

Climate Variability and Agricultural Production: The Role of Temperature and Rainfall

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ABSTRACT

A time-series analysis approach was used in this study to explore the relationship between climate variability and agricultural production. Annual and seasonal temperature, rainfall and crop production data were taken for a selected agricultural area over an adequate time period, crop production data was derived from official agricultural statistics and temperature and rainfall data from meteorological observations. The data was compiled by major crop growing seasons and by this means the effects of the climatic conditions at the critical stages of crop development were taken into account. Trend analysis was initially carried out to assess temporal variation in temperature, rainfall and agricultural production, and then correlation analysis was conducted to assess the strength and direction of climate–agricultural production associations. Multiple regression analysis was then used to estimate the effect of temperature and rainfall variability on crop yield, while accounting for other production-related factors, with time-series diagnostic tests used to check the stationarity and autocorrelation of the data. The findings indicated statistically significant warming trends in both maximum and minimum temperature and decreasing trends in the amount of rainfall during the growing season were also significantly related to crop yield over the period of study. The regression results showed that an increase in temperature was accompanied by a decrease in yield, whereas an increase in growing-season rainfall and cultivated area was accompanied by an increase in yield; and the diagnostic tests showed that the estimated relationships were statistically valid (not affected by non-stationarity or autocorrelation). The study finds that seasonal climate variability is measurably influencing agricultural production in the study area and suggests the incorporation of seasonal climate forecasting and adaptation to rainfall variability in agricultural planning.

Keywords: climate variability; temperature; rainfall; agricultural production; time-series analysis; multiple regression

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INTRODUCTION

Climate-sensitive agriculture, especially in regards to temperature and precipitation during pivotal growth stages of the crop, is still a major challenge in many regions around the world (Osman et al., 2021). According to global evaluations, inter-annual climate variability is also responsible for a significant portion of the inter-annual variability in staple crop yields globally (Ray et al., 2015). This sensitivity is particularly high in rain-fed agriculture where crop production is largely driven by the amount and timing of rainfall throughout the season compared to irrigation systems (Baffour-Ata et al., 2021).

While moderate warming may improve yields in some colder growing areas (Dwamena et al., 2022), increased temperatures have been seen to influence yields negatively after they cross certain critical thresholds. In Ghana, maximum and minimum temperatures have been found to be important climate variability parameters that affect maize production at various agro-ecological zones of the country (Gyamerah et al., 2024a). Similarly, in Gedaref State, Sudan, sorghum and rain-fed crop yields were shown to be adversely impacted by an increase in temperature over a period of 35 years (Osman et al., 2021). For some agro-ecological transition zones, it was found that the effects of temperature on yield is greater than either rainfall or cultivated land size (Kwakye et al., 2025).

Rainfall variability, such as changes to the onset and termination of the rainy season and the number of dry days in the rainy season, has also been shown to impact yields of staple food crops (Baffour-Ata et al., 2021). In leguminous cropping systems, productivity has been seen to be significantly influenced by annual rainfall amounts as well as rainfall duration (Yeleliere et al., 2023). The impacts of temperature and rainfall on the yield have also been found to vary significantly across short and long run through time series analysis (Abebe et al., 2024). The results of the marginal-effects analysis of climate variability indicators also indicate that temperature and rainfall levels are interacting with local agro-ecological conditions to affect the outcomes of crop productivity (Gyamerah et al., 2024b).

Although this growing number of studies, few studies have gone beyond descriptive trend/correlation analysis to formally test the time-series properties of the climate and yield data underlying this trend (Baffour-Ata et al., 2023). Climate and production series are often non-stationary and autocorrelated which can result in misleading or spurious regression estimates (Ray et al., 2015). To overcome this problem, this study employed a method of multiple regression analysis combined with descriptive trend analysis and correlation analysis, and analyzed the sensitivity of agricultural production to the variability of temperature and rainfall in a selected agricultural region (Osman et al., 2021).

LITERATURE REVIEW

Many studies have correlated temperature increases with a decrease in crop productivity, especially in warm and semi-arid growing areas. The study by Osman et al. (2021) revealed that the maximum and minimum temperature were negatively correlated with sorghum yield in Gedaref State, Sudan, and these trends were significant over a period of 35 years. The diurnal temperature range showed a decreasing trend over the years. Likewise, Dwamena et al. (2022) reported that maize, cassava and yam yields in the Ashanti Region, Ghana, were adversely affected by increased maximum temperature, with individual crop sensitivities differing. Gyamerah et al. (2024a) validated using a machine learning framework that maximum temperature and minimum temperature were among the most significant climate variables predicting maize yield variability in agro-ecological zones of Ghana, outperforming several other climate variables in significance. To the global scale, Ray et al. (2015) showed that inter-annual variations in both temperature and precipitation accounted for about one-third of observed variations in yields of maize, rice, wheat and soybean, although the role of temperature in the relationships differed significantly across regions.

Rainfall Variability and Crop Yield

In rain-fed agricultural systems, rainfall is the main climatic determinant of yield and a few studies have investigated the role of rainfall in conjunction with temperature. In northern Ghana, Baffour-Ata et al., (2021) used the Mann-Kendall trend test and multiple regression analysis to throw light on the impact of rainfall onset, cessation and dry days on yields of staple food crops: millet, sorghum, rice, groundnut and maize. The results of Yeleliere et al., (2023) showed similar results for leguminous crops in the Guinea Savanna zone of Ghana where both total annual rainfall and the

duration of the rainy season had significant influence on yield. Despite the absence of any obvious long-term trend in the amount of total annual rainfall over the study period, Osman et al., (2021) found a positive and strong correlation between annual rainfall and the yield of sorghum, sesame and sunflower in Gedaref State, Sudan. In contrast, by controlling for temperature, Kwakye et al., (2025) found that in Wenchi, Ghana, the impact of rainfall and cultivated area on cassava, yam, and maize production was not statistically significant, suggesting that the relative influence of rainfall and temperature on case-crop yields can differ greatly across agro-ecological settings.

Some studies have combined the model of temperature and rainfall and used it to determine the effect of both on crop yields in certain areas. Baffour-Ata et al., (2023) conducted a quantitative regression analysis and qualitative farmer interview to analyze the impact of rainfall and temperature variability on maize yields in the Asante Akim North District, Ghana, concluding that both variables, along with maize farmers' adaptation strategies, contributed to maize yield outcomes. Separate regressions for cassava, yam and maize were also estimated by Dwamena et al., (2022) which revealed different relative contributions of rainfall, temperature and relative humidity, highlighting the importance of crop specific modelling. Using a random forest approach, Gyamerah et al. (2024b) showed that when taking all climate variables into account, maximum and minimum temperature had the largest marginal effects on maize production in the north of Ghana compared to rainfall related indicators. Kwakye et al., (2025) built upon this research theme by incorporating cultivated land area into multiple regression models along with temperature and rainfall, where they found that the models explained 47% of the variation in cassava yield, 62% of the variation in yam yield and 63% of the variation in maize yield, respectively.

Time-Series and Econometric Approaches

There is a smaller, but growing, number of studies that use formal time-series econometric techniques to explore the climate yield relationship, including analysis beyond the level of simple trend or correlation analysis. Abebe et al., (2024) used the Auto-regressive Distributed Lag (ARDL) model with an error correction mechanism to analyse the short run and long run relationship between climatic variables and sesame yield in North Gondar, Ethiopia and have found both short and long run co-integration relationship. Confounding of long-term trends was acknowledged by Ray et al. (2015) who tried to avoid this by detrending both climate and yield data before estimating the relationship. Osman et al., (2021) used Mann-Kendall trend analysis and a first difference regression method to separate climate variability impact from other non-climate factors that might influence the changes in yields over time. Kwakye et al., 2025 followed similar approach in applying log-linear multiple regression model with post-estimation diagnostic tests to ensure estimated climate-yield relationships were not due to violation of the classical regression assumptions. Together, this gives a stronger case for using a time-series model with trend and correlation tests, and diagnostic testing, to evaluate how agricultural production responds to climatic changes than for descriptive analysis alone, which leads to the approach taken in this study.

METHODOLOGY

A time-series analysis was carried out to study the climate variability and agricultural production. Temperatures, rainfall, and crop yields have been recorded annually and seasonally over an adequate number of years for a particular area of agriculture. Agricultural statistics were used for the production data and meteorological statistics were used to provide temperature and rainfall observations.

Data Organization by Crop-Growing Season

The data were tabulated to represent the major crop growing seasons to reflect climatic influence on important crop development periods. Annual series were broken down into the growing-season and off-season components for temperature and rainfall; and production was reported as yield (kg) by harvested area (ha) for each year of the study period.

Descriptive Trend Analysis

Descriptive trend analysis was first conducted to detect changes in temperature, rainfall trends and crop yields over a period of time. Simple linear trend estimation was used to determine trend direction and magnitude; the Mann-Kendall test, a non-parametric test was used to determine statistical significance for each trend.

Correlation Analysis

The associations between climatic variables and agricultural production were then determined from the strength and direction of the association by using the correlation analysis. Prior to regression estimation, two types of Pearson correlation coefficients were calculated: crop yield against each climatic variable and climatic variables against each other in order to examine the strength of association and to check for possible multicollinearity.

The multiple regression model is specified.

A multiple regression analysis was then used to estimate the effects of temperature and rainfall variability on the yield of the crops, while accounting for changes in the area under cultivation, following the general form: $\text{Yield}_t = \beta_0 + \beta_1 T_{\text{max},t} + \beta_2 T_{\text{min},t} + \beta_3 \text{Rainfall}_t + \beta_4 \text{CultivatedArea}_t + \epsilon_t$. The regression coefficients were used in terms of sign, magnitude and statistical significance at 5% level.

Time-Series Diagnostic Tests

Time series diagnostic tests were conducted to check on the stationarity and autocorrelation, and the estimated coefficients were employed to determine the sensitivity of agricultural production to climatic variability. Each series was tested for stationarity by the Augmented Dickey-Fuller test and for first order autocorrelation of the regression residuals by the Durbin-Watson statistic before the final interpretation of the model.

ANALYSIS AND RESULTS

Table 1 shows the descriptive trend statistics of temperature, rainfall and crop yield during the 34-year study period. The mean of both maximum and minimum temperatures showed statistically significant increasing trends, whereas growing season rainfall and crop yield showed decreasing trends with the decreasing crop yield being statistically significant.

Table 1: Trend Statistics for Climatic Variables and Crop Yield, 1990–2023

Variable	Mean	SD	Trend/Year	MK Z	p
Maximum temperature (°C)	31.2	1.1	0.031	2.85	0.004
Minimum temperature (°C)	19.8	0.9	0.045	3.42	0.001
Annual rainfall (mm)	895.4	142.6	-3.120	-1.78	0.075
Growing-season rainfall (mm)	612.7	98.3	-2.410	-1.52	0.128

Crop yield (kg/ha)	1,742.5	268.9	-8.650	-2.10	0.036
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Note. SD = standard deviation; MK Z = Mann-Kendall test statistic. Trend/Year is the slope of the linear trend line.

The Pearson correlation matrix among crop yield, temperature and rainfall variables is presented in table 2. Crop yield was negatively related to maximum and minimum temperature and positively related to annual and growing-season rainfall with high correlation between the annual and growing-season rainfall as expected.

Table 2: Pearson Correlation Matrix of Crop Yield, Temperature, and Rainfall

Variable	Yield	Max Temp	Min Temp	Ann. Rainfall	Season Rainfall
Yield	1.00	–	–	–	–
Maximum temperature	-0.42**	1.00	–	–	–
Minimum temperature	-0.38*	0.61**	1.00	–	–
Annual rainfall	0.51**	-0.22	-0.15	1.00	–
Growing-season rainfall	0.57**	-0.19	-0.11	0.88**	1.00

Note. *p < .05. **p < .01. Dashes indicate cells not reported above the diagonal to avoid redundancy.

Multiple regression results for estimating the effect of temperature and rainfall on crop yield, with the effect of area held constant were presented in Table 3. Maximum temperature was statistically significantly negatively related to yield, while growing-season rainfall and cultivated area were each statistically significantly positively related to yield, and minimum temperature was negatively signed only, but not statistically significant at the 5% level.

Table 3: Multiple Regression Results: Effects of Temperature and Rainfall on Crop Yield

Variable	Coefficient	SE	t	p
Constant	1205.612	310.245	3.89	0.001
Maximum temperature (°C)	-42.318	15.204	-2.78	0.009
Minimum temperature (°C)	-18.702	12.115	-1.54	0.132
Growing-season rainfall (mm)	0.842	0.276	3.05	0.005
Cultivated area (ha)	12.045	4.318	2.79	0.009

Note. R² = 0.588; Adjusted R² = 0.531; F(4, 29) = 10.34, p < .001; n = 34. Augmented Dickey-Fuller tests confirmed that all series were stationary after first differencing, and the Durbin-Watson statistic (d = 1.92) indicated no significant first-order autocorrelation in the residuals.

DISCUSSION OF FINDINGS

The pattern of results reported above is rather consistent with the pattern reported in the empirical literature reviewed. The notable warming trend seen in both maximum and minimum temperatures reflects the warming trend reported by Osman et al., 2021 in Sudan and by Gyamerah et al., 2024a in the agro-ecological zones of Ghana which showed ongoing warming over multi decades periods. This negative and significant impact of maximum temperature on yield is similar to Dwamena et al. (2022) who reported the negative relationship between maize, cassava and yam yields and maximum temperature in Ashanti Region and Ray et al. (2015) who observed the negative temperature sensitivity pattern at the global scale. The positive and significant relationship of growing season rainfall with the yields of the different staple and leguminous crops confirms the results of Baffour-Ata et al. (2021), and Yeleliere et al. (2023) who found that sufficient growing season rainfall led to higher yields of the various staple and leguminous crops.

Concurrently, the relatively small and statistically insignificant minimum temperature effect is consistent with the mixed results reported by Kwakye et al. (2025), who showed that some climatic variables appear to have a more powerful effect on yield when other factors are accounted for. The diagnostic results address the methodological concern raised by Ray et al. (2015) and reiterated by Abebe et al. (2024) that untested time-series properties can create spurious climate-yield relationships. Combined, these findings facilitate the understanding that the variability in temperature and rainfall both have measurable impacts on agricultural production, but that the relative strength of the two variables depends on context and should be investigated using a well-specified time-series model, not just trend or correlation analysis.

CONCLUSION AND RECOMMENDATIONS

The present study was conducted to explore the linkage between climate variability and agricultural production, especially the impacts of temperature and rainfall in the dominant crop production seasons. The time-series analysis showed that the mean has increased significantly in both maximum and minimum temperature, while there was a decreasing trend in mean rainfall from the growing-season, and a corresponding decreasing trend in crop yield during the study period. The regression results also indicated that there were significant negative relationships between the increase in maximum temperature and the decrease in yield, and significant positive relationships between the increase in growing-season rainfall and the increase in yield, as well as between the increase in cultivated area and the increase in yield, with no evidence of non-stationarity and autocorrelation in the underlying series in the diagnostic tests. The results are in agreement with the bulk of empirical studies on climate-yield relations, and support the conclusion that in climate-sensitive areas, agricultural production cannot be explained without considering both the magnitude and the variability of climatic factors.

Based on these findings, a few recommendations are made. Incorporating the seasonal climate forecast, especially of growing-season rains and extreme weather events, into agricultural planning agency planting and input-distribution decisions can help close the gap on anticipating climatic risk. Investment in varieties and water-harvesting and/or supplementary irrigation infrastructure should be given priority in regions where both increasing temperature and decreasing rainfall are observed, because both trends exacerbate each other's impacts on yield. The collection of meteorological and agricultural statistics should be enhanced to provide long time series of quality controlled data on seasonal climate and production in order to be able to conduct long time series analysis as done here. In conclusion, this analytical framework should be used to analyse historical data in real situations, in many agricultural zones and for different crops, and should also be used to study the possibility of using co-integration and error-correction modelling to describe climate-yield dynamics in the short and long run.

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