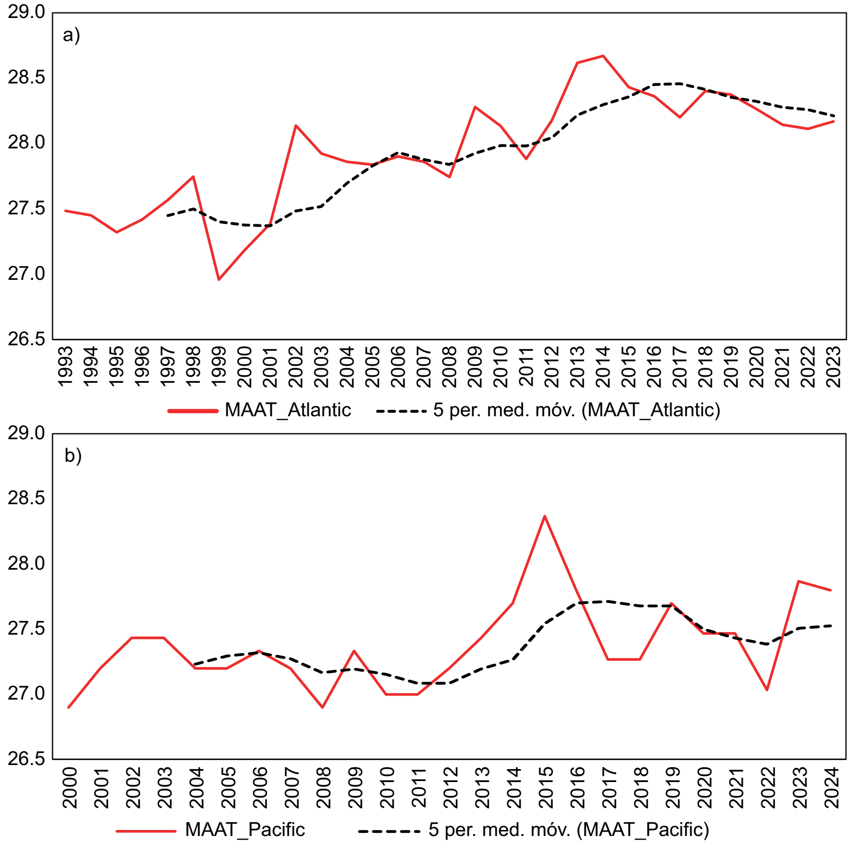

Fig. 4. Mean annual air temperature (MAAT) of: (a) Colombian Atlantic, and (b) Nicaraguan Pacific.

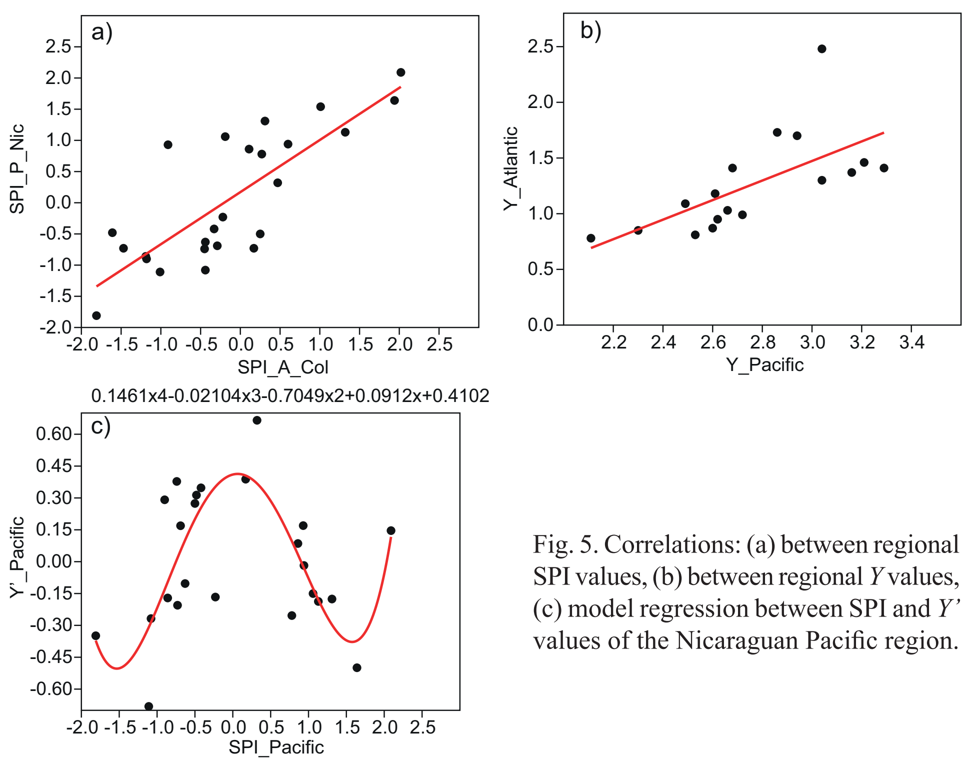

Fig. 5. Correlations: (a) between regional SPI values, (b) between regional *Y* values, (c) model regression between SPI and *Y'* values of the Nicaraguan Pacific region.

Table V. T hypothesis tests for correlations.

	SPI_*A*-SPI_*P*	*Y_A* -*Y_P*
R	0.79759	0.6573
R^2	0.63616	0.43204
t	6.3415	3.3779
Critical t-value (p = 0.025)	2.0106	2.0369
p (uncorrected)	1.80E-06	0.0041412
Permutation p	0.0001	0.0035

(5.1105 > 2.3116), according to Table VI. For the Atlantic region, no statistical correlation or dependence between the SPI and *Y'* was found.

Table VI. F hypothesis tests for the model regression between SPI and *Y'* in the Pacific region.

	SPI_Pacif - *Y'*_Pacif
Chi^2	1.1427
Akaike ICc	14.476
Akaike IC	11.143
R^2	0.51828
F	5.1105
Critical F value (p = 0.05):	2.3116
p	0.0057432

5. Discussion

The inter-annual changes in drought/humidity conditions from 2000 to 2024 generally followed the same direction across the regions, with a strong 80% correlation in their SPI values. However, the Atlantic region experienced more years with values outside the near-normal range under drought conditions than the Pacific region of Nicaragua (six vs. three, respectively) as well as fewer annual cycles with humidity outside the normal range (four vs. six), two of which were consecutive (in 2010 and 2011) and of greater intensity than those recorded in the Pacific region of Nicaragua. In addition to the higher number of moderately or very dry years in the Atlantic, there were also cycles that, while considered near normal, exhibited negative SPI values, forming longer sub-periods of lower humidity in the region, such as 2004-2006 and 2018-2019, as well as sub-periods with greater drought intensity, such as 2000-2002 and 2012-2016, compared to the Pacific region. A similar situation with wet years is observed in the Atlantic region, where a long rainy sub-period was recorded from 2020 to 2024, with greater intensity than that observed in the Pacific region from 2010 to 2011. Under these drought/humidity conditions, greater variability in non-irrigated maize yields is observed in the Atlantic (variance of 0.097) than in the Pacific region (0.03).

Although drought is not solely caused by ENSO (Gutiérrez et al., 2005), its effects are evident in the study area. In the Pacific region of Nicaragua, sea surface temperature (SST) anomalies are largely synchronized with SPI values, as expected given the region's proximity to the ocean, where the Southern Oscillation originates. This finding coincides with assessments by INETER (Gutiérrez et al., 2005), which indicate a close link between meteorological drought and ENSO. A graphical illustration of this synchronicity between the direction and intensity of variations in the Oceanic Niño Index (ONI) (NOAA, 2025) and the SPI in the Pacific region is shown in Figure 6, which does not aim to establish a statistical correlation since the ONI values are quarterly and the SPI values are annual, aligned with the scope of this study. For comparison, the values on the SPI axis have been inverted.

The influence of other complex atmospheric interactions in the Atlantic region produces a high hydroclimatic variability (Ruiz-Vásquez et al., 2024). In this region, temperature increases are more sustained than in the Pacific, as they have not fallen below the average since 2012 (Fig. 7a), according to surface air temperature (SAT) anomalies for the periods and stations available for each region. Even in 2022, with an extremely wet SPI value, temperatures remained above average in the Atlantic, while in the Nicaraguan Pacific, the average temperature was 0.35 ºC lower than its average (Fig. 7b).

However, the lower synchronization of SPI variations with the ONI index does not mean that the Atlantic region and its agriculture are unaffected by ENSO. On the contrary, according to IDEAM (2017) records, the Colombian Atlantic region is one of the areas most affected by the Southern Oscillation, whose intensity does not influence the magnitude of the climatic effect or human activities in a linear manner. During a warm phase of ENSO, the Atlantic and Andean regions of Colombia experience the greatest overall decrease in precipitation in the country,

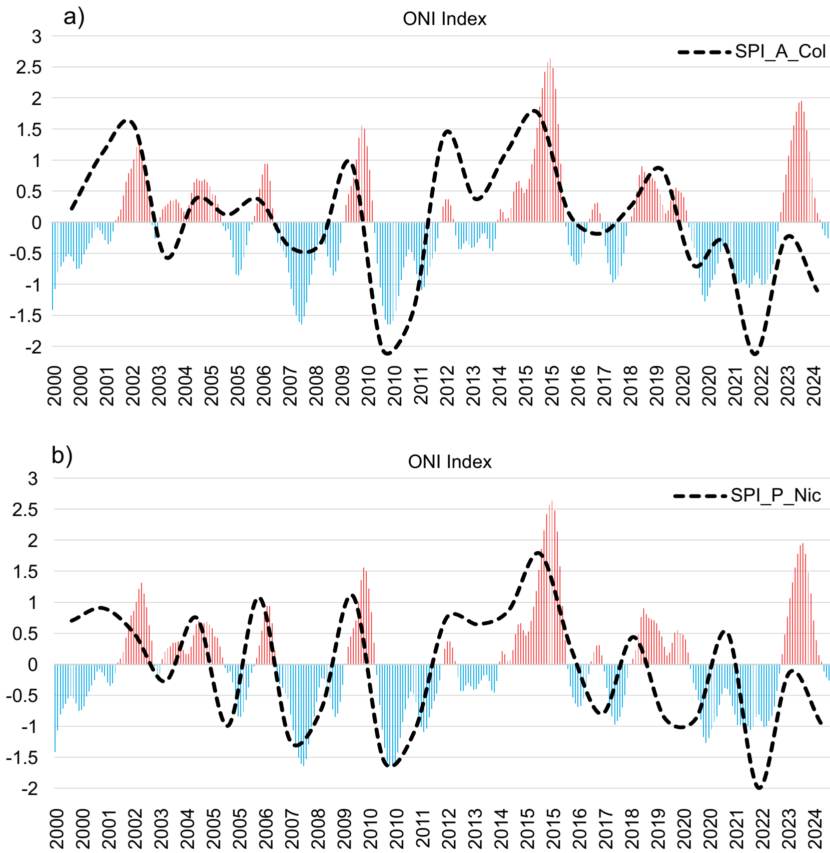

Fig. 6. Comparison of SPI and ONI in: (a) Atlantic region of Colombia, (b) Pacific region of Nicaragua.

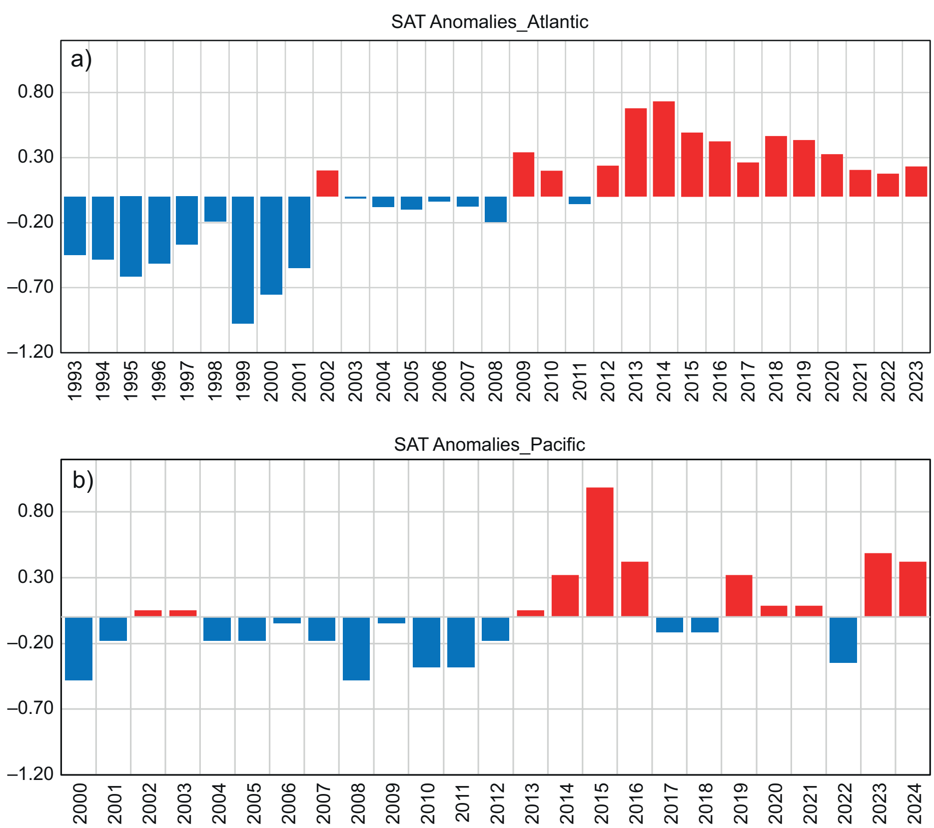

Fig. 7. Surface air temperature (SAT) anomalies in: (a) Atlantic region of Colombia (1993-2023), and (b) Pacific region of Nicaragua (2000-2024).

whereas during La Niña, these same regions have recorded the greatest rainfall surpluses, according to the same specialized source (IDEAM, 2017).

The most significant adverse effects on agriculture in the Atlantic region occur when any of the ENSO events extend into the third and fourth quarters of the year due to the bimodal semi-annual rainfall patterns that govern the cycles of rainfed agriculture (IDEAM, 2017). If drought prevails during the second rainy season (September to November), it favors the proliferation of pests and diseases; if rainfall is excessive, flooding leads to fungal diseases, among others (Broders et al., 2022; Maldonado-Archila et al., 2022).

The repercussions of the warm phase of ENSO in 2009, 2014, 2015, and 2018 included decreased yields of major cereals in Colombia at the national level, as reported by Fenalce (2024), with the Atlantic being no exception. According to the chronology in Table II, during 2009, El Niño was present in the first, third, and fourth quarters with strong intensity, and in the region, rainfed maize yields were the lowest of the period (0.78 t ha^{-1}). From 2013, the Atlantic region faced a dry year that coincided with the longer and more intense El Niño event of 2014-2015, maintaining negative variations in *Y'* for all three years. In 2018, despite a rainy first quarter, the third and fourth quarters were dry, causing a significant decrease in crop yields.

Regarding cold oscillations, the prolonged presence of La Niña in the last quarters of 2008, 2010, 2011, and from 2020 to 2023 also led to decreased maize yields in the Atlantic region. Two consecutive La Niña episodes had already been recorded in 2008, which, although weak and with a near-normal SPI value, still led to reduced crop productivity in the second half of the year. The years 2010 and 2011 also saw two extreme La Niña events with a very destructive impact on human activities, including agriculture USDA, 2010; Cayón-Salinas and Pachón-Ariza, 2015; García-Romero and Molina, 2015). Excessive humidity in consecutive years, flooding, and soil saturation, coupled with high temperatures, impeded the proper crop development.

The last three years of the analyzed period saw the greatest yield losses in the Atlantic, encompassing two consecutive La Niña episodes that began in the third quarter of 2020 and ended in the first quarter of 2023. In 2022, La Niña triggered the highest SPI value of the analyzed period (2.02, extremely wet) and the lowest negative yield variation. The potential impacts of the COVID-19 pandemic on agriculture should be considered during this period.

The years with significant increases in *Y'* in the Atlantic were 2012, 2017, and 2019, with the resulting humidity moisture characteristics. In 2012, ENSO conditions remained neutral, with only the first quarter being rainy. This benefited the first planting period in the Atlantic, despite the annual SPI being at a moderately dry level. In 2017, most of the year was neutral, while the onset of La Niña, lasting until the fourth quarter, was beneficial for the second planting period. The year 2019 recorded exceptionally high yields (2.48 t ha^{-1}). The first quarters were marked by El Niño, but the oscillation became neutral in the second half of the year, favoring good harvests, with an SPI value close to normal. This was an atypical yield in the Atlantic region, as it increased by more than 1 t compared to the previous value, but it approached yields in nearby regions (Fenalce, 2024). It may also have reflected the effects of the launch of the Sustainable Colombia Agri-Food project of the International Maize and Wheat Improvement Centre (CIMMYT) (Carvajal, 2024).

Regarding the effects of the rainfall regime on maize yields in the Pacific of Nicaragua, the moderate correlation obtained (0.52) indicates a greater dependence between variables, a greater coincidence of the SPI value with the surface temperature anomalies of the Pacific Ocean, and therefore with the SAT anomalies.

The largest SPI declines observed in the Nicaraguan region in 2009 and 2015 reached the moderately dry and very dry conditions, and showed the largest decreases in rainfed maize yields, from 2.53 to 2.11 t ha^{-1} in 2009, and from 2.66 to 2.49 t ha^{-1} in 2015, being this the year with the biggest SAT warm anomaly (1 ºC above the average). In both years, the presence of El Niño events was recorded, with moderate intensity in 2009 and strong in 2015. This is consistent with the findings of Barrios et al. (2022), who described the decrease in maize yields as an effect of extreme El Niño episodes in the periods 1982-1983 and 1997-1998 in the specific case of Ciudad Darío, located in the northeast of the Nicaraguan Pacific region.

The United Nations Development Programme (UNDP, 2013) also reported a decrease in the production of basic foodstuffs of more than 50% in 2009, and in 2015 losses of 50% in crops (Calvo-Solano et al., 2018), which was reflected in a decrease in yields at the national level of –16.5% in 2009 and –6.5% in 2015, according to data from the Central Bank of Nicaragua (BCN, 2009, 2015).

The strong La Niña events of 2010 and 2011, with SPI values outside the normal range (1.64 and 1.13, respectively), did not negatively affect maize yields. Instead, yields recovered slightly, compared to 2009 levels. However, the year with the highest SPI value (2022, at 2.09) did reflect a slight decrease in yield (from 3.16 to 3.04 t ha^{-1}). Yields in 2020 were also impacted by the COVID-19 pandemic. Despite a normal wet SPI (0.94), yields decreased in the region. Other direct effects on agriculture caused by excessive rainfall or increased temperatures and droughts include the emergence of diseases and pests (INTA, 2000; Jiménez, 2017), which reduce crop yields.

The largest increases in *Y* in the Pacific of Nicaragua occurred in 2017 and 2018, under conditions close to the normal SPI values (0.86 and –0.042, respectively), where production reached 2.94 t ha^{-1} and 3.21 t ha^{-1} in the same order.

Regional differences in inter-annual variations in maize yields are a response to their climatic contexts, and their increasingly erratic rainfall patterns, although a correlation or dependence of *Y* on the SPI is not necessarily evident. Both the presence of ENSO and the average temperature increase add complexity to the ITCZ, where both regions are located. Extreme drought or humidity conditions associated with El Niño or La Niña ultimately have a negative impact on yields and agricultural activity in general, as noted by Caicedo-García (2007), with a decrease in agricultural yields of around –5% in Colombia, or by Ramírez et al. (2010), with losses of –4% of GDP in crop production between 2006 and 2020 in Nicaragua.

Therefore, the trend of increased yields for rainfed maize in the Atlantic region, which is much more vulnerable, seems paradoxical given the rise in average temperatures and greater variability in rainfall patterns. However, at the national level, rainfed maize in Colombia declined by 3.7% from 2011 to 2021, according to the Colombian Mercantile Exchange (BMC, 2023). According to the same report, Colombia is among the world's leading corn importers (eighth in 2022), purchasing approximately 70% of its total corn consumption (both white and yellow) amidst a decrease in planted area and production volume during that period. Rainfed maize has been the most affected, as irrigated maize has seen increases in planting area, production, and yields. Additionally, Colombia is experiencing a drastic decrease in production and planted area of other cereals (Fenalce, 2024), putting its agrobiodiversity and food security at risk (Govaerts et al., 2019). Within this framework, the differentiated behavior of non-irrigated maize yields in the Atlantic region is fragile yet encouraging in the face of climate change and the annual increase in the frequency of more intense hurricanes (Ortiz and Conde, 2022).

In the Pacific region of Nicaragua, increases in rainfed maize yields are more sustained throughout this period. Nationally, rainfed agriculture is the predominant water management method, and the improved results are associated with a policy focused on the use of improved seeds that are more resistant to drought and pests, improvements in planting density, ongoing training and veterinary assistance, the creation of cooperatives to improve productivity, a microcredit program for small rural businesses, and regular agroclimatic information that has helped producers make decisions about their crops (INIDE, 2003, 2005). Drought, the major regional risk in Nicaragua, appears to be receiving attention from the sector's policymakers.

6. Conclusions

Univariate correlations showed a strong correlation (0.80) between the regions' SPI values. Their proximity and location within the ITCZ make their rainfall patterns similar, though with different timing and intensity. These differences affected rainfed maize yields unevenly, as evidenced by a moderate correlation (0.66) between regional *Y*. That positive correlation expresses an increasing trend of non-irrigated maize yields throughout the period in both regions; however, their inter-annual behavior observed through *Y'* was not statistically correlated, highlighting the differences in precipitation.

The variations in SPI in the Pacific of Nicaragua were more synchronized with the measured SST anomalies, and in turn showed their influence on the yields of rainfed maize, according to the results obtained from the regression between SPI and *Y'*, with $R^2 = 0.52$.

In the Atlantic region of Colombia, the rainfall pattern, also influenced by other atmospheric interactions in the Caribbean, altered the onset and duration of El Niño and La Niña events. This region is considered one of the most affected by ENSO in Colombia, especially when these events extend into the third and fourth quarters of the year, as they impact the second rainy season, which is the period of highest precipitation. One consequence of this in the Atlantic region is the greater variability in non-irrigated maize yields, which showed a higher variance of 0.097 compared to 0.030 in the Pacific region. Furthermore, there was no correlation between the SPI and *Y'* in this region, although rainfall patterns remain a key driver of agricultural production.

The Atlantic region accumulated more annual SPI values outside the near-normal range (10 vs. 9 for the Pacific), six of which occurred under drought conditions and twice consecutively (2001-2002 and 2014-2015). Although drought is the most significant risk in the Pacific region of Nicaragua, it never accumulated consecutive SPI values below –0.99 and only registered three cycles under abnormally dry conditions during the period (2006 with –1.08, 2009 with –1.11, and 2015 with –1.81).

Wet cycles outside the near-normal range were more frequent in Nicaragua's Pacific region (six) than in its Atlantic region (four). In both regions, they were consecutive in 2010-2011, but less intense in the Pacific (1.64 and 1.13) than in the Atlantic (1.94 and 1.32, respectively). The record of positive SPI values between 2020 and 2024 in the Atlantic constituted a sub-period of humidity with SPI values that, while within or outside the near normal range, influenced the interannual decreases in *Y'*, which were the lowest and most prolonged of the study period.

The most intense SPI values in the study areas, whether due to rainfall, in which case extremely wet conditions were reached in 2022 (with an SPI of 20.2 in the Atlantic and 2.09 in the Pacific), or to drought, which led to a very dry classification (–1.81 in 2015 in both regions), negatively impacted yields in both regions. The worst yield loss in Nicaragua occurred in 2009 due to drought, while the worst loss in the Atlantic occurred in 2022 due to excessive humidity.

Crop yields in both study regions are increasing; however, the intensity of the southern oscillations undermines the consolidation of a substantial and sustained improvement in rainfed maize productivity, mainly in the Atlantic region. National agricultural and climate change policies need to be strengthened with a specific regional perspective, as climate change impacts vary even across neighboring regions. Sustainably increasing maize yields contributes significantly to ensuring food security, as it is a strategic crop in countries with high climate vulnerability in scenarios of further temperature increases.

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