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Meteorological variability and its impact on agricultural activities in the Ecuadorian Amazon in Pastaza (2011–2021)

Variabilidad meteorológica y su impacto en las actividades agropecuarias de la Amazonía ecuatoriana en Pastaza (2011–2021)

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Abstract

The climatic variability observed in Pastaza Canton has significantly affected agricultural and livestock productivity, compromising local food security. This study aims to analyze how climatic variables influence the main crops and livestock production between 2011 and 2021. An applied, non-experimental, descriptive-correlational, and cross-sectional methodology was used. Data were obtained from INAMHI meteorological records and the Public Agricultural Information System, considering variables such as mean temperature, total precipitation, relative humidity, and potential evaporation. Results showed that average monthly temperatures (20.63 °C–22.06 °C) were favorable for banana and cassava but below the optimal range for cocoa. Total precipitation reached 508.70 mm in May, causing waterlogging in coffee and sugarcane crops, whereas September (285.35 mm) showed water deficits. Relative humidity levels (85.00 %–89.36 %) increased fungal disease incidence and management costs, while potential evaporation (54.16 mm–89.57 mm) reduced soil moisture, affecting pineapple crops. In livestock systems, June and July presented favorable thermal conditions, and balanced evaporation in February maintained adequate pasture availability. Overall, banana and cassava exhibited greater adaptation to climatic variability, while cocoa, coffee, sugarcane, and pineapple showed productivity reductions associated with irregular rainfall and high humidity.

Keywords: Evaporation, livestock, humidity, precipitation, resilience.

Resumen

Las variaciones en las condiciones climáticas del cantón Pastaza han generado efectos significativos en la productividad agrícola y ganadera, comprometiendo la seguridad alimentaria local. El propósito del estudio es analizar cómo las variables climáticas influyen sobre los principales cultivos y la producción pecuaria entre 2011 y 2021. Se aplicó una metodología de tipo aplicada, con diseño no experimental, nivel descriptivo-correlacional y enfoque transversal. Los datos se obtuvieron de registros meteorológicos del INAMHI y del Sistema de Información Pública Agropecuaria, considerando variables como temperatura media, precipitación total, humedad relativa y evaporación potencial. Los resultados revelaron temperaturas promedio mensuales entre 20,63 °C y 22,06 °C, adecuadas para el plátano y la yuca, pero inferiores al rango óptimo del cacao. La precipitación alcanzó 508,70 mm en mayo, generando encharcamiento en café y caña de azúcar, mientras que en septiembre (285,35 mm) se observó déficit hídrico. Los niveles de humedad relativa (85,00 %–89,36 %) incrementaron la incidencia de enfermedades fúngicas y los costos de manejo, mientras que la evaporación potencial (54,16 mm–89,57 mm) redujo la humedad del suelo, afectando cultivos como la piña. En la ganadería, los meses de junio y julio presentaron condiciones térmicas favorables y evaporación equilibrada, manteniendo la disponibilidad de pastos. Se concluye que el plátano y la yuca mostraron mayor adaptación a la variabilidad climática, mientras el cacao, café, caña de azúcar y piña evidenciaron reducciones en productividad asociadas a lluvias irregulares y humedad elevada.

Palabras clave: Evaporación, ganadería, humedad, precipitación, resiliencia.

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1 Introduction

According to the World Meteorological Organization, climate is defined as the average and variability of meteorological variables such as temperature, precipitation, and wind in a specific region over a 30-year period (Rosvold, 2021). At the global level, meteorological conditions have shown significant fluctuations, with an increase of 0.74 °C in the global mean temperature over the last century (Shah et al., 2019). These variations have generated relevant impacts on agriculture, where drought accounts for more than 80 % of total damage and losses in the agricultural sector, particularly affecting livestock and crop production subsectors (Hernández et al., 2018).

At the regional level, meteorological fluctuations have caused reductions ranging from 20 % to 40 % in cereal and legume yields due to water stress, while crops such as rice have experienced losses of up to 92 % under extreme drought conditions (Kumar et al., 2022; Lal, 2021). In Colombia, environmental conditions between 2010 and 2011 led to the loss of 1,000,000 hectares of crops, with a total economic impact on the agricultural sector estimated at USD 759.893 million, including the death of 160,965 production animals (Arteaga and Burbano, 2018).

Ecuador, known for its climatic and productive diversity, faces increasing challenges in the agricultural sector due to variability and changes in meteorological conditions (García-Rengifo and Durán-Ballén, 2023). According to Vásquez-Dávila and Bravo-Benavides (2023), the relationship between temperature, precipitation, and agricultural production is significant, with long-term impacts if these variables exceed optimal levels.

In the case of Pastaza canton, which largely depends on agricultural activities, climate variability has caused fluctuations in agricultural yields, affecting productivity and the economic sustainability of rural communities. Therefore, it is necessary to identify, analyze, and understand climatic variables in order to predict how meteorological conditions have evolved (Singh et al., 2023). This will make it possible to propose specific adaptation measures that are essential to mitigate negative impacts on agricultural activities. In addition, it is currently necessary to design strategies that strengthen agricultural resilience and ensure economic and food sustainability (Sgroi, 2023).

Agricultural producers in Pastaza canton will be the main beneficiaries of studies on the variation of meteorological conditions and their impact on agricultural activities. Access to accurate information will allow them to adjust their management practices according to climatic conditions, thereby optimizing their production processes. Likewise, governmental and academic institutions will be able to use this information to plan and make strategic decisions in the agro-environmental field, facilitating the design of adaptation and mitigation strategies in response to climate change.

The main problem identified lies in the lack of precise data on climatic variations, which hinders the efficient management of agricultural activities in Pastaza province. Changes in precipitation patterns and increases in temperature have affected essential crops such as sugarcane, an important source of local income (Valle et al., 2021). Similarly, reduced pasture availability has negatively impacted livestock production, particularly dairy farming (Mosquera Ponce et al., 2024). According to Bilali et al. (2020), these climatic variations modify production cycles, increase production costs, and reduce yields, thereby compromising food security and the economic stability of small-scale producers.

Previous studies on this topic, such as that of Pujahari et al. (2022), who applied weather forecasting together with technologies such as the Internet of Things (IoT), wireless sensor networks, and machine learning, enabled farmers to optimize irrigation, fertilization, and pest control.

Meanwhile, Gowtham et al. (2018) supported meteorological predictions with advanced models such as the Decision Support System for Agrotechnology Transfer (DSSAT), contributing to more efficient and adaptive agricultural planning. Likewise, Ordoñez et al. (2022) developed agroclimatic models combined with seasonal forecasts, achieving 80 % accuracy in yield prediction and reducing climatic risk for farmers, which in turn improved productivity.

Based on the latter, the objective of this study is to analyze the variation of meteorological conditions and their impact on agricultural activities in Pastaza canton during the period 2011–2021.

2 Materials and Methods

The methodology was developed sequentially, beginning with the delimitation of the study area, the definition of the type of research, the determination of the study period, sample, and data sources, followed by data processing and statistical analysis. This methodological sequence ensures the replicability of the procedure and the verification of the results obtained.

2.1 Location

This study was conducted in Pastaza canton, at the facilities of the National Institute of Meteorology and Hydrology (INAMHI). This canton belongs to Pastaza Province, which covers an area of 29,643.33 km^2 and is bordered to the north by the provinces of Napo and Orellana, to the south by Morona Santiago, to the east by the Republic of Peru, and to the west by Tungurahua (Gobierno Provincial de Pastaza, 2020). This province is characterized by a humid tropical climate that favors agricultural activities and their analysis in relation to climatic variables (Figure 1).

2.2 Type of Research

The study adopted a quantitative approach with a non-experimental, descriptive-correlational, and cross-sectional design, which allowed for the examination of climatic variables in Pastaza canton during the analysis period (Cvetkovic-Vega et al., 2021). This design facilitated the analysis and description of climatic variables in Pastaza canton throughout the study period.

2.3 Study Period, Sample, and Data Source

The analysis was based on records covering the period from 2011 to 2021, corresponding to the most recent data available in the INAMHI archives. This time interval made it possible to identify interannual variations in climatic conditions and their relationship with agricultural activities in Pastaza canton.

The information was obtained from the "Pastaza" meteorological station (INAMHI), located at 1,060 m.a.s.l., selected due to the continuity and reliability of its records, as well as its representativeness of local agroclimatic behavior. As an accredited synoptic station, its measurements of temperature, precipitation, relative humidity, and potential evaporation comply with the technical accuracy standards established by the World Meteorological Organization (2021).

Quality control procedures were applied following the recommendations of the World Meteorological Organization (2010), including internal consistency checks, detection of extreme values using climatological thresholds, and cross-comparison with nearby stations and historical averages. Inconsistent records were verified and corrected or, when necessary, excluded from the analysis to ensure the integrity of the time series.

2.4 Variables Analyzed

The analysis of variables was conducted considering both climatic and agricultural aspects linked to productive activities in Pastaza canton. In the agricultural domain, variables such as planted area (ha), harvested area (ha), production (t), and yield (t/ha) of crops were included, as well as the total livestock population, considering cattle, swine, sheep, equine, and mule categories. These variables make it possible to understand the productive level and agricultural and livestock performance in the study area, which is essential for establishing their relationship with climatic variables.

Mean monthly temperature influences the physiological development of crops, as each species requires an adequate thermal range for growth. In addition, temperature affects livestock thermal comfort, where extreme variations can cause stress and reduce productivity (González Osorio et al., 2020).

Total monthly precipitation determines water availability for crops and forage, being necessary to ensure proper development. Water deficits limit growth and product quality, while excess precipitation can cause waterlogging and disease outbreaks (Paliz et al., 2021).

Mean monthly relative humidity favors the occurrence of phytosanitary diseases. High humidity levels promote the development of fungi and bacteria, reducing agricultural production quality (Pozo-Santiago et al., 2020).

Mean monthly potential evaporation directly influences irrigation water demand, since periods of high evaporation require greater water supply to prevent crop stress and ensure optimal development (Monterroso-Rivas and Gómez-Díaz, 2021).

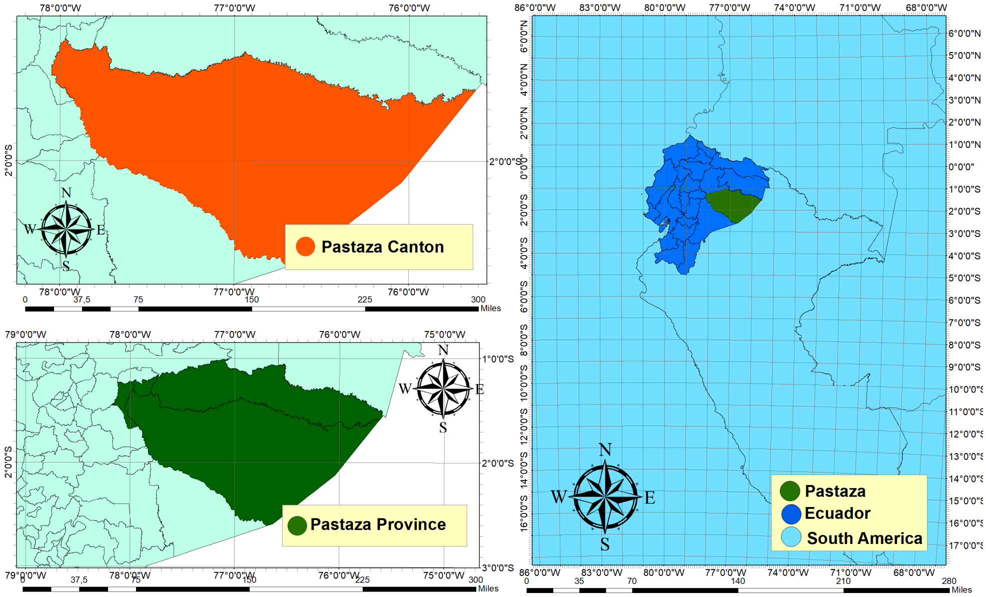

Figure 1. Geographical location of the study area.

2.5 Data Processing

Data processing included measures of dispersion and the coefficient of variation in order to quantify interannual variability. Statistical analysis was performed using Microsoft Excel® (version 2021) through Pearson correlations ($p < 0.05$) and simple linear regressions, applied only when the correlation coefficient r exceeded 0.50 (50 %). In the absence of significant correlations, a comparative descriptive analysis between variables was conducted, allowing for the interpretation of local climatic behavior and its comparison with evidence from humid tropical regions.

2.6 Methodological Limitations

The study was based on records from a single meteorological station, which limits spatial analysis. The 11-year period represents an interannual scale that describes recent variability without reaching the temporal extent required for long-term climatic studies. Nevertheless, this approach is appropriate for characterizing local meteorological conditions and their influence on agricultural activities in Pastaza canton.

3 Results and Discussion

3.1 Agricultural Activities

According to the Sistema de Información Pública Agropecuaria (2024), the main agricultural activities correspond to plantain and cassava crops, which recorded the largest cultivated area and production during 2024 (Table 1). Plantain accounts for 3,439 ha planted, 2,554 ha harvested, and a production of 15,096 tonnes, with a yield of 5.91 t/ha. Cassava, with 1,999 ha planted and a production of 4,281 tonnes, reaches a yield of 2.21 t/ha. Pineapple stands out for its high yield of 9.86 t/ha, whereas crops such as cocoa and coffee show lower yield levels, with 0.30 and 0.58 t/ha, respectively.

Table 1. Production, cultivated area, and yield of agricultural crops during 2024.

Product	Planted Area (ha)	Harvested Area (ha)	Production (t)	Yield (t/ha)
Plantain	3,439	2,554	15,096	5.91
Cassava	1,999	1,937	4,281	2.21
Dry hard maize	282	282	253	0.90
Sugarcane for other uses	192	183	1,044	5.71
Pineapple (fresh fruit)	166	125	1,231	9.86
Cocoa	110	61	19	0.30
Coffee	69	69	40	0.58
Banana	64	64	273	4.28
Peanut (shelled grain)	49	49	27	0.55
Lemon (fresh fruit)	40	35	51	1.45
Orange	35	35	61	1.75
Fresh bean	11	11	11	0.95

According to the Sistema de Información Pública Agropecuaria (2024), cattle, with 3,722,314 animals, represent the largest population within the livestock sector. This is followed by swine, with 983,999 animals, and sheep, with 561,949. Equines are divided into horses, with 143,310 animals, and mules, which constitute the smallest proportion with 54,044 animals (Table 2).

Table 2. Livestock population during 2024.

Livestock type	Number of animals
Cattle	3,722,314
Swine	983,999
Sheep	561,949
Horses	143,310
Mules	54,044

Source: Sistema de Información Pública Agropecuaria (2024).

3.2 Influence of Mean Temperature on Agricultural Activities

Plantain has an optimal temperature range of 22 °C to 30 °C and can develop under temperatures between 20 °C and 35 °C (Zambrano et al., 2021). In Pastaza, mean monthly temperatures (20.63 °C to 22.06 °C) are very close to the lower limit of the optimal range (Figure 2). Months such as May (21.45 °C) and September (21.58 °C) are ideal for this crop, as they favor pseudostem growth and fruit filling (Cedeño García et al., 2021). Even in months such as June (20.94 °C) and October (21.99 °C), temperatures do not represent a significant threat to crop development, and no evident negative impact on plantain is observed. The average temperatures in Pastaza are adequate to sustain the current yield of 5.91 t/ha, indicating regular crop development.

Cocoa thrives within an optimal temperature range of 24 °C to 28 °C and tolerates temperatures from 15 °C to 32 °C (Ferrer-Sánchez et al., 2022). In Pastaza, mean monthly temperatures (20.63 °C to 22.06 °C) are below the optimal range but still within the tolerable range (Figure 2). This mismatch may slightly limit flowering and fruit set (Garay-Peralta et al., 2024). Months such as April (21.62 °C) and September (21.58 °C) provide relatively better conditions for cocoa development, although they do not reach the required optimal range. Cocoa shows a moderate impact due to temperatures that do not reach optimal levels, as reported by Castillo et al. (2024). This explains its low yield of 0.30 t/ha, and although the crop can survive under these conditions, its productivity remains far from ideal.

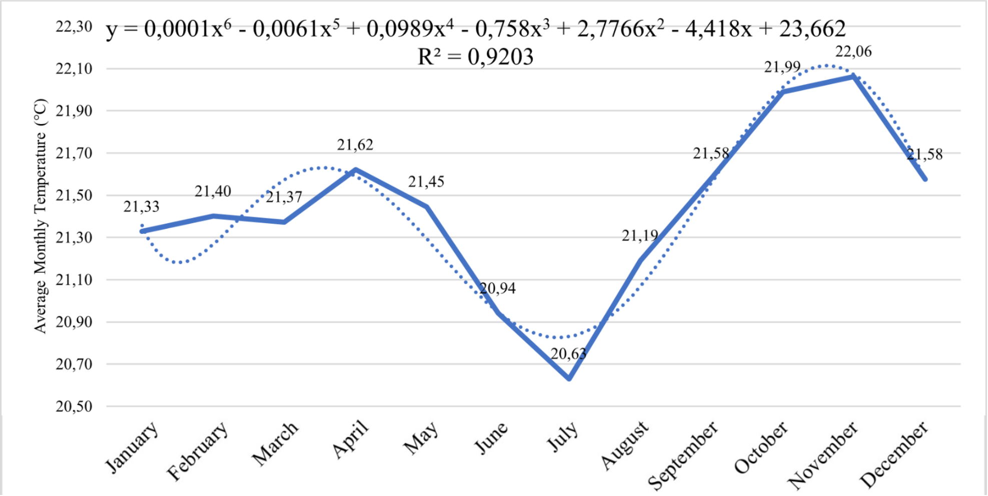

Figure 2. Average monthly temperature during the period 2011–2021.

Cassava thrives within an optimal temperature range of 25 °C to 29 °C and tolerates temperatures from 18 °C to 35 °C (Rosero et al., 2024). In Pastaza, all mean monthly temperatures (20.63 °C to 22.06 °C) fall within the tolerable range, although slightly below the optimal range. This implies that the crop can develop adequately throughout the year (Monsanto et al., 2020). Months such as February (21.40 °C) and April (21.62 °C) are particularly favorable, as they approach the lower limit of the optimal range (Figure 2). No significant negative impact on cassava yield is observed, as temperatures remain within the tolerable range. The current yield of 2.21 t/ha is consistent with these climatic conditions. However, temperatures closer to the optimal range could slightly increase productivity.

Livestock production, dominated by cattle with 3,722,314 animals, also shows a critical dependence on temperature. Warmer months such as October (21,99 °C) and November (22.06 °C) generate thermal stress in livestock, affecting feed intake and productivity, as reported by Midence and Blas (2024). Conversely, cooler temperatures in June (20.94 °C) and July (20.63 °C) may limit the growth of natural pastures (Cárdenas and Telles, 2023), reducing the availability of essential forage for livestock feeding.

The spatial and temporal variability of precipitation in Pastaza indicates a pattern highly dependent on topography and vegetation cover, generating contrasts between lowland and piedmont areas. This behavior is consistent with Cargua et al. (2024), who point out that local climatic gradients condition soil response and environmental stability in Amazonian and Andean regions. Similarly, Hidalgo et al. (2024) showed that changes in rainfall and temperature directly influence hydrological and ecological processes in mountainous environments. In the agricultural context of Pastaza, these variations determine water availability for plantain, cassava, and cocoa crops.

3.3 Precipitation Variability and Its Effect on Crops in Pastaza

Sugarcane depends on a constant water supply, ideally between 1,500 and 2,500 mm annually, distributed uniformly (Díaz Serna, 2024; Espinel Rubio and Feo-Ardila, 2022). In Pastaza, months such as May (508.70 mm) and April (450.94 mm) ensure adequate water levels for sucrose accumulation in the stalks (Figure 3). However, drier months such as September (285.35 mm) may affect crop growth and yield. This is consistent with Misra et al. (2020), who emphasize that rainfall irregularity generates water stress in high water-demand crops such as sugarcane.

Precipitation in Pastaza is adequate during the wet months; however, its irregular distribution limits the average sugarcane yield to 5.71 t/ha. According to Santiago Zárate et al. (2021), the average yield per hectare of sugarcane is 8.26 tonnes, with a maximum recorded value of 16.54 tonnes. This indicates that the implementation of supplemental irrigation systems and optimized agricultural practices could significantly contribute to improving the yield of this crop.

Pineapple thrives under annual precipitation ranging between 1,000 and 1,500 mm, with monthly requirements of 50 to 125 mm (Aguilera-Arango et al., 2022). In Pastaza, months such as April (450.94 mm) and May (508.70 mm) greatly exceed this monthly range (Figure 3), which may lead to excessive vegetative growth and delayed flowering, as noted by Bonet-Pérez et al. (2021). Likewise, relatively drier months such as July (314.90 mm) and September (285.35 mm) also exceed the maximum monthly threshold required for this crop.

Precipitation in Pastaza, although sufficient in quantity, exceeds the optimal levels recommended for pineapple cultivation during all months analyzed (Figure 3). This excess significantly affects yield, which stands at 9.86 t/ha, whereas Vélez-Izquierdo et al. (2020) report an expected average yield of 20 t/ha for this crop. Therefore, it is necessary to implement water management measures such as efficient drainage systems and controlled irrigation strategies to mitigate the effects of excess water and optimize crop conditions, thereby favoring an increase in yield.

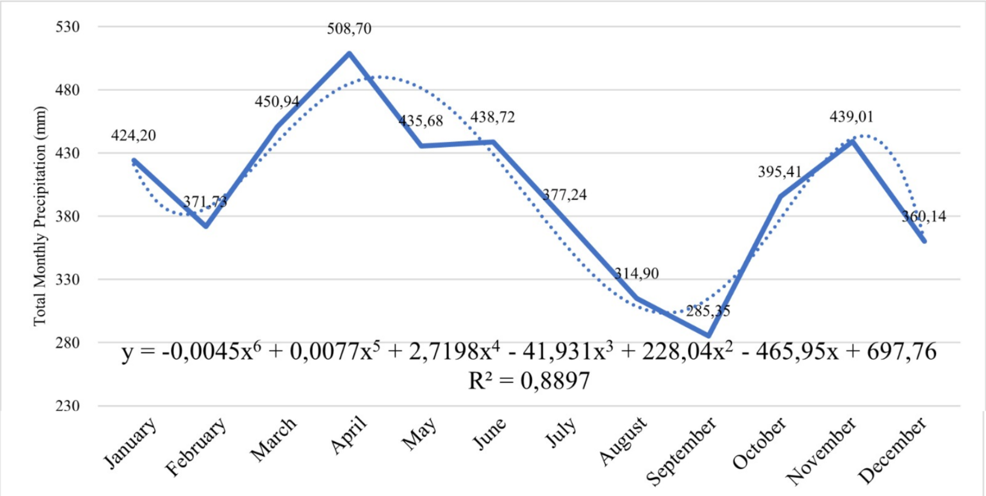

Figure 3. Total monthly precipitation during the period 2011–2021.

Coffee requires annual precipitation between 1,200 and 2,000 mm, with uniformly distributed rainfall and ideal monthly values of 100 to 200 mm to avoid prolonged water stress (Parada-Molina, Cervantes-Pérez, et al., 2020). In Pastaza, months such as May (508.70 mm) and November (439.01 mm) considerably exceed the optimal monthly range (Figure 3), which may cause waterlogging problems and affect bean quality (Quiroz Guerrero et al., 2024). Conversely, drier months such as July (314.90 mm) and September (285.35 mm), although still above the upper ideal monthly limit, meet the minimum water requirements of the crop.

Precipitation levels in Pastaza exceed the optimal monthly range for coffee in all months analyzed, generating a negative impact on bean quality due to excess moisture. This explains the low yield of 0.58 t/ha, consistent with Parada-Molina, Gómez Martínez, et al. (2020), who state that excessive rainfall can interfere with grain filling and reduce quality.

Pasture growth requires an optimal precipitation range between 300 and 400 mm per month (Brenes Gamboa, 2018). In Pastaza, although months such as May (508.70 mm) and November (439.01 mm) exceed this range (Figure 3), others such as September (285.35 mm) are at the lower threshold, which may affect forage production. These variations in water availability increase operational costs due to the use of feed supplements and reduce livestock profitability (Viera González et al., 2023).

Precipitation in Pastaza maintains adequate levels for agricultural production; however, its irregular distribution generates differentiated impacts depending on crop type. Prolonged intense rainfall favors the water accumulation required for sugarcane but exceeds the optimal requirements of pineapple and coffee, causing losses in flowering and bean quality. This behavior is consistent with Mestanza Uquillas et al. (2025), who demonstrated that the alternation between dry and rainy seasons on the central coast of Ecuador modifies crop productivity according to the rainfall regime and species adaptability. Complementarily, Quiroz Antunez et al. (2022) showed that irregular rainfall availability alters the suitability of coffee and cocoa crops under climate variability scenarios, affecting their phenological development. Consequently, the stability of agricultural production in Pastaza depends on efficient water management that allows compensation for the effects of pluviometric variability on local productivity.

3.4 Relative Humidity in Agricultural Productivity in Pastaza

Mean monthly relative humidity in Pastaza ranges between 85.00 % and 89.36 %, generating significant impacts on crops and livestock (Figure 4). During months with higher relative humidity, such as March (89.36 %) and April (88.40 %), the incidence of fungal diseases such as *Moniliophthora perniciosa* and *Hemileia vastatrix* increases in crops such as cocoa and coffee (Santiago-Elena et al., 2020). According to Mamani-Huayhua et al. (2021), these pathogens directly affect productivity. This negative impact occurs because higher relative humidity creates an optimal environment for the development and dispersal of these organisms (Lopez et al., 2021). The main implication lies in increased phytosanitary management costs and reduced agricultural yields, thereby compromising the economic sustainability of local farmers.

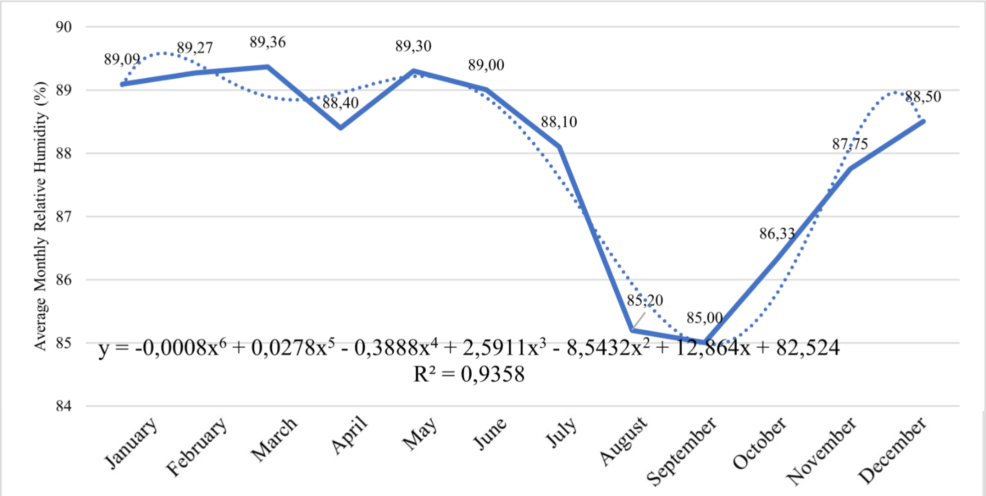

Figure 4. Average monthly relative humidity during the period 2011–2021.

In contrast, during months with lower relative humidity such as September (85.00 %) and October (86.33 %), humidity levels decline to the minimum tolerable threshold for most crops (Figure 4). Although this reduces the risk of certain fungal diseases, it does not completely eliminate their presence. According to Duran et al. (2021), these decreases may generate problems associated with water stress in humidity-sensitive crops, affecting their growth. Therefore, while crops benefit from lower relative humidity levels, adequate management is still required to mitigate adverse effects on productivity.

In livestock systems, high relative humidity promotes the occurrence of respiratory, dermal, and parasitic infections in animals such as cattle and swine. These problems tend to occur between March and June, when relative humidity levels consistently exceed 88 % (Figure 4). According to Conejo-Morales and Wing Ching (2020), these adverse conditions are due to moisture accumulation in pens, which hinders ventilation and increases ammonia levels in the air. The main implication of this phenomenon is a reduction in feed intake, leading to lower animal productivity and higher operational costs due to veterinary treatments and dietary supplements.

Months with lower relative humidity, such as September and October, provide some relief for livestock systems by reducing respiratory infections and moisture levels in pens (Figure 4). However, these conditions may also limit pasture growth, a primary source of feed for livestock. According to Alvarado Irías and Colon García (2023), this implies that although animals experience less thermal stress, producers face the challenge of compensating for reduced natural forage availability with supplemental feed, thereby increasing costs.

The high relative humidity values observed in Pastaza confirm a persistent atmospheric condition that favors the development of fungal diseases and the proliferation of microorganisms that affect both plant and animal physiology. According to Bibi and Rahman (2023), this type of environment limits leaf transpiration and alters metabolic processes in crops, reducing photosynthetic efficiency. In agreement, Vásquez et al. (2024) showed that under tropical conditions, relative humidity levels above 85 % increase the incidence of pests and diseases, reducing the productive stability of agricultural systems. Therefore, controlling relative humidity through microclimatic management practices and controlled ventilation in cultivated areas emerges as a viable alternative to reduce losses and maintain agricultural sustainability in the Ecuadorian Amazon region.

3.5 Potential Evaporation and Water Availability for Crops in Pastaza

Mean monthly potential evaporation in Pastaza ranges from 54.16 mm in February to 89.57 mm in September (Figure 5). High evaporation increases soil moisture loss, significantly reducing water availability for crops such as plantain, cassava, sugarcane, and pineapple. During August and September, when values exceed 80 mm, farmers increased irrigation requirements to maintain adequate soil moisture levels. According to Misra et al. (2020), high evaporation can limit crops' ability to absorb nutrients and carry out key processes such as photosynthesis, resulting in lower yields.

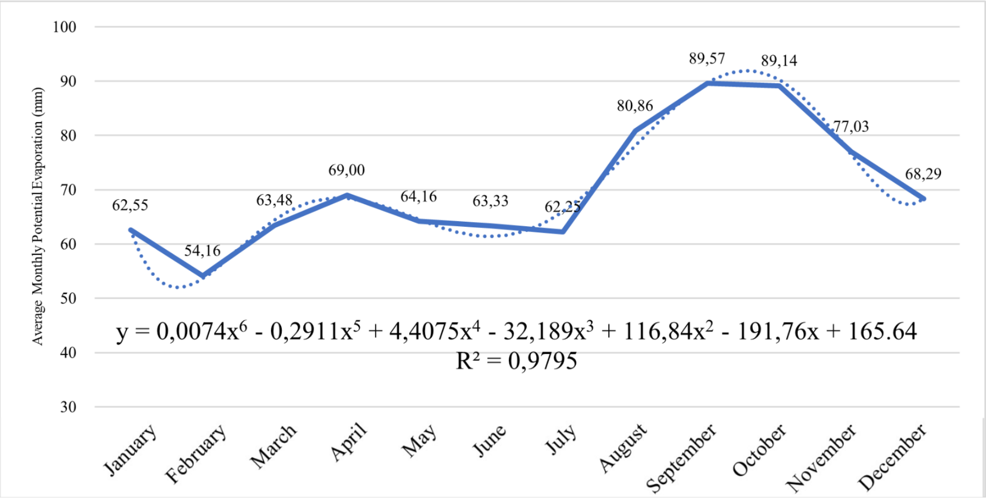

Figure 5. Average monthly potential evaporation during the period 2011–2021.

In sugarcane, this phenomenon directly affects sucrose accumulation in the stalks, reducing both quality and productivity. Similarly, in pineapple, water stress caused by elevated evaporation can delay flowering and reduce fruit size (Coelho et al., 2024). These effects highlight the need for advanced water management techniques, such as drip irrigation, to optimize the use of this limited resource during critical periods.

According to Srivastava et al. (2021), integrated water management is essential to mitigate these conflicts. Strategies such as rainwater harvesting, the use of efficient irrigation technologies, and the implementation of storage systems can help balance the needs of both sectors. In addition, sustainable agricultural practices, such as soil cover and the use of drought-resistant crops, can reduce dependence on additional water resources, thereby improving the overall sustainability of agricultural activities in Pastaza.

The evaporation dynamics in Pastaza show a relationship with solar radiation and vegetation cover, factors that modulate effective water availability in the soil. According to Arias-Muñoz et al. (2025), thermal variability and radiation intensity directly affect the water balance in Amazonian ecosystems, determining evaporation rates and surface moisture retention. In combination with the findings of Misra et al. (2020), increased evaporation reduces the capacity of crops to maintain the necessary root-zone moisture, affecting physiological processes such as transpiration and nutrient assimilation.

3.6 Regression Models of Climatic Variables

The regressions applied to climatic variables exhibit sixth-order polynomial behavior that adequately describes the monthly variation of meteorological conditions recorded in Pastaza canton during the period 2011–2021 (Table 3). The results indicate that the variables present a non-linear trend, mainly determined by seasonal cycles and atmospheric factors characteristic of tropical regions.

Table 3. Polynomial regression models of climatic variables in Pastaza (2011—2021).

Climate variable	Polynomial regression equation (6th order)	R^2	Figure
Mean monthly temperature (°C)	$y = 0.0001x^6 - 0.0061x^5 + 0.0989x^4 - 0.758x^3 + 2.7766x^2 - 4.418x + 23.662$	0.9203	Fig. 2
Total monthly precipitation (mm)	$y = -0.0045x^6 + 0.0077x^5 + 2.7198x^4 - 41.931x^3 + 228.04x^2 - 465.95x + 697.76$	0.8897	Fig. 3
Mean monthly relative humidity (%)	$y = -0.0008x^6 + 0.0278x^5 - 0.3888x^4 + 2.5911x^3 - 8.5432x^2 + 12.864x + 82.524$	0.9358	Fig. 4
Mean monthly potential evaporation (mm)	$y = 0.0074x^6 - 0.2911x^5 + 4.4075x^4 - 32.189x^3 + 116.84x^2 - 191.76x + 165.64$	0.9795	Fig. 5

Overall, the identified trends confirm that climatic fluctuations in Pastaza do not respond to simple linear relationships, but rather to polynomial behaviors that better represent local atmospheric dynamics. These results are consistent with Shah et al. (2019), who explain that solar radiation and atmospheric pressure in tropical regions generate complex variations that hinder the application of linear models. In this context, it is recommended to complement the analysis with stochastic or machine learning approaches to capture non-deterministic patterns in climatic variability (Gowtham et al., 2018; Pujahari et al., 2022).

3.7 Monthly Impact of Climatic Factors on Crops

During January and October, soil saturation due to high humidity and intense rainfall affects crops such as sugarcane and plantain. This is consistent with Arias-Muñoz et al. (2025), who project a 14.65 % reduction in sugarcane cultivated area by 2031 as a consequence of environmental and climatic pressure. In April, high humidity and temperature favor the proliferation of fungi and bacteria in tropical fruits such as cocoa, a situation that would intensify under Representative Concentration Pathway (RCP) scenarios 4.5 and 8.5 due to increased extreme precipitation and temperature (Serrano-Vincenti et al., 2025).

From June onward, an initial and progressive water deficit is observed, affecting crops such as plantain, sugarcane, and cassava. This pattern is consistent with Cachipuendo et al. (2025), who warn about the vulnerability of agricultural systems to reduced water availability resulting from the loss of water retention capacity. In addition, September presents a risk of asynchronous flowering due to irregular precipitation, affecting the phenological synchronization of cocoa. Finally, December shows a higher incidence of pests, in line with Meza et al. (2020), where climatic warming intensifies the reproduction of pathogens and pests in traditional agricultural systems. These effects validate the need for local climate adaptation strategies, especially in areas with diversified production and limited irrigation infrastructure.

Table 4. Relationship between monthly climatic conditions, type of impact, and sensitive crops.

Month	Climatic Factor	Type of Impact	Potentially Affected Crops
January	High humidity + intense rainfall	Soil saturation	Sugarcane, cassava, plantain
February	High humidity + low radiation	Reduced photosynthesis	Cocoa
March	Excess rainfall	Waterlogging, erosion	Orange
April	High humidity + high temperatures	Proliferation of diseases	Cocoa
May	Moderate rainfall	Favorable vegetative development	Maize, cassava
June	Lower relative humidity	Initial water deficit	Plantain, sugarcane, cassava
July	Low precipitation	Progressive water stress	Pastures
August	Moisture deficit + high radiation	Wilting, yield reduction	Cassava, plantain
September	Irregular precipitation	Risk of asynchronous flowering	Cocoa
October	Increased rainfall	Soil saturation	Sugarcane, cassava
November	High humidity and cloudiness	Reduced maturation	Cocoa
December	Intense rainfall and heat	Increase in pests and fungi	Plantain

4 Conclusions

Mean monthly temperature remained between 20.63 °C and 22.06 °C, a range favorable for crops such as plantain and cassava, although below the optimum for cocoa, which limits its productivity. Total monthly precipitation reached maximum values in April and May (450–470 mm), favoring sugarcane development but increasing the risk of waterlogging in sensitive crops such as coffee. The decrease in rainfall during September and October reduced water availability, affecting forage production and the sustainability of livestock systems.

High relative humidity levels (85 %–89 %) increased the incidence of fungal diseases in cocoa and coffee, generating higher management costs, while in livestock systems an increase in respiratory diseases was observed. Finally, potential evaporation, which reached its maximum in September (89.57 mm), highlighted the need for water management strategies and soil moisture conservation practices to prevent water stress.

Author Contributions

B.T.L.Z.: Conceptualization, Formal analysis, Data curation. **J.M.M.V.:** Writing – original draft, Methodology, Investigation. **R.D.V.P.:** Writing – review and editing, Validation.

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