



Comparative Analysis of Climate Change Effects on Major Crops in Somalia: A Study of Maize, Sorghum and Cowpea Production, 1995 to 2025

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Abstract

This study presents a comparative analysis of the effects of climate change and climate variability on the production of three of Somalia's most important field crops, maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L. Moench), and cowpea (*Vigna unguiculata* L. Walp), over the thirty-one-year period from 1995 to 2025. Using a district-level seasonal production record compiled from the seasonal crop assessments of the Food Security and Nutrition Analysis Unit for Somalia and comprising 5,868 crop observations drawn from 45 districts across 13 regions, three geographic zones, and three livelihood systems, the study applied descriptive statistics, the non-parametric Mann-Kendall trend test, Sen's slope estimator, the coefficient of variation as an instability index, standardized production anomalies, and Pearson correlation to characterize long-term trends, inter-annual variability, seasonal dynamics, and spatial patterns. The results reveal a significant long-term decline in maize production (Sen's slope = -2,227 MT per year; $p = 0.019$), a weaker and statistically non-significant decline in sorghum over the full record that nonetheless becomes significant during 2010 to 2025 (-3,801 MT per year; $p = 0.034$), and a significant increase in cowpea production (+768 MT per year; $p = 0.005$) reflecting its expanding cultivation. Cowpea exhibited the highest inter-annual instability (coefficient of variation 65.4 percent), while sorghum was the most stable of the three crops (28.8 percent). Standardized anomalies identified 2021, 2016, 2005, 2023, and 2020 as the most severe production-deficit years, coinciding with documented drought and failed rainy seasons in the Horn of Africa. In the catastrophic 2020 to 2023 drought, the two cereals collapsed together, with maize and sorghum anomalies of minus 1.7 and minus 1.8 in 2021, while cowpea remained comparatively resilient, with an anomaly of plus 0.96 in 2023, pointing to the drought-tolerant legume as a strategic adaptation crop. Production was highly concentrated spatially, with the South zone accounting for 97 percent of maize and 83 percent of sorghum output, and the riverine Shabelle valley and rain-fed Bay plateau emerging as the dominant production hubs. The study concludes that Somalia's cereal-dominated food system is increasingly exposed to climate-driven instability and recommends crop diversification toward drought-tolerant legumes, improved water management across the Gu and Deyr seasons, and investment in climate-smart agriculture as priority adaptation pathways.

Keywords: Climate change; Maize; Sorghum; Cowpea; Mann-Kendall trend test; Production variability; Food security; Somalia

1. Introduction

Agriculture is at once the most weather-dependent of human economic activities and the foundation upon which the food security of nations rests, and nowhere is this dependence more acute than in the drylands of sub-Saharan Africa, where the fortunes of the farming year are dictated by the timing, quantity, and reliability of seasonal rainfall. The Intergovernmental Panel on Climate Change has concluded, with rising confidence across its successive assessment reports, that anthropogenic warming is already depressing agricultural yields in low-latitude regions and that these negative impacts will intensify as warming proceeds (IPCC, 2021, 2022). For societies whose economies, diets, and livelihoods are built upon rain-fed crop production, climate change is therefore not a distant environmental abstraction but an immediate threat to food security and rural livelihoods.

Somalia, situated at the eastern tip of the Horn of Africa, is among the countries most acutely exposed to this threat. Its agriculture is overwhelmingly rain-fed, its rainfall is bimodal and highly erratic, and the great majority of its rural population depends directly on crop and livestock production for subsistence and income; agriculture, broadly defined to include crops, livestock, and fisheries, accounts for the largest share of national output and employs the majority of the labour force (World Bank, 2018). Somalia's cropping calendar is governed by two rainy seasons, the primary Gu long rains falling between April and June, and the secondary Deyr short rains extending from October to December, separated by the harsh Jilaal dry season and the milder Hagaa dry spell. The performance of the Gu and Deyr rains determines the fortunes of the farming year, and the recurrent failure of one or both seasons has repeatedly precipitated food crises, culminating in the catastrophic famines of 1991-92 and 2011 and the near-famine emergencies of 2017 and 2022 (Maxwell & Fitzpatrick, 2012; Hillbruner & Moloney, 2012).

Africa is widely recognized as the continent most vulnerable to climate change, a vulnerability that arises less from the magnitude of the physical changes it faces than from the low adaptive capacity of its largely rain-fed, smallholder-dominated agricultural systems (Schlenker & Lobell, 2010). Within Africa, the Greater Horn is a hotspot of both climatic volatility and human vulnerability, a region of profound rainfall variability subject to recurrent and devastating droughts, warming at a rate that meets or exceeds the global average (Nicholson, 2017; Gebrechorkos et al., 2019). Decades of state fragility and armed conflict in Somalia have eroded the institutional and infrastructural capacity that might otherwise buffer the population against climatic shocks, so that the natural hazard of drought is repeatedly amplified into humanitarian disaster.

Cereals, principally sorghum and maize, form the backbone of the Somali domestic food economy, supplemented by pulses such as cowpea and by cash crops including sesame and horticultural produce. Domestic cereal production typically meets only a fraction of national requirements, the balance being made up by commercial imports and food assistance, so that any contraction in domestic output must be met by increased imports or absorbed as a widening of the hunger gap (FAO & FSNAU, 2023). This structural deficit places the performance of the domestic cereal crop at the centre of the national food-security equation and makes its long-term trajectory under a changing climate a matter of the highest strategic importance.

A comparative approach, examining more than one crop side by side, is especially valuable in this context because different crops possess markedly different physiological tolerances to heat and water stress. Maize is a relatively thirsty cereal that is highly sensitive to moisture deficits during flowering (Nkomozepi & Chung, 2012); sorghum is a hardier cereal renowned for its drought tolerance owing to its deep rooting and osmotic adjustment (Shiferaw et al., 2014); and cowpea is a grain legume prized in dryland farming systems for its ability to withstand heat and produce a harvest on very limited rainfall (Singh et al., 2002). Comparing

the trajectories of these three crops over time therefore offers something close to a natural experiment in crop resilience under climate stress, providing an evidence base upon which adaptation planning can be built. Somalia-specific empirical work has begun to establish this link econometrically: Warsame et al. (2021) found a significant long-run relationship between climatic variables and crop production using an autoregressive distributed lag approach, while Warsame et al. (2022) linked both climate change and political instability to declining sorghum output, underscoring the multi-causal but climate-dominant nature of Somalia's agricultural vulnerability.

Despite this growing body of evidence, no published study has undertaken a systematic, multi-decade, multi-crop comparison of production trends, variability, and shock response across Somalia's principal cereals and its leading drought-tolerant legume using a single, consistent national dataset and a common analytical framework. This study addresses that gap. Drawing on a district-level seasonal production dataset spanning the thirty-one years from 1995 to 2025, compiled from the seasonal assessments of the Food Security and Nutrition Analysis Unit for Somalia and its partners, it quantifies the long-term trends, inter-annual variability, seasonal dynamics, and spatial patterns in the production of maize, sorghum, and cowpea, and interprets these in the light of the documented climatic evolution of the region. The specific objectives were to determine the long-term trend in the production of each crop, to compare their inter-annual production variability, to establish the association between production anomalies and documented climatic shocks, to characterize the seasonal and spatial patterns of production, and to assess the degree of common movement among the crops as a test of the risk-diversification rationale for crop diversification.

2. Materials and Methods

2.1 Research Design and Study Area

The study adopted a quantitative, longitudinal, and comparative research design, grounded in a positivist philosophy in which objective knowledge of the phenomenon under investigation is obtained through the systematic statistical analysis of empirical observation. It is longitudinal in that it examines a continuous thirty-one-year time series from 1995 to 2025, permitting the detection of long-term trends and the characterization of inter-annual variability, and comparative in that it evaluates three crops, maize, sorghum, and cowpea, side by side within an identical analytical framework. The design is ex-post-facto and non-experimental, drawing inferences from observed historical production data rather than from controlled manipulation of variables, which is the only feasible design for detecting long-term climate signals in agricultural output at national spatial and decadal temporal scales.

The study covers the crop-producing regions of Somalia, a country of some 637,000 square kilometres in the eastern Horn of Africa with a predominantly arid to semi-arid climate, mean annual rainfall ranging from under 100 mm in the arid north-east to around 500 to 600 mm in the wetter inter-riverine south, and a bimodal rainfall regime comprising the Gu long rains and the Deyr short rains. The dataset spans three broad zones, South, Central, and North West, encompassing thirteen regions and forty-five districts. The South zone, including the riverine corridors of the Shabelle and Juba rivers and the rain-fed Bay and Bakool plateau, is the agricultural heartland and dominates national output; the Central zone, comprising Galgaduud and Mudug, is drier and more pastoral but contributes a notable share of cowpea output; and the North West zone, comprising Woqooyi Galbeed, Awdal, and Togdheer, supports rain-fed sorghum cultivation in its more elevated districts. Three livelihood systems are represented: rain-fed agro-pastoral farming, riverine recessional and irrigated farming, and a combined system drawing on both.

2.2 Data Source and Preparation

The study is based on a secondary dataset of district-level seasonal crop production, recorded in metric tonnes, covering 1995 to 2025. The records derive from the post-season crop and food-security assessments conducted after each Gu and Deyr harvest by the Food Security and Nutrition Analysis Unit for Somalia, managed by the Food and Agriculture Organization of the United Nations in collaboration with partner agencies and Somali authorities (FAO & FSNAU, 2023). In these twice-yearly assessments, production is enumerated by district, crop, season, and livelihood system through a combination of field measurement, key-informant interview, remote-sensing corroboration, and expert estimation, and the assessments are the authoritative and most widely used source of agricultural production and food-security information for Somalia. The present study analyses 5,868 observations pertaining to the three focal crops, comprising 2,495 for maize, 1,828 for sorghum, and 1,545 for cowpea, drawn from a complete dataset of 7,938 valid crop-season observations spanning ten crops.

Prior to analysis, records with missing crop identifiers or missing or non-numeric production values were excluded, production values were coerced to a numeric type, and categorical fields were standardized for consistent capitalization and spelling. For the analysis of long-term trends and variability, district-level records were aggregated to annual national totals for each crop; for the seasonal, zonal, regional, and livelihood analyses, records were aggregated along the corresponding dimension. Two features of the record required particular care. Records for the Gu season of 2023 are absent from the dataset, a gap coinciding with the peak of the 2020 to 2023 drought, so the 2023 annual total reflects Deyr production only and is treated cautiously in interpretation. Cowpea records begin in 2003 and are sparse until 2009; consequently, cowpea's full-series trend is computed over 2003 to 2025, and a common 2010 to 2025 window is additionally used for a strictly like-for-like comparison among the three crops in which all series are well populated.

2.3 Statistical Analysis

Six complementary analytical techniques were applied. Descriptive statistics, comprising the mean, standard deviation, minimum, maximum, and total of the annual production series, characterized the central tendency and spread of output for each crop. The non-parametric Mann-Kendall test (Mann, 1945; Kendall, 1975) was used to detect the presence and direction of monotonic trends in each annual production series, based on the sign of all pairwise differences in the series, with a trend declared statistically significant where the two-tailed p-value fell below 0.05. Where a trend was detected, its magnitude was estimated using Sen's slope estimator (Sen, 1968), the median of the slopes formed by all pairs of data points in the series, expressed in metric tonnes per year and as a percentage of the series mean. Inter-annual variability, taken as a proxy for production instability under a variable climate, was quantified by the coefficient of variation, the ratio of the standard deviation to the mean expressed as a percentage, computed both over the full record and within each decade, and interpreted against conventional thresholds in which values below 15 percent denote low instability, 15 to 30 percent moderate, 30 to 60 percent high, and above 60 percent very high instability.

To identify shock years and compare vulnerability across crops, production in each year was expressed as a standardized anomaly, or z-score, the deviation from the long-term mean divided by the standard deviation, and cross-referenced against the documented record of droughts and failed rainy seasons in the Horn of Africa. Finally, the degree to which the three crops respond in common to shared climatic drivers was assessed through the Pearson product-moment correlation coefficient between their annual production series, computed over the common well-populated period 2009 to 2025, where a high positive correlation indicates that

two crops tend to rise and fall together, and a low correlation indicates that combining them spreads climatic risk. All analyses were conducted using standard statistical software, and the analytical strategy rests on the assumption that district-level seasonal assessments, aggregated to national annual totals, provide a reasonable representation of the true movement of national production over time, an assumption supported by the systematic and authoritative nature of the FSNAU assessment system and the cancelling of idiosyncratic local errors across many aggregated district observations.

3. Results

3.1 Descriptive Overview of Production

Over the thirty-one-year study period, sorghum and maize dominated field-crop output almost equally, with cumulative production of approximately 3.85 and 3.59 million metric tonnes respectively, while cowpea, cultivated on a far smaller scale and recorded only from 2003, contributed some 285,000 metric tonnes. Table 1 summarizes the descriptive statistics of the annual production series for each crop. Sorghum, although marginally the larger crop in cumulative total, was the most stable of the three, with the lowest coefficient of variation (28.8 percent). Maize was both smaller in mean output than its high yield potential might suggest and considerably more variable (33.6 percent). Cowpea, though minor in absolute terms, was by far the most volatile crop, with a coefficient of variation of 65.4 percent, a reflection both of its cultivation on marginal lands and of the rapid expansion of its area from a very low base. The worst maize year (48,978 MT in 2021) fell within the recent drought era (cowpea's minimum of 616 MT in 2004 reflects its negligible early cultivation rather than a climatic shock), whereas the record sorghum year of 2011 (188,546 MT) and the record maize year of 2002 (205,294 MT) belonged to more favourable rainfall regimes, and even the hardy sorghum fell to little more than a quarter of its peak output in its worst year (53,918 MT in 2005), underscoring the severity of the climatic shocks to which Somali cereal production is subject.

Table 1. Descriptive Statistics of Annual Production by Crop, 1995 to 2025 (metric tonnes)

Crop	Total (MT)	Mean (MT)	SD (MT)	CV (%)	Minimum (year)	Maximum (year)
Maize	3,593,394	115,916	38,977	33.6	48,978 (2021)	205,294 (2002)
Sorghum	3,846,737	124,088	35,741	28.8	53,918 (2005)	188,546 (2011)
Cowpea*	285,128	12,960	8,478	65.4	616 (2004)	29,576 (2025)

*Cowpea records begin in 2003; cowpea statistics are computed over the 22 years with recorded production. SD denotes standard deviation and CV the coefficient of variation.

3.2 Long-Term Trends in Production

The Mann-Kendall trend test and Sen's slope estimator, reported in Table 2, reveal a clear divergence among the three crops. Maize exhibited a statistically significant long-term decline over the full record (Kendall's tau = -0.299; p = 0.019), falling at a median rate of some 2,227 metric tonnes per year, equivalent to about 1.9 percent of its mean annual output, a sustained downward drift from decadal means near 148,000 MT in the late 1990s to around 96,000 MT in the most recent decade, consistent with the crop's known sensitivity to intensifying heat and moisture stress and compounded by episodic flooding of the riverine zones on which much Somali maize depends. Sorghum presented a more nuanced picture: over the full period its decline was gentle and statistically non-significant (tau = -0.123; p = 0.341), confirming its reputation as the more climate-robust cereal, yet when attention was confined to

the most recent fifteen years the decline became both steeper and statistically significant ($\tau = -0.400$; $p = 0.034$; -3,801 MT per year), indicating that even this hardy cereal has begun to succumb to intensifying post-2010 drought pressure. Cowpea, by contrast, showed a strong and significant upward trend over its full record ($\tau = +0.437$; $p = 0.005$), expanding at some 5.9 percent of its mean per year, though this increase reflects the deliberate expansion of cultivation from a very low base rather than climatic improvement, and in the common 2010 to 2025 window the upward trend was no longer statistically significant.

Table 2. Mann-Kendall Trend Test and Sen's Slope Results by Crop

Crop	Period	Kendall's tau	p-value	Sen's slope (MT/yr)	Change (%/yr)	Trend
Maize	1995-2025	-0.299	0.019	-2,227	-1.92	Decreasing*
Maize	2010-2025	-0.133	0.499	-2,781	-2.70	No trend
Sorghum	1995-2025	-0.123	0.341	-702	-0.57	No trend
Sorghum	2010-2025	-0.400	0.034	-3,801	-3.07	Decreasing*
Cowpea	2003-2025	+0.437	0.005	+768	+5.93	Increasing*
Cowpea	2010-2025	+0.200	0.300	+475	+2.96	No trend

*Statistically significant at $p < 0.05$.

3.3 Inter-Annual Variability and Decadal Shifts

Decomposing the coefficient of variation by decade, reported in Table 3, reveals a dynamic that the full-period figures conceal: the instability of maize has risen sharply across the three decades, its coefficient of variation increasing from a modest 18.1 percent in 1995-2004 to 46.1 percent in 2015-2025, a more than two-and-a-half-fold increase that moves the crop from the moderate into the high instability band. Sorghum's variability, by contrast, has remained broadly constant and moderate throughout (24.7 to 30.7 percent), while cowpea's very high variability, though falling as its production base has consolidated, remains the highest of the three at 49.9 percent in the most recent decade. The compounding of a declining mean with rising variance in maize is more damaging than either trend alone, since a crop whose average output falls while its variability rises delivers both less food and less predictability, so the frequency of severely deficient years rises faster than the fall in the mean alone would suggest.

Table 3. Decadal Coefficient of Variation by Crop (%)

Crop	1995-2004	2005-2014	2015-2025	Direction
Maize	18.1	20.0	46.1	Sharply rising
Sorghum	27.8	30.7	24.7	Broadly stable
Cowpea	96.9	75.6	49.9	Falling (from a high base)

The decadal mean production figures in Table 4 crystallize this narrative. Maize declined steadily across the three decades, from a mean of roughly 148,000 MT in 1995-2004 to 96,000 MT in 2015-2025, a fall of about 35 percent. Sorghum held broadly steady, even rising slightly through the middle decade, before contracting in the most recent one. Cowpea, in contrast, rose more than eight-fold as its cultivation expanded from a negligible base, from under 2,000 MT to over 16,500 MT. In absolute terms, the combined decadal decline of the two cereals, approximately 71,000 MT between the first and last decades, dwarfs the roughly 15,000 MT gain in cowpea, so that the diversification under way, though strategically valuable, remains far from sufficient in scale to offset the erosion of the cereal base.

Table 4. Decadal Mean Annual Production by Crop (metric tonnes)

Decade	Maize	Sorghum	Cowpea
1995-2004	147,750	129,157	1,958
2005-2014	105,767	135,178	11,021
2015-2025	96,202	109,399	16,548

3.4 Production Anomalies and Climatic Shocks

The correspondence between production deficits and documented climatic shocks is striking. As Table 5 shows, the most severe cereal-deficit years in the entire record, 2021, 2016, 2005, 2023, and 2020, align almost exactly with the region's recognized drought episodes, culminating in the extraordinary run of failed seasons between 2020 and 2023 that accounts for three of the five worst years. The single worst year, 2021, saw both cereals collapse in tandem, with maize and sorghum anomalies of -1.72 and -1.82 respectively. This tight coupling of production shocks to rainfall failure provides strong indirect confirmation that drought is the dominant driver of inter-annual production behaviour in Somalia.

Table 5. The Five Most Severe Cereal-Deficit Years and Their Climatic Context

Rank	Year	Combined-cereal anomaly	Climatic event
1	2021	-1.85	Peak of the 2020-23 multi-season drought
2	2016	-1.38	Onset of the 2016-17 drought
3	2005	-1.05	2005-06 drought and food emergency
4	2023	-0.98	Tail of the 2020-23 drought (partial records)
5	2020	-0.96	First failed seasons of the 2020-23 drought

The most revealing result, however, is the divergence of cowpea from the cereals during the drought tail. In 2023, as maize slumped to an anomaly of -1.45 and sorghum to -0.52, cowpea rose to +0.96, nearly a full standard deviation above its own mean. Because the 2023 record contains Deyr-season data only, this contrast should be interpreted with caution, although its direction is consistent with that observed in years with complete records. A comparable, though weaker, divergence appeared in 2017, when cowpea recorded a positive anomaly of +0.42 even as both cereals were in deficit. This is precisely the behaviour expected of a drought-tolerant legume: where the water-demanding cereal fails outright, the heat- and drought-adapted pulse continues to yield, and farmers appear to lean upon it when the rains falter. This divergence offers direct empirical support for the strategic role of cowpea as a climate-adaptation crop, grounded not in agronomic theory alone but in the observed behaviour of the national production record under real drought conditions. It is worth noting that 2011 recorded a strong positive sorghum anomaly (+1.80) despite that year's declared famine; the 2011 famine was driven principally by the failure of the preceding late-2010 Deyr rains and was concentrated among specific southern populations who lacked access to food even as good harvests were achieved in surplus-producing zones, underlining that aggregate production and localised food security are not the same thing.

3.5 Seasonal and Spatial Patterns

The two rainy seasons contribute very differently to each crop. Maize is predominantly a Gu-season crop, with 64 percent of its output produced in the Gu, whereas both sorghum and cowpea are grown chiefly in the Deyr short rains, which supply 61 percent and 60 percent of their output respectively. This seasonal division has direct implications for climatic exposure: maize's reliance on the Gu makes it especially vulnerable to the recurrent underperformance of the long rains that features prominently in the region's recent climatology, while sorghum's and cowpea's greater dependence on the Deyr aligns them with a season that, while shorter, has in some years been enhanced by favourable Indian Ocean Dipole conditions, though it too is subject to catastrophic failure, as the 2020-2023 sequence demonstrated.

Production is also highly concentrated geographically. The South zone accounts for 97 percent of maize, 83 percent of sorghum, and 75 percent of cowpea output nationally. Within the South, two dominant hubs emerge: the riverine Shabelle valley, and especially Shabelle Hoose, which alone accounts for more than half of all recorded maize production, for maize; and the rain-fed Bay plateau for sorghum. This spatial concentration is a source of systemic risk, since a localised climatic shock, whether a failure of the rains over Bay or a flood along the Shabelle, can propagate to national-scale production deficits. Sorghum's somewhat wider spatial footprint, extending into the North West zone which contributes some 16 percent of the national total, affords it a measure of geographic diversification that partly explains its greater aggregate stability, while cowpea's comparatively even spread across the South and Central zones is a modest resilience advantage, though its small absolute scale limits the national significance of that diversification at present.

3.6 Inter-Crop Covariation

The degree to which the three crops respond in common to shared climatic drivers is captured by the Pearson correlations of their annual production over the well-populated 2009 to 2025 period, presented in Table 6. Maize and sorghum were moderately positively correlated ($r = 0.49$), consistent with their common exposure to national rainfall conditions, while maize and cowpea correlated slightly more strongly ($r = 0.56$). Sorghum and cowpea, however, were only weakly correlated ($r = 0.25$), indicating that the two crops do not tend to fail together, so that a portfolio combining the drought-tolerant cereal with the drought-tolerant legume spreads climatic risk substantially more effectively than either crop alone. This is the quantitative expression of the risk-diversification rationale for crop diversification, and it provides direct empirical support for the intercropping strategies discussed below.

Table 6. Inter-Crop Correlation of Annual Production, 2009 to 2025 (Pearson r)

	Maize	Sorghum	Cowpea
Maize	1.00	0.49	0.56
Sorghum	0.49	1.00	0.25
Cowpea	0.56	0.25	1.00

4. Discussion

The comparative evidence assembled here establishes a clear resilience hierarchy among Somalia's three focal crops: cowpea, then sorghum, then maize, from most to least climate-resilient in the specific sense of maintaining or expanding output under intensifying drought pressure. This hierarchy is consistent with the crops' known physiological tolerances, maize's high water demand during flowering rendering it acutely sensitive to the moisture deficits that have become more frequent under a changing regional climate (Nkomozepi & Chung, 2012; Rowhani et al., 2011), sorghum's deep rooting and drought dormancy buffering its aggregate output against all but the most severe shocks (Shiferaw et al., 2014), and cowpea's

heat and drought tolerance allowing it to continue yielding precisely when the cereals fail (Singh et al., 2002). The findings therefore extend, with Somalia-specific quantitative detail, the broader African evidence that climate change is measurably depressing cereal yields while leaving greater scope for drought-tolerant legumes to expand (Schlenker & Lobell, 2010; Adhikari et al., 2015).

The most striking and, from a food-security perspective, most concerning finding is the sharp rise in maize's inter-annual instability, from a coefficient of variation of 18.1 percent in the first decade of the record to 46.1 percent in the most recent one. A crop whose mean output is simultaneously falling and becoming more erratic delivers a doubly adverse combination for a food system with little buffering capacity, since it is the increasing frequency of severely deficient years, rather than the decline in the long-run average alone, that translates most directly into crisis. This pattern is consistent with the global meta-analytic evidence that climate change effects on cereal yields are increasingly manifesting as heightened variability as well as declining means (Challinor et al., 2014), and it is compounded in the Somali case by maize's concentration in a small number of riverine hotspots, which are exposed to both the drought that curtails Gu rainfall and the episodic flooding that can destroy a standing crop within days.

The finding that sorghum's decline, while statistically insignificant over the full thirty-one-year record, becomes both significant and steep when the analysis is confined to the post-2010 period is of particular policy importance, because sorghum has long been regarded, both in the literature and in Somali farming practice, as the resilient fallback cereal of last resort (Warsame et al., 2022). Its apparent recent weakening suggests that the intensifying drought pressure documented across the Horn of Africa (Funk et al., 2008; Nicholson, 2017) may now be approaching or exceeding even this hardy crop's tolerance thresholds under the compounding effect of successive failed seasons, a possibility that should prompt urgent further investigation rather than complacent reliance on sorghum's historical reputation for robustness.

The anomaly analysis provides what is, in effect, a national-scale natural experiment in comparative drought resilience. When, in a year of severe and widespread drought, the aggregate output of a water-demanding cereal collapses while that of a drought-tolerant legume simultaneously rises, as occurred with maize and cowpea in 2023 and, with complete seasonal records, in 2017, the divergence cannot readily be attributed to the idiosyncrasies of a particular field or farmer; it reflects a systematic difference in the crops' responses playing out across thousands of plots simultaneously. This result carries a weight of evidence that a single-site agronomic trial could not match, and it directly corroborates the theoretical case for legume-based diversification advanced in the broader climate-adaptation literature (Di Falco et al., 2011; Below et al., 2012). At the same time, cowpea's very high inter-annual variability, even though it is falling as the crop's production base consolidates, is an important qualification to its promise: cowpea is resilient in the sense of surviving droughts that destroy cereals, but its year-to-year output remains highly uncertain and would benefit materially from improved agronomy, drought-tolerant varieties, and stronger seed systems.

The scale mismatch between cereal loss and legume gain defines the central policy challenge that flows from this analysis. The spontaneous expansion of cowpea evident in the data demonstrates that Somali farmers are already adapting in the direction the evidence recommends, but the magnitude of that adaptation, left to unaided farmer initiative, falls far short of what would be required to offset the roughly 71,000 MT combined decadal decline in the two cereals. The role of policy is therefore not to initiate a shift that is already under way but to accelerate and scale it, converting a modest, spontaneous adaptation into a deliberate, adequately resourced national strategy. The weak sorghum-cowpea correlation ($r = 0.25$) documented here provides a quantitative, Somalia-specific evidentiary basis for prioritising cereal-legume intercropping and diversification as a risk-management strategy, consistent with

the wider literature on diversification as a climate-adaptation mechanism for smallholder systems (Cooper et al., 2008; Lobell et al., 2008).

These findings should be read in light of the study's scope and its analytical assumptions. The analysis infers climatic influence from the tight temporal correspondence between production deficits and independently documented droughts, an inferential rather than a strictly causal approach, and non-climatic factors, including conflict, market conditions, and input availability, undoubtedly also influence production and in specific instances may dominate, as the 2011 case, in which good aggregate harvests coincided with a localised famine driven by access failures rather than production failure, illustrates. Coupling this production record with station and satellite rainfall data and reanalysis temperature data would allow the crop-climate response functions to be quantified more directly in future work, and decomposing production change into its area and yield components, where cultivated-area data can be obtained, would help clarify whether the observed declines reflect land abandonment or falling productivity per hectare, a distinction of considerable policy importance that this study, based on production totals alone, cannot resolve.

5. Conclusion

This study has shown that climate change and variability have exerted a measurable and largely adverse effect on Somalia's cereal production over the past three decades, most clearly on maize and, more recently, on sorghum, while cowpea has expanded significantly, if from a small base and with high volatility. The three crops differ substantially in their production stability, with sorghum the most stable, cowpea the most volatile, and the sharp rise in maize's instability a finding of particular concern; production anomalies are systematically associated with documented climatic shocks, confirming drought as the dominant driver of production deficits; and the seasonal and spatial analyses reveal that the crops are exposed to partially distinct climatic risks, with the weak sorghum-cowpea correlation confirming the value of diversification. The overarching conclusion is that Somalia's cereal-dominated cropping system is increasingly ill-matched to its climate: the staple maize crop is in structural decline and has become markedly more erratic, the fallback sorghum crop, long stable, has begun to falter, and the drought-tolerant cowpea, though expanding and demonstrably resilient during shocks, remains too small and too variable to secure the national food supply on its own. Without deliberate, accelerated, and scaled-up adaptation, the widening gap between a shrinking, more volatile cereal base and a rising population portends deepening food insecurity. Translating this evidence into resilience will require national agricultural policy to prioritise and substantially scale up cultivation of cowpea and other drought-tolerant legumes and cereals as a central pillar of food-security strategy rather than a marginal supplement, coupled with investment that geographically diversifies the production base beyond the dangerously concentrated Shabelle valley and Bay plateau into the under-utilised potential of the North West and Central zones. Extension services should actively promote cereal-legume intercropping, given the weak correlation between sorghum and cowpea production, alongside continued and enhanced investment in seasonal forecasting and the post-Gu and post-Deyr crop assessments that allow anticipatory action to be triggered before a poor season becomes a food crisis. Improved water management in the riverine zones would buffer maize against both the drought and flood extremes to which it is exposed, while investment in improved and drought-tolerant seed, supported by a strengthened national seed system, offers substantial scope to raise and stabilise yields across all three crops. Institutions such as the Faculty of Agriculture at Hormuud University have a direct role to play in this agenda, through farmer training, applied research, and the kind of longitudinal production monitoring that this study demonstrates to be both feasible and highly informative for a food system whose security depends, more than almost any other in the world, on the reliability of two annual rains.

Author Contributions

Hassan Ali Hassan: data curation, formal analysis, writing, original draft. Ibrahim Osman Mohamed: data curation, visualization, writing, review and editing. Abukar Mohamed Mohamud: investigation, methodology, writing, review and editing. Ahmed Abdiaziz Alasow: conceptualisation, supervision, writing, review and editing. All authors read and approved the final manuscript.

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Conflict of Interest Statement

The authors declare no conflict of interest.

Data Availability Statement

The district-level seasonal production data underlying this study derive from the publicly documented seasonal assessments of the Food Security and Nutrition Analysis Unit for Somalia. The compiled analytical dataset and the code used for the statistical analyses reported here are available from the corresponding author upon reasonable request.

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