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Rainfall and Temperature Trend Analysis by Mann–Kendall Test and Significance for Rainfed Cereal Yields in Northern Togo

Agossou Gadedjisso-Tossou [1,*], Komlavi II Adjegan [2] and Armand Ketcha Malan Kablan [3,4]

[1] United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES), Ammonstrasse 74, 01067 Dresden, Germany
[2] Institut d'Étude du Développement Économique et Social (IEDES), Université Paris 1–Panthéon Sorbonne, 75231 Paris, France; komlavi-Ii.adjegan@anciens.univ-paris1.fr
[3] Unité de Formation et de Recherche des Sciences de la Terre et des Ressources Minières, Université Félix Houphouët Boigny (UFHB), 22 BP 582 Abidjan, Côte d'Ivoire; armand.kablan@csrs.ci
[4] Centre Suisse de Recherches Scientifiques en Côte d'Ivoire (CSRS), 01 BP 1303 Abidjan, Côte d'Ivoire
* Correspondence: gadedjissotossou@gmail.com

Abstract: This study investigates the trend in monthly and annual rainfall, minimum and maximum temperature (T_{min} and T_{max}) using the Mann–Kendall (MK) test and Sen's slope (SS) method and evaluates the significance of their variability for maize, sorghum and millet yields in northern Togo employing multiple regression analysis. The historical data of Kara, Niamtougou, Mango and Dapaong weather stations from 1977 to 2012 were used. Four non-parametric methods—Alexandersson's Standard Normal Homogeneity Test (SNHT), Buishand's Range Test (BRT), Pettitt's Test (PT) and Von Neumann's Ratio Test (VNRT)—were applied to detect homogeneity in the data. For the data which were serially correlated, a modified version of the MK test (pre-whitening) was utilised. Results showed an increasing trend in the annual rainfall in all four locations. However, this trend was only significant at Dapaong ($p < 0.1$). There was an increasing trend in T_{max} at Kara, Mango and Niamtougou, unlike Dapaong where T_{max} revealed a significant decreasing trend ($p < 0.01$). Similarly, there was an increasing trend in T_{min} at Kara, Mango and Dapaong, unlike Niamtougou where T_{min} showed a non-significant decreasing trend ($p > 0.05$). Rainfall in Dapaong was found to have increased (7.79 mm/year) more than the other locations such as Kara (2.20 mm/year), Niamtougou (4.57 mm/year) and Mango (0.67 mm). T_{max} increased by 0.13, 0.13 and 0.32 °C per decade at Kara, Niamtougou and Mango, respectively, and decreased by 0.20 per decade in Dapaong. Likewise, T_{min} increased by 0.07, 0.20 and 0.02 °C per decade at Kara, Mango and Dapaong, respectively, and decreased by 0.01 °C per decade at Niamtougou. Results of multiple regression analysis revealed nonlinear yield responses to changes in rainfall and temperature. Rainfall and temperature variability affects rainfed cereal crops production, but the effects vary across crops. The temperature has a positive effect on maize yield in Kara, Niamtougou and Mango but a negative effect on sorghum in Niamtougou and millet in Dapaong, while rainfall has a negative effect on maize yield in Niamtougou and Dapaong and millet yield in Mango. In all locations, rainfall and temperature variability has a significant effect on the cereal crop yields. There is, therefore, a need to adopt some adaptation strategies for sustainable agricultural production in northern Togo.

Keywords: trend analysis; Mann–Kendall test; Sen's slope estimator; linear regression; cereal yield; northern Togo

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1. Introduction

Climate change alters rainfall patterns and increases the occurrence of extreme events such as droughts and floods [1]. It is a reality that is affecting rural livelihoods in West Africa and presenting a growing challenge for future development in the region [2,3]. In

West Africa's countries, agriculture contributes more to reducing poverty than other sectors do [4]. This remains true because agriculture still constitutes the backbone of most West African economies.

Like other countries of the West Africa region, Togo is currently experiencing climate disruption [5]. This is characterised by irregularity in onset as well as overall shortening of the rainy season, delay of the arrival of potentially useful rains, poor distribution of rainfall over the year, high temperatures, drought spells and floods [6]. From 1961 to 2000, it was observed an average temperature increase of 0.5 to 0.8 °C from south to north, a decrease in rainfall and number of rainy days—deficit ranging from 2.22 through 3.3 mm per year to 10.6 to 14.4 days per year depending on the environment [5]. While the ratio between the levels of rainfall and evapotranspiration is below 0.75 in several locations, the increasing temperature shows a clear trend towards the arid climate [7]. Similarly, McSweeney et al. [8] observed an increase of 1.1 °C in the mean annual temperature since 1960 with an average of 0.24 °C rise per decade in Togo, while annual rainfalls are extremely variable on the inter-annual and inter-decadal timescale. These results were corroborated by the findings of Rehmani et al. [9]. Decreasing trends in annual rainfalls were observed by Djaman et al. [10]. These trends are likely to have significant impacts across Togo, where rainfed agriculture is widely practiced. Jalloh et al. [3] demonstrated, using climate model outputs, that Togo will experience a decrease in rainfall and an increase in temperature—increase between 1 °C and 2.5 °C by 2050. The same authors stated that Togolese farmers will likely experience rained maize yield losses up to 25% compared to the current yields. Furthermore, with subsistence agriculture based on cereals—maize, sorghum, rice and millet—grown extensively, it is observed a severe land degradation that affects at least 85% of arable land in northern Togo [11].

Togolese agriculture being vulnerable to climate change is of particular interest to policymakers because agriculture employs approximately 70% of the country's active population and plays a crucial economic and social role [12]. Bolor [13] and Jalloh et al. [3] stated that Togolese agriculture is predominantly rainfed. It contributes to food security, creates jobs and generates an income of livelihood for most of the population. Agriculture contributes to 38% of the gross domestic product in Togo—food crops 26.0%, cash crops 3.4%, livestock products 5.1%, fishery products and aquaculture 1.4% and forestry production 2.1% [12]. However, the Intergovernmental Panel on Climate Change (IPCC)'s 2025, 2050 and 2100 scenarios have predicted a reduction in the production of maize, sorghum and rice in Togo by 5%, 7% and 10%, respectively [14]. Similarly, employing a Ricardian modelling approach, Gadedjisso-Tossou et al. [15] showed that a variation in the temperature and rainfall is likely to significantly affect small-scale farmers' crop net income in Togo. This situation is more pronounced in northern Togo where farmers have only one growing season in a year [15].

In northern Togo, the climate is unfavourable to agricultural activities during the year for its uncertainties jeopardising crop yields. In other words, crop yields are usually low in northern Togo because of irregular rainfall, increase in the temperature, low soil fertility, reduced-quality seeds and inadequate land preparation instruments, among others [16]. Ali [17] assessed how climate variability influences main food crops production in northern Togo. His results showed that maize is the cereal at the greatest risk due to the inter-seasonal and the intra-seasonal variability of temperature and rainfall.

To understand the linkages between climate change and agriculture in northern Togo, scientific studies on that matter need to be carried out to improve cereal crop productivity. Regressing the historical crop yields against climate variables is a relatively accurate method for evaluating the influence of climate variability on the crop yields [17,18]. Koudahe et al. [19] used the Mann–Kendall test, Sen's slope estimator and multiple regressions technique to appraise the trends of the climatic variables and their influence on crops yields in southern Togo. Similarly, Ochieng et al. [20] used multiple regressions to evaluate the effects of climate variability and change on agricultural production in Kenya. These authors found that rainfall and temperature variability affect crops production, but the effects vary across crops. Karpouzos et al. [21] and Gajbhiye et al. [22] employed the Mann–Kendall test and Sen's slope estimator to investigate rainfall trends in Greece and India, respectively. The former study revealed a decrease in the rainfall, whereas in the latter study a significantly increasing rainfall trend in the seasonal, as well as annual, rainfall was identified. However, there are few studies to date that have assessed the significance of climate variability and changes for cereal crop yields in northern Togo. Therefore, the main aim of the present study was to appraise the significance of rainfall and temperature variability for some selected cereal crop yields in northern Togo by employing multiple regression analysis. For that, we investigated the trend in monthly and annual rainfall, monthly and annual minimum and maximum temperature applying the Mann–Kendall test and Sen's slope method. Before the trend analysis, the rainfall and temperature data were carefully assessed for homogeneity and serial correlation.

2. Materials and Methods

2.1. Study Area and Data Collection

Togo is a West African French-speaking country. The country is bordered by Ghana in the west and Benin in the east [16]. Togo is located between the latitudes 6° N and 11° N, and longitudes 0° E and 2° E. Its surface area is 56,600 km^2, and Togo has a long, narrow profile, elongating more than 550 km from north to south but not greater than 160 km in width [23]. The study sites are in northern Togo (Figure 1). Historical climate observations, including monthly rainfall (R), maximum and minimum temperatures (T_{max}, T_{min}) were obtained from selected meteorological stations for the study viz. Kara, Niamtougou, Mango and Dapaong (Figure 1)—courtesy of Togolese National Weather Service (Direction Nationale de la Météorologie). They are the only available meteorological stations in the study area. Additionally, these stations were selected based on data availability.

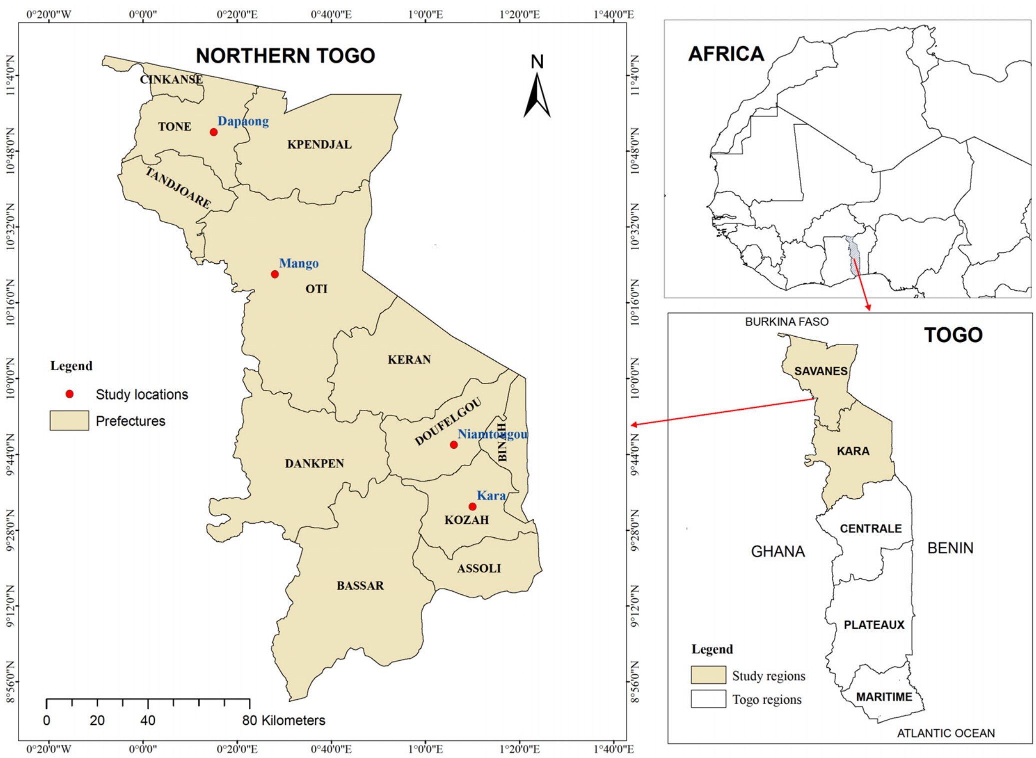

Figure 1. Map of the study sites (northern Togo).

The dataset ranges from 1977 to 2012 for all the stations (Table 1; Figure 2). This range of years was selected for data quality reasons. These stations are set in rural areas and close to agricultural rainfed lands. The vicinity of where the meteorological instruments are installed is covered with grass (Table 1). The climate data used in this study were carefully processed for missing values and quality checked before using them for any analysis. There were no missing values in rainfall as well as temperature data from 1977 through 2012 for all the stations selected in this study. Crop yields data, which include maize, sorghum, and millet—the major rainfed cereals grown in northern Togo—were provided by Direction des Statistiques Agricoles de l'Informatique et de la Documentation du Togo (DSID). These data range from 1990 to 2012.

Table 1. Metadata for the selected meteorological stations used in the study.

Stations	Latitude	Longitude	Elevation AMSL * (m)	Study Period	Number of Years	Ground Cover	Environment	Setting
Kara	9.55	1.17	341	1977–2012	36	Grass	Rainfed	Rural
Niamtougou	9.77	1.10	343	1977–2012	36	Grass	Rainfed	Rural
Mango	10.37	0.47	146	1977–2012	36	Grass	Rainfed	Rural
Dapaong	10.86	0.25	330	1977–2012	36	Grass	Rainfed	Rural

* AMSL = Above Mean Sea Level. Source: National Weather Service of Togo.

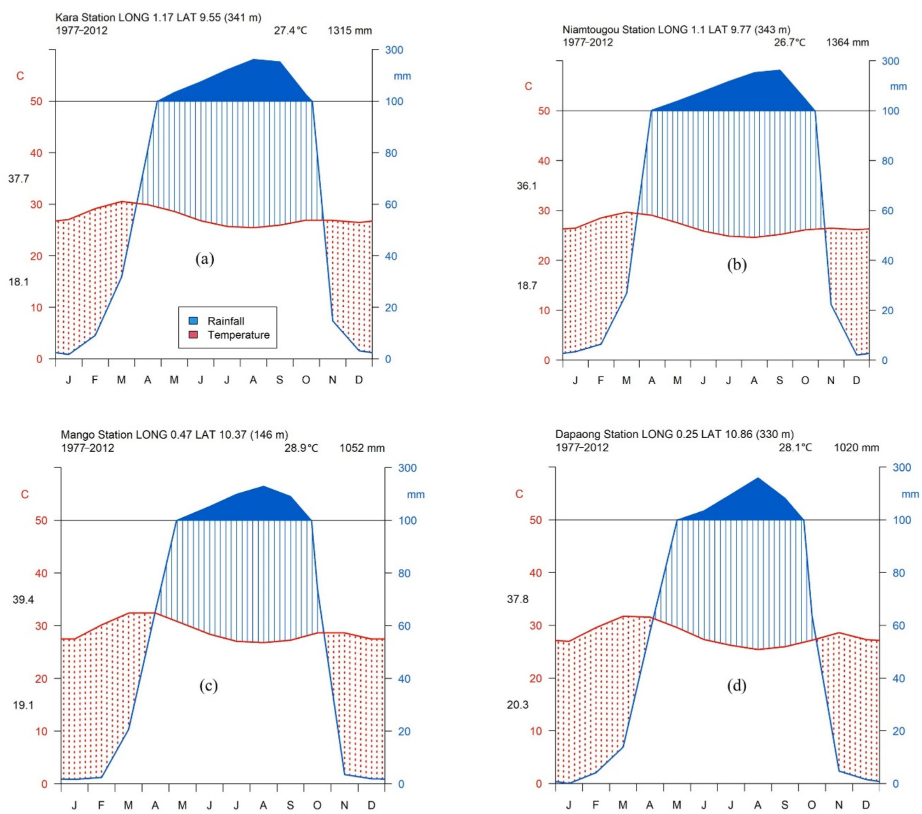

Figure 2. Walter–Lieth (1967) climate diagrams for northern Togo based on data collected at four meteorological stations: (**a**) Kara, (**b**) Niamtougou, (**c**) Mango and (**d**) Dapaong. The values at the top of the graphs indicate the long-term annual mean temperature and total rainfall. The value at the top left of the temperature axis stands for the mean of the average daily maximum temperature of the hottest month; the value at the bottom of the same axis represents the mean of the average daily minimum temperature of the coldest month. The horizontal black line at 100 mm and 50 °C illustrates the threshold beyond which rainfall scales by factor 10. The blue line represents the annual cycle of monthly rainfall. The red line indicates the annual cycle of monthly mean temperature. The area with blue shaded lines illustrates the humid conditions below the threshold, whereas the area dotted in red indicates the arid conditions. The area filled in blue shows the humid conditions above threshold (excess of water).

2.2. Climatic Variables Trend Analysis

2.2.1. Homogeneity Analysis

Alexandersson's Standard Normal Homogeneity Test (SNHT) [24], Buishand's Range Test (BRT) [25], Pettitt's Test (PT) [26] and Von Neumann's Ratio Test (VNRT) [27] at a 5% significance level were used to assess the homogeneity of the monthly and annual time series of R, T_{max} and T_{min}. These tests were performed under two hypotheses: H_0 (null hypothesis), data are homogeneous; and Ha (alternative hypothesis), there is a date at which there is a change in the data. When a *p*-value is lower than the significance level 5%, one should reject H_0 and accept Ha. To evaluate the results of these four tests, we made a classification based on the number of tests rejecting H_0 [28–30]. They are (i) Class A which stands for "Useful"—when none or only one of the above four tests rejects H_0; (ii) Class B which represents "Doubtful"—when two of the four tests reject H_0; and (iii) Class C which is "Suspect"—when three or all the tests reject H_0.

2.2.2. Mann–Kendall Test and Sen's Slope Method

The Mann–Kendall (MK) test [31,32] was employed to assess the trends in rainfall, T_{max} and T_{min}. It is a non-parametric test, which has no prerequisite conditions on the data to be normally distributed [33]. The MK test is grounded on a null hypothesis (H_0), which indicates that there is no trend—the data are independent and randomly ordered—and this is verified against the alternative hypothesis (Ha), which supposes that there is a trend [19]. The true slope (change per unit time) was predicted using Sen's slope (SS) estimator [34]. The results of the MK test are likely to be affected by the presence of autocorrelation in time series data; therefore, a serial correlation test was carried out before the MK. This was done by computing the lag-1 serial correlation coefficient r_1 for a two-tailed test at a 5% significance level [29,35]:

$$r_1 = \frac{\sum_{i=1}^{n-1}\left(X_i - \overline{X}\right)\left(X_{i+1} - \overline{X}\right)}{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2} \quad (1)$$

where X_i is a value of an observation of time series data, $\overline{X}$ represents the mean of the sample of time series data and n is the sample size. The autocorrelation coefficient values were tested against the following equation:

$$r_1(95\%) = \frac{-1 \pm 1.96\sqrt{(n-2)}}{n-1} \quad (2)$$

The time series data were considered serially correlated when r_1 lies between the upper and lower limits of the confidence interval. Thus, the Trend-Free Pre-Whitening (TFPW) [36] approach which is a modified MK test was used. The R package "modifiedmk" [29] was used to perform the above mentioned non-parametric tests.

2.2.3. Linear Regression

The trends in the climatic time series data were analysed using a linear regression technique. The slope of the regression analysis stands for the mean temporal change in the considered variable. In addition, the total change throughout a decade was obtained by multiplying the Sen's slope by 10 years [19,33].

2.3. Assessment of the Significance of Temperature and Rainfall Variability for Crop Yields

Multiple linear regression analysis was performed to evaluate the significance of rainfall and temperature variability for the major cereals grown in northern Togo under rainfed conditions. By adapting the production function used in Ochieng et al. [20], we obtained the following Equation (3):

$$lnY = \alpha + aR + bR^2 + cT + dT^2 + e(R * T) + \mu \quad (3)$$

where lnY represents the natural logarithms of the crop yield (kg ha^{-1}); a, b, c, d and e are the related coefficients of rainfall, squared rainfall, average temperature, the squared average temperature and the combined effect of rainfall and temperature under the growing season (May to October), respectively. α is a constant, and μ represents the error term or the omitted variables which may influence the crop yield. R software [37] was used to perform the statistical analysis, as well as the figures in this study. When the t-statistics probability is smaller than a given significance level, then the variable in question significantly influences the crop yield at that significance level.

To avoid potential cases of heteroskedasticity the crop yield data were log-transformed. As performed by other authors [18,38], the trends in the climatic or yield data were removed by employing the difference between each value and the previous year value to minimise the influence of long-term trends. The variance inflation factor (VIF) was used to test the extent of multicollinearity among the explanatory variables in the regression model. There is no formal VIF cut-off value to detect the presence of multicollinearity; however, Alauddin and Nghiemb [39] suggested a VIF cut-off point of 10, because a value higher than 10 is often used as a sign of potential multicollinearity problems.

3. Results and Discussion

3.1. Homogeneity of Rainfall and Temperature Data

In the first case, the homogeneity tests were performed on the time series of annual rainfall and maximum and minimum temperature (Table 2). The results indicated that for rainfall all the stations were labelled "useful". This means that the rainfall annual time series data used in this study were not erroneous. No large impact on the variations of environmental traits was likely identified for all the stations [30]. The SNHT detected an inhomogeneity (break point) around 1979 and 1991 for Dapaong station. This indicated that there was a recession in rainfall until 1979 and 1991 for Dapaong station. Then, after the break point, more rainwater came in.

Table 2. Summary of homogeneity results of the annual rainfall (mm) and temperature data (°C).

Stations	SNHT		BRT		PT		VNRT		Evaluation
	To	*p*-Value	Q	*p*-Value	K	*p*-Value	N	*p*-Value	
				Rainfall (mm)					
Kara	1.590	0.933	1.788	0.743	29	0.816	1.633	0.129	Useful
Niamtougou	4.181	0.368	0.801	0.898	21	0.879	2.003	0.502	Useful
Mango	1.851	0.877	2.722	0.555	57	0.562	1.997	0.497	Useful
Dapaong	8.901 (1979, 1991) *	0.026	0.000	0.961	0	0.974	1.741	0.222	Useful
				Maximum Temperature (°C)					
Kara	21.034 (1987, 1994, 2001) *	0.000	0.000	0.966	0	0.972	0.752	0.125	Useful
Niamtougou	16.083 (1997, 2002, 2008) *	0.001	0.886	0.894	13	0.926	1.004	0.251	Useful
Mango	15.530 (1997, 1980, 2008) *	0.001	0.293	0.951	5	0.954	1.329 *	0.021	Doubtful
Dapaong	11.303 (1979, 1985, 1991) *	0.005	0.252	0.948	158	0.940	1.208 *	0.005	Doubtful
				Minimum Temperature (°C)					
Kara	10.892 (1986, 2001) *	0.016	0.788	0.881	10	0.941	1.126 *	0.002	Doubtful
Niamtougou	6.209	0.148	3.752	0.377	92	0.264	1.495	0.063	Useful
Mango	16.140 (1980, 2002) *	0.000	0.000	0.968	0	0.973	0.897 *	0.000	Doubtful
Dapaong	12.598 (1979, 1995, 2008) *	0.006	0.214	0.949	15	0.915	0.605	0.162	Useful

* Indicates the inhomogeneous stations at 5% significance level; the values in the parentheses represent the break point years (Von Neumann's Ratio Test (VNRT) gives no information about the break point); To, Q, K, and N stand for the resulting coefficients of the different tests.

Regarding the maximum temperature, Kara and Niamtougou stations were revealed "useful". Similarly, for minimum temperature, Niamtougou and Dapaong stations were classified "useful". This indicates that in the maximum and minimum temperature time series data there might likely be instrumentation error, variation in the nearest areas of the instruments and/or mishandling of the observer for the stations which are not classified "useful" [29]. Multiple break points were detected in the minimum and maximum temperatures at some stations.

In the second case, the homogeneity tests were performed on the time series of monthly rainfall and maximum and minimum temperature (Table 3). A total of 144 series (12 months, 4 stations and 3 climate variables) were tested. The results showed that 122 of the total time series assessed were labelled "useful". Like the annual rainfall data, the monthly time series rainfall data turned out to be mainly "useful" for all the stations. Considering all the stations, the maximum and minimum temperatures time series data of March, July, August, and December were more doubtful than the other months. This may be explained by the fact that in northern Togo where these stations are located, in March every year the climatic conditions are harsh—presence of harmattan, dust and high wind speed—making it difficult for workers to concentrate at work. Additionally, the end-of-year celebrations (Christmas and new year) planning distracts workers at work. This may lead to errors in the recording of the climatic data by the observers.

Table 3. Summary of homogeneity results of the monthly rainfall (mm) and temperature data (°C).

Stations	January	February	March	April	May	June	July	August	September	October	November	December
Rainfall (mm)												
Kara	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful
Niamtougou	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful
Mango	Useful	Useful	Doubtful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful
Dapaong	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful
Maximum Temperature (°C)												
Kara	Useful	Useful	Doubtful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Doubtful
Niamtougou	Useful	Useful	Useful	Useful	Useful	Doubtful	Useful	Useful	Useful	Useful	Useful	Doubtful
Mango	Useful	Useful	Doubtful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Doubtful
Dapaong	Useful	Useful	Useful	Useful	Useful	Useful	Doubtful	Suspect	Suspect	Doubtful	Useful	Useful
Minimum Temperature (°C)												
Kara	Useful	Doubtful	Useful	Useful	Useful	Useful	Doubtful	Doubtful	Useful	Doubtful	Useful	Useful
Niamtougou	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful
Mango	Useful	Useful	Doubtful	Useful	Useful	Doubtful	Doubtful	Doubtful	Doubtful	Useful	Useful	Useful
Dapaong	Useful	Useful	Doubtful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Useful	Doubtful

3.2. Serial Correlation Analysis

Each station has 13 series (12 monthly and 1 annual). Considering rainfall, maximum and minimum temperatures for four stations, there were a total of 156 time series (13 × 3 × 4) which were subjected to serial correlation tests. The results of this study indicated that 42 series were serially correlated. This represents 26.92% of the total number of time series assessed (Table 4). Like in the case of the homogeneity tests, the annual rainfall data revealed no serial correlation for all the stations; however, the annual maximum and minimum temperatures data were mainly serially correlated considering all the stations. In addition, the monthly maximum and minimum temperatures time series data of March, July, August and December were found more serially correlated than the other months.

Table 4. Summary of serial correlation results of the rainfall (mm) and temperature data (°C).

Stations	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Rainfall (mm)													
Kara	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
Niamtougou	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
Mango	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
Dapaong	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
Maximum Temperature (°C)													
Kara	FALSE	FALSE	TRUE	FALSE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Niamtougou	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	TRUE	TRUE
Mango	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Dapaong	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	FALSE	TRUE	TRUE	TRUE	FALSE	FALSE	TRUE
Minimum Temperature (°C)													
Kara	FALSE	FALSE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	TRUE
Niamtougou	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
Mango	FALSE	TRUE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	TRUE
Dapaong	FALSE	FALSE	TRUE	FALSE	TRUE	FALSE	FALSE	TRUE	FALSE	TRUE	TRUE	TRUE	TRUE

FALSE = absence of serial correlation; TRUE = presence of serial correlation.

3.3. Trend in Climatic Variables

Figure 2 shows that in northern Togo there is a single rainy season in a year, which ranges from May through October. This compels farmers to adopt intercropping (cereals and legumes) to obtain a range of crops they need in a year because the agriculture is predominantly rainfed in northern Togo [16]. The long-term annual mean total rainfalls for Kara, Niamtougou, Mango and Dapaong were 1315, 1364, 1052 and 1020 mm, respectively. Figure 2 shows that the mean daily maximum temperatures of the driest months were 37.7, 36.1, 39.4 and 37.8 °C in Kara, Niamtougou, Mango and Dapaong, respectively. Because these locations are in similar climatic zones, the abovementioned mean values (rainfall and temperatures) are relatively close to each other. The long-term average temperatures were 27.4, 26.7, 28.9 and 28.1 °C in Kara, Niamtougou, Mango and Dapaong, respectively. These values are similar to the ones reported by Asamoah and Ansah-Mensah [40] in northern Ghana.

Figure 3 represents the time series annual rainfall in northern Togo. There is an increase in the inter-annual rainfall at all the locations. The annual rainfall varied with location and ranged from a maximum of 1832 mm recorded in 2009 at Niamtougou (Figure 3b) to a minimum of 743 mm at Mango in 2001 (Figure 3c).

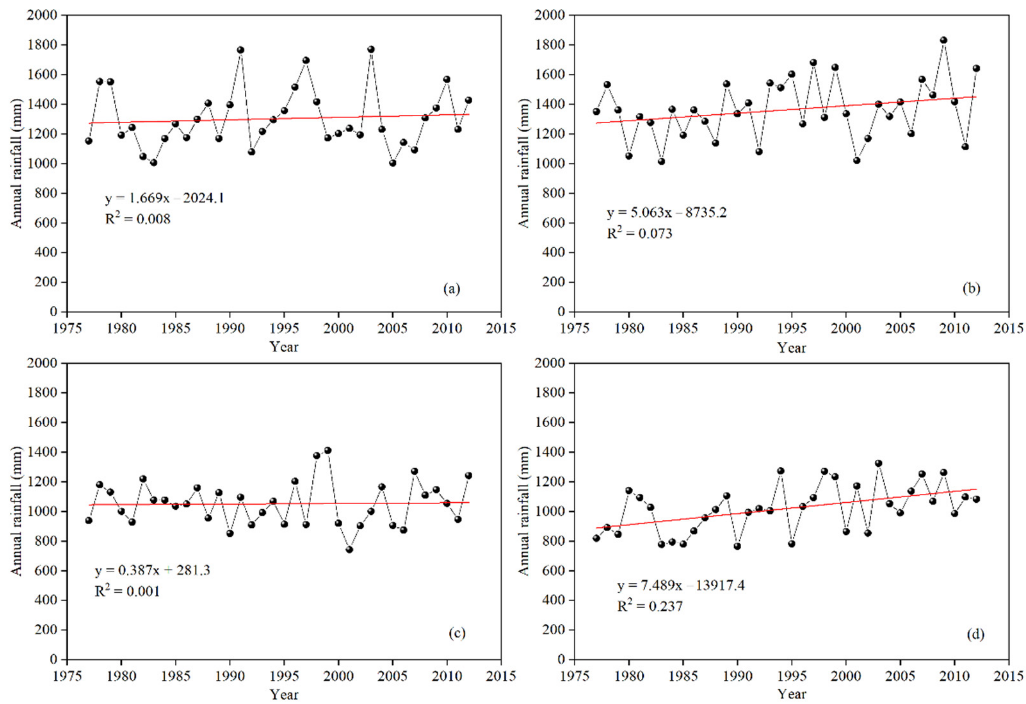

Figure 3. Annual total rainfall at (**a**) Kara, (**b**) Niamtougou, (**c**) Mango and (**d**) Dapaong.

At Kara, annual rainfall varied from 1004 to 1771 mm. A non-significant increasing trend ($p > 0.05$) in the annual rainfall was observed in Kara (Table 5). The annual rainfall at Niamtougou ranged from 1016 mm in 1983 to 1832 mm in 2009 with a non-significant increasing trend ($p > 0.05$). The annual rainfall at Mango fell within the range of 743–1411 mm. A non-significant increasing trend ($p > 0.05$) in the annual rainfall was observed at Mango. At Dapaong, mean annual rainfall varied from 765 mm (1990) to 1325 mm (2003) with a significant increasing trend ($p < 0.1$) (Table 5). Rainfall in Dapaong was found to have increased (7.79 mm/year) more than the other locations such as Kara (2.20 mm/year), Niamtougou (4.57 mm/year) and Mango (0.67 mm) (Table 5). These findings were corroborated by Gadedjisso-Tossou [41] who reported an increasing trend in the long-term annual rainfall in northern Togo. Maize and sorghum are particularly vulnerable to water stress during the vegetative stage of their development [42]. The uneven distribution of the rainfall observed in northern Togo usually leads to dry spells in the growing season. When the vegetative stage coincides with dry spells this leads to a decline in the productivity, which is followed by cereal price escalation. As a result, food security is threatened, and farmers' livelihood is at risk. The fact that there is a single rainy season in northern Togo does not give farmers the chance to catch up with a rainy season. This situation compels farmers to travel to other places in search of non-agricultural jobs if the only rainy season is not good for them.

Table 5. Summary of the modified Mann–Kendall (MK) test and Sen's Slope test (SS) (Trend-Free Pre-Whitening) of the annual total rainfall (mm) and annual minimum and maximum temperature (°C).

Stations	First Year	Last Year	Mean	MK	SS
			Rainfall (mm)		
Kara	1977	2012	1315	0.858	2.199
Niamtougou	1977	2012	1364	1.621	4.567
Mango	1977	2012	1052	0.232	0.667
Dapaong	1977	2012	1020	2.683 **	7.790
			Maximum temperature (°C)		
Kara	1977	2012	33.7	1.621	0.013
Niamtougou	1977	2012	32.4	1.703 †	0.013
Mango	1977	2012	35.2	3.337 ***	0.032
Dapaong	1977	2012	33.5	−1.921 †	−0.020
			Minimum temperature (°C)		
Kara	1977	2012	21.2	0.9126	0.007
Niamtougou	1977	2012	21.0	−0.055	−0.001
Mango	1977	2012	22.6	2.275 *	0.018
Dapaong	1977	2012	22.7	0.177	0.002

***: $\alpha = 0.001$; **: $\alpha = 0.01$; *: $\alpha = 0.05$; †: $\alpha = 0.1$ level of significance.

The results depicted in Table 6 show an increasing trend in rainfall during the growing season at Kara in June, August, September, and October. This trend was significant in September and October at 10%. During the growing season in Niamtougou, July, August, September, and October revealed an increasing trend. Only in October was the trend significant at 5%. In Mango in May, June, and October the rainfall showed an increasing trend in the growing season. This trend was only significant in May at 5%. These findings are in agreement with that of Asamoah and Ansah-Mensah [40], who found a rising trend in the rainfall in northern Ghana. These results also corroborate that of Ezin et al. [43], who observed similar trends for rainfall in northern Benin. However, in Dapaong, only July showed a decreasing and non-significant trend in the growing season (Table 6). During the growing season, September had the highest rainfall with 269 mm in Niamtougou, and August had the highest rainfall in Kara, Mango and Dapaong with 258, 230 and 260 mm, respectively (Table 6). Amongst the four study sites, Niamtougou had the highest monthly average rainfall with 269 mm obtained in September. These findings indicated that the peak of the growing season rainfall occurred in August in northern Togo, as observed by Djaman et al. [10], Adewi et al. [5] and Seguis [44]. The diversity in the trends of rainfall across locations is likely because Dapaong is in a dry savannah area; however, the other study stations are situated in a humid savannah area.

Figure 4 shows the long-term trend in the minimum temperature (T_{min}) at Kara, Niamtougou, Mango and Dapaong. The annual average T_{min} from 1977 to 2012 at Kara, Niamtougou, Mango and Dapaong was 21.2, 21.0, 22.6 and 22.7 °C, respectively (Figure 4; Table 5). Annual average T_{min} varied from 19.3 to 22.9 °C at Kara, from 20.0 to 21.7 °C at Niamtougou, from 21.6 to 23.5 °C at Mango and from 21.0 to 23.8 °C at Dapaong (Figure 4). There was an increasing trend in T_{min} at Kara, Mango and Dapaong during the period 1977 to 2012, unlike Niamtougou where T_{min} showed a non-significant decreasing trend. T_{min} increased by 0.07, 0.20 and 0.02 °C per decade at Kara, Mango and Dapaong, respectively (Table 5). However, T_{min} decreased by 0.01 °C per decade at Niamtougou (Table 5).

Table 6. Summary of the modified Mann–Kendall (MK) test and Sen's Slope test (SS) (Trend-Free Pre-Whitening) of the monthly rainfall (mm) in Kara, Niamtougou, Mango and Dapaong.

Months	Kara			Niamtougou			Mango			Dapaong		
	Mean	MK	SS	Mean	MK	SS	Mean	MK	SS	Mean	MK	SS
						Rainfall (mm)						
January	2	−0.063	0.000	3	1.856 †	0.000	2	0.429	0.000	0	1.380	0.000
February	8	1.479	0.000	8	2.381 *	0.000	2	0.988	0.000	4	2.583 **	0.000
March	29	−1.280	−0.392	30	−1.308	−0.449	21	−1.737 †	−0.353	14	−1.635	−0.213
April	81	−0.477	−0.368	99	0.368	0.298	66	0.177	0.125	57	1.376	0.540
May	133	−1.376	−0.930	142	−0.776	−0.872	110	2.207 *	1.508	100	1.539	0.769
June	176	0.068	0.137	175	−0.123	−0.137	153	0.558	0.510	136	2.207 *	1.861
July	217	−0.722	−0.843	226	0.286	0.344	199	−0.341	−0.606	197	−0.341	−0.287
August	258	0.599	1.043	252	0.776	0.870	230	0.000	−0.009	260	0.940	1.601
September	252	1.784 †	1.640	269	1.321	1.367	191	−1.063	−1.022	182	1.757 †	1.629
October	129	1.839 †	1.767	143	1.962 *	1.840	74	0.776	0.525	64	0.640	0.416
November	16	−0.057	0.000	22	−0.368	−0.112	4	0.124	0.000	5	0.345	0.000
December	3	−0.583	0.000	3	−0.337	0.000	2	−1.572	0.000	1	−2.642 **	0.000

**: α = 0.01; *: α = 0.05; †: α = 0.1 level of significance.

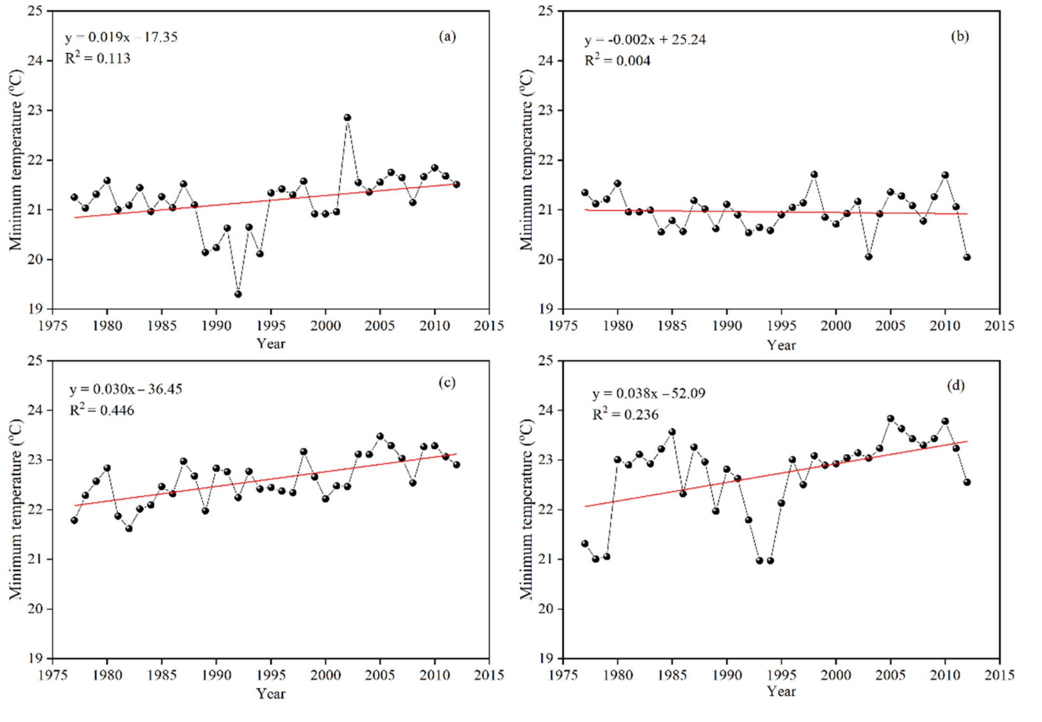

Figure 4. Annual minimum monthly temperature at (**a**) Kara, (**b**) Niamtougou, (**c**) Mango and (**d**) Dapaong.

Figure 5 shows the long-term trend in the maximum temperature (T_{max}) at Kara, Niamtougou, Mango and Dapaong. The annual average T_{max} from 1977 to 2012 at Kara, Niamtougou, Mango and Dapaong was 33.7, 32.4, 33.6, and 35.1 °C, respectively (Figure 5, Table 5). Annual average T_{max} varied from 32.7 to 34.8 °C at Kara, from 31.7 to 33.2 °C at Niamtougou, from 34.3 to 36.2 °C at Mango and from 32.4 to 34.9 °C at Dapaong (Figure 5). There was an increasing trend in T_{max} at Kara, Mango and Niamtougou, unlike Dapaong where T_{max} showed a significant decreasing trend ($p < 0.1$) (Table 5). T_{max} increased by 0.13, 0.13 and 0.32 °C per decade at Kara, Niamtougou and Mango, respectively, and decreased by 0.20 per decade in Dapaong. These findings are consistent with that of the United States Geological Survey (USGS) [45], who assessed the climate trend in Burkina Faso (1975–2009) and indicated that temperature has increased by 0.15 °C per decade across most Burkina Faso. The results suggest that, due to these high temperatures and their increasing trend, it is likely that the evapotranspiration is relatively high in northern Togo. This contributes to lessening the cereal crop yields obtained by farmers in northern Togo as observed by Djaman and Ganyo [46] and Gadedjisso-Tossou et al. [16].

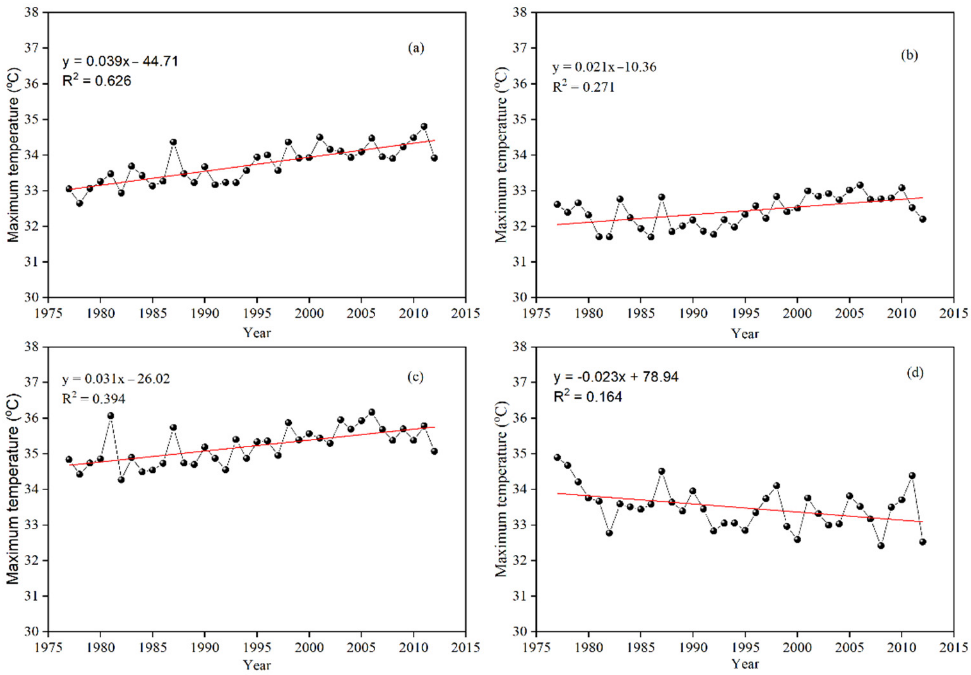

Figure 5. Annual maximum monthly temperature at (**a**) Kara, (**b**) Niamtougou, (**c**) Mango and (**d**) Dapaong.

The trend analysis in monthly T_{min} and T_{max} is presented in Table 7. For all four stations, the trend in T_{min} revealed an increasing trend for all months except January, March, November and December at Niamtougou station, which showed a decreasing trend. However, T_{max} showed an increasing trend at Kara, Niamtougou and Mango for all months. This is in line with the results of the trend analysis of the annual maximum and minimum temperatures presented in Table 5. This is similar to the findings of Nyuor et al. [47], who assessed the impacts of climate change on cereal production in northern Ghana from 1974 to 2013 and came to the conclusion that both temperature and rainfall exhibited an increasing trend. It is evident from the results that maximum temperature increased more rapidly than the minimum temperature in northern Togo (Table 7; Figures 4 and 5). This may lead to an increase in the daily mean temperatures and a higher likelihood of extreme events, which have detrimental effects on cereal crop production in northern Togo. The increase in the daily temperatures leads to a rise in evapotranspiration, which defines the crop yields and farmers' livelihood in northern Togo [42]. This justifies the fact that most farmers in northern Togo use short-cycle variety crops to avoid the vagaries of the climate [42]. In other words, the use of drought-tolerant and short-cycle seeds is becoming more usual in northern Togo, which lessens the risk of crop failure due to continued dry spells and high temperatures. Warmer temperatures are detrimental to crop growth, especially in the vegetative stage because pollination is highly sensitive to temperature extremes for all cereals, with maize in particular [48]. In northern Togo where rainfall is unevenly distributed during the growing season, the negative effect of warmer temperatures on pollination will be worsened when a dry spell occurs within the vegetative stage of the plant development. Whereas, for the T_{max}, Dapaong station showed a decreasing trend (Table 7). Most of these trends were significant, especially in the growing season. This would likely impact the development of the plants and the crop yield farmers obtain at the end of the season. In other words, the crops would experience heat stress which could lead to low crop yields. These findings corroborate that of Sultan et al. [49], who evaluated the impacts of climate change on sorghum and millet yields in West Africa and found that the probability of a crop yield reduction due to climate change is more important in southern Senegal, Mali, Burkina Faso, northern Togo and Benin than the rest of West Africa. Similarly, Roudier et al. [50] predicted that the crop yield drop will be more pronounced in northern West Africa than in southern West Africa. These findings are in line with that of Lemi and Hailu [51], who pointed out that West Africa will experience the greatest crop yield loss in Africa due to climate variability and change. Northern Togo is at the boundary of the African Sahel but is not located in the Sahel itself. Thus, its climate is highly variable and unpredictable due to the influence of the Sahel. This could be the reason for such a variability in the temperatures and rainfall in the area.

Table 7. Summary of the modified Mann–Kendall (MK) test and Sen's Slope test (SS) (Trend-Free Pre-Whitening) of the monthly minimum and maximum temperature (°C) in Kara, Niamtougou, Mango and Dapaong.

Months	**Kara**			**Niamtougou**			**Mango**			**Dapaong**		
	Mean	**MK**	**SS**	**Mean**	**MK**	**SS**	**Mean**	**MK**	**SS**	**Mean**	**MK**	**SS**
Maximum Temperature (°C)												
January	35.1	1.472	0.027	33.7	1.022	0.016	35.6	0.463	0.013	33.6	−0.191	−0.003
February	37.1	2.249 *	0.031	35.6	0.668	0.012	38.1	1.798 †	0.039	36.1	−0.150	−0.005
March	37.7	1.866 †	0.031	36.1	3.341 ***	0.040	39.4	2.111 *	0.030	37.8	0.504	0.009
April	36.0	1.554	0.028	34.6	1.022	0.015	38.6	0.109	0.001	37.1	−1.689 †	−0.022
May	33.9	1.103	0.015	32.6	1.785 †	0.025	35.7	1.200	0.026	34.6	−1.485	−0.028
June	31.7	1.648 †	0.019	30.3	0.546	0.005	33.1	2.821 **	0.039	31.7	−1.785 †	−0.030
July	29.9	1.893 †	0.021	28.8	1.254	0.015	31.4	2.849 **	0.032	30.0	−2.385 *	−0.032
August	29.6	3.041 **	0.028	28.4	0.968	0.012	31.0	2.385 *	0.022	29.2	−1.430	−0.016
September	30.9	1.540	0.016	29.8	1.294	0.011	32.1	2.330 *	0.022	30.4	−1.376	−0.016
October	32.9	2.468 *	0.030	31.7	0.668	0.010	34.9	1.962 *	0.022	32.1	−1.485	−0.041
November	35.0	2.698 **	0.049	33.8	0.273	0.004	36.9	3.964 ***	0.049	35.2	−0.422	−0.004
December	34.8	1.921 †	0.030	33.6	1.076	0.016	35.8	1.648 †	0.039	34.0	1.744 †	0.034
Minimum temperature (°C)												
January	19.0	0.450	0.007	19.2	−1.267	−0.023	19.3	1.349	0.031	20.3	2.316 *	0.075
February	21.2	1.499	0.028	21.4	0.000	0.000	22.2	0.967	0.028	23.0	2.289 *	0.057
March	23.4	0.558	0.007	23.2	−0.068	0.000	25.4	3.338 ***	0.062	25.6	1.240	0.021
April	23.8	−0.095	0.000	23.4	−0.737	−0.006	26.2	−0.232	−0.002	26.0	1.063	0.011
May	23.3	1.716 †	0.017	22.4	0.259	0.003	25.1	0.899	0.011	24.5	−0.667	−0.009
June	21.9	0.232	0.002	21.4	0.014	0.000	23.7	0.558	0.006	22.9	1.335	0.012
July	21.5	0.858	0.010	20.9	2.100 *	0.020	22.7	1.662 †	0.008	22.4	1.908 †	0.018
August	21.3	0.749	0.011	20.8	2.048 *	0.015	22.6	2.193 *	0.015	21.6	1.022	0.006
September	21.0	0.790	0.005	20.6	0.874	0.006	22.4	1.703 †	0.013	21.5	1.826 †	0.015
October	20.9	0.477	0.003	20.5	1.049	0.009	22.4	1.539	0.014	22.2	0.000	0.000
November	18.7	0.940	0.017	19.1	−0.736	−0.012	20.4	2.425 *	0.048	22.0	0.749	0.019
December	18.1	0.886	0.009	18.7	−0.859	−0.012	19.1	3.474 ***	0.061	20.6	0.885	0.017

***: $\alpha = 0.001$; **: $\alpha = 0.01$; *: $\alpha = 0.05$; †: $\alpha = 0.1$ level of significance.

3.4. Significance of Temperature and Rainfall Variability for Cereal Crop Yields in Northern Togo

The highest average maize yield (1305 kg ha^{-1}) was observed in Niamtougou. However, the highest variability in the maize yield was noticed in Kara (362 kg ha^{-1}) (Table 8). Similarly, for sorghum, which average yields were lower than that of maize in all locations, Niamtougou showed the highest yield (1100 kg ha^{-1}) and variability (886 kg ha^{-1}) (Table 8). This indicates that the maize production conditions were more stable in Niamtougou than Kara. However, sorghum production was associated with a higher risk in Niamtougou than in the other locations. For millet, the average yields were lower than that of sorghum in all locations except Dapaong where the maximum millet yield was 1258 kg ha^{-1} (Table 8). Ali [17] found similar results over the period 1972–2013 with the maximum millet yield of 1435 kg ha^{-1} in Dapaong (Savannah region of Togo).

Table 8. Summary statistics of cereal yields in northern Togo from 1990 through 2012.

Crops	Minimum	Mean	Maximum	Standard Deviation
	(Metric kg Per Hectare)			
		Kara		
Maize	740	1226	2625	362
Sorghum	211	846	1438	327
Millet	135	399	807	160
		Niamtougou		
Maize	665	1305	2123	325
Sorghum	692	1100	5004	886
Millet	135	399	807	160
		Mango		
Maize	533	1265	2041	334
Sorghum	269	940	2303	480
Millet	299	610	1058	204
		Dapaong		
Maize	860	1160	1532	218
Sorghum	361	679	1177	218
Millet	339	791	1258	307

Table 9 shows the results of multiple regressions of rainfall and temperature on crop yields in northern Togo. Most, if not all, of the exploratory VIF results are less than 10. This indicates the absence of multicollinearity and implies that the climate variables are not strongly correlated. These results are similar to those of Batho et al. [52], who evaluated the impacts of rainfall and temperature variation on maize yields in Tanzania. For the rainfall and temperature, in all four locations, the results of the regression showed that the sign of quadratic terms is opposite to the sign of linear terms. Thus, a nonlinear relationship was identified between the cereal crop yields and rainfall on one hand and the temperature on the other hand, which is consistent with other findings [15,20,53]. Rainfall had a positive and significant effect on maize yield in Kara and millet yield in Niamtougou but had a negative and significant effect on maize yield in Niamtougou and Dapaong and millet yield in Mango. The temperature had a positive and significant effect on maize yield in Kara, Niamtougou and Mango but had a negative and significant effect on sorghum in Niamtougou and millet in Dapaong. The variation observed in these results across crops may be associated with the fact that although maize, sorghum and millet are all C4 plants, they have different water requirements, energy demands and CO_2 consumption. The variation noticed in the results of the multiple regression across locations is like due to many factors. First, Dapaong is situated in a dry savannah agro-ecological zone, whereas Kara, Niamtougou and Mango are in a humid savannah agro-ecological zone. Thus, crop development is expected to differ in these two agro-ecological zones. Second, the edaphic conditions are not the same in these two agro-ecological zones. Finally, the availability of agricultural inputs, which depends on farmers' socioeconomic characteristics, contributes to defining the crop yields. Farmers' socioeconomic characteristics are not the same in Kara, Niamtougou, Mango and Dapaong. Moreover, the results reveal that in all four locations, the coefficients related to temperature were much greater than those of rainfall; therefore, the temperature had a higher effect on cereal crops production compared to rainfall. This indicates that cereal crop yields show a strong correlation with temperature change, and temperature will be a significant factor for northern Togo cereal crop yields in the future [20,51]. These results are in line with those of Sossou et al. [54], who stated that temperature affects cereal yield in the long and short terms in Burkina Faso. In addition, the combined effect of rainfall and temperature on the cereal crop yields in all the four locations is significant with a positive or negative sign. This reveals that the effect of rainfall depends on temperature and vice versa in all locations. Some of the squared terms are positive; this means that there is a threshold above which these variables have a positive effect on the crop yields. However, the negative quadratic coefficient suggests that there is an optimal level of the variables above which the value function decreases. Besides, the negative coefficients and significant quadratic terms indicate that excess temperature and or rainfall would be detrimental to the production of the crop in question [20]. It is evident from these findings that the risks associated with variability in the climate will lead to a decrease in millet, maize and sorghum yields, as observed by Blanc [55] in West Africa.

Figure 6b shows an increasing trend in the yield of sorghum from 1996 to 2012 for all the locations. However, the maize and millet yields show no clear trend with a high interannual fluctuation (Figure 6a,c). This is likely the result of several agricultural related factors influencing the farming activities including climate variability in northern Togo.

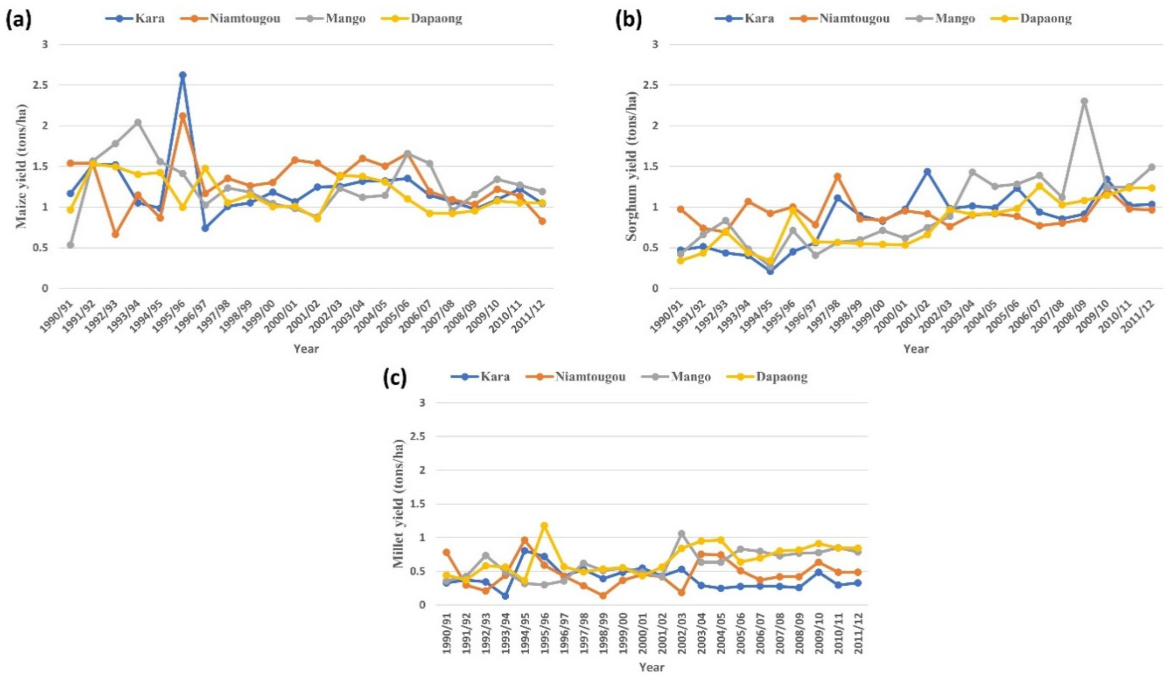

Figure 6. Trend in the yield data of (**a**) maize, (**b**) sorghum and (**c**) millet.

Table 9. Multiple regression analysis between crop yields, rainfall and temperature during growing season in Kara, Niamtougou, Mango and Dapaong.

	Kara									Niamtougou								
Variables	**Maize Yield**			**Sorghum Yield**			**Millet Yield**			**Maize Yield**			**Sorghum Yield**			**Millet Yield**		
	Coefficients	***t* Stat**	**VIF**	**Coefficients**	***t* Stat**	**VIF**	**Coefficients**	***t* Stat**	**VIF**	**Coefficients**	***t* Stat**	**VIF**	**Coefficients**	***t* Stat**	**VIF**	**Coefficients**	***t* Stat**	**VIF**
Rainfall	0.004 **	2.741	5,01	−0.010 *	−2.715	2.32	−0.002	−0.983	6.56	−0.005 *	−1.950	8.29	−0.003	−1.530	8.03	0.005 **	2.236	4.83
Rainfall squared	−0.000 **	−2.143	7.6	0.000	0.447	9.74	0.000 **	−2.040	4.41	0.000	−0.373	4.78	0.000	−0.490	4.3	−0.000 **	−2.505	4.77
Temperature	0.611 **	2.432	8.07	−0.289	−0.804	7.03	0.513	1.640	7.74	1.427 ***	3.274	4.05	−0.414 **	−2.603	10.82	0.057	0.735	10.02
Temperature squared	−0.010 **	−2.488	6.39	0.003	−0.461	10.87	−0.012 **	−2.146	8.51	−0.028 ***	−3.294	4.83	0.001	0.230	1.09	0.013 *	2.023	1.53
Rainfall ×Temperature	−0.000	−0.416	8.93	0.000 **	2.831	10.63	0.000 ***	3.581	4.6	0.000 *	1.941	10.57	0.000 *	1.938	9.18	0.000	0.333	6.08
Constant	−2.903	−0.779		18.343 ***	3.212		0.601	0.145		−9.783	−1.654		15.453 ***	3.124		−7.321	−1.574	
R squared	0.613			0.605			0.599			0.510			0.425			0.469		
	Mango									**Dapaong**								
Rainfall	0.001	0.466	8.38	0.001	0.513	4.54	−0.003 **	−2.129	3.15	−0.009 **	−2.603	10.12	−0.002	−0.828	9.46	−0.004	−1.628	5.26
Rainfall squared	−0.000	0.844	9.01	−0.000	1.157	5.78	0.000	−0.149	6.9	0.000	1.440	5.09	0.000	−1.022	4.98	0.000 *	1.761	6.55
Temperature	0.498 **	2.473	6.44	0.061 *	1.941	2.02	−0.143 **	−2.788	10.31	−0.207	−0.417	2.39	0.325 *	2.060	6.65	0.533 *	1.783	3.83
Temperature squared	−0.006 *	−2.087	1.34	−0.010 **	2.498	1.22	0.004	0.635	1.16	0.002	−0.218	2.38	−0.006 **	−2.641	7.53	−0.009 *	−2.043	2.96
Rainfall × Temperature	−0.000 *	−1.842	5.65	−0.000 *	−1.800	7.93	0.000 *	2.095	5.99	0.000 ***	3.242	5.11	0.000 *	2.032	7,41	0.000	0.615	5.02
Constant	−0.483	−0.143		−1.854	−0.573		8.020	1.729		15.173 **	2.246		2.373	0.704		1.778	0.367	
R squared	0.441			0.413			0.535			0.423			0.442			0.549		

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

In all four locations, the variation of rainfall and temperature had a significant effect on the cereal crop yields. This suggests that rainfall and temperature variability contribute to defining the yields of the selected cereal crops in northern Togo. Similar results were obtained in southern Togo by Koudahe et al. [19] who assessed the impact of climate variability on crop yields under rainfed conditions. This is also in accordance with the findings of Ali [17] who revealed that in northern Togo the inter-seasonal and the intra-seasonal variability of temperature and rainfall represent a grave menace to maize growth. Likewise, Sohou [56] pointed out that maize and sorghum are the most threatened cereals by climate change in northern Benin. It is evident from the results that there is an imperative need to adopt appropriate adaptation strategies to curb the negative effects of climate change on cereal production, as highlighted by Nyuor et al. [47] in Ghana, Hounnou et al. [57] who evaluated the effects of climate change on the agricultural sector in Benin, and Nana [58] who analysed the impact of climate change on cereal production in Burkina Faso. Similarly, Sossou et al. [54] recommended implementing effective adaptation strategies in Burkina Faso as a conclusion to their study of the impact of climate change on cereal yield and production in that country. In this regard, many actions have been taken by the Ministries of Agriculture and the Environment, which implementations were facilitated by the fact that farmers in the study area are gradually receptive to new agricultural technologies such as climate-smart agriculture practices offered by agricultural extension officers [41].

The PNIASA (National Investment Programme for Agriculture and Food Security in Togo), MIFA (Mechanism for Promoting Agricultural Financing in Togo) and ADAPT (Adaptation of Togolese Agriculture to Climate Change) projects and programmes which were launched and are being implemented by the Ministries of Agriculture and the Environment of Togo are giving farmers the appropriate knowledge and tools to curb the negative effects of climate variability and change on agriculture. Some of these actions at institutional and community levels are (i) strengthening national and local institutions by mainstreaming climate change issues into policy frameworks; (ii) capacity development of the agricultural extension officers as well as the farmers in new agricultural technologies; (iii) enhancing financing options through MIFA to facilitate access of farmers to credits, especially the vulnerable ones; (iv) rehabilitation of irrigation schemes to introduce irrigation in agriculture to reduce the risk associated with erratic rainfall in northern Togo; (v) development of drought-tolerant varieties of cereals to adapt to the negative effects of warmer temperatures on crop growth in northern Togo through ADAPT; (vi) introduction of agroforestry practices in agriculture to maintain soil fertility and organic matter and to prevent soil erosion through PNIASA; and (vii) establishment of automated weather stations to provide timely weather and climate information to farmers and other actors of the agricultural sector in Togo for a better planning. These good actions of the Ministries of Agriculture and the Environment should continue and reach the most vulnerable farmers to contribute to achieving the United Nations Sustainable Development Goals in general. The combination of top-down and bottom-up approaches should be used in devising and implementing those projects and programmes. Researchers should also be associated with those projects and programmes from the development to the implementation.

4. Conclusions

This study sought to investigate the trends in monthly and annual rainfall, monthly and annual minimum and maximum temperature using the Mann–Kendall test and Sen's slope method. It also evaluated the significance of rainfall and temperature variability for some selected cereal crop yields in northern Togo employing multiple regression analysis. Results showed an increasing trend in the annual rainfall in all four locations. However, this trend was only significant at Dapaong ($p < 0.1$). There was an increasing trend in T_{max} at Kara, Mango and Niamtougou, unlike Dapaong where T_{max} revealed a significant decreasing trend ($p < 0.01$). Similarly, there was an increasing trend in T_{min} at Kara, Mango and Dapaong, unlike Niamtougou where T_{min} showed a non-significant decreasing trend

($p > 0.05$). Northern Togo is at the boundary of the African Sahel but not located in the Sahel itself. Thus, its climate is highly variable and unpredictable due to the influence of the Sahel. This could be the reason for such variability in the temperatures and rainfall in the area. Results of multiple regression analysis revealed a nonlinear relationship between the cereal crop yields and rainfall on one hand and the temperature on the other hand. The squared terms are positive; this means that there is a threshold beyond which these variables have a positive effect on the crop yields. However, the negative quadratic coefficient suggests that there is an optimal level of the variables above which the value function decreases. In all four locations, the variation of rainfall and temperature has a significant effect on the cereal crop yields. Thus, there is a need to adopt some adaptation measures such as using drought-tolerant crop seeds, low-cost irrigation practices, crop diversification, agroecological practices, development of agro-meteorological information and their incorporation in farmers' decision-making processes for sustainable agricultural production in northern Togo.

When reading the findings of this study, one should know that the climate data used in this study are of relatively low quality because a few of the time series were labelled "doubtful" according to our classification criteria. This may be due to a low priority in investing in data in West Africa [59]. As a result, errors in the observed climate data might originate from humans, instruments or at the data entry stage because there are insufficient means to do so. The production of reliable climate data, information and the regular updating of knowledge are therefore necessary in the study area. The presented results of the multiple regression are also limited to the climate variables, which are of our main interest in this study. This function can be prolonged by integrating the edaphic conditions as well as the socio-economic characteristics and extreme natural events to make it more comprehensive. The developed regression equation only accounts for rainfall and temperature (the available data); therefore, future investigations including the above-mentioned variables could address more precisely the gained insights of the climate-dependent crop yield impacts in northern Togo.

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