Climate change impacts on cereal production in Afghanistan: A 30-year ARDL analysis of rainfall and temperature

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Abstract

Agriculture constitutes the backbone of Afghanistan's economy, as the majority of the population is directly or indirectly involved in agricultural activities to support their livelihoods. Among widely cultivated crops, cereals represent a strategic agricultural output of the country, ensuring national food security. This study aimed to assess the effects of rainfall and mean annual temperature on cereal production in Afghanistan using a 30-year (1993–2023) time series dataset. Clear year-to-year fluctuations in cereal output and high sensitivity to climatic variability were observed in the dataset. The Autoregressive Distributed Lag (ARDL) econometric model was employed to investigate both short- and long-run relationships between climatic variables and cereal yields. The results showed that rainfall is the primary determinant of cereal production, with a positive and statistically significant effect observed consistently across the analysis. On the other hand, mean annual temperature showed a significant positive short-run effect with a one-year lag, while its long-run effect was insignificant. Unit root tests, the bounds test, and the Error Correction Model (ECM) confirmed the robustness of the short-run relationships; however, no evidence of long-run cointegration was found. These observations reflect the structural instability of Afghanistan's cereal production systems and provide valuable insights for policymakers in designing evidence-based strategies for climate change adaptation within the country's agricultural sector.

1. Introduction

The agricultural sector constitutes the backbone of Afghanistan's national economy, providing direct or indirect livelihoods for more than 60% of the population. Hence, ensuring food security is one of the fundamental pillars of sustainable development in the country [1]. Consequently, any alteration in rainfall patterns or climatic conditions has far-reaching implications for food security, employment, and rural household income. Among strategic agricultural commodities, cereals play a crucial role in the dietary structure of the Afghan population. Therefore, analyzing the impacts of rainfall and variations in mean annual temperature on cereal production is of paramount importance.

Due to limited water resources, agriculture in Afghanistan is predominantly dependent on natural precipitation. Therefore, the variability of climatic parameters (particularly rainfall) constitutes a key determinant of agricultural productivity [2][3]. Through these effects, fluctuations in rainfall influence rural income and livelihoods, thereby affecting economic and social stability. Empirical evidence suggests that climate variability, especially rainfall fluctuations, is a major source of instability in cereal production. Decreased annual precipitation directly reduce the growth of rainfed crops and adversely affect yields [4], while severe rainfall contributes to production instability in rangeland crops [5]. This issue is even more pronounced in Afghanistan, where the majority of cultivated land lacks modern and mechanized irrigation systems.

One of the major challenges confronting Afghanistan's agriculture is the instability of rainfall patterns. Precipitation events are often sporadic and confined to specific seasons, with prolonged drought periods occurring in between. Such conditions disrupt crop growth and destabilize the planting and harvesting cycles. Previous research indicates that variations in the amount, intensity, and temporal distribution of rainfall can significantly alter soil moisture, plant growth, and ultimately crop yields [6]. This instability has been further exacerbated by Afghanistan's arid climate and poor water resource management, posing a serious threat to national food security.

From an economic perspective, declines in cereal production have led to increased food imports, depletion of foreign exchange reserves, and rising domestic food prices. These consequences underscore climate change as one of the primary drivers of slowed economic growth in developing countries, given its direct adverse impact on agricultural value added [7].

Extensive international studies have demonstrated that rainfall and temperature play decisive roles in determining cereal yields. Reductions in rainfall during critical growth stages severely affect cereal performance [8][9], and average cereal yields in rainfed areas could decline by up to 30% [10]. In Ethiopia, decreased rainfall combined with rising temperatures significantly reduced both crop yields and smallholder incomes [11]. Studies conducted in Iran have also shown that rainfall during early growth stages has the greatest impact on wheat and barley yields [4][12]. Inadequate precipitation during heading phase reduces crop quality [6][13]. Moreover, reduced rainfall and higher temperatures during critical growth periods negatively affect both crop yields and farmers' incomes [14].

Recent domestic studies in Afghanistan have similarly highlighted the country's high vulnerability to climate change. The country has experienced an average temperature rise of more than 1.8 °C since 1960, while precipitation has shown a declining and uneven trend [15]. Increases in annual temperature are projected to reduce wheat yields by 9–12% under various climate scenarios [16], while reductions in rainfall and snowfall have significantly affected rainfed chickpea production in Badghis Province, with yields reaching zero in 2018 [17]. Higher temperatures have also been shown to decrease wheat and barley yields by 271 kg/ha and 221 kg/ha, respectively, with national wheat yields projected to decline by 21–28% by 2050 [18]. Furthermore, analyses of wheat market instability across several Afghan provinces indicate that fluctuations in market conditions and import dependency have influenced cereal production, reflecting the structural vulnerability of Afghanistan's agricultural system [19].

Despite the large body of international research, few studies have quantitatively analyzed the relationship between rainfall and cereal production in Afghanistan, particularly using dynamic models such as the Autoregressive Distributed Lag (ARDL) framework. This research gap underscores the importance of the present study. Drawing on three decades of data and incorporating both rainfall and temperature variables, the study employs the ARDL model to examine the climatic impacts on cereal production in Afghanistan. The findings are expected to provide an empirical foundation for evidence-based policymaking aimed at climate change adaptation in the national agricultural sector.

2. Material and Methods

2.1. Data

This study adopted a quantitative approach, using a 30-year time-series dataset (1993–2023) to examine the effects of rainfall and temperature on cereal production in Afghanistan. The dataset included annual yields of major cereals (wheat, barley, and maize) and climatic indicators (rainfall in mm and temperature in °C), collected from the Afghanistan Meteorological Authority, the World Bank (WDI), and the Ministry of Agriculture. Prior to analysis, the data were screened for outliers and missing values, which were adjusted using moving averages where necessary, followed by standardization.

2.2. The Autoregressive Distributed Lag (ARDL) model

To analyze both long- and short-term relationships among the variables, the Autoregressive Distributed Lag (ARDL) model was employed. This approach allows for the simultaneous estimation of variables with mixed integration orders, I(0) and I(1), rendering it particularly suitable for small sample time-series data [8]. The ARDL framework also enables the assessment of short- and long-run dynamics through the Error Correction Model (ECM).

The long-run relationship is specified as:

$$Y_t = \beta_0 + \sum_{j=1}^{p} \beta_1 X_{t-j} + \sum_{j=0}^{p} \beta_2 X_{t-j} + \varepsilon_t$$

Where Y_t represents cereal production in year t (million tons), X_{t-j} denotes lagged climatic variables (rainfall in mm and temperature in °C), β_0 is the intercept, β_1 and β_2 are estimated coefficients, and ε_t is the error term.

For capturing short-term dynamics, the Error Correction Model (ECM) derived from the long-run ARDL relationship was employed:

$$\Delta Y_t = \alpha_0 + \sum \beta_j \Delta X_{t-j} + \lambda ECT_{t-1} + \varepsilon_t$$

Here, ΔY_t and ΔX_{t-j} represent the first differences of dependent and explanatory variables, respectively, capturing short-term fluctuations. ECT_{t-1} is the error correction term derived from the long-run ARDL relationship, and λ measures the speed of adjustment toward long-run equilibrium.

Lag lengths were selected based on the Schwarz Information Criterion (SIC), which minimizes overfitting while maintaining model parsimony [9]. Stationarity of the series was verified using the Augmented Dickey–Fuller (ADF) test to ensure no variable is integrated of order two, I(2). Subsequently, the existence of a long-run relationship was tested using the Bounds Test [20]. If confirmed, long- and short-run coefficients were estimated.

All statistical analyses were performed using EViews 12 with default settings. The combined use of the ARDL model, SIC-based lag selection, and Bounds Test enhances the robustness of results by allowing separate estimation of short- and long-term effects while addressing variable integration issues. This approach also reduces the risk of multicollinearity and ensures stable coefficient estimates [10].

Compared to Vector Autoregressive (VAR) and Vector Error Correction Models (VECM), ARDL is more efficient for limited time-series datasets with mixed orders of integration. Overall, this methodology provides a scientifically rigorous framework for analyzing the impact of climatic factors on cereal production in Afghanistan and offers evidence-based insights for agricultural policy and climate adaptation strategies.

3. Results

3.1. Descriptive cereal production, rainfall, and temperature statistics

The average cereal production during the study period was 4,681,020 tons with a standard deviation of 1,378,284 tons. These figures suggest that Afghanistan maintained a moderate level of cereal output over the years under review, although considerable fluctuations are evident. The maximum cereal production reached approximately 7,012,523 tons, while the minimum was 1,940,000 tons, indicating a substantial gap between the highest and lowest values (Table 1). This wide variation demonstrates that cereal production in Afghanistan has been unstable and influenced by various factors such as rainfall variability, temperature changes, security conditions, access to agricultural inputs, and government support policies.

Table 1. Descriptive Statistics of the Study Variables between 1993 and 2023

Variable	Mean	Maximum	Minimum	Standard Deviation	Observations
Cereal Production (tons)	4,681,020	7,012,523	1,940,000	1,378,284	30
Average Rainfall (mm)	350.35	437.12	205.64	59.05	30
Average Temperature (°C)	12.69	13.95	11.45	0.75	30

Regarding the average rainfall variable, the annual mean was 350.35 mm, a level that generally supports rain-fed cereal production in Afghanistan, though it may be marginal in drier regions or during years with below-average precipitation. The maximum and minimum rainfall values were recorded at 437.12 mm and 205.64 mm, respectively. This variation indicates substantial year-to-year fluctuations in precipitation; however, the standard deviation of

59.05 suggests that these variations remained within a moderate range. Therefore, it can be inferred that rainfall declined considerably in certain years, which may have contributed to reductions in cereal production.

With respect to the temperature variable, the annual mean was reported at 12.69 °C. The maximum and minimum temperatures were 13.95 °C and 11.45 °C, respectively. The standard deviation of 0.75 indicates that temperature variations were relatively small, suggesting a stable thermal condition across the country. Overall, the descriptive statistics reveal that rainfall plays a more significant role than temperature in explaining fluctuations in cereal production.

3.2. Stationarity and integration order

The conducted regression analysis was checked to determine whether the tested variables were stationary using the Augmented Dickey–Fuller (ADF) test (Table 2). The results showed that cereal production was non stationary at the initial level, but became stationary at the first difference, classifying it as an I(1) variable. On the other hand, average rainfall was already stationary at its original level and thus belongs to the I(0) category. Similarly, average temperature was stationary at a level and also classified as I(0).

Since the model includes a mix of I(0) and I(1) variables, using ARDL and the Error Correction Model is appropriate, as they are specifically designed for this type of data. These findings confirm that the variables are not all integrated at the same order, which means that applying the Autoregressive Distributed Lag approach is justified. This method allows to estimate the relationships among these variables in both the short and long term, even when their integration orders differ.

Table 2. Results of the Augmented Dickey–Fuller (ADF) Unit Root Test

Variable	Level Statistic	Level p-value	First Statistic Difference	First Difference p-value	Integration Order
Cereal Production	0.1481	-2.40799	0	-7.66643	I(1)
Average Rainfall	0.0026	-4.21882	0.0001	-5.69746	I(0)
Average Temperature	0.0216	-3.34281	0	-8.88416	I(0)

I(0) indicates stationarity at the level; I(1) indicates stationarity after first differencing.

3.3. Short-run dynamics: Error Correction Model (ECM)

The Error Correction Model (ECM) estimation (Table 3) shows that the examined climatic variables exhibit varying short-run effects on cereal production. The coefficient of the one-year lagged cereal production variable [Cereal Production (-1)] is positive and highly significant, highlighting the effect of last year's production on the current year's output. In other words, an increase in production in the previous year tends to persist into the following year. This observation is expected, since cultivated area, available resources, farmers' experience, supportive policies, and other related agricultural factors typically remain stable in the short run.

Similar observation was noted in average rainfall scoring a significantly positive coefficient and indicating a statistically significant short-run effect of rainfall on cereal production. On the other hand, the average temperature variable has scored a negative coefficient of -236,972.3 with a p-value of 0.4463, indicating that its effect is statistically insignificant. This suggests that an increase in temperature within the same year does not have a meaningful direct impact on cereal production, although it exerts a relatively negative influence.

Interestingly, the one-year lagged average temperature variable has a positive coefficient of 549,683.1 with a p-value of 0.0189, indicating a positive and statistically significant short-run effect of last year's temperature on current cereal production. This observation suggests that favorable temperatures in a given season may have positive impact over growing and production conditions in the following season. Therefore, it can be concluded that cereal production is primarily influenced by the amount of rainfall and the previous year's temperature in the short run.

Table 3. Short-Run Estimation Results of the Error Correction Model (ECM)

Variable	Coefficient	Standard Error	t-Statistic	p-Value
Cereal Production (-1)	0.688902	0.118072	5.834603	0
Average Rainfall	8,739.17	3,109.35	2.810611	0.0095
Average Temperature	-236,972.30	306,228.80	-0.77384	0.4463
Average Temperature (-1)	549,683.10	219,024.80	2.509684	0.0189
Constant	-5,422,413	4,149,705	-1.3067	0.2032

The table presents the short-run coefficients of the ECM, including lagged variables, standard errors, t-statistics, and p-values.

3.4. Diagnostic and stability tests

The distribution showed that the model's residuals are approximately centered around zero and follow a normal pattern. Therefore, the assumption of normally distributed errors is satisfied, and the model is statistically valid (Fig. 1).
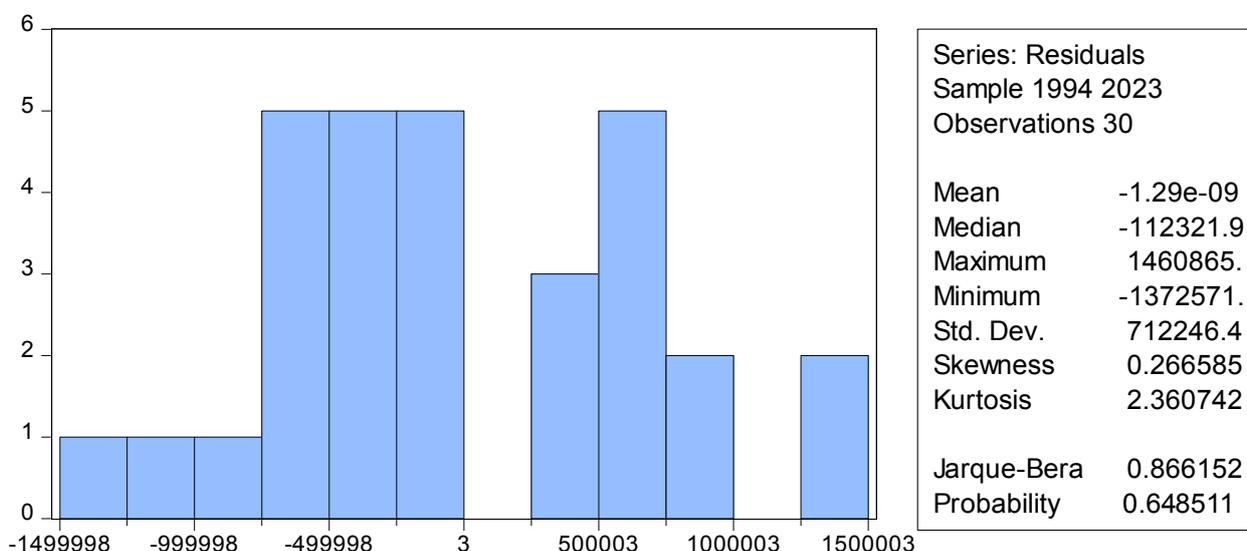

Series: Residuals Sample 1994 2023 Observations 30	
Mean	-1.29e-09
Median	-112321.9
Maximum	1460865.
Minimum	-1372571.
Std. Dev.	712246.4
Skewness	0.266585
Kurtosis	2.360742
Jarque-Bera	0.866152
Probability	0.648511

Figure 1. Normal distribution of regression residuals

The results of the Breusch–Pagan–Godfrey test, presented show that the p-value of the F-statistic is 0.7583, the F-statistic itself is 0.468422, and the chi-square statistic is 0.7189 (Table 4). In other words, there is no issue of heteroscedasticity in the model, and the variance of the residuals is constant. This indicates that the model is both stable and reliable. The results of the Breusch–Godfrey test also indicate that the data do not exhibit serial correlation, and the model is fully valid from a time series perspective.

Table 4. Results of the heteroscedasticity (Breusch–Pagan–Godfrey) and serial correlation (Breusch–Godfrey) tests

Heteroskedasticity Test: Breusch-Pagan-Godfrey			
F-statistic	0.468422	Prob. F (4,25)	0.7583
Obs*R-squared	2.091663	Prob. Chi-Square (4)	0.7189
Scaled explained SS	0.988268	Prob. Chi-Square (4)	0.9116
Breusch-Godfrey Serial Correlation LM Test:			
F-statistic	0.789427	Prob. F (1,24)	0.466
Obs*R-squared	1.927088	Prob. Chi-Square (1)	0.3815

3.5. Long-run relationship and bounds test

The results of the Bounds Test show that the F-statistic is 3.335, while the lower bound I(0) and upper bound I(1) values are 3.538 and 4.428, respectively. Since the test statistic (F-value) is below the lower bound, the results indicate that there is insufficient evidence to confirm the existence of a long-run cointegration relationship among the variables at conventional confidence levels. In other words, within the estimated model framework, a stable and

significant long-term relationship between cereal production, rainfall, and temperature is not confirmed. This implies that although short-term variations in rainfall and temperature may affect cereal yields, these effects are not necessarily stable or guaranteed in the long run. Consequently, the model primarily explains the short-term dynamics of cereal production, while other factors, such as agricultural technology, water resource management, soil quality, improved seeds, capital, and agricultural policies, may play a more decisive role over the long term.

In the long run, the coefficient of the average rainfall variable is significantly positive, which indicates that rainfall is a key and stable determinant of cereal production over the long term. The coefficient of the average temperature variable is also positive but not statistically significant. Consequently, its long-

Table 5. Long-Run Coefficient Estimates

Variable	Coefficient	Standard Error	t-Statistic	p-Value
Rainfall	28,091.37	11,889.75	2.362655	0.0262
Temperature	1,005,184.00	834,851.40	1.204028	0.2399
Intercept	-17,429,918.00	12,650,416	-1.37781	0.1805

term effect cannot be confirmed (Table 5). The Cumulative Sum (CUSUM) test shows that the statistical lines for the model remain within the 5% confidence bounds (Fig. 2). This result indicates that the model is stable in terms of coefficient constancy, with no structural breaks observed over the study period. Therefore, the model can be considered reliable and robust.

Overall, the analyses indicate that average rainfall is the primary determinant of cereal production in Afghanistan, while temperature does not have a statistically significant effect. Past-year production positively influences current-year production. The model is statistically stable and valid; however, its long-run effects are limited, and it primarily explains short-term variations in cereal yields.

4. Discussion

In light of the presented results, it is clear that rainfall is the primary determinant of cereal production in Afghanistan compared to temperature changes. Rainfall exerted a positive and statistically significant influence in both the short- and long-term. This finding

Figure 2. Cumulative Sum (CUSUM) Test

is consistent with previous research reporting a significant positive association between rainfall and cereal production in the short run [21]. Short term effect was much more pronounced compared to long run effect, which contradicts findings from other environments, such as Tunisia, where studies have reported smaller short-run climate impacts on cereal production relative to stronger long-run effects [22]. The stronger short-run effect of rainfall reflects the limited adaptive capacity of Afghan farmers, primarily due to inadequate irrigation infrastructure and reliance on outdated irrigation technologies.

Evidence from international studies supports this conclusion. Decreased precipitation during critical growth stages has been found to markedly reduce cereal yields [8][9], while water scarcity combined with rising temperatures significantly diminishes both crop production and smallholder incomes in developing countries [11]. Overall, these results confirm that rainfall is a key and globally significant factor influencing the productivity of rainfed cereals.

In contrast, average temperature exhibits a significant positive effect only with a one-year lag in the short run, whereas its long-term impact is statistically insignificant. This pattern aligns with previous findings, indicating that temperature effects depend on crop growth stage, interaction with rainfall, and farm management practices [11]. Moderate temperatures in the preceding year may improve soil conditions and nutrient availability for the following season. On the other hand, long-term increases in temperature may adversely affect production through higher
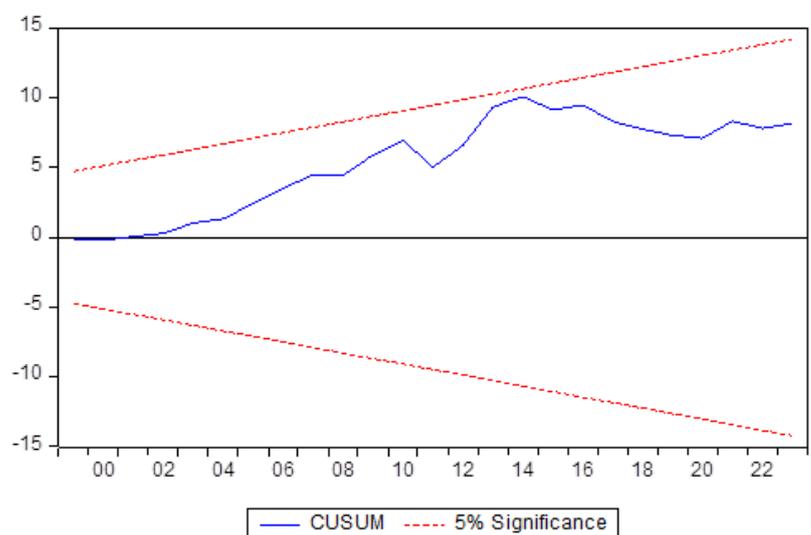
evapotranspiration and reduced soil moisture. Consequently, climatic factors constitute only a part of the determinants of cereal production in the long term. Despite the modest effect of temperature observed in this study, it is worth noting that only average annual temperature was considered, which is an underrepresentation of temperature as a key factor in agricultural production. Consequently, more in-depth studies should focus on temperature components such as minimum, maximum, and accumulated temperature, which might indeed play a more prominent role as determinants of cereal production. The absence of long-run cointegration, as revealed by the Bounds Test, reflects structural and managerial limitations in Afghanistan's agricultural system. Thus, investigating other factors such as farm management, technology, and input utilization is necessary to pinpoint determinant factors in the long term.

5. Conclusions

It is evident that rainfall is a primary and stable determinant of cereal production in Afghanistan, with increases in precipitation significantly enhancing crop yields. In contrast, average temperature shows a positive and statistically significant effect only in the short run with a one-year lag, while its long-run impact is not significant. The structural instability of Afghanistan's crop system, which is shaped by unstable rainfall patterns, weak water resource management, low-quality inputs, and technological constraints, highlights the inherent vulnerability of agricultural systems to climatic variability.

The short-run analysis further revealed that past-year production positively influences current-year output, emphasizing the role of farmers' experience and supportive policies in stabilizing short-term production. Overall, the findings underscore the importance of integrating climatic considerations with effective farm management to enhance the resilience of cereal production. These insights provide a robust scientific foundation for evidence-based policymaking and future research aimed at strengthening agriculture and food security in Afghanistan.

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Data availability statement

The authors declared that all data sources are cited in the text, and the dataset used in this study will be made available by the corresponding author upon reasonable request.

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