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Integrated Assessment of Rainfall Variability, Water Requirements, and Sugarcane Yields in Rainfed and Irrigated Systems over a Five-Year Period to Develop Climate Change Adaptation Strategies at the Ferké 2 Sugar Complex

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Abstract

Sugarcane is grown on an industrial scale in Côte d'Ivoire in an area where rainfall is insufficient to meet water requirements. The crop is therefore grown under irrigation to increase yields. This study was conducted with the aim of improving sugarcane productivity by proposing strategies for adapting to climate change based on an analysis of water inputs. The methodological approach consisted of analyzing, on the one hand, rainfall variability and plant water requirements and, on the other hand, determining the impact of irrigation water quantities on sugarcane yields using multivariate analyses. The results revealed a downward trend in rainfall and an increase in sugarcane water requirements over the five-year study period. Furthermore, the analysis of water inputs on yields demonstrated that yields are influenced by high water inputs exceeding 1100 mm. Thus, optimized irrigation management is essential for the sustainable improvement of sugarcane productivity in Côte d'Ivoire.

Keywords

Climate Change, Optimized Management, Irrigation

1. Introduction

Sugarcane, Saccharum officinarum (Poaceae), is the sole source of sugar production in Côte d'Ivoire [1] and accounts for 80% of global production. It is a plant with high water requirements, whose vegetative growth and development are directly proportional to the amount of water transpired [2]. Cuttings will only take root or resume growth if there is sufficient water in the soil. Conversely, water stress in sugarcane slows germination and tillering and can result in a significant loss of sugar—up to 60% [3]. At the Ferké 2 sugar complex located in northern Côte d'Ivoire, sugarcane is grown on an industrial scale. In this area, rainfall is insufficient to meet the plant's water needs. Indeed, the country has experienced climatic variations characterized primarily by a decline in rainfall since 1970 [4]. Consequently, intra-annual and inter-annual variations in rainfall affect water availability and thus compromise sugarcane yields. This crop is therefore cultivated using various irrigation systems. Increased production results from the interaction of several factors, including water availability, the water requirements of sugarcane, and the performance of the various irrigation systems. The study aims to develop strategies for adapting to climate change by analyzing the interactions between rainfall, irrigation, and crop yields under various irrigation systems, compared to those obtained under rain-fed conditions, with the goal of achieving sustainable improvements in production in the context of climate change.

2. Materials and Methods

2.1. Geographical Location and Climate

The Ferké 2 sugar complex is located in northern Côte d'Ivoire between, on the one hand, 9˚14' and 9˚35' north latitude and, on the other hand, 5˚15' and 5˚24' west longitude, with an average elevation of 325 m above sea level.

The complex is situated on the east bank of the Bandama River, 610 km from Abidjan, halfway (40 km) between the cities of Ferkessédougou and Korhogo. The area has a subhumid tropical climate with two seasons: a dry season, from November to March, and a wet season, from April to October. The dry season is marked by a period that is very favorable for sugarcane maturation. This is the harmattan season, which lasts from mid-November to mid-February, with daily temperature fluctuations exceeding 20˚C and relative humidity sometimes reaching 30% to 35%. The air is dry and hot during the day and cold at night due to its low moisture content.

2.2. Material

2.2.1. Plant Material

The plant material used consists of sugarcane (*Saccharum officinarum* L.) varieties from five different countries: Brazil, France, Mauritius, Réunion, and Guadeloupe. These varieties possess agronomic traits that are particularly well-suited to increasing production.

2.2.2. Ferké 2 Agro-Climatic Station

Meteorological data were recorded daily at the agro-meteorological station. This station is equipped with the following instruments: a direct-reading rain gauge, a Class A evaporation pan, a weather shelter, an anemometer, a wind vane, and a heliograph. In addition to the direct-reading rain gauge, several others are installed throughout the sugarcane plantation to improve irrigation management

2.3. Methods

2.3.1. Determination of Rainfall Amounts

Rainfall measurements are taken at three times during the day (7:00 a.m., 12:00 p.m., 5:00 p.m.). Rainfall inputs are determined by summing the rainfall recorded on each of the sugarcane plots. This total is calculated based on readings taken at the rain gauge associated with that plot. The daily rainfall total is calculated by summing the three recorded rainfall values. The results are recorded in a database to assess monthly rainfall.

2.3.2. Assessment of Irrigation Water Volumes

Irrigation was provided in accordance with the plants' water requirements. These requirements were assessed using the climatic water balance equation, calculated over a ten-day period:

$$R + I = ETM$$

$$I = ETM - R$$

where:

R: Rainfall recorded over the period

I: Irrigation rate required for the following period

ETM: Maximum evapotranspiration calculated over the period

Once the water requirement had been determined, the volume of water supplied to each plot was calculated based on the flow rate of the existing irrigation system and the daily irrigation duration, as indicated by the following formula:

$$V(i) = Q \times di$$

Where:

$V(i)$: Volume of water supplied to an irrigated plot on day i (m^3),

Q: Flow rate of the existing system (m^3/h),

di: Daily irrigation duration (h)

2.3.3. Total Amount of Rainwater and Irrigation Water Received per Plot

The total amount of water received by each plot includes the volumes supplied by irrigation and those from recorded rainfall. Irrigation rates were calculated based on the volumes of water delivered by the various irrigation systems. The total water application rate (DT) is calculated using the following formula:

$$W_T = 10\frac{V}{S} + R$$

where:

W_T: Total water input per plot (mm),

V: Volume of irrigation water supplied to the plot (m^3),

S: Area of the irrigated plot (ha),

P: Rainfall recorded by the rain gauge associated with the plot (mm).

2.3.4. Sugarcane Yields by Plot

The sugarcane yield of a given plot is the ratio of the cumulative sugarcane production from that plot as weighed on the factory's weighbridge for the various trailer loads to the plot's area:

$$\text{Yield}\left(\text{t/ha}\right) = 10\frac{T_{\text{yield}}}{S}$$

where:

T_{yield}: Total sugarcane yield from a plot (t),

S: Harvested area (ha).

2.3.5. Interannual Variability of Rainfall: The Nicholson Index

The interannual variability of precipitation can be expressed using the Nicholson index, which is a centered-reduced variable defined as follows [5]:

$$In = \frac{Xi - M}{\sigma}$$

where

In: Nicholson index;

Xi: Annual cumulative rainfall for year *i*;

M: Average annual rainfall corresponding to the normal period;

σ: Standard deviation of the average rainfall *M* (normal period).

This index highlights, for a given rainfall series, periods of excess rainfall (wet) or rainfall deficit (dry). A period is considered normal when fluctuations in the index on either side of the x-axis cancel each other out. In this case, the annual average is roughly equal to the average for the reference period. The period is said to be surplus (or wet) when the annual average is higher than the average for the normal period. It is said to be deficit (or dry) when the annual average is lower than the average for the normal period. The study of the Nicholson index was conducted over a 16-year period.

2.3.6. Frequency Analysis of Decadal Rainfall at Ferké 2

Rainfall values were calculated every 10 days within the month, for a total of 3 decades per month and 36 decades per year. Subsequently, a database was created. This database included the cumulative rainfall for the 36 decades per year over a 16-year period from 1999 to 2015. Using the collected data, the years classified as wet, dry, or average were determined after establishing an annual distribution of cumulative rainfall showing, for each decade during the 16-year study period, values that were high, low, or intermediate, respectively.

2.3.7. Statistical Analysis of the Data

A database containing information on rainfall, irrigation, and sugarcane yields

was created. The analyses focused on yields from irrigated plots, rain-fed plots, and plots that are both rain-fed and irrigated. Factor Analysis of Correspondences (FAC) was used for multivariate analyses of water inputs and yields.

To calculate the AFC, yields were divided into four different classes according to the following model:

R < 70 = yield less than 70 metric tons per hectare,

70 < R < 90 = yield between 70 and 90 metric tons per hectare,

90 < R < 110 = yield between 90 and 110 metric tons per hectare,

R > 110 = yield greater than 110 metric tons per hectare.

The amounts of water supplied by irrigation systems (in mm) were divided into seven classes:

Irr < 150 = Irrigation less than 150 mm,

150 ≤ Irr < 300 = Irrigation between 150 and 300 mm,

300 ≤ Irr < 450 = Irrigation between 300 and 450 mm,

450 ≤ Irr < 600 = Irrigation between 450 and 600 mm,

600 ≤ Irr < 750 = Irrigation between 600 and 750 mm,

750 ≤ Irr < 900 = Irrigation between 750 and 900 mm,

Irr ≥ 900 = Irrigation greater than or equal to 900 mm.

Available water (irrigation and effective rainfall, excluding deep percolation) was classified into six categories:

(Irr + PU) < 500 = Irrigation and effective rainfall less than 500 mm,

500 ≤ (Irr + PU) < 700 = Irrigation and effective rainfall between 500 and 700 mm,

700 ≤ (Irr + PU) < 900 = irrigation and useful rainfall between 700 and 900 mm,

900 ≤ (Irr + PU) < 1100 = irrigation and useful rainfall between 900 and 1100 mm,

1100 ≤ (Irr + PU) < 1300 = Irrigation and effective rainfall between 1100 and 1300 mm,

Irr + PU ≥ 1300 = Irrigation and effective rainfall greater than or equal to 1300 mm.

Useful rainfall has been divided into six categories:

PU < 350 = Useful rainfall less than 350 mm,

350 ≤ PU < 550 = Useful rainfall between 350 and 550 mm,

550 ≤ PU < 750 = Useful rainfall between 550 and 750 mm,

750 ≤ PU < 950 = Beneficial rainfall between 750 and 950 mm,

950 ≤ PU < 1100 = Beneficial rainfall between 950 and 1100 mm,

PU ≥ 1100 = Beneficial rainfall greater than or equal to 1100 mm.

3. Results

3.1. Analysis of Rainfall Data and Distribution of Decadal Rainfall Maximums and Minimums at the Ferke 2 Sugar Complex

Analysis of the rainfall series for Ferké 2 allowed the years to be subdivided into wet, median, and dry years. For each type of year (dry, median, and wet), the rain-

fall pattern is unimodal and centered on August-September (Figure 1). The cumulative rainfall totals for wet, dry, and median years are 3424.9, 204.3, and 1250.8 mm, respectively.

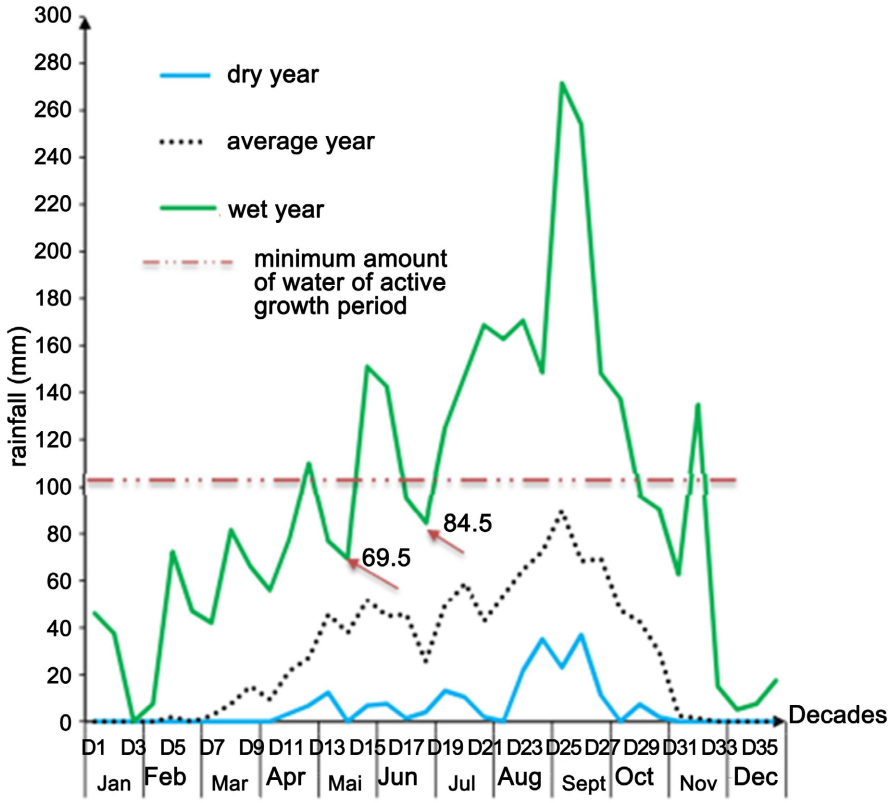


Figure 1. Frequency analysis of 10-day rainfall at the Ferké 2 sugar complex based on the rainfall series from 1999 to 2015. D = Decade.

During August and September, when rainfall is heaviest, rainfall levels are 481.8 and 673.0 mm, respectively, for wet years; 56.7 and 71.0 mm for dry years; and 190.7 and 227.3 mm for average years. Furthermore, the months of March through July constitute a critical period during which the growth and development of sugarcane are negatively affected by water stress. During this period, rainfall varies greatly from one ten-day period to the next, and the cumulative rainfall totals for so-called wet, dry, and intermediate years are 1540.3, 597.0, and 67.5 mm, respectively. During wet years, rainfall is sufficient to meet the water needs of sugarcane. However, during the months of May and July, a relatively high risk of drought is observed. In fact, rainfall during these months averages 150 mm, and rainfall amounts below 100 mm notably the 69.5 mm recorded in May and the 84.5 mm recorded in July can be detrimental to sugarcane.

3.2. Nicholson Index

The Nicholson index, applied to rainfall data from the Ferké sugar-growing region (Figure 2), identified two distinct periods:

- a normal period from 1999 to 2011, with an average rainfall of 1398.3 mm
- a dry period from 2012 to 2015, with an average rainfall of 1112.5 mm, which is lower than the total annual average.

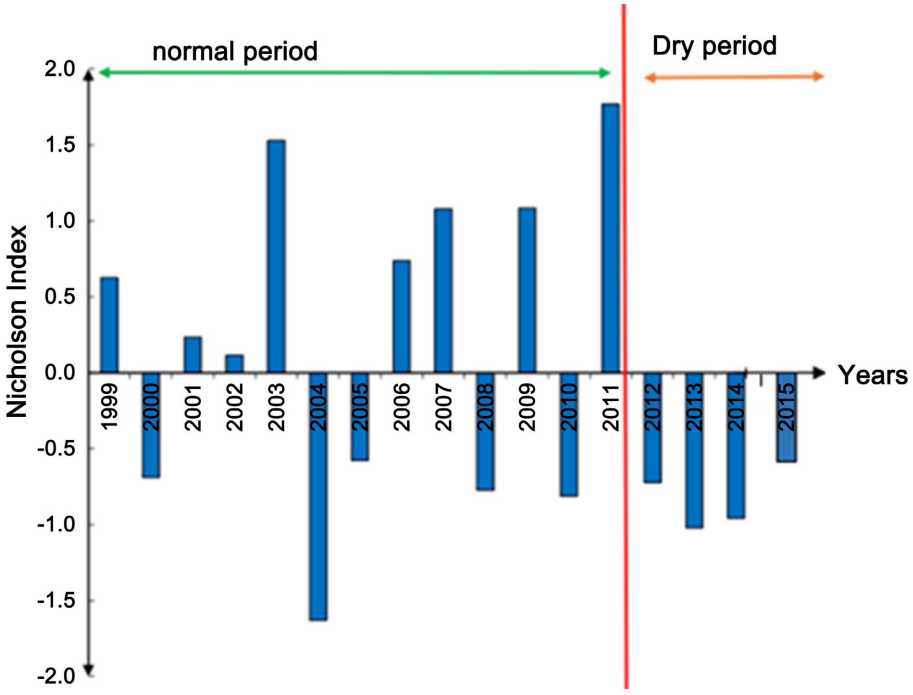


Figure 2. Changes in the Nicholson Index for the precipitation series from 1999 to 2015 at the Ferké 2 Sugar Complex.

3.3. Average Rainfall and Number of Days with Rainfall Greater than or Equal to 6 mm

The average annual rainfall total for the 2012-2015 period was 1112.5 mm. During these four years, the average annual rainfall total was 546.7 mm during the critical period from March through July (Table 1). On average, each year saw 51 days including 22 during the critical period with rainfall of 6 mm or more. Overall, it appears that this second four-year period shows a decrease in rainfall compared to the previous period, both in terms of the number of rainy days (−3 days) and annual total rainfall (−285.8 mm).

Table 1. Average rainfall and number of days with rainfall greater than or equal to 6 mm at the Ferké 2 sugar complex during the periods from 1999 to 2011 and from 2012 to 2015.

	Average Annual Rainfall (mm)	Average Rainfall during the critical period from March to July (mm)	Average Annual number of days with rainfall ≥ 6 mm	Average number of days with rainfall ≥ 6 during the critical period from March to July
1999-2011	1398.3 ± 19.8 a	612.5 ± 6.3 a	54 ± 2.5 a	26 ± 0.7 a
2012-2015	1112.5 ± 83.2 b	546.7 ± 25 b	51± 2.7 a	22 ± 3.8 a

3.4. Variation in the Yields of Sugar Cane Varieties as a Function of the Amounts of Water Provided by Irrigation System and Rainfall

The projection of sugarcane variety yields and the amounts of water supplied by irrigation systems in the 1 × 2 plane of the Factor Analysis of is shown in Figure 3. The total inertia associated with the plan formed by axes 1 and 2 of the Factor Analysis of Correspondences (FAC) is 97.53, representing 74.07% inertia for the first axis and 23.46% for the second (Figure 3). The highest yields, exceeding 110 t/ha, were recorded for irrigation water quantities ranging from 750 to 900 mm and for cumulative effective rainfall ranging from 350 to 550 mm. Yields ranging from 90 to 110 t/ha were achieved with irrigation water amounts ranging from 600 to 750 mm and total available water (rainfall and irrigation) ranging from 900 to 1300 mm. Irrigation water (Irr) amounts ranging from 450 to 600 mm, with effective rainfall ranging from 750 to 1100 mm, resulted in yields between 70 and 90 t/ha. Yields below 70 t/ha are associated with irrigation water amounts ranging from 150 to 450 mm. This yield was also observed for available water amounts below 900 mm and effective rainfall amounts below 350 mm.

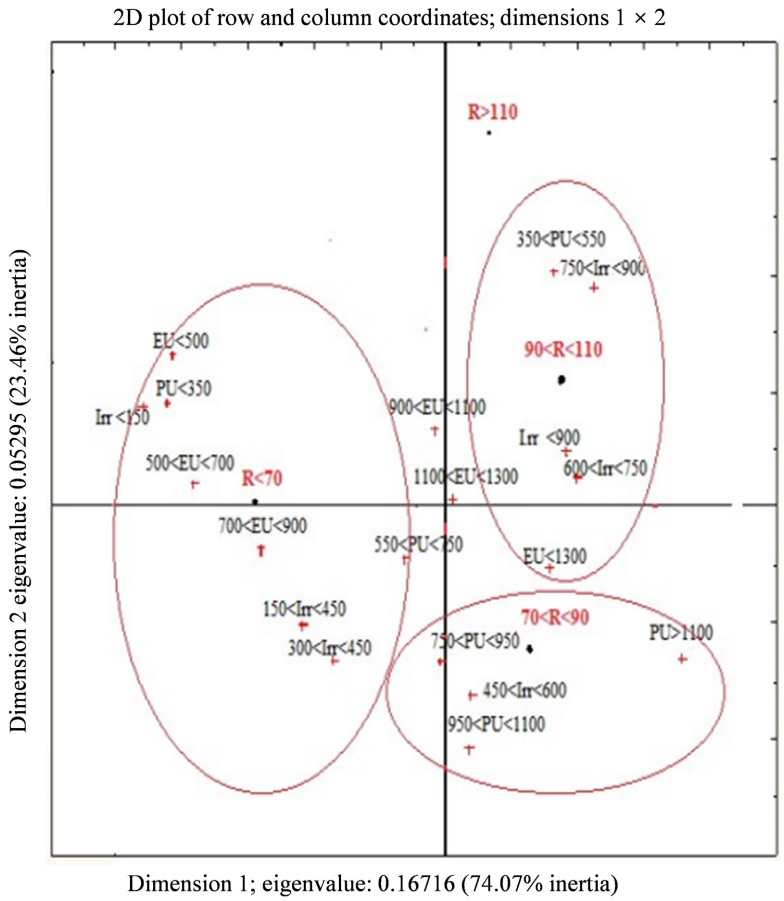


Figure 3. Projected yields based on water supplied by irrigation systems, net precipitation, and net precipitation in addition to irrigation in the AFC factorial design. PU: Precipitation usable, Irr: Irrigation, R: Return or yield, EU: water usable.

4. Discussion

An analysis of rainfall data collected at the Ferké 2 sugar complex, in northern Côte d'Ivoire, over the period 1999-2015, reveals a downward trend in annual averages. This decline can be explained by interannual climate variability, which results in natural fluctuations in precipitation from one year to the next. This finding is consistent with observations made over several years and particularly since 1970 in West African countries in general [6] and in Côte d'Ivoire in particular [7]. Indeed, located in the northern part of Côte d'Ivoire, the Ferké 2 sugar complex is no exception to this general trend. Thus, from the 12-year period of 1999 to 2011 to the 4-year period of 2012 to 2015, the average annual rainfall decreased by approximately 285.8 mm. Since rainfall in this area is insufficient to meet the water needs of sugarcane, its reduction in recent years could have a negative impact on sugarcane production, especially in rain-fed systems. The reduction in rainfall has resulted in a steady and significant decline of nearly half in both industrial and subsistence production in rain-fed agriculture [8]. In addition to being assessed from the most common perspective total rainfall climate variability at Ferké 2 was evaluated based on the frequency of rainfall events. Thus, the number of days with precipitation exceeding 6 mm during the year varied over the study periods. It decreased by three days, from 54 to 51 days, during the critical period when sugarcane growth and development are negatively affected by water deficit. This deficit could be detrimental to sugarcane development, especially since during this period, the cane is in a phase of rapid growth the critical period. In the plant's phenology, it remains sensitive to any water deficit during this critical phase. The risk at this stage is a slowdown in stem growth [9]. This risk is all the more evident given that the average rainfall during the critical period for sugarcane water supply in the region (March through July) has decreased from 612.5 mm during the 1999-2011 period to 546.7 mm during 2012-2015. During the months of May and July, low average rainfall was observed. Consequently, these months presented drought risks during the 1999-2015 period, even though they had long been considered wet months with high rainfall in the Sudanese region [10]. The drought risks observed during these months were incorporated into irrigation management to prevent sugarcane crops from experiencing water stress. Irrigation water volumes ranging from 750 to 900 mm resulted in high sugarcane yields. In contrast, irrigation water volumes ranging from 350 to 550 mm resulted in the lowest yields (less than 70 t/ha).

Thus, large amounts of water promoted high yields, whereas low volumes resulted in low yields. However, to be efficient, irrigation must make up for the missing water while taking into account the water requirements of sugarcane crops. Similar observations were made by [11], who studied the assessment of water demand and the management of irrigation for annual crops. These authors found that tomato yields were affected when the water supplied to the plant was insufficient.

Based on the various analyses conducted, it is clear that to sustainably increase

sugarcane production, it is necessary to:

- Provide water in amounts exceeding 750 mm to all varieties of sugarcane grown under irrigation in the agroclimatic conditions of the Ferké sugar complex if this water deficit persists.

- Promote efficient irrigation systems that minimize water loss to the absolute minimum, such as center-pivot systems or localized (drip) irrigation

- Reduce the area of rain-fed sugarcane cultivation or select drought-tolerant or even drought-resistant varieties, not only for rain-fed or smallholder sugarcane farming but also for irrigated cultivation

- Apply high-performance irrigation systems to high-yield sugarcane varieties to optimize production

- Use gravity-fed runoff irrigation to recover water lost during the operation of center-pivot systems and direct it to rain-fed plots adjacent to these systems

- Conduct surveys to identify faulty irrigation systems and the nature of the malfunctions in order to improve water management.

- Whenever the topography of the land permits, collect stormwater runoff for use on rain-fed plots.

5. Conclusion

This study revealed a downward trend in rainfall, particularly during the period from 2012 to 2015 and also during the critical phase of the sugarcane cycle for water supply. This poses a threat to sugarcane cultivation, which is dependent on rainfall in both industrial and village plantations. Rainfall and irrigation were major factors in determining yields. Large amounts of available water led to high sugarcane yields. This demonstrates the need to provide sugarcane with sufficient water to improve yields. Based on these results, a total of six climate change adaptation strategies were proposed for sustainable sugarcane production at the Ferké 2 complex. In the current context of climate change, characterized by declining and erratic rainfall, improving sugarcane production requires meeting the crop's water needs through efficient irrigation systems adapted to the climatic and edaphic conditions of the Ferké 2 sugar complex.

Author Contributions

Konan, A. E. designed the project and wrote the article; Kpan, O. J. G. analyzed all the climate data and plotted the curves and histograms; Zadi, M. determined the water requirements of sugarcane; Gogoue, D. O. collected the climate data. N'guessan A. S. R. reviewed the article to improve its editorial quality.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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