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Climate Impact on the Productivity of Sugarcane Varieties in Ferke1 Industrial Plantations

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Abstract

This study assesses the climate impact on the productivity of five sugarcane varieties (R579, SP711406, M2593/92, M1400/86, and SP701006) in the industrial plantations of Ferké 1 sugar complex. It is a contribution to research efforts aimed at increasing the productivity of sugarcane varieties in the sugar fields. Also to support agricultural development and guarantee the income of planters. The sugarcane production data are from 2013 to 2017. Climatological data are measured and calculated continuously daily at the production site. In addition, the CMIP-5 (Coupled Model Intercomparison Project) climate database at 1˚ × 1˚ horizontal resolution was used for the predictability of crop yields of the 5 sugarcane varieties in the near future (2021-2050) and far future (2056-2075) to improve the quality of climate services to producers. The statistical methodological approach by multiple linear regression associated with the significativity test shows important and significant coefficients of determination ($R^2 > 0.90$) between the yields of sugarcane varieties with certain climatic parameters such as minimum and maximum temperatures, insolation, global solar radiation, and potential evapotranspiration. The impact of rainfall has not been directly evaluated because the linear models do not explicitly show sensitivities to this parameter and the total water requirements for the plot are completely assured by irrigation. The future climate projections analyzed only from extreme thermal parameters (Tmax and Tmin) highlight their strong sensitivities with yields from an idealized model. In this model, we have assumed that the water supply needed by sugarcane is always met by irrigation on different plots. Moreover, linear models do not evolve fast enough in time and changes due to external environmental constraints are not too important at the plot scale. The projected thermic parameters can thus constitute a limiting factor for the producibility of sugarcane varieties either by excess or by default. In addition, the linear models used allowed us to observe the behavior of yields with respect to observed past climatic conditions. However, for future yields, there is no way to know if these regressions have the ability to predict them since they are based on projected weather conditions (*i.e.* CMIP5 data) marked by uncertainties. Additionally, none of the regression equations have been tested against independent observations.

Keywords

Climate Parameters, Projections, Yield, Sugarcane, Ferkessédougou

1. Introduction

The privatization of the Ivorian sugar sector in July 1997 aimed to put an end in the medium term to its recurrent lack of competitiveness linked to the high production costs of sugarcane since its creation in the early 1970s [1] [2]. However, the socio-political crisis started in September 2002, and its associated drop in sales of local sugar products led to a decline in the investment from the private sector in the sugarcane [3] [4] [5]. Thus, low agricultural productivity (42 to 62.6 T/ha) in the sugar fields of Ferké has been reported [6] [7] [8]. The low production of sugar (92,000 T/year) in Côte d'Ivoire, especially during dry years (eg. 2007-2008 with 8500 T) may be related to relatively obsolete sugarcane varieties (low performing varieties) that have been shown to have low sugar yields [7] [9]. This lower production could also be associated to inefficient irrigation systems and cultural practices that were quite costly and less environmental friendly. The reform of the European Union (EU) sugar regime, initially based on export quotas for African, Caribbean, and Pacific (ACP) countries with highly remunerative prices compared to those of the international market which took place in 2006, necessitated the implementation of a policy to revive the sugarcane sector through sectoral financial support from 2009 à 2016 [4].

Furthermore, other abiotic factors may also contribute to this low production of sugarcane. Hence, [10] underlined that the sugar yield of a sugarcane field may depend on the solar energy, the soil humidity, the physico-chemical state of the soil, the value of the work, and the chosen cultivation method. In addition, previous works [11] [12] showed that forest plants are strongly influenced by climate conditions affecting their productivity. Other studies, focusing in the Ferké sugar complexes, have reported that the performance of industrial sugarcane plantations may be tributary to climatic risks [3] [13] [14] [15] [16]. They further argued that the climate conditions are mainly characterized by irregular distribution of the rainfall from March to July (dry season), with a cumulative water deficit compared to the wet season exceeding 700 mm.

However, these existing studies did not provide a qualitative and quantitative evaluation of the impacts and contributions of the cultivation techniques and methods (e.g., cultivation by burning, irrigation techniques, cultivation of new varieties, etc.) in improving plantation productivity. Also, the use of climate projection data from numerical models in the predictability of crop yields of sugarcane varieties to ensure sustainable quality and increased production has not been investigated.

Therefore, the current study, within the framework of the CLIMSUCAF project (2019-2021), assesses the impacts of climatic conditions on sugarcane cultivation at the company SUCAF-CI (SUCrerie d'AFrique en Côte d'Ivoire) in Ferkessédougou. The project CLIMSUCAF aims to promote adapted strategies to fight against the disadvantages of climate change on the sugarcane crop in Côte d'Ivoire. Therefore, the proposed work focuses on the impact of insolation, potential evapotranspiration, maximum and minimum temperatures, and global solar radiation on the variations in the productivity of industrial sugarcane plantations in the Ferkessédougou sugarcane area from 2013 to 2017. On the other hand, to quantify and foresee the crop yields of sugarcane varieties used in the near and far future.

2. Materials and Methods

2.1. Materials

2.1.1. Study Area

The Sugar Complex of Ferké 1 of SUCAF-CI is located between 9˚20' and 9˚60' North latitude and between 5˚22' and 5˚40' West longitude. It is located at 15 km from Ferkessédougou (**Figure 1**) and between 280 and 380 m in altitude above mean sea level. The area is drained by the Bandama River and its affluents (Lokpoho, Monongo, Waha, Farakwo) in a dendritic pattern [17] [18]. The sugar perimeters are delimited to the West by the Bandama River, to the East by the Tafiré-Ferké national road, to the South by the Farakwo River and to the North by the Ferké-Sinématiali national road. The climate has two seasons, one dry, from November to April, and the other wet, from May to October. The rainy season over the region is characterized by a unimodal rainfall regime (**Figure 2**), centered on August and September, which account for almost half of the average annual rainfall. Its climate is tropical sub-humid. The soils are mostly ferralitic and alluvial hydromorphic on the terraces of the Bandama River.

2.1.2. Data

- **Sugarcane**

Sugarcane production data (tons (T)) have been collected in Ferké 1 yearly and by variety over the 2013-2017 period. The data are from Service d'Études Agronomiques (SEA) of SUCAF, which controls periodic data (information) on cane diseases, maturity, growth and development of sugarcane. The sugarcane varieties studied are five (5) with climatic origins similar to the Ferké zone and with good yields in these climates. Table 1 presents the characteristics of the selected varieties. Each variety of sugarcane is cultivated in an area of a few tens of square kilometers where local climatic characteristics can be decisive, *i.e.* have a strong impact on the sugarcane in relation to the regional climate. Indeed, the scale of local climates is strongly related to the environmental particularities of

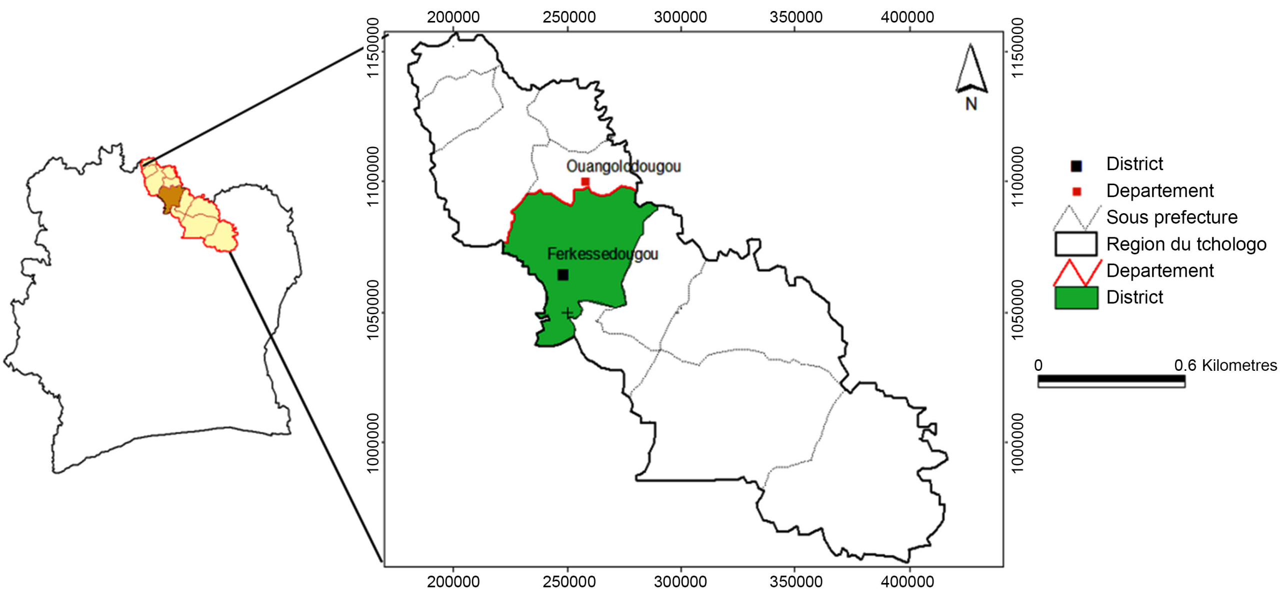

Figure 1. Map of district of Ferkessédougou [19].

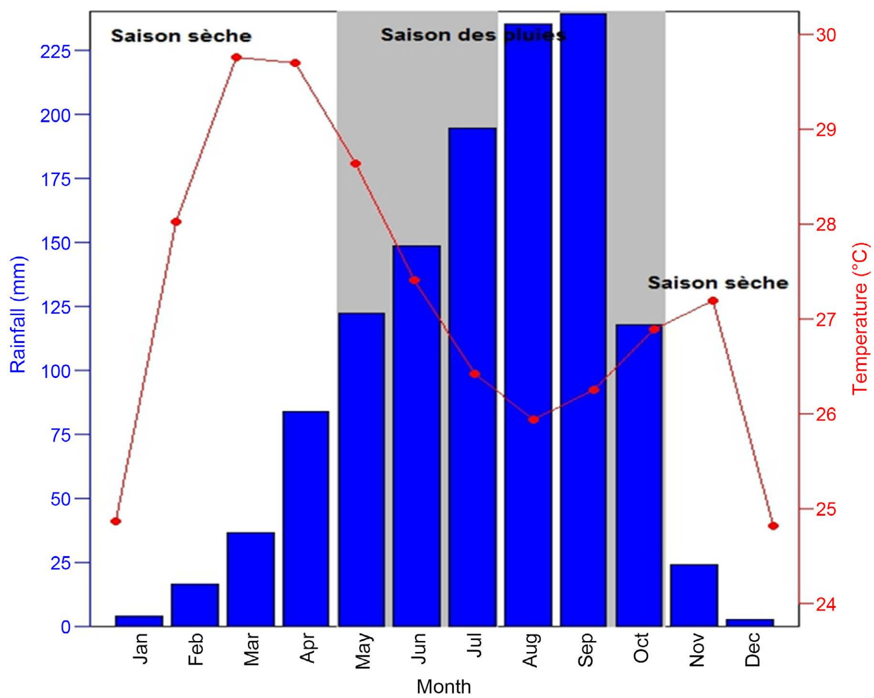

Figure 2. Annual cycle of both precipitation (blue histogramme) and temperature (red line) computed over the period 2013-2017.

Table 1. Characteristics and history of sugarcane varieties selected in Ferké 1.

Cane varieties	Cultivated parcels	Station of creation	Surface area (ha)
M1400/86	B1 21	Maurice	17.0
M2593/92	B1 144	Maurice	14.30
SP701006	B1 132	Sao Paulo	18.90
SP711406	B2 110	Sao Paulo	20
R579	B1 24	Réunion	18.90

the cultivation sites. Several authors [20] [21] [22] have shown strong relationships between microclimate and biodiversity in terrestrial emergent ecosystems. The microclimate influences the species that are present and inversely, some ecosystems decrease or increase the albedo of the substrate on the one hand, and on the other hand modify the diurnal thermohygrometric curves, in particular by their evapotranspiration capacities.

- **Climate data**

The climate variables, from Ferké 1 used in this work are the minimum temperature (Tmin), maximum temperature (Tmax), insolation duration (Insol), global solar radiation (Rg), and potential evapotranspiration (ETP) over the period 2013-2017. The database over the period 2007-2019 is characterized by less than 1% missing values [23]. Rainfall data for Ferké 1 are obtained from 27 rain gauges. The maintenance of these rain gauges is carried out by SUCAF with occasional technical support from Sodexam.

These data have the advantage of being local and reflect the variability of the climate of the zone and are suitable to assess the impact of the climate variability on agriculture especially sugarcane production.

- **CIMP-5 data**

In addition to the ground base observation dataset, the study uses the Coupled Model Intercomparison Project Phase 5 (CMIP5) data interpolated to a common 1˚ × 1˚ grid. They are available in a variety of formats. The documentation provides an overview of the data set (1901-2100), a description of its creation, potential applications, as well as inherent limitations (https://data.ec.gc.ca/data/climate/scientificknowledge/projected-precipitation-change-based-on-cmip5-multi-model-ensembles/CMIP5_-_READ_ME_Technical_Doc_EN.pdf). CMIP5 data are used here to project the sugarcane production, in the near future (2025-2050) and far future (2056-2075), based on the changes in daily temperature and rainfall.

2.2. Methods

Thus, because of the intersection of multiple environmental issues, we sought to determine the local climatic characteristics of the sown areas using the climatic index defined by [24]. This composite index is based on the rainfall-temperature relationship in a given area, which is not a simple relationship of proportionality. Indeed, the author supposed that evaporation, which indicates the water requirements, does not vary as temperature. Then, he supposed that the rainfall efficiency is a quadratic function of temperature. Equation (1) summarizes this empirical relationship in which Ps is the rainfall threshold between wet and dry seasons, $\bar{T}$ is the mean annual temperature calculated from the period considered. Then Ia, an annual pluviothermal index is calculated following equation (2) and whose different values illustrate the type of tropical climate of a given region in West Africa. This index was used in the work of [25] to characterize the climate type of the Lamto reserve ecosystem in Côte d'Ivoire subject to anthropogenic factors over the 1964-2011 period.

$$P_s = \bar{T}^2 - 10\bar{T} + 200 \quad (1)$$

$$I_a = \frac{P_m}{P_s} = \frac{P_m}{\bar{T}^2 - 10\bar{T} + 200} \quad (2)$$

With $P_m = \left(\frac{1}{n}\right)\sum_{i=1}^{n} P_i$, where n is the total number of years and P_i, the total rainfall (mm) in a year i, and $\bar{T} = \left(\frac{1}{n}\right)\sum_{i=1}^{n} T_i$, where n is the total number of years and T_i, the mean temperature in a year i. The limit between tropical areas and dry tropical areas in West Africa $I_a = 1$ A classification of different areas in Africa using the annual pluviothermal index is given in the work of [24]. For a desert area, $I_a \le 0.25$. For a sub-desert area, $0.25 < I_a \le 0.5$. For an arid area, $0.5 < I_a \le 1$. For a subhumid area, $1 < I_a \le 2$. For a humid area, $2 < I_a \le 3$. For a rainy area, $I_a > 3$. The determination of the local climate of the cultivation areas of each sugarcane variety allows us to characterize the sources of uncertainties and to improve the analysis of the predictability of crop yields.

In addition, a statistical approach by multiple linear regression or linear statistical model to highlight positive relationships between the yields of sugarcane varieties (explained variable) and different climate parameters (minimum and maximum temperatures, duration of insolation, global solar radiation, and potential evapotranspiration, total amount of water received) measured in the study area (explanatory variables) to analyze and evaluate their sources of variations was also carried out. Thus, sugarcane yields increase or decrease with variations in these climatic parameters. Here, the total quantity of water received by the sugarcane represents both that provided by the climatic seasons and that coming from the irrigation of the plots. Thus, the real rainfall measured on a plot is not the one effectively received by the plant. We, therefore, use the term "total water received" instead of rainfall, which has a marked spatio-temporal character under environmental conditions. The water received by the plot is used to maintain the actual evapotranspiration of the plants and the direct evaporation on the surface of the wet soil. It, therefore, serves to ensure the water balance and must be taken into account in the prediction of sugarcane crop yields. The selection of the variables that give the "best model" to predict the yields of the sugarcane varieties was done using the forward stepwise procedure. This means that we start from the null model without any variables and run several linear regressions that, at each step, test the addition and deletion of variables. This method is frequently used in regression models with a large number of explicative variables [26] [27] [28]. The most explicative and significant model from these variables is retained according to a model quality criterion based on 1) the largest coefficient of determination R^2, 2) the largest number N of explicative variables selected, and 3) the smallest associated p-value index. The significant test used for the p-value is the Kendall criterion [29] [30]. It is said to be significant when the p-value is less than or equal to 0.05. Thus, the variation in crop yield (ΔY) for a given sugarcane variety is obtained by the Equation (3):

$$\Delta Y = \sum_{j=1}^{N} \beta_j X_j + b \quad (3)$$

where the coefficients β_j (parameters to be estimated) represent the sensitivity of sugarcane production to both the explicative variables X_j and b represents the potential nonlinear effects of the climatic X_j, such as those resulting from interactions with other variables. This equation ignores other aspects of weather, such as rainfall, wind speed, and non-climatic factors, such as soil type, soil moisture, area planted, and number of growing cycles (*i.e.* number of regrowths). It translates into a useful first-order qualitative statistical estimate of the year-to-year variability of sugarcane yield for a given variety during the study period. The coefficients of determination R^2 and associated p-values of each selected equation are given in **Table 1**. Furthermore, the modeling of the relationship between several quantitative variables (*i.e.* predictant and predictors) has shown satisfactory results in studies estimating 1) crop yields [31] and 2) carbon fluxes [32] with climate variables.

Furthermore, the calculation of potential evapotranspiration (ETP), expressed in millimeters of water, the importance of which for water resource planning and management has been emphasized in several studies, was based on the Penman-Monteith formula [33] (Equation (4)). This method proposed by Penman is recommended by the FAO as a reference model for its performance under different climatic conditions.

$$\text{ETP} = \frac{\Delta Rn + \gamma Ea}{\Delta + \gamma} \quad (4)$$

where Δ, is the slope of the saturation vapor pressure versus air temperature curve, γ, the psychrometric constant (0.66 at sea level). Rn is the net radiation and Ea is the evaporating power of the air.

3. Results

3.1. Microclimate Characteristics of the Plots

Figures 3(a)-(e) show the interannual variabilities of the pluviothermal index (Ia), standardized anomalies of rainfall (I), and temperature over the period

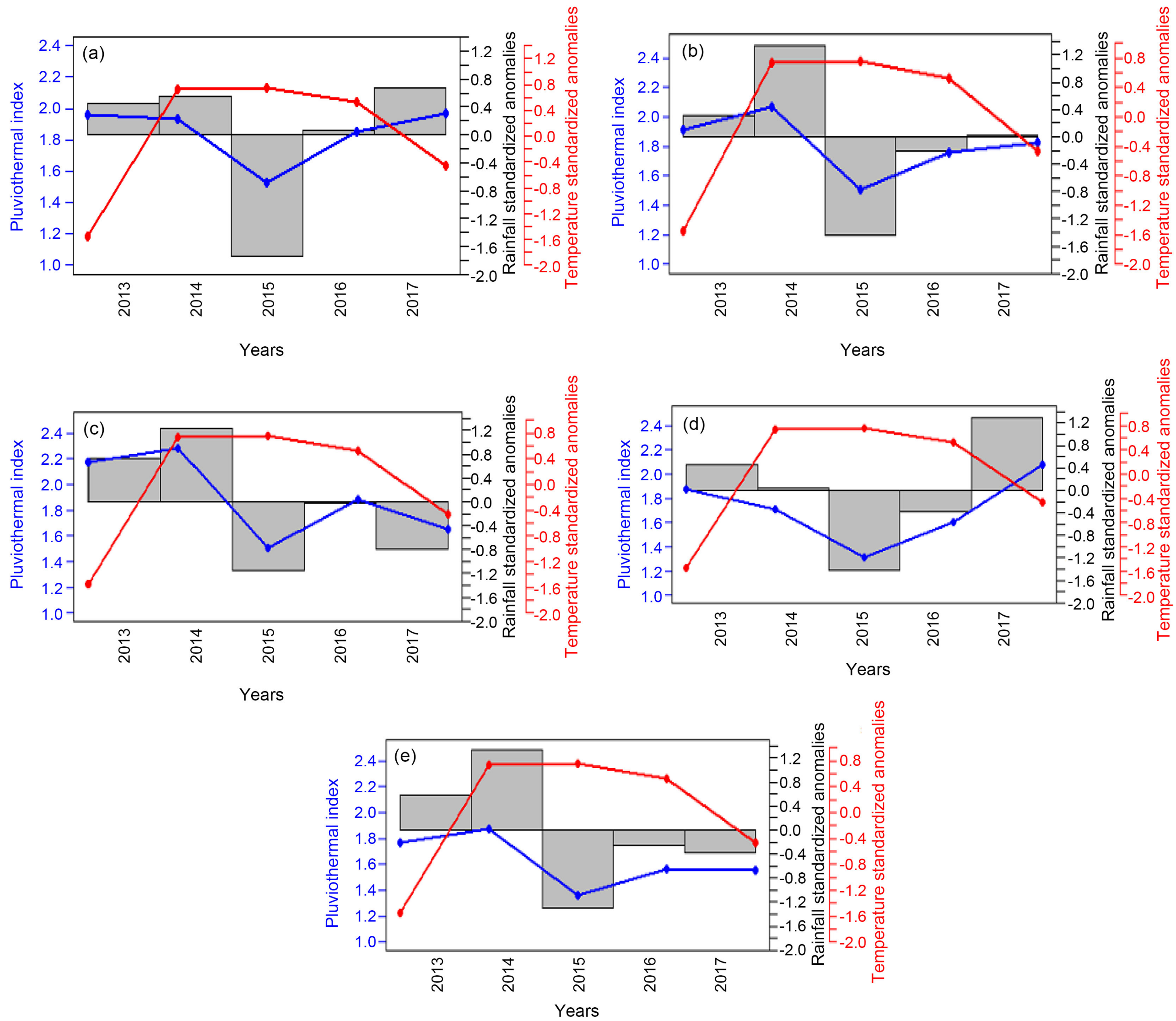

Figure 3. Annual pluviothermal index (blue line), the annual standardized anomalies of rainfall (histogram) and temperature (red line). The anomalies are computed based on the mean of the corresponding indice over 2013-2017 in the sugarcane parcels (from left to right: B124, B132, B1144, B2110 and B121).

2013-2017 calculated for each plot. The standardized anomalies of rainfall (I) agree with the Ia index curve for each plot. The values of the Ia index are between 1 and 2 except for the years 2013 and 2014 on plot B1144. For these two particular years, the Ia index shows values higher than 2. This confers to parcel B1144 a humid zone status. Apart from this, for the majority of years, the results indicate that the five plots (B1 24, B1 32, B1 144, B2 110, and L1 21) on which the different sugarcane varieties are grown have a subhumid type climate (*i.e.* $1 < Ia \leq 2$). However, 2015 is a particular year because it is marked by a strong deficit of rainfall marked by standardized anomalies between [−1.8:−1.2] depending on the type of plot. The pluviothermal indices associated with these anomalies are significantly low and in the range [1.3 to 1.5]. As for temperature, the lowest standardized anomaly is observed in 2013 with a value of −1.6 and the highest in 2015 with a value of +0.7. Across the five years study period, there are positive standardized temperature anomalies over three years (2014, 2015, and 2016) show, suggesting a warm episode all over the cultivable plots.

3.2. Evolution of Productivity of Sugarcane Varieties According to the Number of Regrowths

In general, the varieties grown under irrigation in the Ferke sugar fields have a harvest cycle of 11 to 12 months and a planting cycle of 5 to 6 years. After 5 or 6 years of cultivation, the variety is no more productive, the yield becomes very low and the cycle of the variety on the plot ends. This constraint makes it impossible to study a variety on a plot over a period of more than five years. The industrial plots on which the five varieties are grown are particularly irrigated at 75% - 90% by pivots. **Figures 4(a)-(e)** shows the yields of the different sugarcane varieties (M1400/86, M2593/92, R579, SP7601006, and SP711406) against the number of regrowth or production cycles over the period 2013-2017. It is worth noting that the productivity of each sugarcane variety is provided yearly and the first crop corresponds to virgin cane (R0) while the productivities of the following years correspond to those of the R1 regrowth, R2 regrowth, R3 regrowth, etc. In this work, we have the virgin cane R0 (2013), the regrowths R1 (2014), R2 (2015), R3 (2016), and R4 (2017). The average yields observed are 81.69 T/ha, 104.98 T/ha, 97.44 T/ha, 79.53 T/ha, and 96.69 T/ha for varieties M1400/86, M2593/92, R579, SP7601006, and SP711406 respectively.

The results show that the yields of the variety M1400/86 are between 55 and 98 T/ha. This production increase from 2013 with 55 T/ha to 2015 with 93.27 T/ha corresponding to the second regrowth (R2). This increase is followed by a slight decrease in 2016 (84.96 T/ha) at the third regrowth (R3) and a recorvery 2017 (98.15 T/ha) at the fourth regrowth (R4).

The varieties M2593/92, R579, SP7601006, and SP711406 on the other hand show similar profiles characterized by a decrease in yield below average from virgin cane (R0) in 2013 (**Figures 4(b)-(e)**) to first regrowth (R1) in 2014, from 122.63 T/ha, 107.80 T/ha, 82.38 T/ha and 123.50 T/ha to 77.17 T/ha, 78.79 T/ha, 73.24 T/ha and 70.15 T/ha respectively. Then, the yields of these 4 varieties increase again at the second regrowth (R2) in 2015 above average to decrease again at the third regrowth (R3) in 2016. These yields remain below average for varieties R579 and SP711406 until 2017 despite a slight recovery. On the other hand, there is a strong recovery of yields at the fourth regrowth (R4) in 2017 for the variety SP7601006 while the yield decreases to below average for the variety M2593/92 although a slight plateau is observed between the regrowths R2 and R3 corresponding respectively to the years 2015 and 2016.

3.3. Impacts of Climate Conditions on the Productivity of Sugarcane Varieties

Linear model prediction from plot-level climate variables is used to assess the impacts of climate conditions on the yields of each sugarcane variety. The most relevant and significant model from these variables for each variety is presented in **Table 2** along with the associated R2 coefficient of determination and p-value. Thus, the annual yield of the M1400/86 variety is significantly controlled by solar radiation (Rg) and potential evapotranspiration (ETP). These two parameters explain 99% of the variance in yield (Equation (5)). This model is significant (p-value = 0.006) and takes into account one parameter related to heat (*i.e.* solar radiation Rg) and another related to water (*i.e.* potential evapotranspiration ETP). Any variation of the solar radiation Rg on the one hand and of the potential evapotranspiration ETP, on the other hand, could systematically lead to a decrease of the yield of M1400/86.

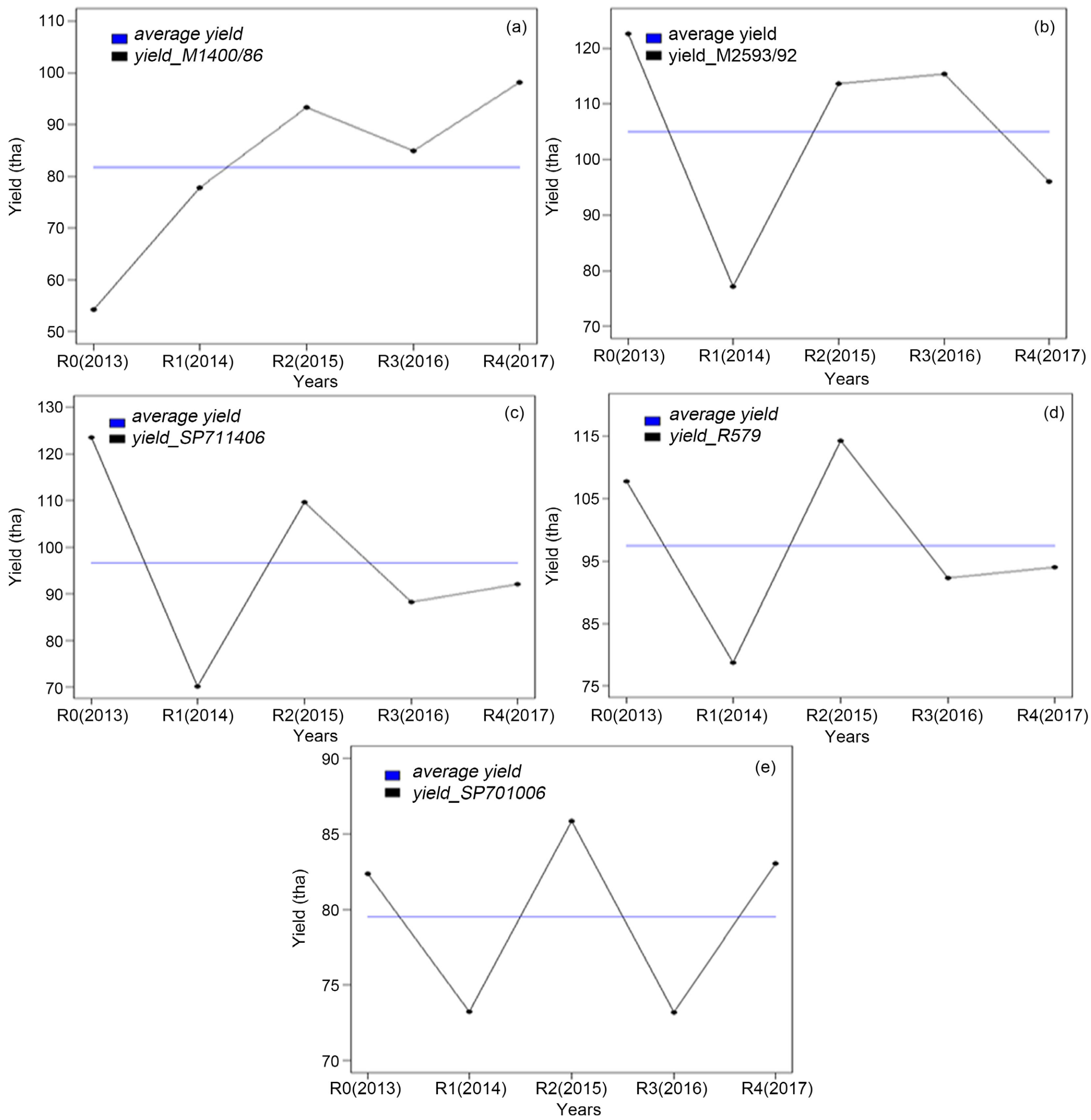

Figure 4. Evolution of production yields of sugarcane varieties M1400/86 (a), M2593/92 (b), R579 (c), SP7601006 (d), and SP711406 (e) as a function of regrowth over the period 2013-2017. The bleue lines account for the average yield from 2013 to 2017.

Table 2. Linear models showing the relationships between annual yield (Rdt) of sugarcane variety and local meteorological conditions such as global solar radiation (Rg), maximum temperature (Tmax), minimum temperature (Tmin), duration of insolation (Insol), potential evapotranspiration (ETP) and total water (Et) recorded at Ferké 1 station over the period 2013-2017, as well as their coefficients of determination (R^2) and their significance (p-value).

Variétés	Modèle linéaire	R^2	p-value	
M1400/86	$Rdt = -0.001 * Rg - 1.69 * ETP + 3419.0$	0.99	**0.006**	(5)
M2593/92	$Rdt = 0.05 * Et + 69.56 * Tmax - 2361$	0.99	**0.007**	(6)
R579	$Rdt = -0.02 * Et - 19.31 * Tmin - 0.51 * ETP + 131.1$	0.99	**0.009**	(7)
SP711406	$Rdt = -0.02 * Et + 0.05 * Insol - 41.21 * Tmin + 895.7$	0.99	**0.01**	(8)
SP701006	$Rdt = 0.01 * Et + 0.03 * Insol + 25.98 * Tmax - 900.7$	0.93	0.32	(9)

The variety M2593/92 has its yield (Rdt) controlled by the total water (Et) (rain + irrigation) received by the plot and the maximum annual temperature (Tmax). These two parameters alone explain 99% of the yield of the variety M2593/92. These parameters play a significant role in predicting the yields of the variety M2593/92. Irrigation to make up for the rainfall deficit is highly appreciable and very indispensable to control yield variations. Increases (resp. decreases) in total water supply (Et) and mean annual maximum temperature (Tmax) improve (resp. reduce) the performance of M2593/92. This model (Equation 6) is very significant (p-value = 0.007) and shows the roles of total water Et and mean annual maximum temperature Tmax in the management of the different growth phases of the M2593/92 variety. However, the influence of non-linear terms not taken into account in the model is very important and is evaluated at 2361 T/year.

Variety R579 shows a model of 3 variables prediction (Equation (7)) involving total water (Et), minimum temperature (Tmin), and potential evapotranspiration (ETP) showing their significant influences on yield variations. Total water (Et), minimum temperature (Tmin), and potential evapotranspiration alone explained 99% of the variance in yields of the variety R579 over the period 2013-2017 with significant significance (p-value = 0.009). This model indicates that any increase in these variables systematically leads to a decrease in the yields of the variety R579. The non-linear terms show a positive effect on yields of about 131.1 T/year.

The variety SP711406 also presents a model of 3 variables (Equation (8)) that uses total water (Et), insolation (Insol), and annual minimum temperature (Tmin) as explicative variables. These variables explain a very large part, 99% of the yields of the variety SP711406 with a p-value = 0.01. This linear model systematically shows a decreasing or decreasing effect of the yield of the variety SP711406 involving total water (Et) and minimum temperature (Tmin). The yield increases when the variety receives sufficient solar radiation (Insol). Non-linear effects and terms not considered in equation 8 also show a positive and non-negligible contribution of about 895.69 T/year. The yield of SP701006 on the other hand is explained by total water (Et), insolation (Insol), and maximum temperature (Tmax). A significant part of the variance in yield is explained by these 3 variables at 93% with a p-value = 0.32 (Equation (9)). Although this significance (p-value = 0.32) is greater than 0.05 (acceptable threshold of significance), the linear model shows that the yield of the variety SP701006 increases systematically with an increase of these 3 variables. Their effects are positive on the yield of the variety but the non-linear terms or those not taken into account in the model show a non-negligible negative response (−900.7 T/year).

3.4. Responses of Sugarcane Production to Climate Variation Trends in the Near Future (2021-2050) and Far Future (2056-2075)

The results of the linear model approach (section 3.3) showed strong significant correlations (p-value < 0.5 and $R^2 > 0.90$) between the yields of sugarcane varieties with some climatic parameters. In particular, minimum temperature, maximum temperature, insolation, potential evapotranspiration, and rainfall in their quantitative form although it is used in this work as a component of the total water (rainfall + irrigation) received by the plots. Considering idealized situations and based on the hypothesis that the linear models established previously are supposed not to evolve in time, we analyze the predictability of the yields of sugarcane varieties by the projected climatic parameters in the near future (2021-2050) and in the distant future (2056-2075) (See **Figure 5** and **Figure 6**).

Thus, the effects of the five-year time series of climatic variables are evaluated in terms of favourable and unfavourable trends for sugarcane varieties. A trend considered in the time series of standardized anomalies of the climatic variables will be said to be unfavourable (resp. favourable) to a sugarcane variety if the values of anomalies of the climatic variables retained in the linear model (**Table 2**) contribute to the decrease (resp. increase) of the yield of the variety. The five-year trends were chosen given the length of the average crop cycle of the varieties (renewal of the plant of the variety considered).

3.4.1. Near Future (2021-2050)

Figures 5(a)-(c) represent the standardized rainfall, maximum temperature, and minimum temperature anomaly curves and their associated five-year trends, respectively. The period 2021-2025 is marked by a strong increase in rainfall totals and less significant increasing and decreasing trends in maximum and minimum temperature, respectively. This rainfall variability is well marked with a growth rate of 0.41 while the thermal trends Tmax (growth rate 0.01) and Tmin (decay rate −0.05) are not well observed. The varieties M2593/92 (Equation (6)) and SP701006 (Equation (9)) would have an increase in yield due to the systematic and very marked increase in rainfall, while the varieties R579 (Equation (7)) and SP711406 (Equation (8)) would have a decrease in yield reflected by negative

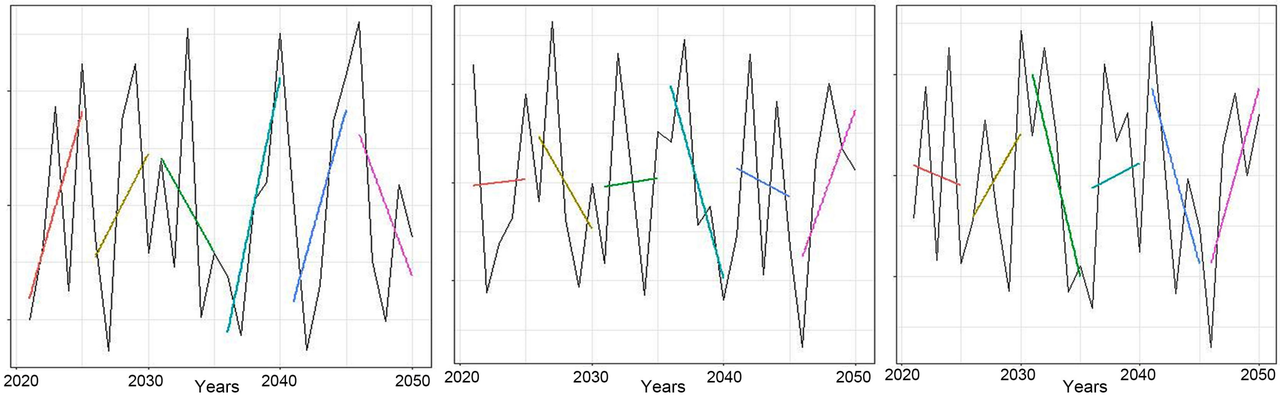

Figure 5. Evolution of standardized anomalies of rainfall (a), maximum temperature (b), and minimum temperature (c) in the near future (2021-2050).

sensitivity coefficients with rainfall (−0.02 Tonnes/mm) and minimum temperature (−19.37 Tonnes/˚C and −41.21 Tonnes/˚C respectively for varieties R579 and SP711406).

The period 2026-2030 is marked by an increasing trend in rainfall and minimum temperature with respective growth coefficients of 0.22 and 0.20, while maximum temperature is decreasing with a decreased coefficient of −0.23. The varieties M2593/92 and SP701006 could know under these conditions an increase or a decrease in yields depending on whether the impacts due to rainfall are more important than those due to the maximum temperature and vice versa. On the other hand, the varieties R579 and SP711406 systematically show a decrease in yield with the simultaneous increasing trends of rainfall and minimum temperature. The sensitivities of these varieties to rainfall and minimum temperature are negative, and any upward trend in either of these parameters results in a decrease in yield. The period 2031-2035 shows a slight upward trend in maximum temperature (growth coefficient of 0.02) while rainfall and minimum temperature show strong downward trends with respective decrease coefficients of −0.20 and −0.49. Thus, varieties M2593/92 and SP701006 would show a relative decrease (resp. increase) in yield with rainfall (resp. maximum temperature) as a controlling factor. The varieties R579 and SP711406, on the contrary, show a systematic increase in yield with any decrease in rainfall and/or minimum temperature. Both of these control factors show similar decreasing trends that could further reduce their yield sensitivities for varieties R579 and SP711406. Over the period 2036-2040, we see a strong decreasing trend in maximum temperature (decrease coefficient of −0.49) while rainfall and minimum temperature show increasing trends marked by respective growth rates of 0.56 and 0.06. Thus, the varieties M2593/92 and SP701006 would know an increase (resp. a decrease) in yields controlled by rainfall (resp. maximum temperature) while the yields of the varieties R579 and SP711406 would systematically decrease. The period 2041-2045 shows an increasing trend in rainfall (growth coefficient of 0.42) while the extreme thermal trends (maximum and minimum temperature) are decreasing with respective decrease coefficients of −0.07 and −0.43. These trends indicate an increase (resp. decrease) in the yields of the varieties M2593/92 and SP701006 due to rainfall (resp. maximum temperature), while the varieties R579 and SP711406 experience a decrease (resp. increase) in yields due to rainfall (resp. minimum temperature). Finally, over the period 2046-2050, the extreme thermal trends (maximum and minimum temperature) are increasing and present respective growth coefficients of 0.37 and 0.43, whereas the rainfall trend is decreasing with a decreased coefficient of −0.31. The yields of the varieties M2593/92 and SP701006 will decrease (resp. increase) with the rainfall (maximum temperature). On the other hand, those of the varieties R579 and SP711406 will increase (resp. decrease) with rainfall (resp. minimum temperature).

3.4.2. Far Future (2056-2075)

Figures 6(a)-(c) show the annual evolution of standardized anomalies of rainfall and maximum and minimum temperatures in the far future. We can see that over the period 2056-2060, the trends in rainfall and maximum temperature are decreasing with respective decrease coefficients of −0.50 and −0.05, while that of minimum temperature is increasing with a growth coefficient of 0.57. These trends have an impact on the variations of the yields of varieties M2593/92, SP701006, R579, and SP711406. In effect, the yields of the varieties M2593/92 and SP701006 would decrease (resp. increase) due to rainfall (resp. maximum temperature) while those of the varieties R579 and SP711406 would increase (resp. decrease) due to rainfall (resp. minimum temperature). The period 2061-2065 is marked by a decreasing trend in rainfall and maximum and minimum temperatures with decreasing coefficients of −0.36, −0.14 and −0.30 respectively. The yields of the varieties M2593/92 and SP701006 would systematically decrease due to rainfall and/or maximum temperature, while those of the varieties R579 and SP711406 would increase with a decrease in minimum temperature and/or rainfall. Over the period 2066-2070, we note slight upward trends in rainfall, and maximum and minimum temperatures with respective growth coefficients of 0.05, 0.02, and 0.14. The varieties M2593/92 and SP701006 will experience an improvement in yields due to rainfall and maximum temperature, whereas the yields of the varieties R579 and SP711406 will systematically decrease due to rainfall and minimum temperature. The period 2071-2075 is marked by an increasing trend in rainfall and decreasing extreme thermal trends (maximum and minimum temperature) with growth and decline coefficients of 0.29, −0.46, and −0.44 respectively. The yields of varieties M2593/92 and SP701006 will improve (resp. decrease) with rainfall (resp. maximum temperature) while those of varieties R579 and SP711406 will decrease (resp. increase) with rainfall (resp. minimum temperature).

4. Discussions

The climate change observed over the past decades is significant and the warming of the current and future climate systems is unequivocal. Indeed, the IPCC in its last report in 2007 informs of a global average surface temperature increase of +0.74˚C over 100 years (1906-2005) with a rate that has accelerated over the last 50 years to reach 0.13˚C per decade. Because of this climate change, the variability of the productivity of five sugarcane varieties (*i.e.* R579, SP711406, M2593/92, M1400/86, and SP701006) from the industrial plantations of the Ferkessédougou 1 sugar complex was analyzed. This analysis is a contribution to research efforts aimed at improving yields and increasing productivity in the Ferké sugar fields to support agricultural development and guarantee planters' incomes. In addition, the analysis of changes in climatic characteristics from 2013 to 2017 for each crop plot (**Figure 3**) hosting a given sugarcane variety highlights the climatic changes that have occurred relative to the reference climate for each variety. Globally, the changes were not significantly large on each crop plot. The average rainfall-thermal index (Ia) used to characterize the intensity of climate change did not show significant fluctuations from year to year. Indeed, these pluviothermal indices over the average period 2013-2017 indicate values within the range [1:2] characteristic of subhumid climatic zones in tropical and subtropical Africa [25] [34]; although some years (2013 and 2014 on plot B1 144 with the variety M2593/92) have Ia indices >2, given their respective rainfall of 1467.50 mm and 1578.5 mm and their respective temperatures of 27.41˚C and 27.88˚C (as an annual average), which give this corresponding plot a humid climate. Thus, these different results of the average climatic characteristics of the crop plots (B132, B1144, B231, B1111, and B221) (**Table 1**) over the period 2013-2017 show that the five sugarcane varieties are produced under their original climatic conditions, which are those of the humid tropical and subtropical regions of Île de la Réunion (variety R579), Île Maurice (varieties M1400/86 and M2593/92) and Sao Paulo (varieties SP711406 and SP701006). All these regions have a very marked climatic variability with two seasons: a rainy season from January to March in Reunion [35], from November to April in Mauritius [36], and from October to March in Sao Paulo [37], and a dry season from May to November in Reunion, from May to October in Mauritius and from May to September in Sao Paulo. The Ferkessédougou region, where the sugar complex is located, has the same climatic characteristics, namely two seasons: a rainy season from May to October and a dry season from November to April. The climate at the plot level offers favourable conditions for the cultivation of these five sugarcane varieties. However, **Figure 4** shows that the variability of yields of sugarcane varieties is very sensitive to the number of regrowths during the five-year vegetative cycle. The quality of annual yields from virgin cane R0 (2013) to the fourth regrowth R4 (2017) is highly variable and does not show any particular trend. But for the variety M1400/86, the yield generally increases from virgin cane R0 (2013) to the fourth regrowth R4 (2017). This suggests the existence of favourable conditions of global solar radiation (Rg) and potential evapotranspiration (ETP) in plot B132 (**Table 1**). The impacts of these conditions lead to values of Ia > 2 exceptionally in 2013 and 2014 (**Figure 3(a)**). These values of Ia highlighted the wet nature of the climate of the crop plot B132 housing the variety M1400/86 and whose linear model (Equation (5)) shows that global solar radiation (Rg) and potential evapotranspiration (ETP) are the only formal predictors of yield variability. For the other varieties, yields are paced by an alternating succession of decline and growth from the virgin cane R0 (2013) to the fourth regrowth R4 (2017). The causes are not well determined but various factors can be put forward such as cultivation methods (e.g. irrigation status, harvesting by burning, etc.). These cropping practices can lead to environmental problems and yield losses [23]. Previously, in the Niari Valley (Congo-Brazzaville), [38] highlighted the role of agricultural practices related to burning in sugarcane plantations in reducing soil organic matter enrichment through the double restitution of above- and below-ground plant residues, resulting in yield losses. More recently [39] highlight small yield losses after each cutting that intensify from year to year. Moreover, the cultural methods shown as one of the causes of variations in yields of sugarcane varieties from one regrowth to another, can be associated with the environmental and climatic parameters impacted by these methods. Indeed, the linear models developed (Equations (5) to (9)) only on these climatic parameters to the detriment of soil parameters (lack of reliable data) highlight the influence of climate on yield variability. **Table 2** clearly shows the primary role played by thermal extremes (maximum and minimum temperatures) and the total water supply (Et) received by each plot in defining the yields of the different sugarcane varieties in the Ferké 1 sugar complex. The different relationships established (Equations (5) to (9)) show strong values of the coefficient of determination $R^2 > 0.93$ significant (p-value < 0.5). For varieties M2593/92 and SP701006, the linear models (Equations (6) and (9)) show positive sensitivities to total water supply (Et) and maximum temperature (Tmax). While R579 and SP711406 varieties have linear models (Equations (7) and (8)) that show negative sensitivities to total water supply (Et) and minimum temperature (Tmin). These results show that while water supply by irrigation during the year can be very beneficial for the varieties M2593/92 and SP701006 (intensification of cultivation of these species, vector to fertilizing elements, renewal of fertility, etc.), it is on the other hand a process that can compromise the quality of annual yields of varieties R579 and SP711406. Indeed, given the proven impact of climate change on the frequency and intensity of extreme events in Africa [40] and particularly in Côte d'Ivoire [41] [42] [43], increasing the frequency of these extreme events, especially those related to rainfall, the supply of water to the cultivation plots by irrigation could create harmful conditions for certain sugarcane varieties and reduce their productivity. Also, too much irrigation can lead to problems in maintaining soil fertility, particularly the level of organic matter in the soil [44]. In addition, a decrease in fertility can be practically irreversible, despite the application of high doses of mineral fertilizer.

Furthermore, in the context of global climate change, particular attention is paid in this work to the predictability of yields of different sugarcane varieties in the study area to ensure food self-sufficiency. Indeed, the linear models (Equations (5) to (9)) showed quite strong and significant sensitivities with the total water supply (Et) to the crop plot, the maximum (Tmax) and minimum (Tmin) temperatures for the varieties M2593/92, SP701006, R579, and SP711406. Moreover, the different future climate projections through different scenarios of the 5th report of the Intergovernmental Panel on Climate Change (IPCC) are not in favour of any improvement in agricultural productivity. High uncertainty and variability of climate parameters such as precipitation and temperature are probable [45]. **Figure 5** and **Figure 6** show the projected changes in rainfall, and annual maximum and minimum temperatures in the near future (2021-2050) (**Figure 5**) and far future (2051-2075) (**Figure 6**). The effects of rainfall on yield predictability will not be discussed here, as the linear models do not explicitly show their sensitivities to these yields. The total water supply (Et) in the linear model equations is the contribution of rainfall and irrigation water supply to make up the rainfall deficit on a given plot. We will then assume that the water supply needed by the sugarcane is always satisfied on the different plots. We will also assume that linear models do not evolve fast enough in time and that changes due to external environmental constraints are not too important at the plot level. In this context, the significant yield sensitivities in the idealized models obtained (Equations (6) to (9)) will be discussed only for the extreme thermal parameters (maximum and minimum temperature) provided by the future climate projections. Since the M1400/86 variety (Equation (5)) does not show any explicit sensitivity to the maximum (Tmax) and minimum (Tmin) temperatures provided by future climate projections, its predictability in the near and far future will not be discussed. Thus, in the near future (2021-2050), the yields of varieties M2593/92 and SP701006 will vary quite significantly with maximum temperature (Tmax). This variability in yields will be reflected in increasing trends over the periods 2021-2025, 2031-2035, and 2046-2050 due to the increase in maximum temperature (Tmax) projected at average annual growth rates of 0.01˚C, 0.02˚C, and 0.37˚C respectively. In contrast, the periods 2026-2030, 2036-2040, and 2041-2050 show a decrease in yields associated with a decrease in Tmax at average annual rates of −0.23˚C, −0.49˚C, and −0.07˚C respectively. On the other hand, the effect of the variability of the minimum temperature (Tmin) will be reflected on the yields of the varieties R579 and SP711406 by trends towards an increase over the periods 2021-2025, 2031-2035 and 2041-2050 due to decreases in Tmin at the respective average annual rates of −0.05˚C, −0.49˚C, and −0.43˚C. And by trends of decreasing yields over the periods 2026-2030, 2036-2040, and 2046-2050 associated with increases in Tmin at average annual rates of 0.02˚C, 0.06˚C, and 0.43˚C respectively. The far future period (2056-2075) does not show a specific pattern for the variability of extreme thermal parameters (Tmax and Tmin) on sugarcane variety yields. Indeed, the yields of the varieties M2593/92 and SP701006 will decrease over the period 2056-2060, 2061-2070, and 2071-2075 due to decreases in Tmax at respective average annual rates of −0.05˚C, −0.14˚C and −0.46˚C. Only the period 2066-2070 shows a

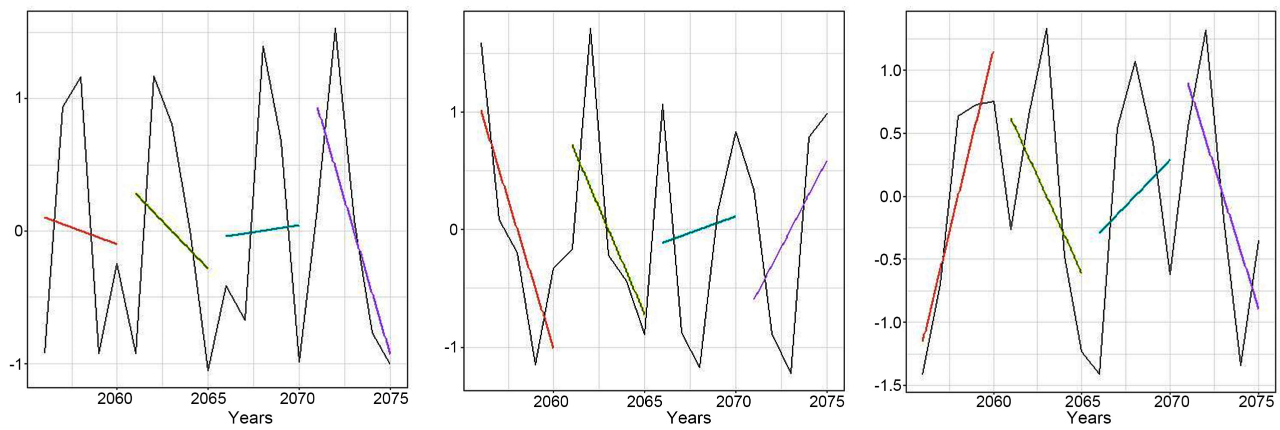

Figure 6. Evolution of standardized anomalies of rainfall (a), maximum temperature (b), and minimum temperature (c) in the distant future (2056-2075).

trend of increasing yields at the average annual Tmax growth rate of 0.02˚C. However, the yields of varieties R579 and SP711406 show growth trends over the periods 2061-2065 and 2071-2075 due to decreases in Tmin at the respective average annual rates of −0.30˚C and −0.44˚C while the periods 2056-2060 and 2066-2070 show a decrease in yields due to the increase in Tmin at the respective average annual rates of 0.57˚C and 0.14˚C. The impacts of temperature extremes (Tmax and Tmin) on agricultural yields have been much invested in [43] [46] since the various future climate projections through various reports of the Intergovernmental Panel on Climate Change (IPCC) have not shown indicators or patterns in favour of any improvement in agricultural productivity, particularly in West Africa [45]. The impacts of thermal extremes observed in the near and distant future on agricultural yields in general and on sugarcane varieties, in particular, are demonstrated. Indeed, every variety of sugar cane has its requirements about the climate in which it grows. These requirements translate into a certain number of climatic needs, including thermal needs for the accomplishment of its development. The thermal parameters can then constitute a limiting factor for the productivity of the sugarcane varieties either by excess or by default. Thermal extreme events associated with their respective variabilities can result in frequent occurrences of heat waves and frost events or cumulative effects whose contributions to agricultural production losses are demonstrated [43] [47]. In addition, work indicates that extreme temperature variabilities are often associated with the effects of greenhouse gas variations in the atmosphere [32] [48] [49].

5. Conclusion

The current study assessed the impact of climate conditions on the yields of five sugarcane varieties in the Ferkessédougou 1 sugarcane perimeter. The analysis mainly focused on the variation of the yields against global solar radiation (Rg), temperature, duration of insolation (Insol), potential evapotranspiration (ETP) and total water (Et). The results showed significant sensitivities of the yields of sugarcane varieties to climate parameters. At the scale of the cultivation plots, the values of the pluviothermal index Ia calculated indicate that these sugarcane varieties develop under climatic conditions identical to their regions of origin. The linear models established to evaluate the sensitivity of yields with climatic parameters show high values of significant coefficient of determination ($R^2 > 0.90$ and p-value < 0.5) for each variety. This highlights their dependencies on climate. This proven dependence on climate has also been highlighted by several works in the agricultural context. Furthermore, one of the causes of the variability of sugarcane yields is the number of production cycles of the varieties on a given plot. Indeed, the calculated yields vary with the quality of the regrowth of the sugarcane plants for each variety from virgin cane. However, this influence manifests itself differently from one variety to another, probably due to the involvement of other non-climatic factors and probably resulting from the consequences of irrigation and burning practices. The CMIP-5 climate projections also show the impacts of extreme thermal parameters (maximum and minimum temperatures) on the predictability of sugarcane variety yields in the near future (2021-2050) and in the distant future (2056-2075). These projected parameters may thus constitute a limiting factor for the producibility of sugarcane varieties either by excess or by default. These conclusions were obtained without taking into account the direct effects of rainfall, whose spatio-temporal variability has a severe impact on crops. Also, many studies continue to highlight its indispensable direct and/or indirect role on agricultural production. Thus, in this work, the direct impact of rainfall on the yields of sugarcane varieties is not explicitly evaluated by the established linear models (Equations (5) to (9)) because we have estimated that the total water supply to the plots by irrigation is completely assured. To improve the quality of climatic services dedicated to sugarcane to guarantee farmers' income in the context of climate change, it would be necessary and important to explicitly take into account the direct and/or indirect effects of rainfall on the Ferkessédougou sugar perimeter. Furthermore, the idealized linear models used in this study allowed us to observe the behavior of yields with respect to observed past climate conditions. Thus, for future yields, there is no way to know if these regressions have the ability to predict them since they are based on unrealistic projected weather conditions. Also, none of the regression equations were tested against independent observations. Furthermore, the idealized linear models used in this study allowed us to observe the behavior of yields with respect to observed past climate conditions. Thus, for future yields, there is no way to know if these regressions have the ability to predict them since they are based on projected weather conditions (*i.e.* CMIP5 data) marked by uncertainties. Additionally, none of the regression equations have been tested against independent observations.

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Conflicts of Interest

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

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