# Agroclimatic modeling of the water requirement of the oil palm (*Elaeis guineensis* Jacq.) crop in the Cesar department, Colombia

## Modelación agroclimática del requerimiento hídrico del cultivo de palma de aceite (*Elaeis guineensis* Jacq.) en el departamento del Cesar, Colombia

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**ABSTRACT**

The limited availability of water in the Cesar department (Colombia), along with the high-water consumption associated with the lack of knowledge of water requirements and the low efficiency of irrigation systems in the oil palm (*Elaeis guineensis* Jacq.) crop, has led to an inefficient use of water resources and affected the crop productivity. The main objective of this research was to determine the water demand of oil palm cultivated in areas with homogeneous agroclimatic conditions in the Cesar department. For this purpose, climatic information of the department was obtained from meteorological stations and climatic satellite data. The water demand was also determined by obtaining the crop coefficient (Kc) for plants aged 10 and 15 years, using the water balance methodology. The Kc obtained was 0.91 and 0.84, respectively. As a result of the zoning, 10 agroclimatic zones were identified in the department, of which 8 were found to be suitable for oil palm cultivation. In these zones, water requirements are expected to be homogeneous due to similar soil and climate characteristics. This information was used to estimate the regional water balance, allowing farmers to plan water management and optimize the use of available resources.

**Key words:** water balance, water use efficiency, cluster, climatic variables, soil water capacity.

**RESUMEN**

La limitada disponibilidad de agua en el departamento del Cesar (Colombia) y los elevados consumos de agua asociados al desconocimiento del requerimiento hídrico sumado a sistemas de riego de baja eficiencia en el cultivo de la palma de aceite (*Elaeis guineensis* Jacq.), han incidido en un uso ineficiente del recurso hídrico y en la afectación de la productividad del cultivo. El objetivo principal de este trabajo fue determinar la demanda hídrica del cultivo de la palma de aceite en zonas con condiciones agroclimáticas homogéneas en el departamento del Cesar. Para esto se obtuvo la información climática del departamento mediante estaciones meteorológicas y datos climáticos satelitales. También se determinó la demanda hídrica de este cultivo mediante la obtención del coeficiente del cultivó (Kc) en plantas de dos edades, 10 y 15 años, mediante el uso de la metodología de balance hídrico, obteniéndose un Kc de 0,91 y 0,84 respectivamente. Como resultado de la zonificación, se identificaron 10 zonas agroclimáticas en el departamento, de las cuales 8 resultaron ser aptas para el cultivo de la palma de aceite. En estas zonas, se espera que los requerimientos hídricos sean homogéneos debido a las características similares de suelo y clima. Con esta información se hizo la estimación del balance hídrico regional, permitiendo a los agricultores planificar la gestión del agua, optimizando el uso de los recursos disponibles.

**Palabras clave:** balance hídrico, eficiencia del uso de agua, clúster, variables climáticas, capacidad hídrica del suelo.

## Introduction

Oil palm production is of great importance for the Cesar department, as it contributes 17% of the national agricultural GDP and ranks fourth in the country's agricultural exports (Murcia, 2023). The department currently has 77,869 ha planted in 23 of the 25 municipalities (Fedepalma, 2021). This crop requires certain climatic conditions to achieve its proper development and production. In the Cesar department, the accumulated annual precipitation is estimated between 1250 and 1750 mm per year (IDEAM, 2022), which is insufficient to meet the crop water requirements. Woittiez *et al.* (2017) determined that oil palm cultivation in Southeast Asia requires 1900 to 3500 mm of water annually, due to a transpiration rate of 4.0 to 6.5 mm $d^{-1}$ in the rainy season and 1.0 to 2.5 mm $d^{-1}$ in the dry season, with an average evapotranspiration of 6 mm of water per day under normal conditions.

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In adult oil palm, Lascano and Munévar (2000) found values of crop coefficient (Kc) in a range between 0.75 and 1.2 daily, with water requirement for a crop in northern Colombia ranging between 350 and 500 L per palm per day. Henson (1995), in Malaysia, where ETo varies between 6 and 7 mm $d^{-1}$, reported Kc between 0.8 and 1.2. Dufrene *et al.* (1992), in Ivory Coast, estimated Kc for the area in the rainy season between 0.69 and 0.72. Arshad (2014), in studies conducted in the Malay Peninsula, obtained evapotranspiration of oil palm crop in a range between 1583 and 2003 mm $year^{-1}$. The crop coefficient (Kc) estimated in this study was 1.0 (Arshad, 2014). Water requirements for the study area remain unknown since the Kc varies depending on the climatic conditions where the crop is grown.

In recent years, there has been a reduction in the availability of water sources in northern Colombia, aggravated by the low efficiency of water use in oil palm crops due to poorly performing irrigation systems (Alvarez *et al.*, 2007). The lack of knowledge about climatic conditions and natural resources, such as water and soil, also contributes to inadequate water management planning for most crops (Ongley, 1997). Therefore, it is essential to carry out the characterization of these resources through zoning methodologies. According to the Instituto Geográfico Agustin Codazzi (IGAC, 2014), zoning is defined as the identification of homogeneous clusters that allow the delineation of similar agroclimatic regions (Zhou *et al.*, 2009). These regions become essential tools for the planning of spatial projections in agriculture, thus facilitating a more effective and sustainable management of irrigation in crops (Molina *et al.*, 2022).

Most of the currently published climate or ecological research work has been conducted by using assessments of experts and qualitative analysis of on-site data (Zhou *et al.*, 2009). These traditional methods of manual regional delineation are laborious and time-consuming processes. Therefore, in this work, we applied a methodology designed to generate hierarchical structures (clusters), enabling the correlation of agroclimatic variables according to their geographic location (Morales *et al.*, 2006). This methodology was used because the traditional methods of climatic classification do not meet the proposed needs, providing insufficient detail and relying on predefined climatic groups that fail to reflect variations under the conditions of the Cesar department (Terán *et al.*, 1998).

The most relevant climate classification studies in Colombia are those provided by the IGAC, which integrate the Caldas-Lang methodological proposal (IGAC, 2018). This climate classification is applied to the American tropics and is based on temperature values with respect to their elevation variability, which indicates the thermal floors and is complemented with precipitation (Castañeda Tiria, 2014). The Cesar department is composed of three morphostructural units: La Sierra Nevada de Santa Marta, la Serranía de los Motilones (or del Perijá), and the sedimentation basin of the Magdalena and Cesar (IGAC, 2017). This means that the Caldas-Lang climate classification does not show significant variations for the department since the valley of the basin of the Magdalena and Cesar rivers occupy the highest portion of the area of Cesar. This landscape is located in the basins of the Cesar and Magdalena rivers at altitudes ranging from 150 to 400 m a.s.l. (Gobernación del Cesar, 2020). This area is one of the hottest zones in the country, with averages above 28°C and minimum temperature changes (IDEAM, 2023); according to the Caldas-Lang methodology, it is a single climatic zone comprised by the valleys found in the basins of the Cesar and Magdalena rivers.

Cluster analysis is used in various areas such as biology, medicine, engineering, and social sciences to identify patterns and relationships between data and thus make decisions (Plazas Niño, 2021). Considering the above, this work sought to produce a zoning that accounts for the temporal-spatial variation of the climatic elements, which were classified through grouping techniques of the agroclimatological variables based on their nature and affinity (statistical and mathematical methods of grouping) (Cardona Arévalo, 2019). In Colombia, the zoning of climatic elements by cluster analysis methods has been implemented mainly due to the country's location on the equatorial strip, which causes climatic variation over short distances, influenced by topography, vegetation and other conditions (Terán *et al.*, 1998).

The purpose of this zoning design is to contribute to the efficient use of water resources in the Cesar department, through the determination of agroclimatic parameters that can help optimize available resources and the rational distribution of natural resources (Zhou *et al.*, 2009) such as, in the present case, the water resource for the oil palm crop.

## Materials and methods

This study was conducted for the department of Cesar, which is located between the coordinates 7°40'38" and 10°52'17" N and between 72°53'06" and 74°07'47" W. It has an area of 22,905 $km^2$ (Gobernación del Cesar, 2020). The department has a predominantly flat topography below

400 m a.s.l., highlighting the mountain systems that make up the Sierra Nevada de Santamarta and the Serranía del Perijá, with an average temperature of 28°C and rainfall ranging between 1000 and 1500 mm per year. In the center of the department, and especially on the eastern fringe, precipitation volumes increase to values close to 2000 mm (CORPOCESAR, 2023).

The research was conducted in two phases: first, a strategy was developed to delimit agroclimatic homogeneous zones using GIS combined with multivariable analysis for the entire Cesar department and the municipality of Codazzi. This was done following the research trials established in two commercial oil palm plantations for the determination of the crop's water requirements at different ages. After that, the evapotranspiration values were determined for the crop of two ages: 10 and 15 years.

To formulate the zoning, climatic information (precipitation, air temperature, relative air humidity, solar radiation, and wind speed), topography of the Cesar department, and water retention capacity of soil were used. The climatic information was obtained from the network of meteorological stations of the Instituto de Meteorología y Estudios Ambientales (IDEAM), with information from 72 meteorological stations: 52 pluviometric (PM) and 20 from the categories of main climatic (MC), ordinary climatic (OC), and agroclimatological (AC). To complement the climatic information, satellite climatic systems (Copernicus ERA-5) were used. The climatic information was for a stable period of 31 years, following the indications of the World Meteorological Organization (WMO, 2018). The selected stations underwent quality control, including determination of missing data, checking and cleaning of atypical data, filling of missing data, consistency and homogeneity tests to validate the data obtained, in order to determine whether the data were inaccurate, incomplete or incompatible (WMO, 2017).

With the climatic data of the Cesar department, the reference evapotranspiration (ETo) and the precipitation in both annual accumulated and monthly accumulated multi-annual terms were obtained. For this, the first step was to calculate ETo, estimated using the FAO Penman-Monteith method, which determines ETo using climatic parameters such as net solar radiation, average air temperature, wind speed, and relative air humidity. This method was used as it is considered one of the most accurate for the estimation of ETo in any location evaluated and because it is widely used in agriculture and hydrology (Allen *et al*., 2006). ETo was calculated daily at the point locations of the weather stations employed.

In relation to the water retention capacity of soils in the Cesar department, a generalized soil study of the department was used (IGAC, 2017), in which the characteristics of the edaphic mosaic and its relationships with the geomorphologic and geologic variety of the soil are found. The results of the soil physical analysis of the points analyzed by the IGAC were used with a total of 55 locations, where the soil water storage was determined up to 60 cm depth considered to be the effective depth for the oil palm crop (Fedepalma, 2001). The amount of rapidly usable water (available water holding capacity, AWHC) was obtained, which refers to the amount of water available for plants to absorb and is determined as the difference between the field water capacity (FC) and permanent wilting point (PWP) to the depth in the soil profile (z) (Eq. 1).

$$AWHC = \frac{(FC - PWP)}{100} \times z \tag{1}$$

With the climatic information (precipitation, ETo), the topographic profile of the department, and the water storage capacity, we proceeded to spatially represent it through a Geographic Information System (GIS), using the Inverse Distance Weighted (IDW) model to perform the interpolation. In this model, the sampling points are weighted during interpolation in such a way that the influence of a point in relation to others decreases with the distance from the unknown point to be created (Villatoro *et al*., 2008).

This research sought to develop a zoning map according to the data shown by Torres Bernal (2024) and following procedures similar to those used by Molina Moral *et al*. (2022) and Teran *et al*. (1998), among others, which determine agroclimatic homogeneous zones. For this, the georeferenced data from the 18402 established points and the monthly values of these variables at these points were used. The zoning was performed through clustering algorithms using unsupervised machine learning to create models that do not require training data, with the purpose of grouping data automatically into different categories or clusters based on their similarity (Jolly, 2018). This process was carried out by applying different clustering methodologies. To evaluate the most appropriate methodology for zoning, four different clustering algorithms were employed. Initially, the k-means algorithm was used, based on Euclidean distance (Kong *et al*., 2021). The second methodology was similar to the first one, but based on the distance of the data to the centroids of the created clusters. The third algorithm was based on the creation of hierarchical clusters; at this point, the Ward model was implemented (Gallardo San Salvador & Vera Vera, 2004). Finally, the Gaussian mixture model

(GMM) algorithm was used. This probabilistic model assumes that the data are generated from a mixture of several Gaussian distributions (Avila & Hauck, 2017).

The best methodology was determined using an expert analysis that allowed choosing which of the zonings was more in accordance with reality, considering that the climatology of Cesar department is regulated or influenced by several circulation patterns associated with the topography and hydrographic systems of the region.

The water requirement was determined using the method of water balance for the two ages of the crop, using a randomized block treatment model for the two experimental units (10-year-old and 15-year-old palms (*Elaeis guineensis* Jacq.)). For each age, five treatments were applied: Treatment T1 (50 Liters-Palm-Day (LPD), Treatment T2 (150 Liters-Palm-Day (LPD), Treatment T3 (300 Liters-Palm-Day (LPD), Treatment T4 (450 Liters-Palm-Day (LPD), and Treatment T5 (600 Liters-Palm-Day (LPD)). These treatments were applied with different irrigation flow rates. Each treatment had four replicates, and each replicate consisted of sixteen palms. A statistical analysis (ANOVA) was performed between replicates and treatments to determine significant differences between replicates and treatments.

Crop evapotranspiration was obtained using the water balance method. This method consists of evaluating the water flows into and out of the crop within a given period of time. Water inflows are mainly due to irrigation (I) and precipitation (P), while outflows are due to runoff (RO), deep percolation (Dp), and evapotranspiration (ETc) (Ordoñes, 2011).

$$ETc - (P + I) - RO - Dp = \pm \Delta W \quad (2)$$

Using this methodology, the ETc was obtained by measuring the daily moisture content of the soil. This was determined with the use of a FDR Diviner 2000 moisture sensor (Vienna Scientific Instruments GmbH), which provided moisture content values on a volumetric basis down to 100 cm depth. With the ETc values obtained, the crop coefficient (Kc) was calculated by relating it to the reference evapotranspiration (ETo):

$$ET_c = Kc \times ET_0 \quad (3)$$

## Results

### Analysis of climatic variables

#### Precipitation

The climatic variables analyzed included multi-year monthly averages of evapotranspiration and precipitation for the period 1991 to 2021. From these data, multi-year monthly distributions of ETo and precipitation were generated. Figure 1 shows the monthly variation of precipitation in the analyzed period, which exhibits a bimodal trend. The precipitation peaks are observed in May and October with values above 190 mm, while the driest month is January with precipitation below 60 mm, although in June and July the decrease in precipitation is less pronounced than in December and January.

In multiannual terms, precipitation shows significant variation, which is largely influenced by the El Niño and

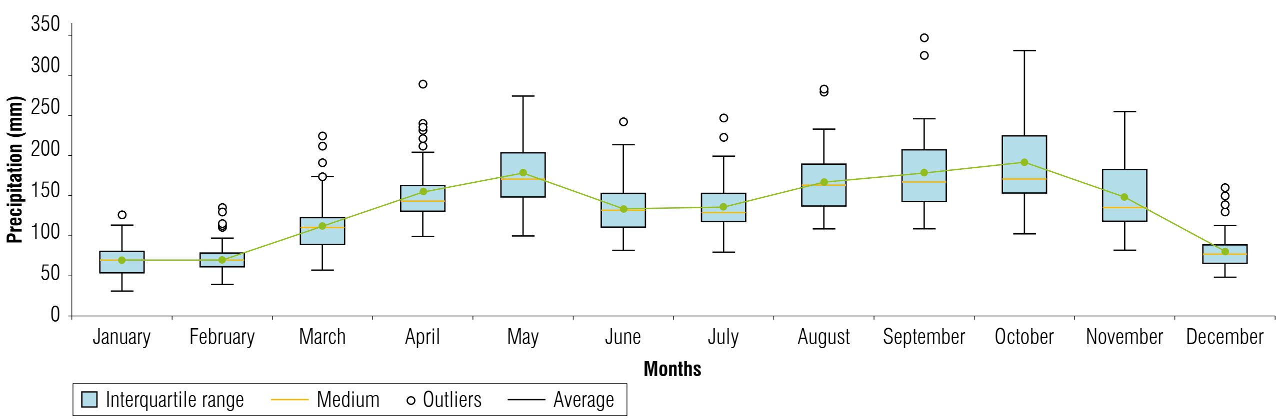


**FIGURE 1.** Boxplot of the monthly behavior of precipitation (P) in the Cesar department.

La Niña (ENSO) phenomena. These natural phenomena, characterized by fluctuations in ocean temperatures in the central and eastern region of the equatorial Pacific, have a substantial impact on climatic conditions in various parts of the planet (WMO, 2023). In the case of the Cesar department, the average annual accumulated precipitation was 1574 mm, with a maximum annual accumulated precipitation of 2440 mm in 2010 and a minimum value of 1154 mm in 2015. Notably, these years coincide with the extreme phenomena of El Niño and La Niña. Figure 1 represents the behavior of precipitation in wet and dry years obtained using the quintile methodology. The years 1995, 1996, 1998, 1999, 1999, 2008, 2010, 2011, and 2017 are considered wet years, with maximum precipitation values above 1730 mm per year and an average precipitation of 1942 mm per year.

### Reference evapotranspiration (ETo)

The average ETo value for the entire department was 5.61 mm $d^{-1}$ for the period analyzed (31 years). The data series has an average annual accumulated value of 2046 mm $year^{-1}$, with a minimum in 2012 of 1822 mm $year^{-1}$ and a maximum reported in 2015 of 2196 mm $year^{-1}$. Regarding the multiannual monthly accumulated ETo, analysis, the series has a monthly average of 170 mm/month, and an inverse bimodal trend to that observed for precipitation is evident throughout the year, with March being the month with the highest evapotranspiration, with a value of 185 mm, and November the month with the lowest ETo, with a value of 156 mm (Fig. 2).

### Spatial distribution of precipitation and ETo in the Cesar department

The spatial analysis for the Cesar department shows a differentiated behavior in the climatic variables analyzed (Fig. 3). The southern part of the department, including the municipalities of San Alberto and San Martín, shows the highest precipitation and the lowest ETo. For the ETo variable, another area with low values is observed in the foothills of the Sierra Nevada de Santa Marta. On the other hand, the center-north of the department, including the Cesar River sedimentation basin, shows the lowest precipitation and the highest ETo.

### Climatic water balance

The climatic water balance was obtained by using the maps of cumulative P and ETo, annual and monthly multiannual for the Cesar department. At the annual level, the values obtained vary in a range from 400 mm to a minimum peak value of -900 mm. Negative values indicate maximum water deficit events, which indicate that the annual precipitation level is not able to compensate for the losses caused by evapotranspiration. Positive values are recorded in the south of the department, mainly in the municipalities of San Alberto and San Martín. With regard to monthly behavior (Fig. 4), generally for the department, it is observed that May, September and October exhibit a positive water balance, which is concentrated mainly in the southern and central areas of the department, with a maximum value of around 25 mm in October; however, in October, some areas in the north of the department reported a negative

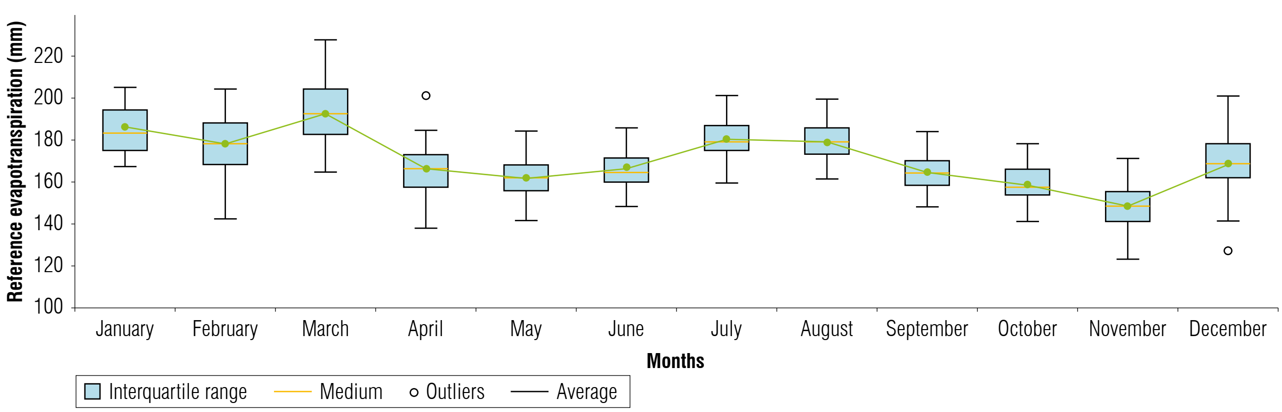


**FIGURE 2.** Boxplot of the monthly behavior of the reference evapotranspiration (Eto) in the Cesar department.

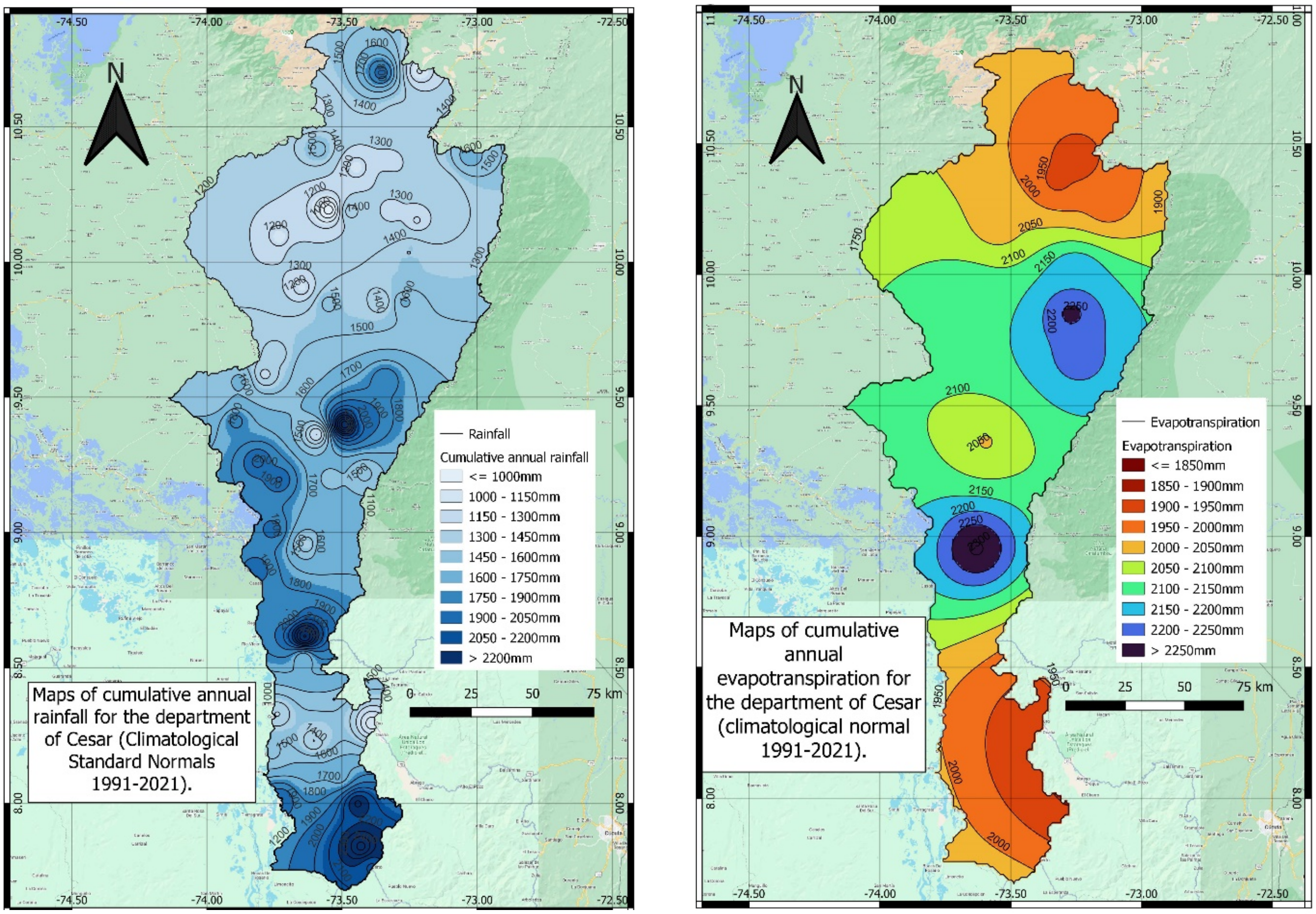


**FIGURE 3.** Maps of cumulative annual rainfall and cumulative annual evapotranspiration for the Cesar department.

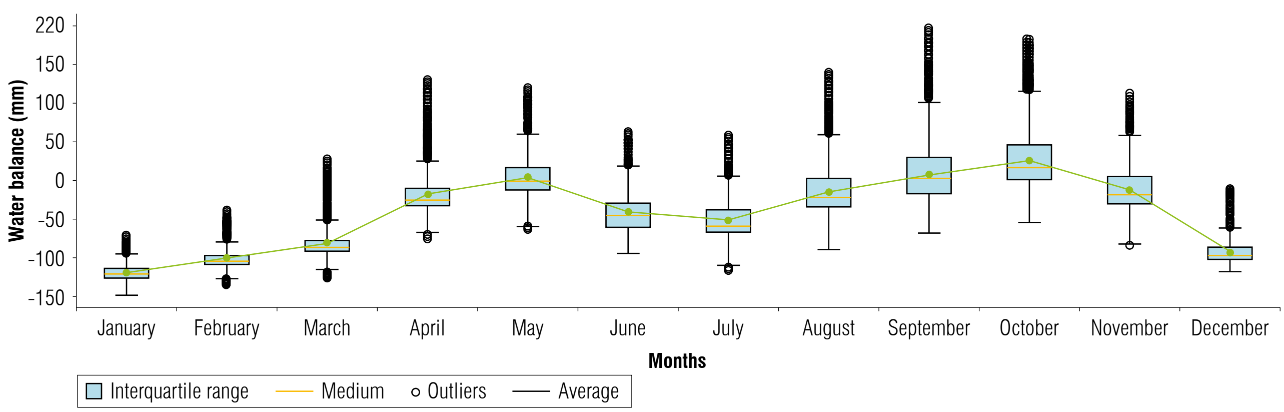


**FIGURE 4.** Average behavior of the monthly climatic water balance in the Cesar department.

water balance. In the rest of the year, mainly in January, February, March, and December, negative water balances were recorded throughout the department. January had the highest accumulated water deficit of -121 mm, which was more critical in the regions located in the basin of river Cesar, particularly in the municipalities of Copey, Bosconia, Valledupar, La Paz, San Diego, and Agustín Codazzi.

## Agroclimatic zoning of the Cesar department

Based on the information of the accumulated annual and accumulated monthly multiannual data of the climatic water balance, soil storage capacity and topography, the four zoning models were carried out. Using expert analysis (Galicia Alarcón *et al.*, 2017), the zoning was determined using the k-means Euclidean distances methodology as the best approximation, thus determining the homogeneous zones in the Cesar department.

As a result of this zoning, 10 different agroclimatic zones were determined (Fig. 5). Zones 1 to 8 correspond to areas with altitudes below 640 m a.s.l., where oil palm cultivation can be developed. Zone 9 corresponds to areas with altitudes between 640 and 1950 m a.s.l., and Zone 10 corresponds to areas with altitudes between 1950 and 4897 m a.s.l. These zones were excluded from the analysis because they are part of the Sierra Nevada de Santa Marta and the Serranía de los Motilones or del Perijá, and are areas that are not suitable for oil palm cultivation due to their climatic and altitudinal conditions.

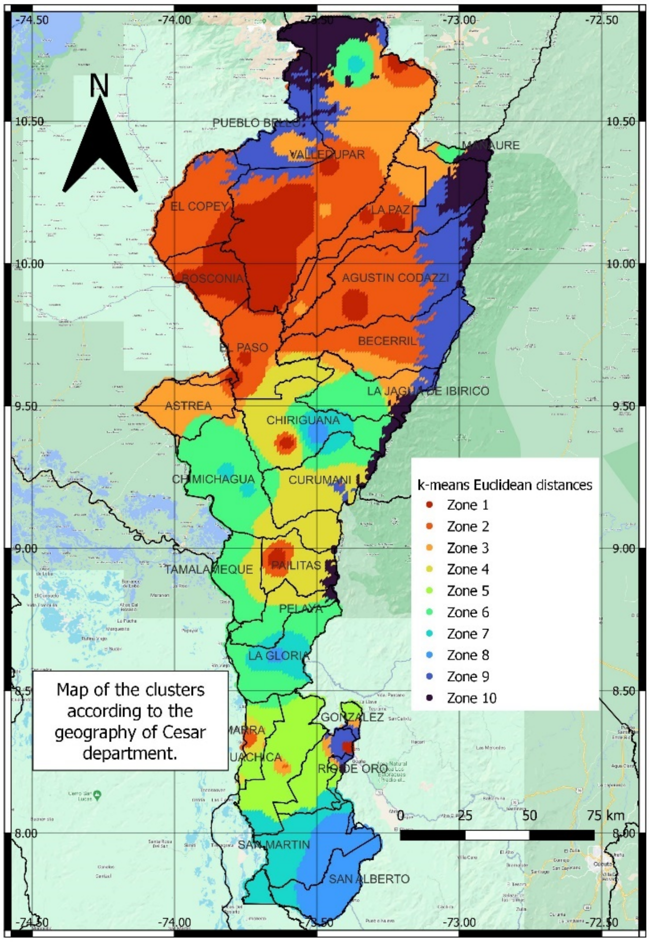


**FIGURE 5.** Spatial representation of the clusters according to the geography of the Cesar department.

In Table 1, the climatic parameters of the different zones are summarized, including the area covered by the crop in each zone. It is worth noting the climatic variability found in the regions where oil palm is grown, with significant differences between the areas sampled. Annual accumulated rainfall shows a difference of 906 mm between the zone with the lowest rainfall (Zone 1) and the zone with the highest (Zone 8). As for evapotranspiration, minor differences of 253 mm were observed between the zone with the highest ETo (Zone 2) and the zone with the lowest ETo (Zone 5), which shows that the extreme values do not necessarily correspond to the zones with the highest or lowest water deficit.

The area under oil palm crop across the different zones reveals that Zone 2 has the largest cultivated area in the department, occupying 23.8% of the planted area. Zone 8 is the smallest identified zone, with 4.88% of the total area of the department and it is the only zone that, in annual terms, does not show a water deficit. On the contrary, Zone 8 has a positive water balance of 235 mm and is also characterized as the second zone with more hectares of oil palm planted, with 17.4% of the oil palm planted in this department.

### Water demand of the oil palm crops

Two ANOVA tests were performed on the results obtained (Tabs. 2 and 3). The first analyzed the similarity of the

**TABLE 1.** Summary of the agroclimatic indicators for the zones suitable for oil palm cultivation in the Cesar department.

| Zone | Water deficit (mm) | P accum (mm) | ETo accum (mm) | ETo (mm) | Mean T (°C) | TMax (°C) | TMin (°C) | Altitude (m a.s.l.) | Area (km$^2$) | Planted area (ha) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | -821.5 | 1271 | 2098.1 | 5.8 | 28.9 | 34.5 | 23.2 | 138.6 | 2096.3 | 4380 |
| 2 | -711.9 | 1394.1 | 2110.6 | 6 | 28.6 | 34.4 | 22.8 | 237.3 | 5439.9 | 27112 |
| 3 | -561.9 | 1472.9 | 2036.4 | 5.5 | 28.1 | 34.1 | 22.7 | 215.9 | 2605.4 | 4362 |
| 4 | -515.2 | 1695.8 | 2144.8 | 6.1 | 27.6 | 32.9 | 22.3 | 185.7 | 2453.6 | 8231 |
| 5 | -404 | 1539.8 | 1957.9 | 5.4 | 24 | 31.9 | 20.6 | 92.5 | 1292.1 | 4458 |
| 6 | -313.5 | 1782.3 | 2107.5 | 5.8 | 27.4 | 33.3 | 22.2 | 159.1 | 3378.5 | 10850 |
| 7 | -78.5 | 1890.5 | 2020 | 5.5 | 25.6 | 30.2 | 19.4 | 106.3 | 1461.4 | 12435 |
| 8 | 235.4 | 2177.8 | 1968.9 | 5.4 | 24.5 | 29.9 | 18.8 | 325.1 | 959.8 | 15089 |

P – Precipitation, ETo – Evapotranspiration, T – temperature, accum – accumulated.

different replicates according to the treatments, with the null hypothesis (Ho) indicating that the replicates of the same treatment are equal. The results of the test did not reject the hypothesis, since it showed a significant level of more than 5% (Tab. 2). This procedure was performed for the soil depth up to 60 cm. The second ANOVA test, with the null hypothesis (Ho) suggesting that the treatments have no significant differences, rejected this hypothesis, showing a significance level of less than 5% (Tab. 3).

According to Table 4, ETc values ranging from 1.5 to 8.58 mm $d^{-1}$ were observed for the 10- and 15-year-old palms. Treatment T1 (50 Liters-Palm-Day (LPD)) had the lowest ETc values, with an average of 3.31 mm $d^{-1}$ during the period analyzed, while treatment T4 (450 LPD) had the highest ETc values, with an average of 4.21 mm $d^{-1}$ during the period sampled. A similar trend was observed in the 15-year-old palms, where treatment T1 (50 LPD) showed the lowest ETc with 3.29 mm $d^{-1}$, while the experimental units of treatment T4 (450 LPD) had average ETc values equal to 4.07 mm $d^{-1}$.

With the ETc obtained (Tab. 4) and the ETo calculated using the Penman-Monteith equation as found in FAO guide No. 56 (Allen *et al.*, 2006), the crop coefficient (Kc) was determined. The results were presented as a monthly average (Tab. 3), with an average Kc value of 0.91 for the 10-year-old palms and 0.84 for the 15-year-old palms, showing variable

**TABLE 2**. Results of variance ANOVA test analyzing the similarity of the different replicates according to treatments.

| | Origin of variations | Sum of squares | Degrees of freedom | Mean squares | F | Significance level | Critical value for F |
|---|---|---|---|---|---|---|---|
| Treatment 1 (50 LPD) | Between replicates | 3.677 | 3 | 1.226 | 2.162 | 0.098 | 2.699 |
| | Within replicates | 54.43 | 96 | 0.567 | | | |
| Treatment 2 (150 LPD) | Between replicates | 2.056 | 3 | 0.685 | 1.809 | 0.151 | 2.699 |
| | Within replicates | 36.36 | 96 | 0.379 | | | |
| Treatment 3 (300 LPD) | Between replicates | 0.223 | 3 | 0.074 | 0.22 | 0.882 | 2.699 |
| | Within replicates | 32.453 | 96 | 0.338 | | | |
| Treatment 4 (450 LPD) | Between replicates | 1.241 | 3 | 0.414 | 1.113 | 0.348 | 2.699 |
| | Within replicates | 35.669 | 96 | 0.372 | | | |
| Treatment 5 (600 LPD) | Between replicates | 0.825 | 3 | 0.275 | 0.637 | 0.593 | 2.699 |
| | Within replicates | 41.469 | 96 | 0.432 | | | |

LPD – Litters-Plant-Day.

**TABLE 3.** Results of variance ANOVA test analyzing the similarity of the different treatments.

| Origin of variations | Sum of squares | Degrees of freedom | Mean squares | F | Significance level | Critical value for F |
|---|---|---|---|---|---|---|
| Between treatments | 397318.020 | 4 | 99329.505 | 251.277 | 4.62E-162 | 2.378 |
| Within treatments | 543139.076 | 1374 | 395.297 | | | |

**TABLE 4.** Monthly crop evapotranspiration of the different treatments in the two experimental units of oil palm measured between September 2022 and September 2023 in the Cesar department (treatment T1 50 LPD, treatment T2 150 LPD, treatment T3 300 LPD, treatment T4 450 LPD, and treatment T5 600 LPD).

| Months | | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Crop evapotranspiration (mm) 10-year-old palms | **T1** | 2.7 | 3.3 | 5.2 | 6.7 | 6.3 | 3.8 | 2.1 | 2.1 | 2.3 | 2.6 | 2.3 | 2.4 | 2.6 | 3.3 |
| | **T2** | 3.6 | 4.5 | 3.6 | 7.3 | 6.1 | 3.0 | 3.3 | 3.0 | 3.5 | 2.4 | 2.9 | 3.2 | 2.9 | 3.7 |
| | **T3** | 3.2 | 4.6 | 7.0 | 6.7 | 3.9 | 5.0 | 3.4 | 3.0 | 2.6 | 2.5 | 2.6 | 2.4 | 2.6 | 3.7 |
| | **T4** | 2.9 | 4.2 | 5.3 | 6.0 | 6.3 | 5.0 | 5.8 | 3.4 | 3.2 | 2.5 | 3.4 | 3.2 | 3.8 | 4.2 |
| | **T5** | 4.6 | 4.4 | 4.9 | 8.6 | 5.4 | 4.4 | 3.8 | 2.9 | 2.9 | 2.5 | 2.1 | 3.2 | 3.0 | 4.1 |
| Crop evapotranspiration (mm) 15-year-old palms | **T1** | 3.5 | 5.6 | 5.1 | 6.2 | 4.4 | 3.4 | 2.7 | 2.5 | 3.3 | 2.2 | 1.9 | 2.1 | 2.1 | 3.3 |
| | **T2** | 3.5 | 4.0 | 3.5 | 7.2 | 5.5 | 3.9 | 2.6 | 2.6 | 2.8 | 2.0 | 1.8 | 2.1 | 1.8 | 3.2 |
| | **T3** | 4.6 | 5.5 | 4.4 | 2.0 | 5.7 | 3.5 | 3.8 | 2.5 | 3.1 | 2.8 | 3.4 | 3.1 | 2.7 | 3.8 |
| | **T4** | 2.8 | 3.1 | 3.3 | 7.8 | 5.8 | 5.8 | 4.3 | 4.5 | 3.4 | 3.2 | 3.6 | 3.4 | 3.8 | 4.1 |
| | **T5** | 3.4 | 1.5 | 7.4 | 5.1 | 4.3 | 3.4 | 2.8 | 4.1 | 3.1 | 2.4 | 4.1 | 3.1 | 2.9 | 3.5 |

behavior throughout the year, characterized by increasing values in the dry months (December, January, February, and March). In these months, a maximum Kc was identified in December for both plantations, with values of 1.52 for 10-year-old palms with daily irrigation and 1.27 for 15-year-old palms. In contrast, in the less dry months, a lower Kc was observed, with average values of 0.75 and 0.71 in 10- and 15-year-old palms, respectively (Tab. 5).

### Water balances according to the agroclimatic zone

Finally, the monthly behavior of the climatic variables was analyzed. This was done by presenting the water balance of the zones monthly, in accordance with the general characteristics of the study and the different parameters obtained. This approach will support more effective planning of the agronomic operations of the crop according to the agroclimatic conditions identified in each zone.

In Figure 6, the monthly behavior of climatic variables in the different zones is presented together with their corresponding water balance. The previously mentioned pattern is confirmed, where Zone 1 exhibits the greatest water deficit, maintaining a negative water balance during all months of the year. In contrast, Zone 8, although it does not present a water deficit in annual terms with respect to the climatological norm, shows a deficit in January and February with an average of 63 mm in these months. The other zones show variable monthly behavior of water deficit influenced by climatic conditions.

## Discussion

The zoning was carried out using a cluster analysis methodology, allowing for an unbiased selection of zones, corresponding to both annual and monthly multiannual climatic behavior. The delimitation of zones depends on the selection of defined parameters and the appropriate weight for each parameter. These methods can be replicated for other regions as well as for different regionalization themes at various scales. The cartographic procedures are quantitative and automated; therefore, the resulting maps have less uncertainty, and the biases of human judgment are reduced (Morales *et al*., 2006). This zoning approach provides valuable knowledge that can be used to create a more specific approach to farming regions, making it possible to objectively identify areas with similar characteristics, without the need for predefined values, as is common in other zoning strategies.

This zoning for the department seeks to contribute to the development of strategies to meet the water demand of the crop according to its location. Among these strategies is the implementation of efficient irrigation systems to optimally meet crop water requirements. Additionally, the implementation of efficient irrigation systems will not only contribute to ensure water supply for crops but also maximize agricultural productivity and minimize the negative impact on local water resources (Sanchez Arzapalo & Acosta Sanchez, 2023).

**TABLE 5.** Average crop coefficient Kc in the different treatments for 10- and 15-year-old palms between September 2022 and September 2023 in Cesar department (treatment T1 50 LPD, treatment T2 150 LPD, treatment T3 300 LPD, treatment T4 450 LPD, and treatment T5 600 LPD).

| Months | | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Crop Kc 10-year-old palm | T1 | 0.63 | 0.7 | 1.07 | 1.43 | 1.25 | 0.93 | 0.71 | 0.53 | 0.54 | 0.68 | 0.5 | 0.53 | 0.6 | 0.78 |
| | T2 | 0.84 | 0.9 | 0.99 | 1.59 | 1.29 | 1.02 | 1.01 | 0.76 | 0.71 | 0.63 | 0.7 | 0.71 | 0.79 | 0.92 |
| | T3 | 0.8 | 0.9 | 1.43 | 1.45 | 1.09 | 0.98 | 1.19 | 0.77 | 0.66 | 0.64 | 0.7 | 0.71 | 0.86 | 0.94 |
| | T4 | 0.81 | 0.9 | 1.09 | 1.29 | 1.32 | 1.21 | 1.18 | 0.86 | 0.75 | 0.65 | 0.8 | 0.71 | 0.84 | 0.96 |
| | T5 | 0.92 | 0.9 | 1.01 | 1.85 | 1.04 | 1.17 | 1.02 | 0.75 | 0.64 | 0.66 | 0.7 | 0.69 | 0.97 | 0.94 |
| Mean | | 0.8 | 0.9 | 1.12 | 1.52 | 1.2 | 1.06 | 1.02 | 0.73 | 0.66 | 0.65 | 0.7 | 0.67 | 0.81 | 0.91 |
| Crop Kc 15-year-old palm | T1 | 0.67 | 1.2 | 1.14 | 1.41 | 0.96 | 0.72 | 0.49 | 0.6 | 0.78 | 0.59 | 0.5 | 0.54 | 0.52 | 0.77 |
| | T2 | 0.67 | 0.8 | 0.98 | 1.58 | 1.21 | 0.97 | 0.65 | 0.65 | 0.65 | 0.53 | 0.4 | 0.52 | 0.45 | 0.78 |
| | T3 | 0.9 | 1.1 | 0.98 | 0.45 | 1.26 | 0.77 | 0.61 | 0.6 | 0.72 | 0.74 | 0.8 | 0.78 | 0.68 | 0.8 |
| | T4 | 0.53 | 0.6 | 0.72 | 1.78 | 1.28 | 1.29 | 0.98 | 1.0 | 0.81 | 0.86 | 0.8 | 0.87 | 0.87 | 0.96 |
| | T5 | 0.65 | 0.3 | 2.04 | 1.14 | 0.95 | 0.8 | 0.71 | 0.93 | 0.74 | 0.63 | 1.0 | 0.77 | 0.73 | 0.87 |
| Mean | | 0.68 | 0.8 | 1.17 | 1.27 | 1.13 | 0.91 | 0.69 | 0.76 | 0.74 | 0.67 | 0.7 | 0.7 | 0.65 | 0.84 |

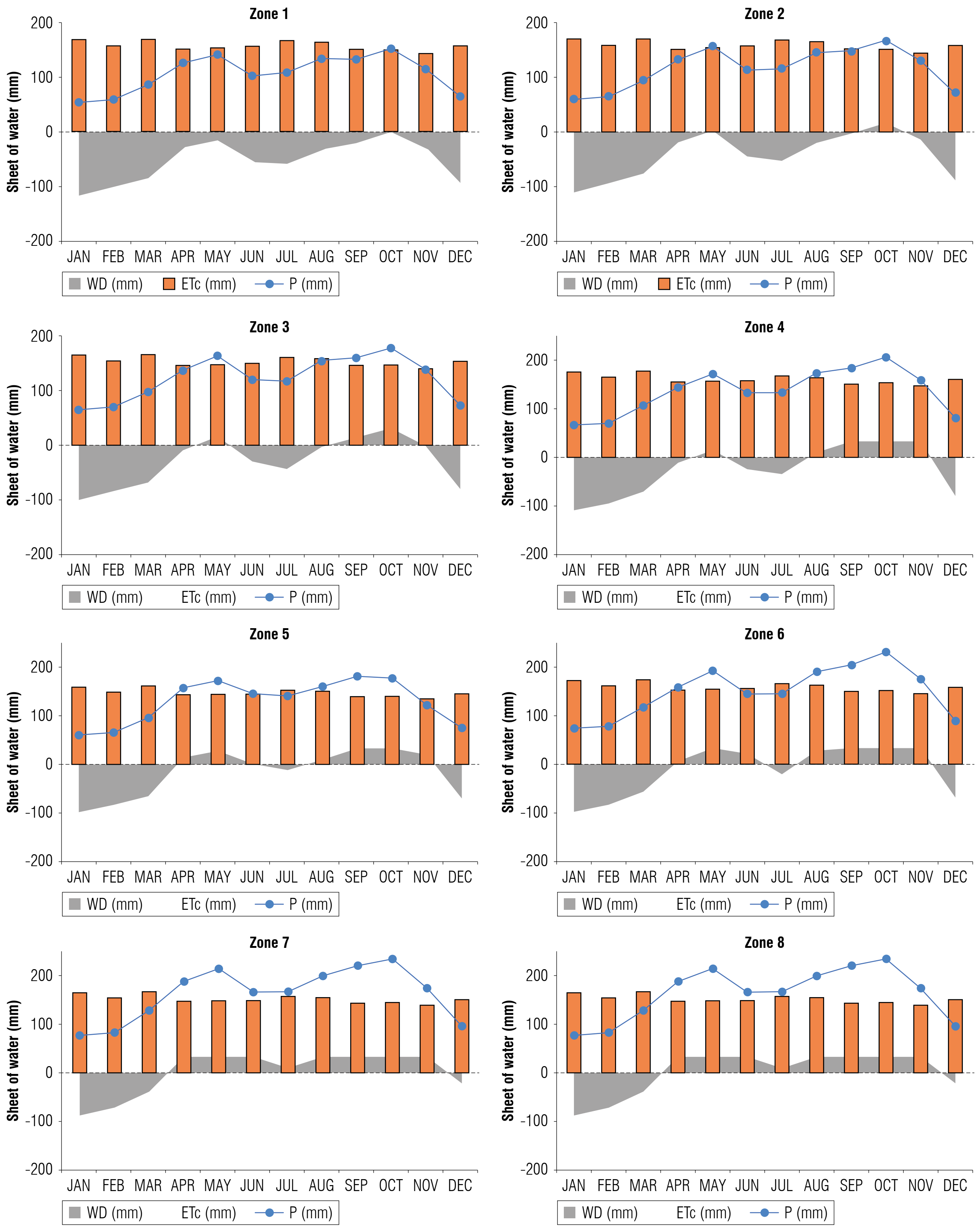


**FIGURE 6.** Behavior of water deficit (WD), evapotranspiration (ETc), and precipitation (P) in the Cesar department.

The determination of the crop coefficient (Kc) through the WD methodology can provide valuable information on water consumption by oil palms in these areas. However, as noted by Allen *et al*. (2011), this methodology has a potential source of error in the determination of ETc. This uncertainty is caused by the deep percolation of the measured area, as well as the rising capillary movements, making these errors difficult to determine. To reduce the error associated with the established methodology, Nachabe (1998) used the theory of drainage and redistribution of water in the soil, stating that the water flow occurs when the soil moisture is above FC, while below FC, this flow could be 0.05 mm $d^{-1}$ or less. This is considered negligible. Therefore, the use of the accumulated film of water up to 60 cm (palm root depth) was proposed to determine water consumption by the plants, with measurements at 60 and 70 cm to determine percolation losses.

The statistical analysis showed that treatment T5 (600 LPD), which was subjected to excess water, did not show a relevant benefit compared to treatment T4 (450 LPD), which was subjected to a lower excess water. This evaluation was based on the response variables, including the number of arrows (the arrows on the oil palm refer to leaves in their early stages, unopened, which are indicators of water deficit or excess in the crop (Fedepalma, 2021)). This lack of benefit is explained by the fact that crop water consumption depends on climatic conditions, plant type, soil conditions, and phenological stage. Crops have a maximum water absorption capacity (Marin *et al*., 2019); if more water is applied than the plant can use, it will simply be wasted by percolation. However, excess water can be detrimental to crops, causing phytosanitary affectations, such as root rot, which could result in decreases in production (Cobo Romero, 2016).

Meanwhile, treatments T1 (50 LPD) and T2 (150 LPD), which experienced water deficiency, had a lower Kc value compared to the other treatments. This can be explained by the defense mechanism of plants in a situation of water deficit, where closure of stomata prevents the escape of water vapor. However, this leads to a lower $CO_2$ input, which reduces the photosynthetic rate (Moreno, 2009). The reduction of the photosynthetic rate alters yield since the plants use energy to obtain water, significantly impacting production.

These findings highlight the importance of not relying on an average Kc for a given plant age, as this approximation may not accurately reflect crop water requirements at different times of the year. The relationship between the reference evapotranspiration (ETo) and crop coefficient (Kc) was evaluated using daily data, showing that at higher ETo values, Kc tends to be lower. This phenomenon has been corroborated by previous studies (Gonçalves *et al*., 2023; Marin *et al*., 2019; Marin *et al*., 2020), who reached similar conclusions. Their research indicates that the use of an average Kc can result in an overestimation or underestimation of irrigation requirements, especially in crops exposed to high evaporation conditions in soils with different drainage levels.

Assuming the average Kc, the evaluation of water consumption in the different zones determined suitable for the crop was carried out. In all these zones, the implementation of irrigation systems is essential to maintain crop productivity. However, irrigation strategies must be adapted to the specific conditions of each zone. In areas with a greater water deficit (Zones 1 and 2), it is necessary to implement highly efficient irrigation systems that minimize the use of water resources. In addition, it is crucial to consider water storage methodologies for use during the months with the greatest deficit (Jasso Ibarra *et al*., 2007). In contrast, in zones with a lower deficit (Zones 7 and 8), although irrigation systems are still necessary, less efficient systems can be used due to favorable climatic conditions; furthermore, the installation of drainage systems has to be considered.

It is important to point out that the analysis carried out in this research contemplated both wet and dry years in the Cesar department, which reinforces the need for irrigation systems in oil palm cultivation.

Agroclimatic zoning, such as the one presented in this study, has a series of highly relevant applications. First, it plays a fundamental role in the formulation of research projects, allowing the definition of homogeneous zones for the precise location of experiments. This facilitates the extrapolation of results to similar areas or regions with similar characteristics, thus promoting technology transfer. In addition, agroclimatic zoning plays a crucial role in the efficient management of water resources by defining zones according to their topographic characteristics, soil and climatic conditions, and by providing a valuable tool for optimizing agricultural production. This implies making informed decisions based on the conditions of each zone. To summarize, agroclimatic zoning is proposed as an essential resource in agricultural planning and management as well as in the research and development of projects aimed at the agricultural sector.

## Conclusions

From this research, it was possible to achieve the zoning of the water demand of the oil palm crop (*Elaeis guineensis* Jacq.) in the Cesar department. This methodology allowed for a spatial-temporal analysis of the results obtained, providing an integral and detailed view of water consumption by differentiating agroclimatically homogeneous areas. The development of this methodology for agroclimatic modeling in the Cesar department is not only applicable at the local level but also lays the groundwork for its replication at the national level in similar agricultural contexts.

The crop coefficients (Kc) obtained for 10- and 15-year-old palms, with average values of 0.91 and 0.84, respectively, highlight the need to adapt water management strategies precisely throughout the crop cycle. The evaluation of Kc in different treatments shows that variations in moisture content generated substantial changes in Kc values. In this regard, decision-making in agricultural water management should incorporate the variability of soil moisture content to ensure accurate and efficient irrigation application, especially in areas with higher water deficits.

This methodological approach lays the groundwork for agroclimatic research and establishes a valuable precedent for future studies in the field. It contributes significantly to the understanding and efficient management of water resources in comparable agricultural environments, providing a robust framework for addressing challenges related to water consumption in oil palm cultivation and, potentially, in other agricultural crops under similar conditions.

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### Conflict of interest statement

The authors declare that there is no conflict of interests regarding the publication of this article.

### Author's contributions

FLT, TED, and CAG designed the experiments, FLT and GSL carried out the field experiments, FLT and CAG contributed to the data analysis, FLT, TED, and CAG wrote the manuscript, NAA, TED, and GSL supervised the experiments. All authors reviewed the final version of the manuscript.

## Literature cited

Allen, R. G., Pereira, L. S., Howell, T. A., & Jensen, M. E. (2011). Evapotranspiration information reporting: I. Factors governing measurement accuracy. *Agricultural Water Management, 98*(6), 899–920. https://doi.org/10.1016/j.agwat.2010.12.015

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (2006). *Evapotranspiración del cultivo. Guías para la determinación de los requerimientos de agua de los cultivos.* Food and Agriculture Organization, Rome. https://www.fao.org/4/x0490s/x0490s00.htm

Allen, R., Smith, M., Perrier, A., & Pereira, L. S. (1994). An update for the definition of reference evapotranspiration. *ICID Bulletin, 43*(2), 1–34.

Alvarez, O. M., Posada, J. F., Mosquera Montoya, M., Garcia, T., & Ardila, G. (2007). Eficiencia en el uso de agua en una plantación de palma de aceite. Importancia económica de su optimización. *Palmas, 28*(2), 11–22. https://publicaciones.fedepalma.org/index.php/palmas/article/view/1208

Arshad, A. M. (2014). Crop evapotranspiration and crop water requirement for oil palm in Peninsular Malaysia. *Journal of Biology, Agriculture and Healthcare*, *4*(16), 23–29. https://api.semanticscholar.org/CorpusID:58896842

Avila, J., & Hauck, T. (2017). *Scikit-learn cookbook* (2nd ed.). Packt Publishing Limited. https://www.packtpub.com/product/scikit-learn-cookbook-second-edition/9781787286382

Cardona Arévalo, A. (2019). *Caracterización de los municipios de Castilla y León atendiendo a factores demográficos* [Undergraduate thesis, Universidad de Valladolid, Valladolid]. https://uvadoc.uva.es/handle/10324/43781

Castañeda Tiria, P. M. (2014). *Zonificación climatológica según el modelo Caldas-Lang de la cuenca rio Negro mediante el uso del sistema de información geográfica SIG.* Superintendencia de Servicios Públicos Domiciliarios, Bogotá, Colombia. https://repository.unimilitar.edu.co/bitstream/10654/11701/2/ARTICULO%20ZONIFICACION%20CLIMATOLOGICA%20SEGUN%20MODELO%20CALDAS%20-%20LANG%20CUENCA%20DE%20RIO%20NEGRO.pdf

Cobo Romero, S. (2016). *Análisis y recopilación del consumo de agua en algunos cultivos de flores de la Sabana de*

*Bogotá* [Undergraduate thesis, Universidad de La Salle, Bogotá]. https://hdl.handle.net/20.500.14625/21032

CORPOCESAR. (2023, December 20). *Generalidades del departamento del Cesar*. Corporación Autónoma Regional del Cesar. https://www.corpocesar.gov.co/generalidades.html

Dufrene, E., Dubos, B., Rey, H., Quencez, P., & Saugier, B. (1992). Changes in evapotranspiration from an oil palm stand (*Elaeis guineensis* Jacq.) exposed to seasonal soil water deficits. *Acta Oecologica, 13*(3), 299–314.

Fedepalma. (2001). *El cultivo de la palma de aceite y su beneficio. Guía para el nuevo palmicultor*. Fedepalma-Cenipalma, Bogotá D.C.

Fedepalma. (2021). *La palma de aceite en el departamento del Cesar (2021).* Fedepalma-Cenipalma. http://repositorio.fedepalma.org/handle/123456789/107681

Galicia Alarcón, L. A., Balderrama Trápaga, J. A., & Navarro, R. E. (2017). Validez de contenido por juicio de expertos: propuesta de una herramienta virtual. *Apertura, 9*(2), 42–53. https://doi.org/10.32870/ap.v9n2.993

Gallardo San Salvador, J. A., & Vera Vera, J. F. (2004). *Técnicas aplicadas de análisis de datos multivariante*. Universidad de Granada. https://produccioncientifica.ugr.es/documentos/618f507a9ff8c939aaca8980

Gobernación del Cesar. (2020). *Plan de desarrollo departamental 2020-2023*. Gobernación del Cesar. https://cesar.gov.co/d/index.php/es/menvertpolpla/menvertplandes/232-artmenplandes

Gonçalves, I. Z., Mendonça, F. C., Sanches, A. C., & Marin, F. R. (2023). Optimizing evapotranspiration and crop irrigation requirements of tropical forages cropping systems in Southern Brazil. *International Journal of Biometeorology, 68*(1), 57–67. https://doi.org/10.1007/s00484-023-02570-9

Gudelj, O., Arce, J., & Gudelj, V. (2018). *Metodología de muestreo y determinación de agua del suelo. Información para extensión en línea Nº 29*. Instituto Nacional de Tecnología Agropecuaria INTA Ediciones, Argentina. https://aws.agroconsultasonline.com.ar/documento.html?op=d&documento_id=1193

Helsel, D., Hirsch, R., Ryberg, K., Archfield, S., & Gilroy, E. (2020). *Statistical methods in water resources*. U.S. Geological Survey Techniques and Methods. https://doi.org/10.3133/tm4A3

IDEAM. (2022, November 11). *Atlas climatológico de Colombia*. Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM). http://www.ideam.gov.co/web/tiempo-y-clima/atlas#_48_INSTANCE_xoDpvO7rhD5O_%25253Dhttp%2525253A%2525252F%2525252Fwww.ideam.gov.co%2525252FAtlasWeb%2525252Findex.html%2525253F%253D%2526_48_INSTANCE_xoDpvO7rhD5O_%253Dhttp%25253A%25252F%25252Fwww.ideam.gov.co%25252FAtlasWeb%25252Finfo%25252Flluviamen.html%3D%26_48_INSTANCE_xoDpvO7rhD5O_%3Dhttp%253A%252F%252Fwww.ideam.gov.co%252FAtlasWeb%252Finfo%252FTextos%252Fpmes-text.pdf

IGAC. (2014). *Zonificacion climática para levantamiento de suelos*. Instituto Geografico Agustin Codazzi, Grupo Interno de Trabajo de Levantamientos Agrológicos. https://doi.org/10.13140/RG.2.2.32219.49448

IGAC. (2017). *Departamento del Cesar: escala 1:100.000: estudio general de suelos y zonificación de tierras*. Instituto Geográfico Agustín Codazzi. https://isbn.cloud/9789588323909/estudio-general-de-suelos-y-zonificacion-de-tierras-departamento-del-cesar/

Jasso Ibarra, R., Faz Contreras, R., Berzoza Martínez, M., Chávez Sánchez, N., Núñez Hernández, G., & Orozco Hernández, G. (2007). *Requerimientos hídricos y manejo del agua de riego en cultivos forrajeros*. Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, México.

Jolly, K. (2018). *Machine learning with scikit-learn quick start guide: Classification, regression, and clustering techniques in Python* (1st ed.). Packt Publishing.

Kong, Q., Siauw, T., & Bayen, A. (2021). *Python programming and numerical methods. A Guide for engineers and scientists* (1st ed.). Academic Press.

Lascano, R. J., & Munévar, F. (2000). Criterios técnicos para la selección de sistemas de riego: Aplicación al cultivo de palma de aceite en Colombia. *Palmas, 21*(special issue), 270–279. https://publicaciones.fedepalma.org/index.php/palmas/article/view/840

Marin, F. R., Angelocci, L. R., Nassif, D. S., Vianna, M. S., Pilau, F. G., Silva, E. H. F. M., Sobenko, L. R., Gonçalves, A. O., Pereira, R. A. A., & Carvalho, K. S. (2019). Revisiting the crop coefficient-reference evapotranspiration procedure for improving irrigation management. *Theoretical and Applied Climatology, 138*, 1785-1793. https://doi.org/10.1007/s00704-019-02940-7

Marin, F. R., Inman-Bamber, F., Silva, T. G. F., Vianna, M. S., Nassif, D. S. P., & Carvalho, K. S. (2020). Sugarcane evapotranspiration and irrigation requirements in tropical climates. *Theoretical and Applied Climatology, 140*, 1349–1357. https://doi.org/10.1007/s00704-020-03161-z

Molina Moral, J. C., Moriana Elvira, A., & Pérez Latorre, F. J. (2022). Estimation of the water reserve in the soil using GIS and its application in irrigated olive groves in Jaen, (Spain). *Agronomy, 12*(9), 1–24. https://doi.org/10.3390/agronomy12092188

Morales, L., Canessa, F., Mattar, C., Orrego, R., & Matus, F. (2006). Caracterización y zonificación edáfica y climática de la región de Coquimbo, Chile. *Revista Chlena del Suelo y Nutrición Vegetal, 6*(3), 52–74. https://www.scielo.cl/scielo.php?script=sci_arttext&pid=S0718-27912006000300005

Moreno, L. P. (2009). Respuesta de las plantas al estrés por déficit hídrico. Una revisión. *Agronomia Colombiana*, *27*(2), 179–191. https://revistas.unal.edu.co/index.php/agrocol/article/view/11131

Murcia, J. D. (2023, June). *La palma de aceite, un sector agroindustrial que aporta 17% al PIB agrícola nacional*. Agronegocios. https://www.agronegocios.co/agricultura/la-palma-de-aceite-un-sector-agroindustrial-que-aporta-17-al-pib-agricola-nacional-3632020#

Nachabe, M. H. (1998). Refining the definition of field capacity in the literature. *Journal of Irrigation and Drainage Engineering, 124*(4), 230–232. https://doi.org/10.1061/(ASCE)0733-9437(1998)124:4(230)

NOAA. (2023, December 17). *Cold & warm episodes by season*. National Weather Service, Climate Prediction Center. https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php

Ongley, E. (1997). *Lucha contra la contaminación agrícola de los recursos hídricos (Estudio FAO Riego y Drenaje – 55)*. Food and Agriculture Organization.

Ordoñes, G. J. (2011). *Balance hídrico superficial. Contribuyendo al desarrollo de una cultura del agua y la gestión integral de recurso hídrico.* Cartilla Técnica. Sociedad Geográfica de Lima. Foro Peruano para el Agua, Lima.

Ortega Ortega, O. A. (2019). *Estudio de los requerimientos hídricos del cultivo de tabaco burley en el municipio de Ovejas (Sucre)* [Master thesis, Universidad Nacional de Colombia, Manizales]. https://repositorio.unal.edu.co/handle/unal/77370

Plazas Niño, F. A. (2021). *Introducción al análisis clúster: una aplicación en la clasificación de campos petroleros*. https://www.researchgate.net/publication/350936275_INTRODUCCION_AL_ANALISIS_CLUSTER_UNA_APLICACION_EN_LA_CLASIFICACION_DE_CAMPOS_PETROLEROS

Sanchez Arzapalo, L. E., & Acosta Sanchez, A. P. M. (2023). Optimización del consumo de agua agrícola en Lima: buenas prácticas y métodos de riego eficientes. *Revista de Investigación en Ciencias Agronómicas y Veterinarias, 7*(20), 464–473. https://doi.org/10.33996/revistaalfa.v7i20.229

Terán, C., Jiménez, C., González, C., & Villaneda, E. (1998). Metodología objetiva para la zonificación agroclimática de la región de La Mojana mediante el sistema de información geográfica ARC/INFO. *Revista Corpoica, 2*(2), 19–26. http://hdl.handle.net/20.500.12324/16559

Torres Bernal, F. L. (2024). *Zonificación de la demanda hídrica del cultivo de la palma de aceite (Elaeis guineensis Jacq.) bajo las condiciones agroclimáticas del departamento del Cesar* [Master thesis, Universidad Nacional de Colombia, Bogotá]. https://repositorio.unal.edu.co/handle/unal/86091

Villatoro, M., Henríquez, C., & Sancho, F. (2008). Comparación de los interpoladores IDW y Kriging en la variación espacial de pH, Ca, CICE y P del suelo. *Agronomía Costarricense*, *32*(1), 95–105. https://doi.org/10.15517/rac.v32i1.6773

WMO. (2017). *Guía del sistema mundial de observación*. World Meteorological Organization.

WMO. (2018). *Guía de prácticas climatológicas.* World Meteorological Organization.

WMO. (2023, October 15). *El Niño/La Niña updates*. World Meteorological Organization. https://wmo.int/resources/documents/el-ninola-nina-updates

Woittiez, L. S., van Wijk, M. T., Slingerland, M., van Noordwijk, M., & Giller, K. E. (2017). Yield gaps in oil palm: A quantitative review of contributing factors. *European Journal of Agronomy, 83*, 57–77. https://doi.org/10.1016/j.eja.2016.11.002

Zhou, D., Khan, S., Abbas, A., Rana, T., Zhang, H., & Chen, Y. (2009). Climatic regionalization mapping of the Murrumbidgee irrigation area, Australia. *Progress in Natural Science, 19*(12), 1773–1779. https://doi.org/10.1016/j.pnsc.2009.07.007