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Articles

Water balance in coffee-growing regions using evaporation deficit

Balance hídrico en regiones cafeteras mediante el déficit de evaporación

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Abstract

Mexican coffee-growing area is zoned geographically, but given its climatic diversity, this classification hardly captures environmental homogeneity and does not represent the adaptive conditions of the crop. Evapotranspiration is intended to identify the regional moisture output and, although it is accepted by academia, it is estimated, and the quality of the information generated depends on the predictive capacity of the algorithm or the efficiency of the model used. Therefore, an evaluative indicator of the water balance (B_H) of the coffee-growing area of Oaxaca, Puebla and Veracruz was proposed with the wet and dry periods defined by their rainfall. Monthly precipitation and evaporation data were collected from the area studied, whose quotient was called "evaporation deficit (D_E)" ($D_E > 1.0$: excess, $D_E < 1.0$: deficit). The wet season (P_H = June-September) and dry season (P_S = November-April) were delimited, with P_H; and the rainiest month of the year, areas with homogeneous rainfall were delimited (P_{P6} = June, P_{P7} = July, P_{P8} = August, P_{P9} = September); with the calculation of the D_E and its modification, the D_{EP1} (quotient of the D_E in P_S vs. annual D_E and its relation to the D_E in January) areas with homogeneous humidity were delimited and D_{EPH} was validated with the trend in P_S, and the calculation of the D_E by month and specific site. D_{EP1} is a climatic index that detects temporal and spatial variations in the B_H

of coffee-growing areas (R^2 = 0.92) and will contribute to managing water resources and evaluating the environmental adaptation of the crop.

Keywords: Rainfall, evaporation, climatic zones, evapotranspiration, coffee growing, Mexico.

Resumen

La zonificación del área cafetera mexicana se realiza de forma geográfica, pero dada la diversidad climática de esta, dicha clasificación difícilmente capta la homogeneidad ambiental y no representa las condiciones adaptativas del cultivo. Con la evapotranspiración se pretende identificar la salida de humedad regional y, aunque es aceptada por la academia, es estimada y la calidad de la información generada depende de la capacidad predictiva del algoritmo o de la eficiencia del modelo empleados. Por ello, se propuso un indicador evaluativo del balance hídrico (B_H) del área cafetera de Oaxaca, Puebla y Veracruz, con los periodos húmedos y secos definidos por su pluviosidad. Se colectaron datos mensuales de precipitación y evaporación del área estudiada (1921-2018), cuyo cociente se denominó "déficit de evaporación (D_E)" (D_E > 1.0: exceso, D_E < 1.0: déficit). La estación húmeda (P_H = junio: septiembre) y seca (P_S = noviembre: abril) fueron delimitadas con P_H; el mes más lluvioso anual se concretó con zonas con pluviosidad homogénea (P_{P6} = junio, P_{P7} = julio, P_{P8} = agosto, P_{P9} = septiembre); con el cálculo del D_E y su modificación, el D_{EP1} (cociente del D_E en P_S vs. D_E anual y su relación con el D_E en enero) se delimitaron zonas con humedad homogénea, y se validó D_{EPH} con la tendencia en P_S y el cálculo del D_E por mes y sitio específicos. D_{EP1} es un índice climático que detecta variaciones temporales y espaciales del B_H de áreas cafeteras (R^2 = 0.92), y contribuirá a gestionar los recursos hídricos y evaluar la adaptación ambiental del cultivo.

Palabras clave: lluvia, evaporación, zonas climáticas, evapotranspiración, cafetal, México.

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Introduction

Mexico ranks eleventh among global coffee-exporting countries, with 177.3 thousand tons of green coffee exported during the 2021–2022 cycle (ICO, 2024). National production reached 1.06 million tons of cherry coffee across 699.5 thousand hectares, distributed among fourteen states during the 2023–2024 cycle (SIAP, 2024). In these regions, production environments vary and can be analyzed through climate assessments. Likewise, areas with homogeneous environmental conditions can be identified (Bunn, Läderach, Pérez-Jimenez, Montagnon, & Schilling, 2015) to support agricultural planning decisions and prevent adverse impacts on the sector's productivity (Lara-Estrada, Rasche, & Schneider, 2017).

Irregular precipitation patterns affect plantation growth and development, increase the incidence of pests and diseases, and reduce productivity (Weldemichael & Teferi, 2019). Precipitation and its seasonality have been identified as the most important climatic factors. For example, in Ethiopia during the 1979–2013 period, these two variables contributed 55 and 17 %, respectively, to coffee crop success (Chalchissa, Diga, & Tolossa, 2022). However, it has been found that in three-quarters of the world, changes in aridity are not detectable due to the absence of robust patterns at that scale (Greve *et al*., 2014).

In Tanzania, a study on the impact of global warming determined that, even under an agroforestry production system, the suitable area for cultivation would be reduced by 91 % by 2100 due to a 100 mm decrease in precipitation and a 1 °C increase in minimum temperature (Cassamo *et al*., 2023). In Zimbabwe, projections suggest that by 2050, accumulated precipitation from June to August will be the most critical factor in determining areas suitable for cultivation (Chemura, Kutywayo, Chidoko, & Mahoya, 2016). Meanwhile, in Martinique, forecasts indicate that by 2100, coffee production will be determined by whether annual precipitation exceeds 3 000 mm (Claude, 2016).

In Mexico and Guatemala, it is projected that suitable coffee-growing areas will decrease by 29 and 19 %, respectively, by 2050 due to reduced precipitation (from 1 670 to 1 600 mm year^{-1}) and a 2 °C increase in maximum temperature (Ovalle-Rivera, Läderach, Bunn, Obersteiner, & Schroth, 2015).

According to Ruelas-Monjardín, Nava-Tablada, Cervantes and Barradas (2014), changes in precipitation have been observed in coffee-growing regions of Veracruz, with a reduction of 1.7 mm year^{-1} detected over the 1948–2008 period. In contrast, Tanzania experienced increased precipitation of 22.7 mm year^{-1} between 2001 and 2019, influenced by El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), also shifting the rainiest month from April to May (Wagner, Jassogne, Price, Jones, & Preziosi, 2021). In Central America, a decrease of 70 mm is expected (Ovalle-Rivera *et al*., 2015), and in Zimbabwe, a 5.6 to 28.7

% reduction is projected by 2050 (Chemura *et al*., 2016). In Veracruz, a 5.5 % decrease is expected between 2050 and 2080 (Granados-Ramírez, Barrios, De-la-Paz, & Peña-Manjarrez, 2014), with a potential decline of up to 700 mm by 2100 (Esperón-Rodríguez, Bonifacio-Bautista, & Barradas, 2016) and a 10 % reduction by the end of the 21st century (Brigido, Nikolskii, Terrazas, & Herrera, 2015).

Coffee-growing zones in Mexico have been geographically delineated (Guajardo-Panes, Díaz-Padilla, López-Morgado, Hunter, & Hernández-Martínez, 2020), and in some cases, agroecological zoning has been used to identify areas suitable for the crop. For instance, in Guerrero, potential coffee-growing areas were defined based on altitude, slope, precipitation, average temperature, and soil type (González & Hernández, 2016). A similar analysis was conducted in Chiapas using the same variables but with different ranges Quiroz-Antunez, Monterroso-Rivas, Calderón-Vega, & Ramírez-García, 2022). In Veracruz, zoning was carried out using remote sensing and geographic information systems (GIS), land classification, and local knowledge (Bautista-Calderon, Gutiérrez-Castorena, Ordaz-Chaparro, Gutiérrez-Castorena, & Cajuste-Bontemps, 2018). In Tabasco, the process followed the 1981 FAO proposal, incorporating both current and future conditions under the global warming scenario using the RCP8.5 model, and considering five climate and six soil variables (Aceves-Navarro *et al*., 2018). In Martinique (Pineda & Suárez, 2014), Venezuela (Claude, 2016), and Angola (Baltazar-Silva *et al*., 2020), geomorphological, edaphic, and climatic criteria, along with crop requirements, were integrated into GIS-based analyses. In Peru, Salas-López *et al*. (2020) developed zoning using a hierarchical structure based on climatic, soil, physiographic, socioeconomic, and phytosanitary variables.

All of the above zoning efforts analyze soil, climate, and crop variables, but the lack of reliable data often limits their effectiveness. Therefore, it is essential to leverage existing historical records of precipitation and evaporation. In this context, indicators like the Standardized Precipitation Index (SPI) have been developed to assess spatial and temporal rainfall variability by categorizing precipitation as a standardized deviation from a probability distribution (McKee, Doesken, & Kleist, 1993). Regarding evaporation, Wang-Erlandsson, van der Ent, Gordon and Savenije (2014) highlighted that few land surface models evaluate its partitioning based on land use and its subsequent atmospheric trajectory. To address this, they developed the Simple Terrestrial Evaporation to Atmosphere Model (STEAM), which helps understand the link between land use and water resources for monitoring atmospheric humidity.

Accordingly, this study proposes using the ratio between moisture inputs (precipitation) and outputs (evaporation) as a water balance indicator —referred to as "evaporation deficit"— to evaluate hydrological conditions in all coffee-growing municipalities of Oaxaca, Puebla, and Veracruz.

Materials and methods

Information collection

The study was based on data from 158 active climatic stations (1921–2018), located across all coffee-growing municipalities of Oaxaca, Puebla, and Veracruz, Mexico (Figure 1). According to SIAP (2024), these three states account for 50 % of the cultivated coffee area in the country.

Although the distribution of climatic stations in these municipalities is not homogeneous, all available stations were included and represent the coffee-growing regions under study. For each station, information such as code, name, altitude, geographic coordinates, years of operation (Conagua & SMN, 2024), and physiographic subprovince (INEGI, 2001) was recorded. The data were digitized using QGIS (QGIS Development Team, 2024) as the geographic information system due to its efficiency and open-source accessibility. All statistical analyses were conducted using R software (R Core Team, 2024).

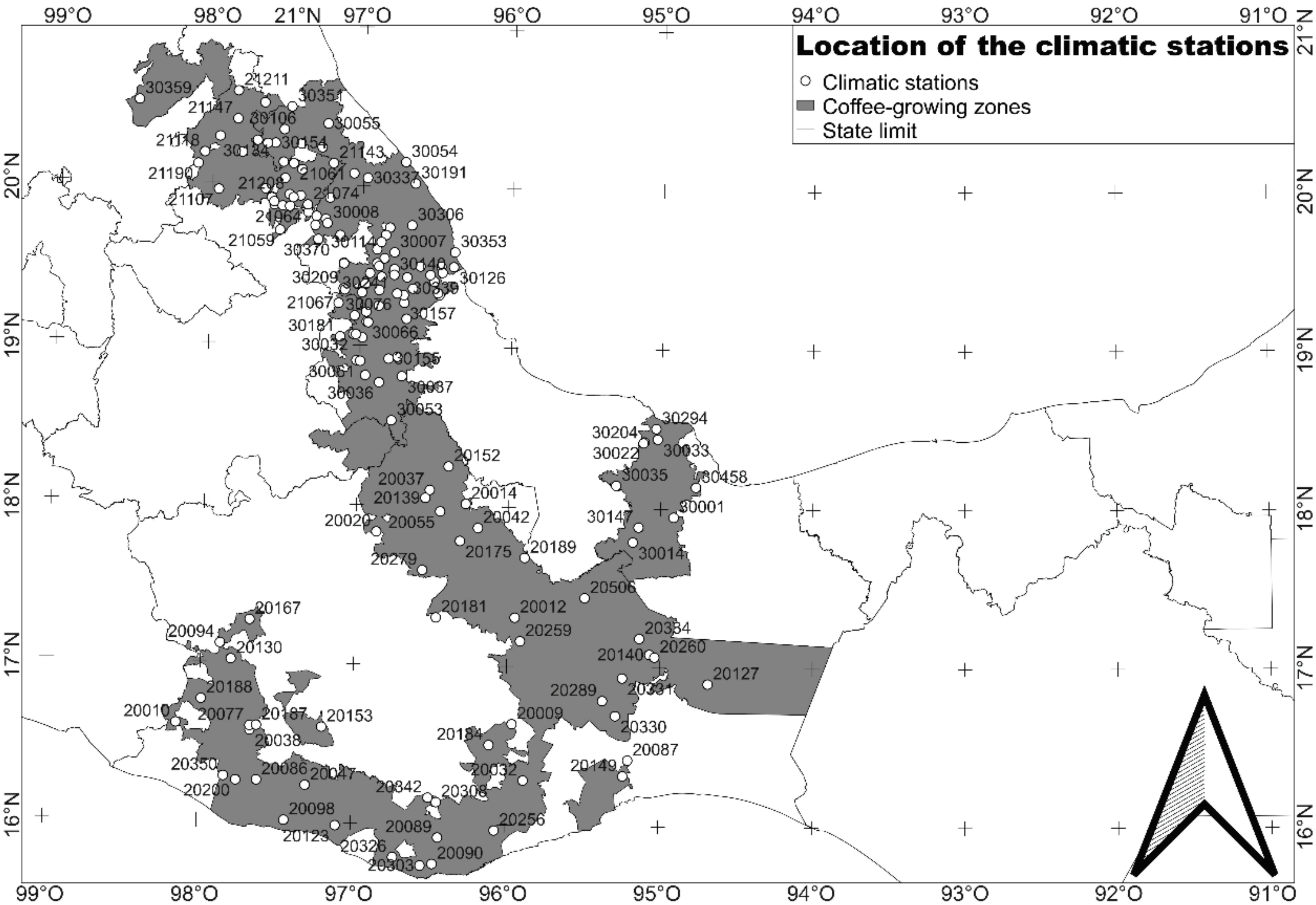

Figure 1. Location and code of the 158 climatic stations used to study the environment in the coffee-growing zones of Oaxaca, Puebla, and Veracruz, Mexico. Data collected from Conagua and SMN (2024).

To ensure the reproducibility of the study and to evaluate the quality and reliability of the results, several preliminary procedures were performed. These included identifying influence points, defined as atypical values that deviate significantly from the rest of the dataset due to a lack of evidence supporting their validity. These points are considered extreme—either excessively high or low relative to the rest of the observations—and their disproportionate effect on statistical analysis can distort measures of central tendency (mean, median) and dispersion (standard deviation), ultimately affecting analytical outcomes. Outliers exceeding three standard deviations from the mean were removed prior to imputing values through linear interpolation, followed by logarithmic transformation to improve the normality of the data distribution. The normality of variables was verified using the Shapiro-Wilk test.

Estimation of missing data

Missing data may arise for various reasons, including measurement errors, information loss, or the absence of data collection. These missing values must be evaluated to avoid bias and to ensure reliable results. The approach adopted in this study was imputation, whereby missing values were replaced with the central tendency measure of the corresponding variable. When possible, regression models were applied to predict missing values based on other variables, estimating model parameters while accounting for the available information related to the missing data.

Information analysis

The variables considered in all cases were total monthly rainfall (P_P), total monthly evaporation (E_V), and the annual values of both variables (1921–2018). The range of annual rainfall in the study region varied from 423.3 to 5985.3 mm, with monthly values distributed unevenly (Table 1).

Table 1. Frequency distribution (percentage) of monthly rainfall as a proportion of total annual rainfall in the coffee-growing zones of Oaxaca, Puebla, and Veracruz, Mexico.

Range %	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Frequency (%)											
<3	70	78	79	53	4						25	56
3.1-6	29	22	21	47	57					4	47	39
6.1-9	1			1	34	3	3	1		37	25	4
9.1-18					5	63	61	70	38	59	3	
>18.1						34	36	29	62			
Total	100	100	100	100	100	100	100	100	100	100	100	100

Rainfall is distributed into two periods: P_S = November to April and P_H = June to September. In all cases, rainfall during P_S is lower than during P_H, while precipitation in May and October is considered transitional to P_H and P_S, respectively. During P_H, differences were observed in the occurrence of the rainiest month, which allowed the classification of the region according to this criterion. To verify this, the average rainfall pattern for each month in P_H was calculated and correlated with the monthly pattern recorded at each climatic station.

As an alternative procedure to improve rainfall assessment, the evaporation deficit (D_E) was used. This is defined as the ratio between total precipitation (P_P) and total evaporation (E_V): $D_E = P_P / E_V$. It serves as an indicator of the balance between water inputs and outputs, distinguishing between humidity excess ($D_E > 1.0$) and deficit ($D_E < 1.0$). Monthly and annual D_E values were calculated for each climatic station. For analytical purposes, the data were grouped into two databases according to the observed rainfall distribution pattern. Two approaches were used:

a) The first grouped climatic stations according to the month with the highest precipitation (P_H), then analyzed the D_E trends by correlating each station's data with the average monthly rainfall pattern of its assigned group.

b) The second approach calculated the average D_E during P_S for each station, then determined its proportion relative to the station's annual D_E (denoted as D_{EP1}). D_{EP1} was correlated with the monthly D_E values, with January showing the strongest relationship (r = 0.96) in all cases. Based on this, three D_{EP1} ranges (< 0.2; 0.21-0.59; > 0.6) were established to reclassify the stations across the study region and estimate the monthly D_E for each location.

The analysis involved establishing quantitative relationships among variables using regression and correlation techniques, as well as computing basic statistical parameters such as minimum, mean, maximum, standard deviation, and frequency distribution. In the regression models, the general form $Y = f(x) + e$ represents a deterministic function plus a random error component. Based on this, the influence of the independent variable (X, time) on the dependent variable (Y, climate) was evaluated. The coefficients measure the strength of the relationship between variables. The sum of residuals (observed Y minus estimated Y) is expected to be zero in statistical terms, with the goal of minimizing errors to estimate b_0 and b_1 via the ordinary least squares method.

The models assessed both the individual significance of each explanatory variable and the overall significance of the regression. For individual significance, each variable was tested under the null hypothesis (H_0):

$$H_0: B(X_i) = 0$$

If this holds true, *B* has no effect on *Y*. The criterion for statistical significance was Prob > |*t*| < 0.05, where *t* refers to the Student's *t*-test. For joint (global) significance, the hypothesis was:

$$H_0: B(X_1) = B(X_2) = B(X_3) = 0, \text{tested using } ProbF > |F| < 0.05$$

If this condition is met, the regression is globally significant, even if individual variables may not be. To avoid biases in the results, tests for multicollinearity and heteroscedasticity were also performed. Multicollinearity was evaluated by checking the correlation between independent variables using the Variance Inflation Factor (VIF):

a) Model X_1 as a function of other *X* variables: $X_1 = f(X_{\square})$

b) Obtain R^2 of this model

c) Compute VIF for X_1: VIF = 1 / (1 − R^2)

d) Decision rule: VIF > 10 indicates multicollinearity

e) If so, X_1 was removed from the model

Heteroscedasticity was assessed under the Gauss–Markov assumption of constant error variance (homoscedasticity):

$$Var(error) = s^2 \text{ (constant)}$$

If not met:

$$Var(error) = s^2\, W \text{ (variable)}$$

Decisions in model evaluation involved managing Type I and Type II errors, which are inherently inversely related. Minimizing one increases the likelihood of the other; therefore, a decision must be made regarding which error type to prioritize. Hypotheses were tested through data analysis and mean comparison to either accept or reject the proposed statements, depending on the evidence.

Results

The rainy period in the region comprising the three states occurs between June and September; however, the pattern varies depending on the rainiest month of the season (Figure 2).

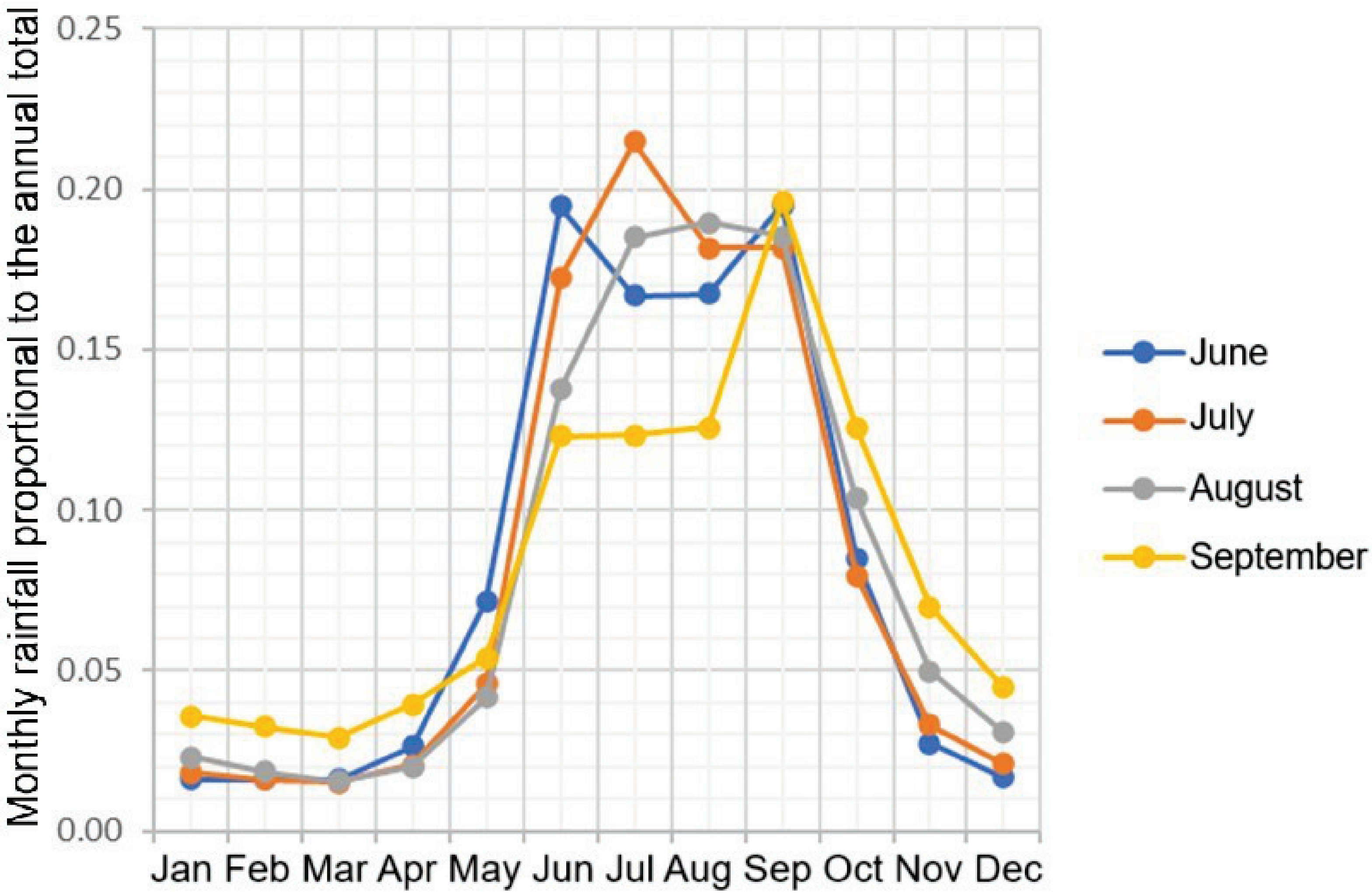

Figure 2. Rainfall pattern in the coffee-growing zones of Oaxaca, Puebla, and Veracruz, Mexico, grouped by the rainiest month as a proportion of the annual total.

The correlation test confirmed that the grouping of stations according to the rainiest month in P_2 was appropriate. For June, July, August, and September, a correlation coefficient greater than or equal to 0.9 was observed in 100, 100, 95, and 98 % of the evaluated climatic stations, respectively. The geographical distribution of rainfall based on the rainiest month is shown in Figure 3.

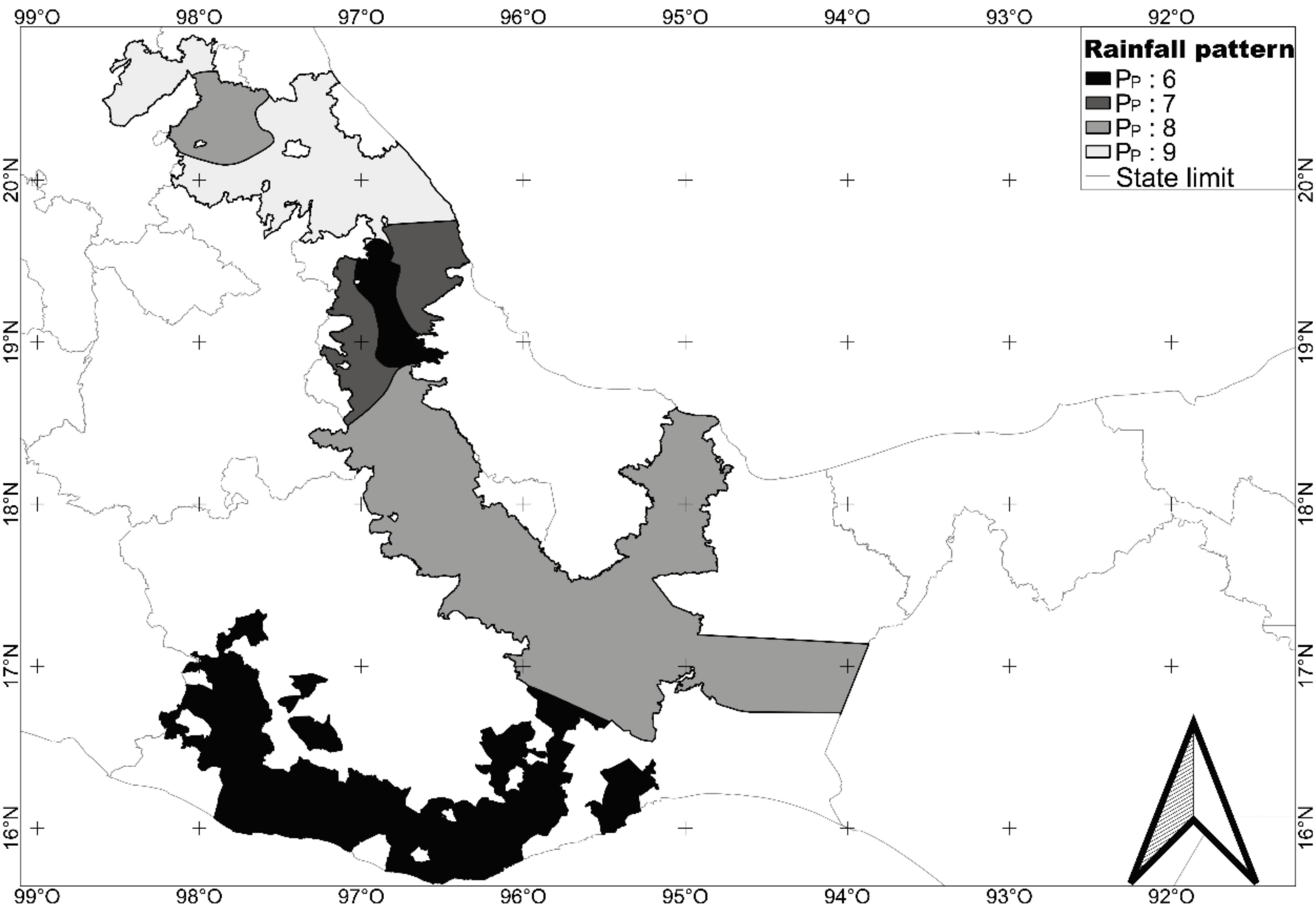

Figure 3. Rainfall pattern in the coffee-growing zones of Oaxaca, Puebla, and Veracruz, Mexico, according to the rainiest month of the season.

The D_E analysis was conducted using the same grouping criteria as the rainfall data. This revealed four zones characterized by a quadratic trend in the less rainy months (November to April), with differences in magnitude (Figure 4).

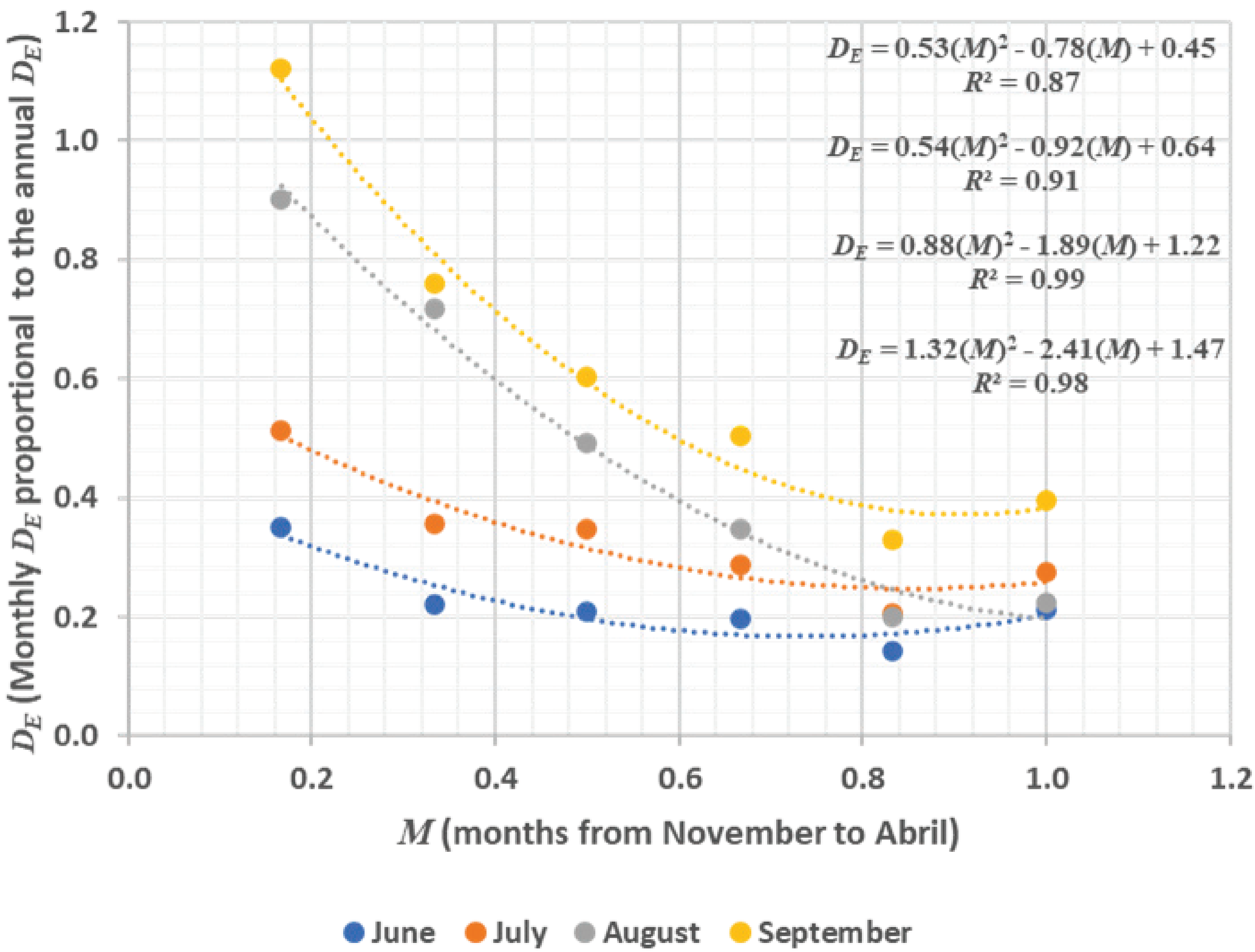

Figure 4. Variation of evaporation deficit (D_E) during the less rainy months in the coffee-growing zones of Oaxaca, Puebla, and Veracruz, Mexico, grouped by the rainiest month of the season. *M* is the code for the months starting with November, each incremented by one up to April.

When stations were grouped based on the rainiest month, a quadratic trend was observed in all cases. However, when correlating these groups with the D_E recorded at each climatic station, the following results were obtained: June, $r > 0.95$ in 95 % of cases; July, $r > 0.95$ in 100 %; August, $r < 0.95$ in 39 %; September, $r < 0.95$ in 49 %. These results indicate that D_E does not follow the same spatial distribution as precipitation across the study region.

As an alternative approach, the D_{EP1} indicator (ratio of D_E in P_S to annual D_E) and its relationship with D_E in January were used. Based on this relationship, three D_{EP1} ranges were established (< 0.2; 0.4; > 0.6), which served as a basis for grouping the climatic stations in the study region (Table 2) and analyzing trends in P_S (Figure 5).

Table 2. Proportion of monthly evaporation deficit (D_{EM}) relative to annual evaporation deficit (D_{EA}), grouped by the ratio D_{EM}/D_{EA} during the November to April period (D_{EP1}) in the coffee-growing zones of Oaxaca, Puebla, and Veracruz, Mexico.

D_{EP1}	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
< 0.2	0.10	0.10	0.07	0.13	0.64	2.47	2.31	2.45	2.94	1.11	0.26	0.11
0.21-0.59	0.42	0.34	0.23	0.29	0.50	1.65	1.89	1.77	2.41	1.32	0.73	0.49
> 0.6	0.72	0.56	0.35	0.39	0.47	1.13	1.29	1.31	2.23	1.65	1.21	0.98

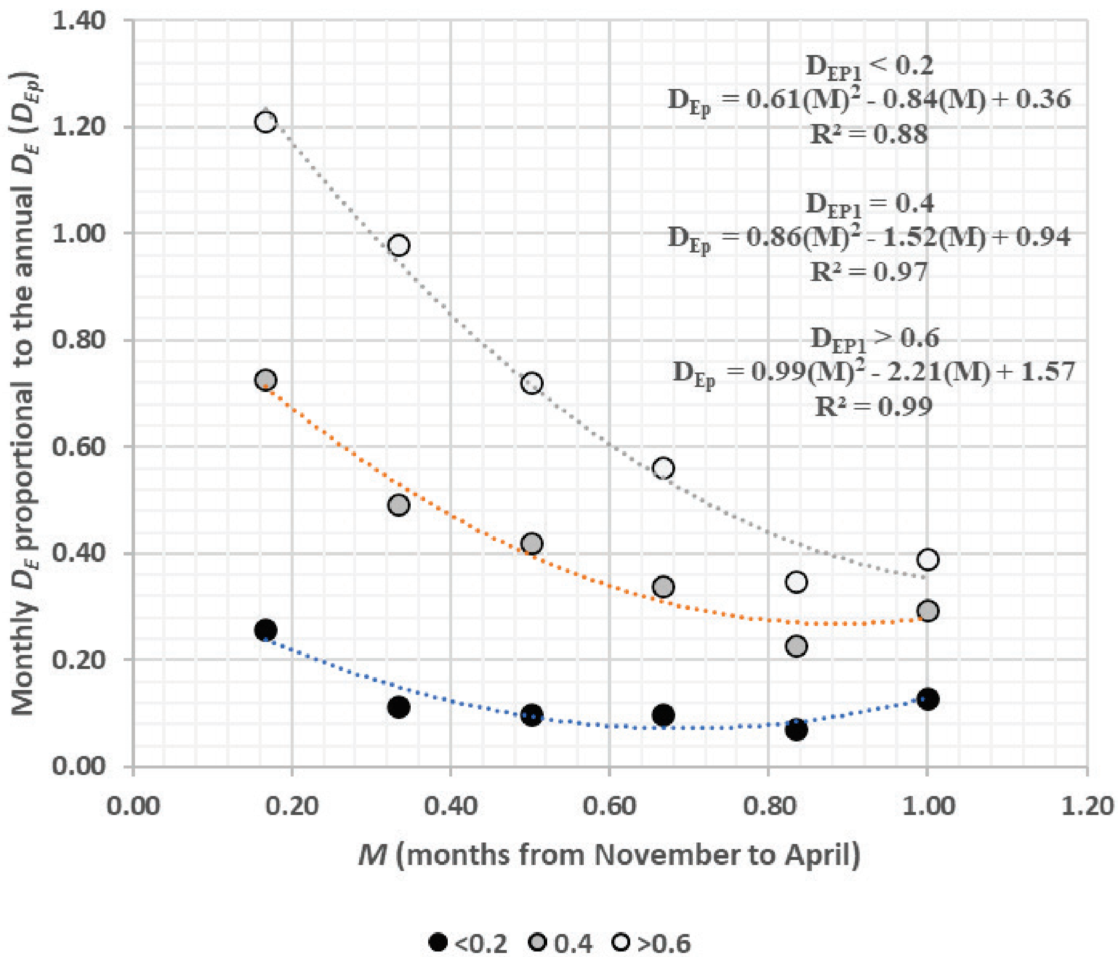

Figure 5. Variation of evaporation deficit (D_E) between November and April in the coffee-growing zones of Oaxaca, Puebla, and Veracruz, Mexico, grouped by the ratio of monthly D_E during that period and annual D_E (D_{EP1}). M: coding for months starting with November, assigned sequential values starting from 6.

Based on the station groupings presented in the figure, a map was created to show the geographical distribution of D_E changes in the study region (Figure 6).

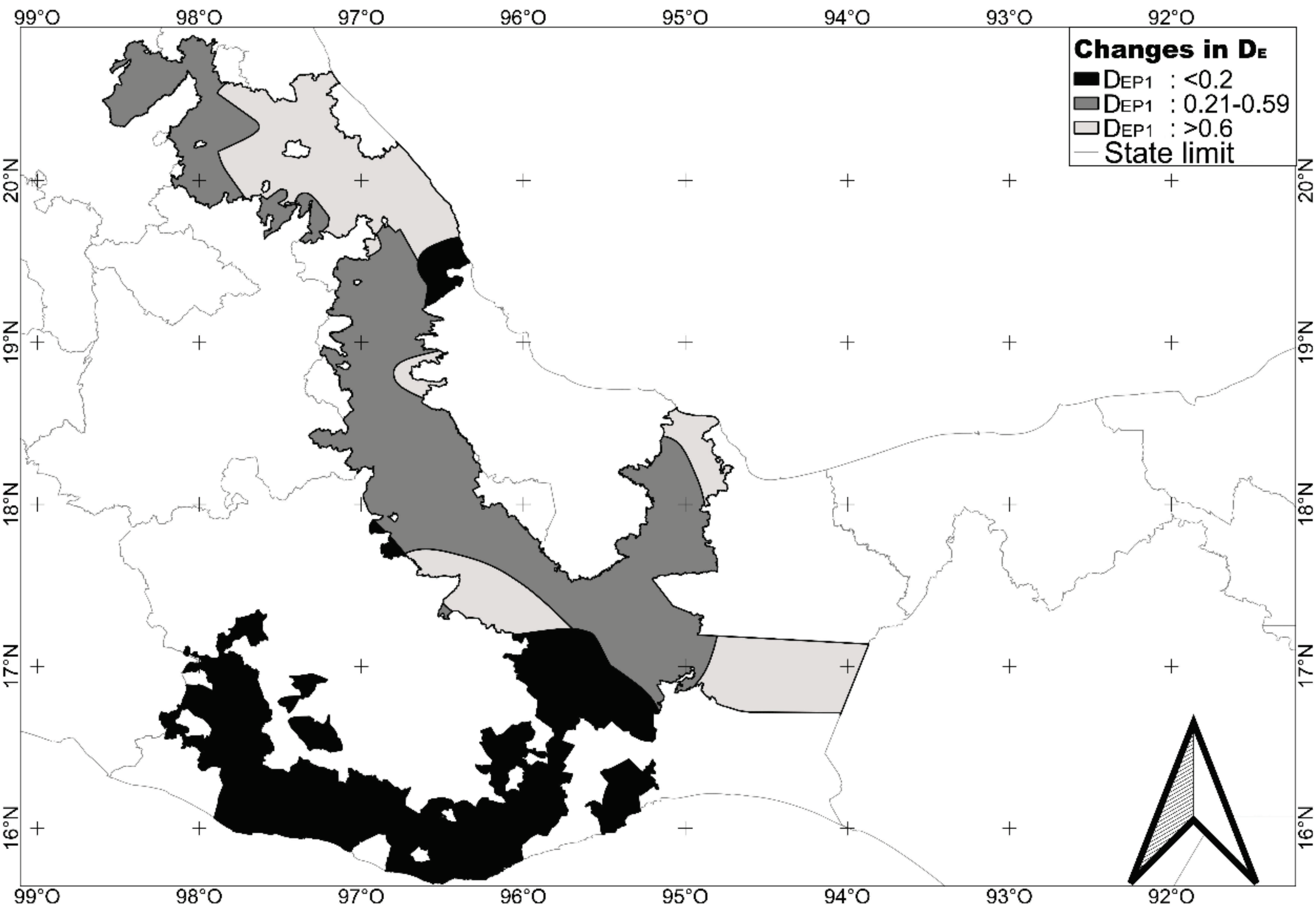

Figure 6. Geographical distribution of the ratio between monthly evaporation deficit (D_E) from November to April and annual D_E (D_{EP1}) in the coffee-growing states of Oaxaca, Puebla, and Veracruz, Mexico.

To estimate D_E for a specific month and site within any coffee-growing area in Oaxaca, Puebla, or Veracruz, it is only necessary to know the annual D_E and the geographical location of interest (Figure 6). The annual D_E is then multiplied by the corresponding coefficient from Table

2, depending on the site's D_{EP1} range and the desired month. The correlation between the estimated and observed monthly D_E for each climatic station is shown in Figure 7.

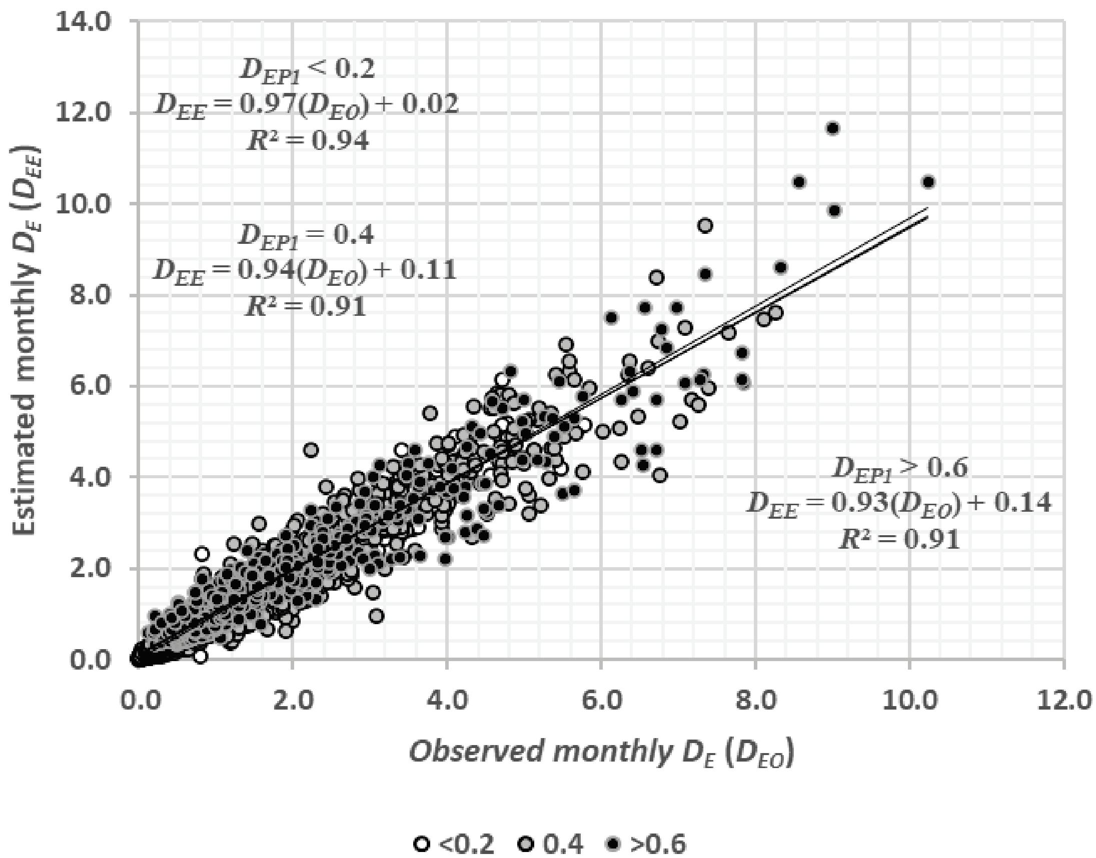

Figure 7. Relationship between estimated and observed monthly evaporation deficit (D_E), after grouping climatic stations by the D_{EP1} indicator (ratio of D_E from November to April to annual D_E, and its relationship with D_E in January).

Using the procedure described above, it is possible to estimate monthly D_E values. The adoption of this method will enhance decision-making and improve agricultural and environmental conditions for coffee cultivation. These findings clearly show that humidity in the study region should not be considered constant; instead, it varies spatially and temporally. Consequently, defining homogeneous zones based on rainfall capture is not feasible. Rather, this study aims to delineate zones with similar humidity distribution patterns.

Discussion

The main objective of this study was to propose and evaluate a water balance indicator for the coffee-growing regions of Oaxaca, Puebla, and Veracruz, Mexico, using the evaporation deficit, defined as the ratio of precipitation to evaporation (*P/E*). Our results indicate that the wet season in the study area extends from June to September, while the dry season spans from November to April, with May and October acting as transitional months. Additionally, we found that September is generally the rainiest month. In this section, we discuss these findings in the context of the existing literature, highlight the study's limitations, and propose directions for future research.

Duration of wet and dry seasons

In our study, the wet season from June to September partially coincides with that reported by Murray-Tortarolo (2021), who identified a national wet season in Mexico lasting from June to November (1951–2017). However, it is shorter than the season reported by De Jesús, Breña-Naranjo, Pedrozo-Acuña and Alcocer-Yamanaka (2016), which extended from May to November (1998–2013), and by Muñoz-Villers, Geris, Alvarado-Barrientos, Holwerda and Dawson (2020) (May to October, 1971–2000, in Veracruz). These discrepancies may be explained by regional climatic differences, varying time periods analyzed, and differing methodologies for defining the wet season (e.g., precipitation thresholds or water balance criteria). Regarding the dry season (November to April), our findings align with those of Muñoz-Villers *et al*. (2020) for Veracruz, but show slight variations from the definitions provided by Murray-Tortarolo (2021) and De Jesús *et al*. (2016), who define the dry season as lasting from December to May and December to April, respectively. These differences highlight the complexity of rainfall patterns in Mexico and emphasize the need for regional-scale studies.

Rainiest month

Our finding that September is generally the rainiest month in the study area is consistent with results reported by Fernández and Trejo (2020) for Valles Centrales, Oaxaca (2007–2013). However, it differs from patterns observed in the Sierra Norte de Puebla, where the rainiest month varies by location, occurring in July, August, or September (Castelán-Vega, Tamariz-Flores, Linares-Fleites, & Cruz-Montalvo, 2014). A contrasting global example is Tanzania, where the rainiest month shifted from April to May over an 18-year period (2001–2019) (Wagner *et al*., 2021). This variability in the timing of peak rainfall underscores the influence of local factors such as topography, altitude, and proximity to water bodies on precipitation dynamics.

Influence of climatic phenomena

Unlike other studies that have found significant associations between climate phenomena-such as ENSO, ODP, and OMA-and precipitation variability (Alvarez-Olguin & Escalante-Sandoval, 2017; Park, Byrne, & Böhnel, 2017), our analysis did not show a significant effect of these phenomena on the studied variables. This may be due to our focus on a specific region, while the influence of such large-scale climatic events might be more evident at broader spatial scales. Additionally, the region's topographic complexity may attenuate or mask these influences. It is also possible that the P/E ratio used in our study is less sensitive to interannual climate oscillations compared to total precipitation alone.

Precipitation-evaporation relationship

Although not the primary focus of this study, we used directly measured-not estimated-evaporation data. The relationship between precipitation and evaporation is critical for understanding the regional water balance. During the wet season, average evaporation was 470 mm, whereas in the dry season it reached 620 mm. Previous research, such as that by David, Valente and Gash (2006), and Baiamonte (2021), has emphasized the role of vegetation cover in intercepting rainfall and influencing evaporation, thereby shaping the hydrological cycle. Extreme variations in rainfall and evaporation, reported in other regions (Arellano-Monterrosas & Ruiz-Meza, 2019; Sharmila & Hendon, 2020), may also be present in our study area, though further research is needed to confirm this. The relatively high evaporation during the dry season suggests a substantial evaporative demand in the region, which has potential implications for water availability in coffee cultivation, as indicated by prior studies.

Study limitations

This study has certain limitations. The use of monthly data may obscure shorter-term rainfall variability, such as intense short-duration events. Furthermore, the distribution of climatic stations was heterogeneous, with higher station density in Puebla (one station per 250 km^2) and lower density in Oaxaca (one station per 907 km^2), which could introduce spatial bias in representing rainfall patterns across the region.

In summary, this study found that the wet season in the coffee-growing region of Oaxaca, Puebla, and Veracruz spans from June to September, while the dry season extends from November to April, and that September is typically the rainiest month. Although these findings generally align with prior studies at national and regional levels, they also reveal meaningful differences in seasonal duration and precipitation peaks. This underscores the complexity of the rainfall regime in Mexico and the importance of local influences. Although we did not observe a significant relationship between large-scale climatic phenomena and the variables studied, our findings improve the understanding of precipitation behavior in the coffee-growing areas of these three states. This has important implications for agricultural planning and water resource management. Future research should explore the influence of microtopography on precipitation distribution, assess the long-term impacts of climate change on rainfall regimes in the region, and further validate the proposed evaporation deficit indicator as a decision-making tool for coffee cultivation management.

Conclusions

The spatial and temporal variability of climatic conditions related to the B_H in the main coffee-producing states of Mexico (Oaxaca, Puebla, and Veracruz) was analyzed. Zones and periods characterized by excess or deficit of environmental humidity were identified through the development of a B_H indicator known as the evaporation deficit (D_E). For this purpose, a methodology was proposed to calculate D_E and estimate its monthly values using annual precipitation and evaporation data.

Based on the analysis of D_E variability, homogeneous zones were identified according to this indicator, enabling the evaluation of B_H for any point within the studied region. Through D_E calculations, areas showing significant differences in moisture retention capacity were detected. As a result, zones with marked humidity excesses during the wet season were delineated, along with others where dry periods may critically affect agricultural productivity in general and coffee cultivation in particular.

This research contributes to a better understanding of environmental conditions associated with the balance between water inputs (precipitation) and outputs (evaporation) in Mexico's main coffee-growing areas, through the application of D_E. The use of this indicator offers an alternative to evapotranspiration (E_T) data, as it is based on measured variables linked to B_H. In contrast, E_T is typically estimated, introducing uncertainty regarding the accuracy of the resulting information. Therefore, D_E provides a more reliable basis for water resource management, agricultural planning, and the evaluation of climatic conditions relevant to coffee-growing regions.

In the study area, which includes the coffee-producing municipalities of Oaxaca, Puebla, and Veracruz, the wet season (P_2) occurs from June to September, while the dry season (P_1) spans from November to April. Four zones with homogeneous rainfall patterns (P_{P6} = June, P_{P7} = July, P_{P8} = August, P_{P9} = September) were identified, based on the occurrence of the rainiest month. Additionally, three zones with homogeneous humidity were distinguished using the D_{EP1} index ($D_{EP1} < 0.2$; $D_{EP1} = 0.4$; $D_{EP1} > 0.6$). The modified evaporation deficit (D_{EP1}) was shown to be a climatic index capable of evaluating the B_H of the region and detecting its spatial and temporal variability. To determine the D_E for a particular month and specific location within the coffee-growing region, it is sufficient to know the annual D_E and the geographical location of interest (Figure 6). The annual D_E is then multiplied by the appropriate coefficient from Table 2, corresponding to the D_{EP1} value and the month of interest.

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