

Spatio-Temporal Analysis of the Influence of Precipitation and Temperature on the Productivity (or Yields) of Irrigated Sugarcane at the Zuenoula IAU (Ivory Coast)

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Abstract The objective of this study is to analyze the impact of precipitation and temperature on the productivity and yield of irrigated sugarcane in the Integrated Agricultural Unit (IAU) of Zuenoula over the period 1983-2023. The approach was based on the use of agricultural statistical data on yields, on the one hand, and the average annual rainfall and temperatures from the IAU weather station during this period, on the other. The results obtained from this study, represented by maps of spatio-temporal variations of production and yields for the years 2013, 2018 and 2023, showed a decrease in production and yields over the years. The graphs of rainfall indices, standardized temperature anomaly and yields also showed the influence of climate, especially rainfall, on yields.

Keywords: Spatio-temporal variation- Yield- Sugar cane- Rainfall index- Standardized temperature anomaly (SA), Ivory Coast

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1. Introduction

Sugar, present in many foods and beverages, is an essential source of energy in the human diet [1]. Its consumption is increasing worldwide, supported by population growth [1]. The relative share of sugar production from sugarcane compared to other sacchariferous plants is steadily increasing, rising from 2/3 to 3/4 between 2000 and 2010 [2]. As a result, [3] estimates that global sugarcane production will exceed 1.96 billion metric tons in 2021. However, maintaining sufficient production volumes remains a major concern for the sustainability of the sugar industry [4]. In addition, sugarcane productivity on irrigated plots has shown inter-annual variability in recent years. This could be due to climatic parameters such as rainfall and temperature.

Ivory Coast has two agro-industrial sugar companies for its sugar self-sufficiency, all inherited from the former state company Sodesucre (State company for the development of sugarcane plantations in Ivory Coast) :

Two sugar complexes in the north : Ferké 1 and 2, owned by the Sucaf-ci group (Sugar factories of Africa Ivory Coast), which is a subsidiary of the French Castel

group, associated with the Somdiaa consortium (Society for the organization, management and development of the food and agricultural industries).

To the west is the Borotou-Koro sugar complex, and in the center-west of the country is the IAU of Zuenoula, the area under study.

Ivory Coast, an essential link in the West African sugar production chain, is not immune to the climatic problems affecting sugar production. Sugar cane production and yields on irrigated plots are subject to inter-annual and intra-plot variations over the years. Therefore, in this study, it is necessary to analyze the evolution of sugarcane productivity in irrigated plots and to try to understand the impact of climatic factors (rainfall and temperature) on said productivity.

The following questions arise

- How can geographic information systems (GIS) contribute to the analysis of sugarcane production and yield trends in irrigated plots in the Zuénoula IAU ?

- What is the effect of rainfall and temperature on sugarcane productivity in irrigated plots within the Zuenoula IAU ?

This study aims to provide answers to these questions by collecting and processing data using a carefully designed methodology.

2. Presentation of the Study Area

Situated between longitude -6.14°69" and -6.17°48"W and latitude 7.54°56" and 7.66°02"N (Figure 1), the Zuenoula Integrated Agricultural Unit (IAU) is located in the Marahoué region of central-western Ivory Coast. It straddles the departments of Zuenoula to the south and Vavoua to the west, and is bordered to the north by the department of Kongasso and to the east by the right bank of the Marahoué River (Red Bandama). Located 25 km from the city of Zuenoula and 417 km from Abidjan, IAU currently covers an area of nearly 12,900 ha and is part of the sugar complexes of the Sucrivoire subsidiary of the Sifca consortium.

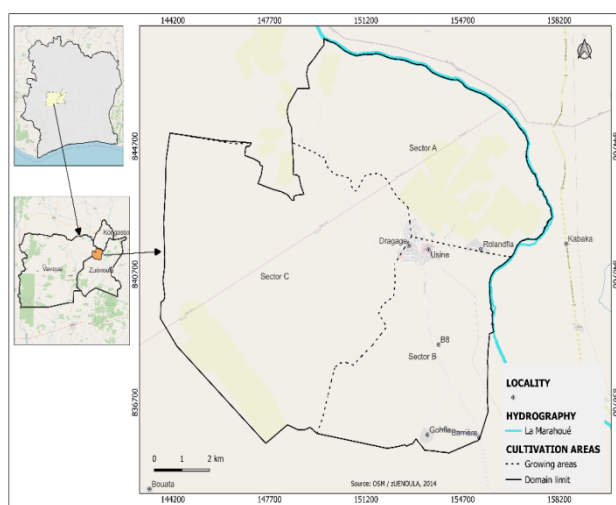


Figure 1. Location of the Zuenoula Integrated Agricultural Unit (IAU)

3. Methodology and Data Used

3.1. Data used

The data used in this study are monthly rainfall and temperature data from 1983 to 2023 from the IAU Zuenoula synoptic station. Agricultural statistics data on sugarcane yields for irrigated plots cultivated from 1983 to 2023 from the IAU were also used. In addition, agricultural statistics data on sugarcane production and yields for the years 2013, 2018, and 2023 were used in this study.

3.2. Methodology

Data processing for the analysis of the dynamics of production, yield and area in the study area was carried out in two phases:

Data processing to analyze the spatio-temporal variation of sugarcane production and yields on irrigated plots in 2013, 2018 and 2023, followed by a graphical analysis of the evolution of production, yields and sugarcane on irrigated plots in 2013, 2018 and 2023;

Data processing to analyze the impact of annual rainfall and temperature on yields of irrigated plots from 1983 to 2023.

3.2.1. Procedure for Producing Maps of Spatio-temporal Variation in Sugarcane Production and Yields

Spatio-temporal variation was mapped using sugarcane agricultural statistics data: plot vector file, annual production in tons, annual yields in t/ha, the outline of the 2013, 2018 and 2023 production and yield study area. Data analysis can lead to the production of synthetic maps at different scales [5]. The agricultural data on annual production and yields are those for irrigated plots cultivated in each year of the study. Therefore, the objective is to produce maps of sugarcane production and yields for the years 2013, 2018, and 2023.

The mapping of production and yields involved exporting vector files into the ArcGIS 10.5 software interface and reprojecting the localities, study area and Marahoué River layers to UTM WGS84 zone 29 N. This was followed by importing and joining attribute tables from Excel files of production and yield values to those in the parcel files in ArcGIS 10.5. In addition, queries using the category tool in ArcGIS were used to define classes of annual production and yield values. These classes are then exported in different colors in the software interface and overlaid on the various parcel vector files. Finally, the results of these analyses are displayed to facilitate the creation of the different maps of annual sugarcane production and yield for irrigated plots in 2013, 2018, and 2023.

3.2.2. Approach to Sugarcane Production and Yield Graphs

The Excel spreadsheet was used to store the production and yield data for 2013, 2018 and 2023 for the irrigated plots, so that graphs could be generated to highlight the different changes during these years.

3.3. Method of Processing Climatic Data (Rainfall and Temperature)

3.3.1. Method of Processing the Climatic Precipitation Data: Nicholson Index

The methodology used to process the precipitation data consisted in calculating the rainfall in mm for the year X_i , the mean rainfall for the study period X and the standard deviation of the rainfall over the study period σ from 1983 to 2023, using the Nicholson method. The annual precipitation index used here is defined as a reduced centered variable [6]: $Ip = (X_i - X) / \sigma$, where rainfall in year i ; mean interannual rainfall over the reference period; σ standard deviation of interannual rainfall over the reference period.

The precipitation index thus reflects a precipitation surplus or deficit for the year in question compared to the reference period [7].

The aim is to highlight fluctuations in rainfall patterns and seasonal variations over the entire study period (1983 to 2023) for the Zuenoula IAU. The calculation of the rainfall index allowed the analysis of the relationship between seasonal variations in rainfall and sugarcane yields on irrigated plots over the same study period.

3.3.2. Climate Data Processing Method for Temperature Anomaly and Standard Anomaly (SA)

The temperature anomaly is the difference between the temperature measured at a given point in degrees Celsius (°C), whether positive or negative, and the normal average temperature (over a reference period of at least 30 years).

However, anomalies alone are not sufficient to prove that temperature values are exceptional. In this case, the Standardized Anomaly (SA) calculation must be used. In [8], the Standardized Anomaly (SA) is a relevant indicator of interannual variability that allows to express the temperature anomaly and to identify its exceptional nature : the SA is calculated by dividing the anomaly by the standard deviation of the normal. Rising temperatures have a direct effect on crop yields and an indirect effect on the availability of irrigation water [9].

The aim of this study is therefore to highlight the temperature variations (hot, cold, etc.) in the Zuenoula IAU from 1983 to 2023 and to compare them with the different annual yields during the same period.

4. Results

4.1. Spatio-temporal Dynamics of Irrigated Plot Production in 2013, 2018 and 2023

Intra-plot and inter-annual variation of irrigated plot production for the years 2013, 2018 and 2023 is observed in the study area (Figure 2). Spatially and temporally, sugarcane production is highest in 2013 and lowest in 2023 throughout the study period. There is a clear decline in production in the years 2013, 2018 and 2023.

Furthermore, at the sector level, in 2013 the highest and the highest sugarcane yields from plots are recorded in sector A. On the other hand, sector C recorded very low yields in 2013.

In 2018, sector C recorded very high and high sugarcane production. As a result, the total production is high. However, in the same period, sector A recorded very low and low production compared to 2013.

In 2023, the different plot sectors of the estate generally recorded very low and low yields. Very high and high yields are therefore less representative of all sectors of the Zuenoula IAU estate.

4.1.1. Graphical Analysis of Production from Irrigated Plots in 2013, 2018 and 2023

The analysis of the cumulative production from irrigated plots over the study period under consideration shows a decreasing production over the years (Figure 3). The trend shows a significant drop between 2013 and 2018, with a production gap of 202438.82 tons.

A very slight decrease was observed between 2018 and 2023. The production gap is 4161.44 tons. The coefficient of determination $R^2 = 0.76$ shows the relationship between the production and the different years.

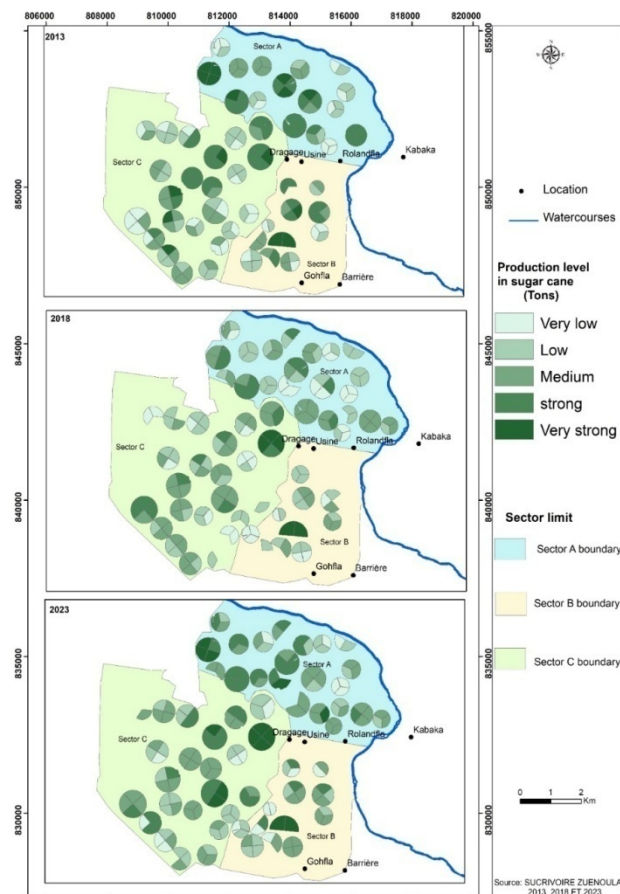


Figure 2. Spatial distribution of irrigated land production in the Zuenoula IAU in 2013, 2018 and 2023

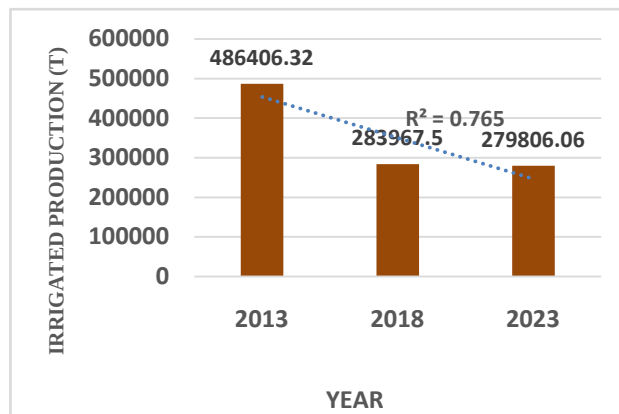


Figure 3. Histogram of irrigated plot production in 2013, 2018 and 2023

4.2. Spatio-temporal Evolution of Sugarcane Yields on Irrigated Plots in the Zuenoula IAU in 2013, 2018 and 2023

The analysis of the spatio-temporal distribution of sugarcane yields on irrigated plots in the IAU shows variation both in terms of years and study plots (Figure 4). Yields decrease from year to year from 2013 to 2018 and 2023. In fact, 2013 is characterized by relatively significant yields ranging from very high to high

compared to 2018 and 2023. From a spatio-temporal point of view, the year 2023 has very low and low yields over the study period. With respect to the IAU study sectors, sectors A, B and C in 2013 have relatively very high and high returns compared to sectors A, B and C in 2018 and 2023. Thus, in 2013, the return on sectors A, B and C is generally strong. In 2023, returns on sectors A, B and C within the IAU have declined and are generally dominated by very low and low returns.

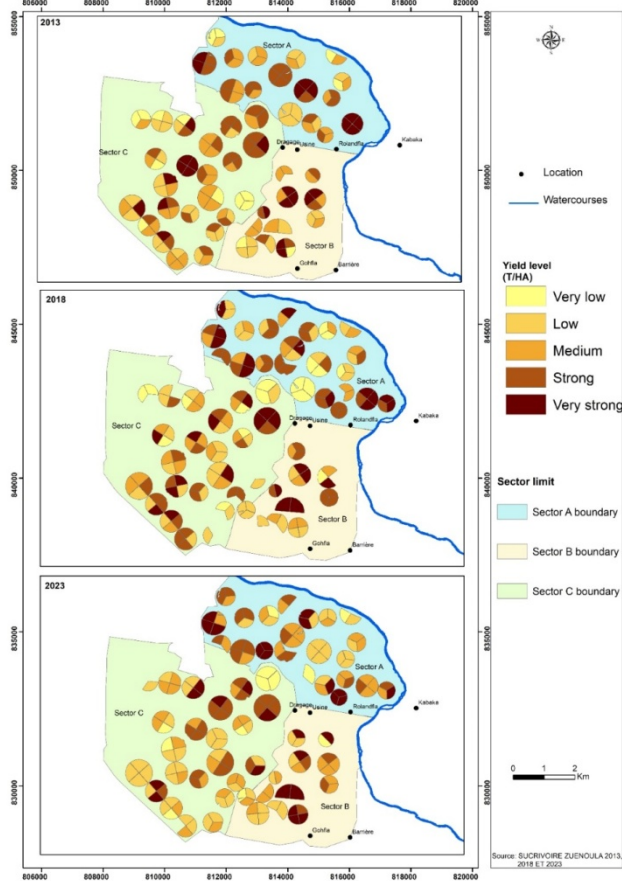


Figure 4. Spatial variation of irrigated yields of sugarcane plots in the Zuenoula IAU in 2013, 2018 and 2023

4.2.1. Graphical Analysis of Sugarcane Yields and Area on Irrigated Plots in the Zuenoula IAU from 2013, 2018 and 2023

Like production, sugarcane yields on the IAU estate are decreasing from 2013 to 2018 and 2023 (Figure 5). The differences between 2013 and 2018 are very significant at around 60.63 t/ha. Between 2018 and 2023, the difference is about 40.73 t/ha.

Thus, between 2013 and 2023, the yield has decreased by 101.36 t/ha. This is very significant.

However, it should be noted that while the yield is decreasing, the area under cultivation is increasing throughout the study period. It even increases slightly between 2013 and 2018 and significantly between 2018 and 2023, with a difference of 3785.69 tons. This value indicates that the cultivated area of irrigated plots has doubled between 2018 and 2023. The coefficient of determination is $R^2 = 0.98$. There is a strong correlation between the yields and the different study dates.

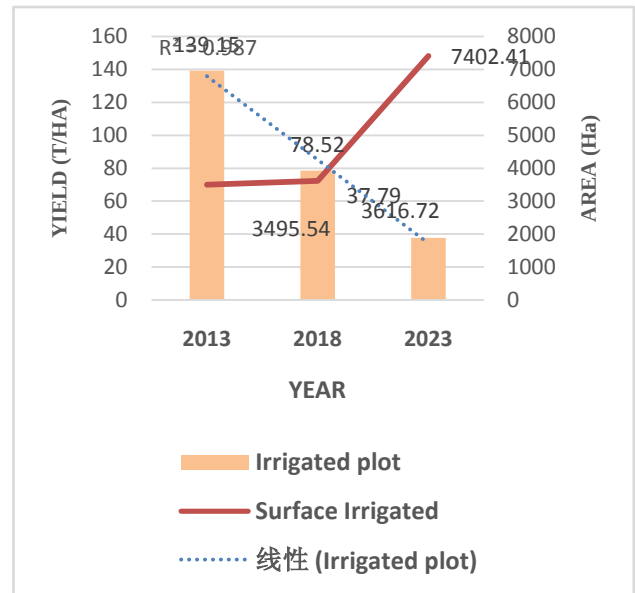


Figure 5. Histogram of yields and area curves for irrigated plots in 2013, 2018 and 2023

4.3. Climatic Factors and Sugarcane Productivity in Zuenoula IAU

4.3.1. Precipitation Index (PI) and Irrigated Sugarcane Yield In the Zuenoula IAU from 1983 to 2023

The analysis of the histograms of PI and yield shows the inter-annual variation of both variables over the study period (Figure 6). The evolution of irrigated yields as a function of the UAI rainfall index (PI) histogram shows the impact of rainfall on yields. Yield trends are generally a function of rainfall in the Zuenoula IAU estate.

Indeed, during the study period, the lowest annual yield of 32.96 t/ha was recorded in 1983, when the average annual rainfall index was also negative. Also, 2012, which recorded the highest average yield of 93.19 t/ha over the entire study period, was a year with a positive rainfall index. In addition, the precipitation index shows three periods:

- A dry period from 1983 to 1993: during this period, yields are generally low, varying between 30 and 65 t/ha. Therefore, there is an influence of the lack of rainfall on the sugarcane yields in the IAU. Also in this period, the maximum yield of 65.40 t/ha is observed in 1991 with a positive rainfall index. The minimum yield of 32.96 t/ha was recorded in 1983 when the rainfall index was negative.

A wet period from 1994 to 2014 is generally characterized by an increase in annual yields as a function of the increase in average rainfall over the period. The minimum yield recorded during this period is around 56.24 t/ha, obtained in 1997. The maximum yield of 93.19 t/ha was obtained in 2012.

The dry period from 2015 to 2023 is characterized by a maximum yield of 88.25 t/ha in 2014. Also in this period, the minimum yield observed is 68.85 t/ha in 2023.

Clearly, the different periods identified using the Nicholson rainfall index have made it possible to highlight the impact of rainfall on sugarcane yields within the IAU from 1983 to 2023.

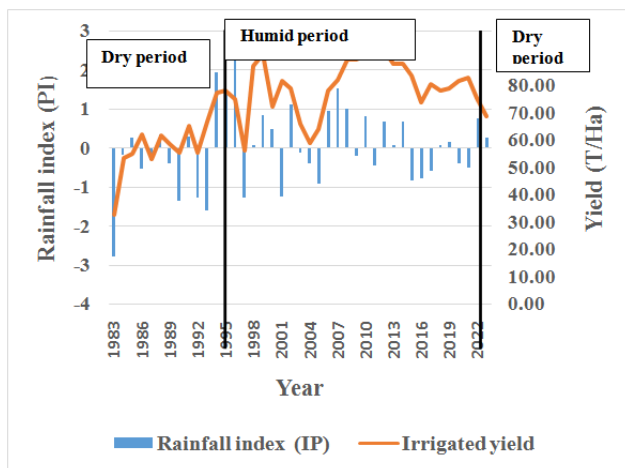


Figure 6. Relationship between Rainfall Index (PI) and irrigated sugarcane yields at the Zuenoula IAU from 1983 to 2023

4.3.2. Relationship Between Standardized Temperature Anomaly (SA) and Zuenoula IAU Yields from 1983 to 2023

Analysis of irrigated plot yields and the standardized temperature anomaly (SA) indicates inter-annual variation in both variables (Figure 7). Two periods were determined over the period 1983 to 2023, namely:

- a cold period from 1983 to 2014, marked by a minimum standardized temperature anomaly of -2.16 in 1986 and a maximum of 1.5 in 1998. With regard to yields over the entire cold period, the minimum yield is 32.96 t/ha in 1983 with an AS of -0.34, and the maximum yield is 93.19 t/ha in 2012 with an AS of -0.80. On the cold period, the remark is that temperature has not had a remarkable effect on sugarcane yields in the IAU.

- A warm period from 2015 to 2023, characterized by a standardized minimum temperature anomaly of 0.36 in 2023 and a maximum of 2.41 in 2019. As for the yields, during this period we record a minimum of 68.85 t/ha with an SA of 0.36. The maximum yield for the period is 83.19 in 2021 with a SA of 2.02.

Considering these values and the relationship between the Standardized Temperature Anomaly and the yields, we can observe an influence of temperature on sugarcane yields in the period 2015 to 2023.

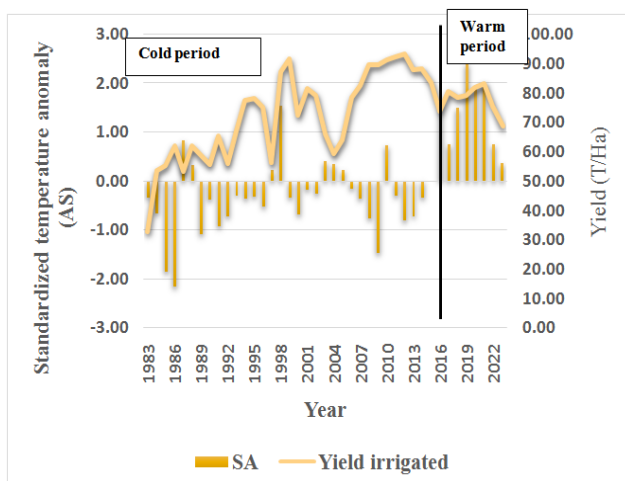


Figure 7. Relationship between Standardized Temperature Anomaly (SA) and yields at the Zuenoula IAU from 1983 to 2023

5. Discussion

The mapping of spatiotemporal dynamics for the years 2013, 2018, and 2023 justified the use of productions, yields, zone boundaries, locations, and vector files of cultivated plots from the UAI, which allowed the mapping of the different productivities of plots over the study period considered. The resulting plot mapping allowed us to highlight intra-plot and inter-annual changes in production and yields over the study period. In fact, GIS analysis of productivity trends from a spatio-temporal perspective reveals a strong capacity for rapid analysis, detection and understanding of intra-plot and inter-annual variability in productivity in the study area. In [10], the increasing ease of spatial representation offered by the rapid development of GIS and the visual impact of maps have brought this medium to the forefront of technical argumentation and policy-making. GIS also allows for highly effective synoptic analysis between plots and across study years. GIS as a tool GIS makes it possible to process agronomic data and thus better monitor the effects of production factors [11]. However, the lack of data from certain plots over the years makes it difficult to analyze the mapping of spatio-temporal variations in production and yield.

Regarding rainfall, the Nicholson index method was used to determine rainfall indices from 1983 to 2023, with rainfall decreasing over the years and having an impact on sugarcane cultivation on the estate. The relationship between the periods derived from the rainfall indices and the average sugarcane yields of the irrigated plots shows broadly similar trends between the two variables, and thus the influence of rainfall on the yields of the irrigated plots. This is justified by the fact that rainfall is essential for the growth and ripening of sugarcane. In fact, the short duration of the rainy season disrupts the vegetative cycle of sugarcane [12]. The effects of rainfall deficits are reflected in lower yields [13].

Furthermore, the analysis of the temperature anomaly within the Zuenoula IAU reveals a long cold spell in the study area. This is unfavorable for sugarcane growth and ripening in the world in general and in Ivory Coast in particular. However, a warm period has been observed in the last five years, which is favorable for sugarcane growth in the study area. In [14], studies conducted by the Direction Météorologique Nationale (DMN) of Ivory Coast show that over the past five decades, Ivory Coast has warmed by an average of 0.5°C since 1980.

The relationship between annual yields and periods of Standardized Temperature Anomaly (SA) shows that hot periods record perfectly high yields compared to cold periods, and vice versa. This shows that temperature has had a greater or lesser influence on sugarcane yields in our area during the study period. Sufficient or good temperature conditions the increase of sugarcane yield. According to the Senegalese Agricultural Research Institute [15], the temperatures required for good sugarcane growth and ripening are: an optimum daytime temperature for germination, estimated to be between 26°C and 33°C; for growth, between 28°C and 35°C; and a minimum temperature between 15°C and 18°C.

Thus, sugarcane production in the Zuenoula IAU is subject to inter-annual and inter-plot variability caused in

part by climatic factors, in this case rainfall and temperature.

6. Conclusion

The study of the spatio-temporal dynamics of production, yields of irrigated plots and the influence of rainfall and temperature within the Integrated Agricultural Unit of Zuenoula (IAU) revealed the interannual and intra-plot variability of production and yields in 2013, 2018 and 2023. It also determined the influence of rainfall and temperature on average yields in irrigated plots over the period from 1983 to 2023. Rainfall indices and standardized temperature anomalies in their respective order showed their impact on yields. The different periods of rainfall regimes (wet and dry periods), derived from rainfall indices using Nicholson's method, as well as cold and hot periods analyzed from temperature anomalies over the given study period, influenced the average annual yields of irrigated plots, especially that of sugarcane, which is highly dependent on rainfall.

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