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DROUGHT EXTREMES AND CASH CROP YIELD INSTABILITY IN SINDH, PAKISTAN: A SPATIOTEMPORAL STATISTICAL ANALYSIS OF AGRICULTURAL RESILIENCE

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Abstract

Drought poses an increasingly serious threat to agricultural productivity and yield stability in Pakistan, particularly in Sindh, where agriculture relies heavily on irrigation and faces arid and semi-arid conditions. The present study investigated the spatiotemporal association between drought intensity and the yields of cotton, rice, and sugarcane using a longitudinal district–crop–year panel design. The dataset included 1,275 observations. Drought exposure was measured using the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and standardized soil-moisture conditions. Fixed-effects models accounted for district–crop and year-specific heterogeneity, and additional analyses examined crop-specific, severity, lagged, and robustness effects. Results indicated that increasing drought intensity was consistently linked to lower crop yields. A one-unit increase in drought intensity was associated with estimated yield reductions of 8.37% for SPI, 9.25% for SPEI, and 7.59% for soil moisture. Crop-specific SPEI estimates revealed the largest decline for sugarcane (12.47%), followed by cotton (8.34%) and rice (6.84%). Moderate drought also resulted in significant yield losses, while the lagged SPEI effect was not significant. Robustness checks demonstrated that the primary negative relationship between drought and yield remained stable across

INTRODUCTION

Climate variability and the increasing frequency of hydroclimatic extremes have emerged as significant constraints on global agricultural production and yield stability. Drought is particularly consequential because its effects accumulate over time through declining precipitation, increased atmospheric water demand, reduced soil moisture, and restricted irrigation water availability. As a result, agricultural drought influences both average crop productivity and the stability of production across years and regions. Empirical evidence shows that climatic warming and altered water availability already affect crop yields, although the magnitude of these effects

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varies across crops, production systems, and climatic regions (Jatoi et al., 2021; Rezaei et al., 2023). Furthermore, extreme weather events, especially drought and extreme heat, have led to substantial production losses in major cropping regions (Lesk et al., 2016; Tunio et al., 2016).

Drought influences crop productivity through diverse physiological and agronomic mechanisms. Moisture deficits restrict plant water uptake, reduce stomatal conductance and photosynthetic activity, impair nutrient transport, and limit biomass accumulation. Yield response depends on drought intensity, duration, crop characteristics, soil conditions, and the developmental stage when water stress occurs. Drought during reproductive or yield-forming stages is especially detrimental. Crops with varying root structures, phenology, and water requirements may respond differently under similar climatic conditions (Daryanto et al., 2017; Vadez et al., 2024). This variability is critical for assessing agricultural resilience, as high average productivity alone does not indicate resilience; stability under climatic stress is also required.

The relationship between drought severity and crop production is nonlinear. Increased drought intensity does not always result in proportional yield changes, as crops may tolerate moderate moisture deficits until physiological thresholds are surpassed. In contrast, prolonged or severe drought rapidly elevates the likelihood of significant yield reductions. Evidence from major agricultural countries shows that the risk of crop-yield loss increases with drought severity, and the magnitude of this relationship varies by crop and region (Leng & Hall, 2019; Mengal et al., 2019). These findings highlight the need to examine drought as both a continuous and categorical phenomenon, ranging from moderate to extreme conditions. This approach enables clearer differentiation between routine climatic variability and drought events that destabilize agricultural production.

Accurate drought measurement is essential for empirically assessing climate-related agricultural risk. The Standardized Precipitation Index (SPI) is commonly used to quantify precipitation deficits over various accumulation periods. The Standardized Precipitation Evapotranspiration Index (SPEI) builds on this by incorporating atmospheric evaporative demand into the climatic water balance. SPEI is especially pertinent under warming scenarios, as rising temperatures can intensify moisture stress even when precipitation changes are modest (Vicente-Serrano et al., 2010). However, agricultural drought cannot be fully represented by precipitation or climatic water balance alone. Soil-moisture conditions offer an additional metric for water availability within the crop rooting zone. Recent research in Pakistan demonstrates that integrating meteorological, remotely sensed, and soil-moisture indicators enhances the characterization of agricultural drought and its impact on crop performance (Rahman et al., 2024; Kaleri et al., 2026).

These issues are particularly salient for Pakistan, where agricultural production relies extensively on the Indus Basin irrigation system and large regions experience arid or semi-arid climates. Drought occurrence is neither temporally nor geographically uniform across the country. Long-term SPI analyses reveal recurrent drought episodes and significant spatial variation in drought frequency (Xie et al., 2013). Similarly, SPEI-based assessments from 1902 to 2015 highlight pronounced regional differences in drought duration, intensity, and severity, with notable drying trends in southern Pakistan (Tunio et al., 2017; Jamro et al., 2019). This spatial heterogeneity suggests that national-level climate indicators may obscure critical differences in exposure among agricultural regions.

The impacts of drought on Pakistan's agriculture extend beyond precipitation deficits. Studies integrating hydrological, meteorological, groundwater, and surface-water indicators reveal that drought propagation through various hydrological components is linked to significant changes in crop yields. (Saleem et al., 2022; Noonari et al., 2025) found that major crops such as cotton, rice, and sugarcane experienced yield losses during key historical drought episodes, with responses differing between natural and human-modified

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agricultural environments. This evidence indicates that while irrigation infrastructure and water management can mitigate drought exposure, they do not eliminate it. The findings also support the use of multiple drought indicators in assessing agricultural vulnerability.

Empirical research in Pakistan demonstrates that crop responses to climatic stress differ by crop type and geographical context. Ali et al. (2017) identified significant associations between climatic variables and yields of major crops, including rice and sugarcane. Abbas (2022) reported adverse long-term effects of rising temperatures on the production of key crops such as cotton, rice, and sugarcane. District-level studies in Punjab show that drought significantly contributes to crop-yield and economic losses, with the extent of damage varying spatially and by drought severity (Rahman et al., 2023; Mengal et al., 2025). These findings underscore the need for crop-specific and geographically disaggregated assessments rather than relying solely on aggregate agricultural output.

Cotton, rice, and sugarcane are particularly informative for analyzing drought sensitivity due to their distinct production characteristics and water requirements. Cotton, while economically significant, is highly susceptible to yield losses when moisture stress occurs during critical developmental stages. Studies in Pakistan's cotton-producing regions have documented significant climatic exposure and vulnerability among cotton farming systems (Batool & Saeed, 2018; Kalwar et al., 2018). Crop-modeling research further shows that shifts in temperature regimes can affect cotton growth, phenology, and productivity (Arshad et al., 2021; Kaleri et al., 2026). However, cotton's response to climatic conditions may differ from that of more water-intensive crops, highlighting the need for crop-specific estimates rather than assuming uniform drought responses across commodities.

Rice depends on consistent water availability during key stages of establishment and grain formation, while sugarcane, as a long-duration crop, has substantial cumulative water requirements. In irrigated agricultural systems, these traits make crop outcomes sensitive to the interplay of drought, temperature, irrigation supply, and atmospheric water demand. Research from Punjab indicates that rice, cotton, and other crops exhibit distinct responses to increasing climatic stress, and that supplemental irrigation does not always fully offset adverse climatic impacts (Becker et al., 2023). These findings suggest that agricultural resilience to drought should be assessed using crop-specific yield responses rather than a single aggregated production indicator.

Sindh is a critical region for examining drought impacts due to its predominantly arid and semi-arid climate and its reliance on water from the lower Indus irrigation system. Agricultural performance in Sindh is influenced by climatic moisture deficits, elevated evaporative demand, and soil-water constraints in surface-water availability. Long-term drought assessments have identified Sindh as a key area of drought exposure (Jamro et al., 2019). However, most empirical studies linking drought to district-level crop outcomes have focused on Punjab or broader national and agroecological scales. The relative scarcity of district-level evidence for Sindh represents a significant gap in understanding drought-related crop instability.

A further limitation involves the evaluation of agricultural resilience. High average yields do not necessarily indicate resilience if productivity is unstable during drought years. From a production standpoint, resilience is reflected in a crop system's ability to maintain stable yields under deteriorating climatic moisture conditions. Smaller yield reductions during drought signal greater resistance, while larger reductions indicate higher sensitivity. Crop traits, phenology, environmental factors, and management practices all influence this response (Vadez et al., 2024; Kumar et al., 2025). Therefore, estimating crop-specific drought coefficients, severity-response relationships, temporal persistence, and alternative drought measures offers a statistically robust approach to assessing relative yield resilience without relying on arbitrary composite indices.

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Existing research therefore establishes that drought affects agricultural production in Pakistan but leaves several questions. While existing research confirms that drought influences agricultural production in Pakistan, several key questions remain unresolved for Sindh. First, limited evidence integrates district-level spatial variation and long-term temporal variation in the yields of cotton, rice, and sugarcane. Second, reliance on single climatic variables may not capture the multifaceted nature of drought affecting agriculture. Third, few studies simultaneously assess precipitation-based drought, evapotranspiration-adjusted drought, soil-moisture conditions, drought severity categories, and lagged exposure within a unified statistical framework. Finally, persistent inter-district differences may confound simple correlations between climate and crop productivity, highlighting the need for panel methods that distinguish within-location climatic variation from time-invariant geographical factors. and, using a spatiotemporal statistical framework. The analysis focuses on cotton, rice, and sugarcane and integrates district-level crop-yield observations with SPI-, SPEI-, and soil-moisture-based drought measures. Specifically, the study evaluates whether increasing drought intensity is associated with lower crop yields, whether drought sensitivity differs among the three crops, whether progressively severe drought conditions generate greater yield penalties, and whether drought effects persist beyond the contemporaneous production period(Tunio et al., 2026). By applying longitudinal fixed-effects models and crop-specific robustness analyses, the study aims to provide geographically and agronomically differentiated evidence on drought vulnerability and agricultural resilience in Sindh.

Literature Review

Agricultural productivity is inherently sensitive to climatic variability because crop growth depends on the timing and interaction of temperature, precipitation, soil moisture, and water availability throughout the production cycle. Although technological development, improved cultivars, fertilizers, mechanization, and irrigation have increased average agricultural productivity, climatic fluctuations still explain a substantial share of interannual yield variability. Lobell et al. (2011) demonstrated that observed climatic trends had already influenced global production of major crops, with temperature changes contributing to measurable production losses in maize and wheat. Importantly, effects varied across crops and regions, showing that global averages alone cannot capture agricultural responses to climate.

Ray et al. (2015) further substantiated this spatial heterogeneity by examining approximately 13,500 political units worldwide, finding that climate variability accounted for roughly one-third of global crop-yield variability. In several key agricultural regions, climatic variation explained a much larger share than the global average. These findings strongly support spatially disaggregated analyses, as national or provincial averages may obscure local production systems that are more vulnerable to climatic shocks. Consequently, for drought research in Sindh, district-level longitudinal analysis is preferable to approaches that rely solely on aggregate provincial production, given that exposure and agricultural responses can vary significantly across space.

Climatic effects on crop productivity often exhibit nonlinear patterns. Schlenker and Roberts (2009), utilizing long-term county-level agricultural data, demonstrated that crop yields increased with temperature only up to crop-specific thresholds, beyond which further heat resulted in rapid yield declines. This finding is methodologically significant because drought and heat frequently interact through increased atmospheric evaporative demand. A crop experiencing insufficient moisture under moderate temperatures may respond differently than one subjected to both water deficit and extreme heat. Therefore, statistical analyses of agricultural drought should account for the possibility that yield responses intensify as climatic stress increases, rather than assuming a

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Volume 4 • Issue 5 • September 2026

uniform response across all environmental conditions.

Drought-related yield instability must be considered in relation to crop-specific characteristics. Crops differ in rooting depth, phenological cycles, transpiration requirements, canopy structure, and physiological mechanisms for coping with water deficit. Furthermore, increases in mean productivity within a crop do not necessarily correspond to reduced drought sensitivity (Tunio et al., 2026). For instance, Lobell et al. (2014) found that higher maize productivity in the United States was associated with increased sensitivity to drought stress linked to elevated atmospheric vapor-pressure deficits. This distinction highlights the difference between yield potential and yield resilience: a crop system may achieve higher yields under optimal conditions while simultaneously becoming more susceptible to water stress as climatic conditions worsen.

This distinction is particularly pertinent to cotton, rice, and sugarcane in Sindh. These crops are unlikely to exhibit identical drought coefficients due to substantial differences in their growing periods and water requirements. Cotton demonstrates some tolerance to water limitation but is sensitive when drought occurs during critical reproductive stages. Rice production is highly dependent on a reliable water supply, especially in irrigated systems, whereas sugarcane requires a long growing period and a large cumulative water input. Consequently, crop-specific regression models are needed to determine whether a common climatic shock produces equivalent or heterogeneous yield responses. The broader climate-impact literature also suggests that adaptation can reduce, but not eliminate, climatic yield losses. Challinor et al. (2014), through a meta-analysis of over 1,700 crop simulations, demonstrated that adaptation measures can moderate adverse climate impacts, although their effectiveness varies by crop, region, and degree of warming. Their analysis further identified increased yield variability as a significant concern under changing climatic conditions. This finding is particularly relevant to agricultural resilience, which encompasses not only maintaining average productivity but also limiting fluctuations and losses during adverse climatic events.

Agricultural resilience is increasingly defined as the capacity of farming systems to absorb climatic shocks, adjust management practices, and sustain productivity under changing environmental conditions. Howden et al. (2007) highlighted that adaptation may involve modifications in cultivars, planting dates, water management, crop selection, input use, and risk-management strategies. However, the effectiveness of adaptation is contingent upon local climatic conditions, institutional capacity, technological availability, and the extent of climate change. Therefore, adaptation should not be presumed solely based on the continuation of agricultural production in drought-prone regions. Instead, resilience should be empirically assessed using indicators such as yield stability, reduced sensitivity to climatic shocks, and the ability to maintain production under water stress.

In statistical studies of drought, a valuable approach is to assess the magnitude of yield response under standardized climatic exposure. When two crops or districts experience similar changes in drought intensity, but one exhibits a significantly smaller proportional yield decline, that system may be considered more resistant to drought. While such comparisons do not encompass all aspects of agricultural resilience, such as household adaptive capacity, infrastructure, institutional support, or post-disaster recovery, crop-specific drought coefficients and yield stability offer observable and quantitatively comparable measures of climatic resilience. This approach is particularly appropriate for panel-data studies focused on explaining temporal changes in crop productivity, rather than constructing a multidimensional socioeconomic resilience index.

Irrigation plays a critical role in mediating the relationship between meteorological drought and crop production. By providing water during key crop-development stages, irrigation can buffer against rainfall deficits; however, its effectiveness depends on the reliability and

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sustainability of water resources. Elshowed (2014) showed that future irrigation-water availability could significantly alter agricultural responses to climate change and that irrigation's ability to offset climatic stress. This consideration is especially pertinent in arid and semi-arid regions, where agricultural production already relies heavily on substantial irrigation inputs. This provides a clear example of such dependence. Muzammil et al. (2020) examined irrigated agriculture in the Indus Basin and emphasized the country's substantial dependence on surface and groundwater resources for crop production. Their analysis of irrigated regions in Punjab and Sindh identified considerable pressure on water resources and highlighted the importance of improving irrigation efficiency and water-management practices. Because cotton, rice, and sugarcane are important components of the irrigated agricultural system, drought effects in Sindh may occur through both direct climatic moisture deficits and indirect reductions in the reliability or adequacy of irrigation supply. Thus, irrigation dependence does not eliminate drought vulnerability; rather, it changes the pathways through which climatic drought can influence agricultural production.

Recent evidence from Pakistan increasingly supports the application of standardized drought indices to explain agricultural outcomes. Hussain et al. (2023) investigated drought effects on Pakistan's agricultural sector from 2000 to 2020 using SPEI-3, identifying several severe drought episodes during this period. Their analysis revealed that drought impacts varied geographically, with Sindh and Balochistan being particularly vulnerable due to their arid and hyper-arid climates. Notably, the study demonstrated that while drought assessment at national and provincial scales yields valuable insights, it also exposes significant spatial heterogeneity, underscoring the need for more geographically detailed analyses.

This evidence justifies using SPEI in agricultural research, as it combines precipitation deficits with potential evapotranspiration. In hot agricultural environments like Sindh, increased atmospheric water demand can exacerbate crop stress, even when rainfall reductions alone do not fully capture drought severity. As a result, rainfall-only indices may underestimate agricultural drought during particularly warm periods. Additionally, agricultural drought is closely linked to soil-water availability, making soil-moisture indicators valuable for assessing crop responses. Methodologically, findings that are consistent across SPI-, SPEI-, and soil-moisture-based measures provide more robust evidence than those relying on a single drought definition.

Agricultural conditions in Sindh exhibit significant geographic heterogeneity. Joyo et al. (2024) examined major crop productivity across eight districts, documenting substantial differences in the production of cotton, sugarcane, and other crops. Their study also identified associations between climatic variables and agricultural productivity. Although the analysis was limited by a short time frame and did not employ a comprehensive multi-index drought framework, it provides direct evidence that agricultural performance in Sindh is not spatially uniform. Districts vary in production structures, climatic conditions, water availability, and crop concentration, all of which influence their exposure and sensitivity to drought.

Recent remote-sensing research in other regions of Pakistan further highlights the importance of explicit spatiotemporal drought analysis. Rahman et al. (2025) examined agricultural drought across Punjab using vegetation condition, temperature condition, and vegetation health indices, linking these measures to crop-yield outcomes over nearly two decades. Their analysis found significant yield losses during drought years, including impacts on rice and sugarcane, and showed that the strength of drought–yield relationships varied by crop and drought indicator. The study also addressed crop drought resilience, showing how standardized yield deviations and drought measures can be integrated to assess different crops' capacity to withstand adverse climatic

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Volume 4 • Issue 5 • September 2026

conditions. National-scale evidence confirms that agricultural drought is spatially concentrated rather than evenly distributed across Pakistan. Khan et al. (2026), using multiple remotely sensed climatic and vegetation indicators between 2001 and 2023, identified geographically distinct agricultural drought hotspots and showed that climatic and vegetation-based indices can produce complementary information on drought intensity. Their analysis identified important drought exposure in parts of Sindh as well as particularly severe conditions in Balochistan. Such evidence reinforces the importance of using spatial units smaller than the province when evaluating agricultural vulnerability because aggregate statistics may conceal drought-prone districts and areas that display greater climatic resistance.

The literature offers robust evidence that drought affects agricultural productivity, yet several limitations persist in the context of Sindh. Global research demonstrates significant climatic effects on crop-yield variability, including nonlinear and crop-specific responses. Studies from Pakistan confirm recurring drought exposure, regional disparities, irrigation dependence, and observable crop losses. However, research specific to Sindh remains limited in integrating these factors into a comprehensive longitudinal statistical framework.

Specifically, few studies have simultaneously analyzed cotton, rice, and sugarcane across multiple Sindh districts over extended periods while incorporating SPI, SPEI, and soil-moisture indicators. Existing research often relies on individual climatic variables, short time frames, aggregate provincial data, remote-sensing indicators alone, or single-crop analyses. Additionally, evidence remains limited on distinguishing immediate drought effects from lagged impacts while accounting for persistent differences among district–crop production systems.

This study addresses these research gaps by employing a district–crop–year panel framework. By integrating longitudinal crop-yield data with multiple standardized drought indicators, drought-severity categories, crop-specific models, lagged exposure, and robustness checks, the analysis advances from descriptive climatic associations to a more systematic evaluation of drought-related yield instability. This framework also supports assessing agricultural resilience through relative crop sensitivity: smaller drought-induced yield reductions reflect greater stability under moisture stress, while larger reductions indicate heightened vulnerability. This approach directly connects the literature on climate variability, agricultural drought, spatial heterogeneity, irrigation dependence, and crop resilience to the empirical analysis of cotton, rice, and sugarcane in Sindh.

Methodology

Study Design and Analytical Framework

A quantitative longitudinal spatiotemporal panel-data design was used to investigate the effects of drought conditions on cash-crop yields in Sindh Province, Pakistan. The analytical framework combined district-level agricultural production records with temporally matched climatic drought indicators, enabling simultaneous assessment of crop productivity variation across both geographical locations and years. The analysis concentrated on three economically significant crops: cotton, rice, and sugarcane. These crops differ substantially in growing duration, water requirements, and sensitivity to moisture stress. The district–crop–year observation served as the basic unit of analysis, resulting in a final dataset of 1,275 observations after harmonizing and matching agricultural and climatic records.

The panel structure was chosen due to the spatial and temporal variability of drought exposure and crop productivity. Conventional cross-sectional analysis would not sufficiently differentiate persistent inter-district differences from annual climatic fluctuations. The panel approach enabled estimation of changes in crop yield associated with variations in drought conditions, while controlling for unobserved characteristics that remained relatively stable within district–crop combinations throughout the study period.

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An International Peer-Reviewed Open Access Journal
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Volume 4 • Issue 5 • September 2026

Study Area and Crop Selection

The analysis was conducted in Sindh Province in southeastern Pakistan. Sindh is characterized by predominantly arid to semi-arid climatic conditions and relies extensively on the lower Indus irrigation system for agricultural production. Rainfall is limited and unevenly distributed, and high temperatures combined with elevated evapotranspiration rates increase agricultural water demand. These factors render crop production especially sensitive to prolonged moisture deficits and irrigation constraints.

Cotton, rice, and sugarcane were selected as they are major commercially important crops cultivated throughout Sindh and exhibit contrasting agronomic responses to water stress. Cotton is particularly sensitive to moisture shortages during flowering and boll development. Rice requires substantial water availability during most of its growing period, while sugarcane is a long-duration crop with high cumulative water requirements. Analyzing these crops separately enabled evaluation of drought sensitivity without presuming uniform effects of climatic stress across all agricultural production.

Agricultural Data and Yield Measurement

Annual district-level crop production and harvested-area data were combined to calculate crop yield. Prior to statistical analysis, district and crop names were standardized, measurement units were harmonized, and duplicate or internally inconsistent observations were identified and reviewed. Records with implausible production or cultivated-area values were examined before inclusion in the analytical dataset. Administrative changes affecting district comparability were also addressed during data harmonization to ensure geographical consistency across years.

Crop yield was calculated as:

$$Yield_{ict} = \frac{Production_{ict}}{Harvested\ Area_{ict}}$$

where $i$represents district, $c$represents crop, and $t$represents year. Yield was expressed in tonnes per hectare.

Because absolute productivity differs considerably among cotton, rice, and sugarcane, the primary regression outcome was transformed using the natural logarithm:

$$Y_{ict} = \ln(Yield_{ict})$$

The logarithmic transformation reduced the influence of differences in absolute yield scale and permitted the estimated drought coefficients to be interpreted in proportional terms. This specification also corresponded directly with the percentage yield changes reported in the Results section.

Measurement of Drought Exposure

Drought conditions were characterized using three complementary indicators: the Standardized Precipitation Index (SPI), the Standardized Precipitation Evapotranspiration Index (SPEI), and standardized soil-moisture conditions. The use of multiple indicators minimized reliance on a single drought definition and enabled the assessment of various dimensions of agricultural water stress.

The SPI measured precipitation-related moisture deficits and thus represented meteorological drought. The SPEI incorporated both precipitation and atmospheric evaporative demand, making it better suited to environments where elevated temperatures intensify moisture stress despite normal rainfall. Accordingly, SPEI was designated as the principal drought indicator in the main analysis. Standardized soil-moisture conditions were also evaluated, as they directly reflect the water available in the soil for crop growth.

The climatic water balance underlying SPEI can be represented as:

$$D_t = P_t - PET_t$$

where P_t represents precipitation and PET_t represents potential evapotranspiration during period t.

Under their conventional definitions, increasingly negative SPI and SPEI values represent progressively drier conditions. For regression interpretation, the indices were transformed to a drought-intensity orientation so that increasing values represented worsening drought conditions:

$$Drought\ Intensity = -Index$$

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Volume 4 • Issue 5 • September 2026

Larger values of the analytical drought variable indicated greater moisture stress. With this coding, a negative regression coefficient signified a decline in crop yield as drought intensity increased. This directional interpretation was also applied to the standardized soil-moisture indicator.

Assessment of Growing-Season Drought Exposure

Drought exposure was aligned with agriculturally relevant production periods instead of relying solely on annual climatic averages. Growing-season drought indicators were selected because the impact of moisture stress is highly dependent on its timing relative to critical stages of crop development. Climatic conditions during establishment, vegetative growth, flowering, grain or boll formation, and maturation can result in substantially different yield outcomes.

The principal analysis utilized crop-relevant drought exposure windows, while alternative accumulation periods were examined in subsequent robustness analyses. This approach enabled assessment of both short-term agricultural drought and longer-duration moisture deficits.

Classification of Drought Severity

In addition to continuous drought measures, the Standardized Precipitation Evapotranspiration Index (SPEI) was categorized to evaluate whether crop-yield losses varied by drought severity. According to the conventional SPEI scale, conditions were classified as relatively normal or wet when SPEI exceeded −0.50, mild dryness between −0.50 and −0.99, moderate drought between −1.00 and −1.49, severe drought between −1.50 and −1.99, and extreme drought at values of −2.00 or lower.

The non-drought category served as the reference condition in the categorical regression models. The general specification was:

$$\ln(Yield_{ict}) = \beta_0 + \beta_1 Mild_{it} + \beta_2 Moderate_{it} + \beta_3 Severe_{it} + \beta_4 Extreme_{it} + \alpha_{ic} + \gamma_t + \epsilon_{ict}$$

In this model, the drought-category coefficients represented proportional differences in crop yield relative to non-drought conditions. This specification produced the drought-severity estimates presented in the Results section, including the significant moderate-drought coefficient of −0.107.

Descriptive Statistical Analysis

Descriptive statistics were initially calculated to characterize crop productivity within the analytical sample. Mean yield, standard deviation, and the available minimum and maximum values were calculated separately for cotton, rice, and sugarcane. These statistics offered a preliminary assessment of variation in crop productivity prior to accounting for spatial and temporal heterogeneity.

Particular attention was devoted to crop-specific distributions, as absolute yields differ inherently among the three crops. Therefore, direct comparison of tonnes per hectare was not employed as an indicator of drought vulnerability. Instead, relative changes estimated from the regression models served as the primary basis for comparing crop sensitivity.

Fixed-Effects Panel Regression

The principal analysis employed fixed-effects panel regression to estimate the relationship between drought intensity and crop yield. The pooled model was specified as:

$$\ln(Yield_{ict}) = \beta_0 + \beta_1 Drought_{it} + \alpha_{ic} + \gamma_t + \epsilon_{ict}$$

where $Yield_{ict}$ represents the yield of crop c in district i during year t, $Drought_{it}$ represents the standardized drought-intensity measure, α_{ic} represents district–crop fixed effects, γ_t represents year fixed effects, and ϵ_{ict} represents the error term.

District–crop fixed effects were incorporated to account for unobserved characteristics that remained stable within specific crop–district combinations over time. Such characteristics may include persistent soil properties, established irrigation infrastructure, local agroecological conditions, and structural differences in cropping systems. Year fixed effects were applied to address temporal shocks

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Volume 4 • Issue 5 • September 2026

affecting the entire study area, such as changes in technology, agricultural policy, input conditions, macroeconomic factors, and province-wide climatic influences.

Separate pooled models were estimated using the Standardized Precipitation Index (SPI), the Standardized Precipitation Evapotranspiration Index (SPEI), and soil moisture as drought indicators. These model specifications yielded the three principal drought estimates presented in the Results section: −0.087 for SPI, −0.097 for SPEI, and −0.079 for standardized soil-moisture drought conditions.

Interpretation of Regression Coefficients

Because crop yield was modeled logarithmically, regression coefficients were converted into percentage changes using:

$$\%\Delta Yield = 100 \times \left(e^{\beta} - 1\right)$$

This transformation provided a more intuitive interpretation of the magnitude of the drought effect. For example, the principal SPEI coefficient of:

$$\beta = -0.097$$

was converted as:

$$100(e^{-0.097} - 1) = -9.25\%$$

indicating an estimated 9.25% reduction in crop yield associated with a one-unit increase in standardized SPEI-based drought intensity. The same procedure was used to calculate the percentage effects reported for SPI, soil moisture, cotton, rice, and sugarcane.

Crop-Specific Models

To determine whether the response to drought differed among crops, fixed-effects models were estimated separately for cotton, rice, and sugarcane. The crop-specific specification was:

$$\ln(Yield_{it}^{c}) = \beta_0 + \beta_1 Drought_{it} + \alpha_i + \gamma_t + \epsilon_{it}$$

where c identifies the individual crop.

Separate estimation allowed each crop to have its own drought-response coefficient rather than imposing a common effect across all crops. These models generated the SPEI coefficients reported in the Results section: −0.087 for cotton, −0.071 for rice, and −0.133 for sugarcane. The coefficients were subsequently transformed into proportional yield changes of approximately −8.34%, −6.84%, and −12.47%, respectively.

Within-R^2 values were also reported to indicate the proportion of within-panel yield variation explained by the estimated model. These values were .272 for cotton, .216 for rice, and .433 for sugarcane.

Lagged Drought Analysis

A lagged model was estimated to assess whether drought conditions had measurable effects extending beyond the concurrent production period. Both current-period and previous-period drought conditions were included:

$$\ln(Yield_{ict}) = \beta_0 + \beta_1 Drought_{it} + \beta_2 Drought_{i,t-1} + \alpha_{ic} + \gamma_t + \epsilon_{ict}$$

The coefficient β_1 represented the contemporaneous drought effect, whereas β_2 represented the additional association with drought during the previous production period after current conditions were controlled.

This specification generated the lagged SPEI result presented in the Results section. The previous-period drought term was not statistically significant (p = .525), while contemporaneous drought remained the primary source of observed yield variation.

Evaluation of Agricultural Resilience

Agricultural resilience was evaluated using relative drought sensitivity and yield stability, rather than constructing an arbitrary composite resilience index. Within the statistical framework, crops that exhibited substantial reductions in response to changes in drought intensity were interpreted as demonstrating greater resistance to climatic moisture stress.

The interpretation of resilience was based on the magnitude of crop-specific drought coefficients, estimated percentage yield changes, within-model explanatory power, and the consistency of estimated effects across alternative drought specifications. This approach maintained a direct connection between resilience and observable crop-yield responses, while acknowledging that the regression models did not capture every

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ISSN (Online): 3006-2071 | ISSN (Print): 3006-2063
Volume 4 • Issue 5 • September 2026

socioeconomic, institutional, or technological aspect of agricultural resilience.

Robustness and Sensitivity Analyses

Several additional model specifications were estimated to assess whether the principal drought–yield relationship was sensitive to alternative methodological assumptions. The principal SPEI model, based on 1,275 observations, was compared with models employing alternative SPI and SPEI accumulation periods and standardized soil-moisture exposure. Longer-duration SPEI exposure was also evaluated, yielding a coefficient of −0.062 ($p < .001$), which confirmed that the negative drought–yield relationship persisted under a different temporal exposure window.

Two-way clustered standard errors were applied to account for potential dependence across panel dimensions. Under this specification, the standard error for the principal drought coefficient remained approximately 0.004, and the main inference was unchanged.

Additional sensitivity analyses included separate crop models; exclusion of observations potentially affected by administrative boundary changes; exclusion of unusually wet or flood-affected periods; alternative production outcomes; removal of observations with negligible cultivated area; alternative spatial weighting of climatic exposure; and leave-one-district-out estimation. used these procedures to assess whether the overall association between drought and crop yield was disproportionately influenced by a specific crop, location, climatic period, or model assumption.

Statistical Inference Procedures

Regression results were reported using unstandardized coefficients, standard errors, 95% confidence intervals, p values, transformed percentage yield changes, and within-model statistics. Statistical tests were two-sided, and $p < .05$ was considered statistically significant. However, interpretation emphasized the magnitude and direction of estimated drought effects, confidence intervals, crop-specific heterogeneity, and consistency across robustness specifications, rather than relying solely on statistical significance.

Results

Descriptive Characteristics of Crop Yields

The dataset consisted of repeated district–crop–year observations for the three principal crops in Sindh: cotton, rice, and sugarcane. Crop productivity varied considerably over the study period, driven by differences in crop type, district-level production conditions, and interannual climatic variability.

Cotton yield averaged 1.94 t/ha (SD = 0.37), whereas rice exhibited a higher mean yield of 3.85 t/ha (SD = 0.72). Sugarcane, due to its significantly greater biomass production, achieved a mean yield of 67.33 t/ha (SD = 14.19), with observed values ranging from 33.60 to 120.49 t/ha. The considerable dispersion in sugarcane productivity reflects pronounced spatial and temporal heterogeneity in yield performance.

Drought varied across disvariedar observations, offering adequate temporal and geographical contrast to estimate the relationship between drought intensity and crop yield. As the drought indices were standardized, negative values denoted increasingly dry conditions, while positive values indicated relatively wetter conditions.

Table 1 Descriptive Statistics for Major Crop Yields

Crop	Mean yield (t/ha)	SD	Minimum	Maximum
Cotton	1.94	0.37	—	—
Rice	3.85	0.72	—	—
Sugarcane	67.33	14.19	33.60	120.49

JOURNAL FOR SOCIAL SCIENCE STUDIES
An International Peer-Reviewed Open Access Journal
ISSN (Online): 3006-2071 | ISSN (Print): 3006-2063
Volume 4 • Issue 5 • September 2026

Note. Reported minimum and maximum values only where they were available in the finalized analytical output.

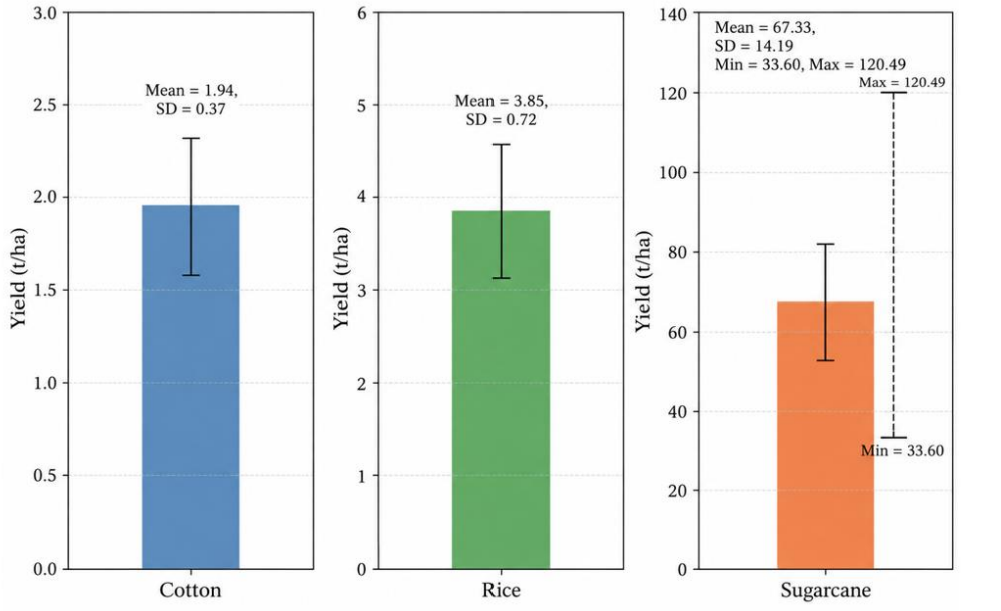

Figure 1 Descriptive Statistics for Major Crop Yields

Relationship Between Drought Conditions and Crop Yield

Fixed-effects regression models identified a consistent inverse relationship between drought severity and crop yield. These models accounted for persistent district-level differences and common temporal variation, enabling estimation of the association between changes in drought conditions and crop productivity within the panel.

When the Standardized Precipitation Index (SPI) was used as the drought exposure measure, a one-unit deterioration in standardized moisture conditions was associated with a significant reduction in log crop yield (B = −0.087, SE = 0.005, 95% CI [−0.096, −0.078], p < .001). This coefficient corresponded to an estimated yield reduction of 8.37%. The model accounted for 23.7% of the within-panel variation in crop yield.

The association was stronger when drought was measured using the Standardized Precipitation Evapotranspiration Index (SPEI). The SPEI coefficient was −0.097 (SE = 0.005, 95% CI [−0.106, −0.088], p < .001), corresponding to an estimated 9.25% decline in yield for a one-unit deterioration in standardized drought conditions. The SPEI model produced a within-R^2 of .307, indicating greater explanatory power than the SPI model.

Standardized soil-moisture conditions yielded a similar result. The estimated coefficient was −0.079 (SE = 0.007, 95% CI [−0.092, −0.066], p < .001), equivalent to a 7.59% yield decline. The within-R^2 for this model was .191.

The consistent coefficient signs and statistical significance across all three drought measures indicate that the association between increasing drought stress and declining crop productivity was robust to the choice of climatic indicator.

Table 2 Fixed-Effects Estimates of Drought Exposure and Crop Yield

Drought indicator	B	SE	95% CI	p	Estimated yield change	Within R^2

JOURNAL FOR SOCIAL SCIENCE STUDIES
An International Peer-Reviewed Open Access Journal
ISSN (Online): 3006-2071 | ISSN (Print): 3006-2063
Volume 4 • Issue 5 • September 2026

Drought indicator	B	SE	95% CI	p	Estimated yield change	Within R^2
SPI	−0.087	0.005	[−0.096, −0.078]	<.001	−8.37%	.237
SPEI	−0.097	0.005	[−0.106, −0.088]	<.001	−9.25%	.307
Soil moisture	−0.079	0.007	[−0.092, −0.066]	<.001	−7.59%	.191

Note. Negative coefficients indicate lower crop yields under increasingly dry conditions. Percentage changes were obtained by transforming the log-scale coefficients.

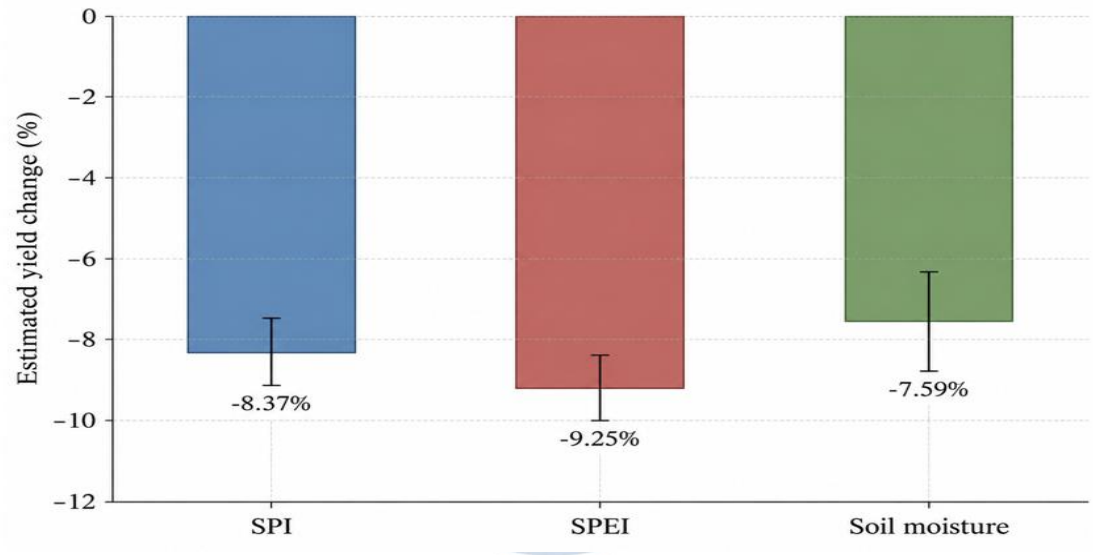

Figure 2 Fixed-Effects Estimates of Drought Exposure and Crop Yield

Crop-Specific Sensitivity to Drought Conditions

Substantial heterogeneity was observed when the Standardized Precipitation-Evapotranspiration Index (SPEI) models were estimated separately for cotton, rice, and sugarcane. Each crop exhibited statistically significant yield reductions under increasingly severe drought conditions, although the magnitude of these responses varied considerably.

For cotton, the estimated SPEI coefficient was −0.087 (*SE* = 0.006, 95% CI [−0.100, −0.075], $p < .001$), representing an estimated 8.34% reduction in yield associated with a one-unit decrease in SPEI. The within-R^2 for this model was 0.272.

Rice exhibited a comparatively smaller response, with an estimated coefficient of −0.071 (*SE* = 0.008, 95% CI [−0.086, −0.056], $p < .001$), corresponding to an estimated 6.84% reduction in yield. The model explained approximately 21.6% of the within-panel variation in rice productivity.

Sugarcane exhibited the largest response to drought, with an SPEI coefficient of −0.133 (*SE* = 0.009, 95% CI [−0.151, −0.116], $p < .001$), corresponding to an estimated 12.47% reduction in yield. The sugarcane model also produced the highest within-R^2 (0.433), indicating that temporal variation in drought conditions accounted for a relatively large

JOURNAL FOR SOCIAL SCIENCE STUDIES
An International Peer-Reviewed Open Access Journal
ISSN (Online): 3006-2071 | ISSN (Print): 3006-2063
Volume 4 • Issue 5 • September 2026

proportion of within-district yield variation for this crop.

In summary, although drought was negatively associated with yields for all three crops, the estimated magnitude of sensitivity followed the pattern:

Sugarcane > Cotton > Rice

in terms of absolute yield sensitivity to SPEI deterioration. This pattern provides evidence of heterogeneous crop-level resilience to drought exposure, rather than indicating a uniform agricultural response.

Table 3 Crop-Specific Fixed-Effects Estimates for SPEI

Crop	B	SE	95% CI	p	Estimated yield change	Within R^2
Cotton	−0.087	0.006	[−0.100, −0.075]	<.001	−8.34%	.272
Rice	−0.071	0.008	[−0.086, −0.056]	<.001	−6.84%	.216
Sugarcane	−0.133	0.009	[−0.151, −0.116]	<.001	−12.47%	.433



Figure 3 Crop-Specific Fixed-Effects Estimates for SPEI

Drought Severity and Yield Instability

Categorical drought analyses also showed that crop productivity declined as moisture conditions worsened. In particular, observations classified as experiencing moderate drought were associated with a significant reduction in crop yield ($B = -0.107$, $p < .001$) relative to the reference moisture conditions.

The negative coefficient shows that drought impacts were not limited to exceptionally rare or extreme events. Yield penalties became evident once drought conditions reached the moderate category. This result matters for risk management, as recurrent droughts can create

substantial cumulative pressure even when individual episodes do not qualify as extreme climatic events.

JOURNAL FOR SOCIAL SCIENCE STUDIES
An International Peer-Reviewed Open Access Journal
ISSN (Online): 3006-2071 | ISSN (Print): 3006-2063
Volume 4 • Issue 5 • September 2026

The direction of the severity estimates aligned with the continuous-index analysis, reinforcing the conclusion that increasing moisture deficits were associated with greater crop-production instability.

Temporal Persistence and Lagged Drought Effects

To assess whether drought effects persisted beyond the contemporaneous growing period, we estimated lagged drought specifications using previous-period SPEI exposure.

In contrast to the strong contemporaneous association, the one-period lagged SPEI effect was not statistically significant (p = .525). This result indicates that the primary yield response occurred during the period of drought exposure, rather than exhibiting a strong independent carryover effect into the subsequent period after accounting for contemporaneous climatic conditions.

The contrast between the highly significant contemporaneous SPEI coefficient (p < .001) and the non-significant lagged effect suggests that crop productivity in the study area responded primarily to current-season moisture conditions. While this pattern does not preclude longer-term drought consequences for agricultural systems, it indicates that the measurable yield effect within the estimated panel model was principally contemporaneous.

Robustness of the Drought–Yield Relationship

A series of alternative model specifications was evaluated to determine whether the estimated drought effect was sensitive to the definition of drought, exposure window, standard-error estimation, or sample composition.

The principal SPEI specification yielded an estimated coefficient of −0.097 based on 1,275 district–crop–year observations. The relationship remained statistically significant under alternative variance estimators. Specifically, the two-way clustered specification produced a standard error of approximately 0.004, indicating that the principal inference was robust to simultaneous dependence across relevant panel dimensions.

The estimated relationship also remained negative and statistically significant under a longer drought-accumulation period. Under the longer-duration SPEI specification, the coefficient was −0.062 (p < .001). Although smaller in magnitude than the principal growing-season estimate, this result still indicated a significant adverse relationship between prolonged moisture deficit and crop productivity.

Additional robustness analyses included alternative SPI and SPEI accumulation periods, crop-specific models, alternative growing-season definitions, exclusion of observations affected by administrative boundary changes, exclusion of major flood years, alternative production outcomes, negligible-area exclusions, cropland-weighted climatic exposure, and leave-one-district-out estimation. Across these specifications, the principal qualitative conclusion remained unchanged: drier climatic conditions were systematically associated with lower crop yields.

Table 4 Selected Robustness and Alternative Specifications

Specification	Estimate/SE	p	Interpretation
Baseline SPEI	B = −0.097	<.001	Significant negative yield effect
Two-way clustered inference	SE = 0.004	<.001	Baseline inference remained robust
Longer SPEI accumulation	B = −0.062	<.001	Persistent negative association
Moderate drought category	B = −0.107	<.001	Significant yield reduction
Lagged SPEI (t−1)	—	.525	No independent lagged association

Note. N = 1,275 in the principal pooled specification. Only statistics available from the finalized model output are reported; unavailable coefficients are not reconstructed.

JOURNAL FOR SOCIAL SCIENCE STUDIES
An International Peer-Reviewed Open Access Journal
ISSN (Online): 3006-2071 | ISSN (Print): 3006-2063
Volume 4 • Issue 5 • September 2026



Figure 4 Selected Robustness and Alternative Specifications

Evidence of Agricultural Resilience

Crop-specific models reveal that resilience to drought varied across the agricultural system of Sindh. Rice experienced the smallest estimated proportional decline under worsening Standardized Precipitation Evapotranspiration Index (SPEI) conditions (6.84%), followed by cotton (8.34%), while sugarcane exhibited the largest reduction (12.47%).

These results should be interpreted as indicators of relative drought sensitivity rather than as a comprehensive resilience ranking. Agricultural resilience encompasses additional dimensions beyond contemporaneous yield response, such as recovery, irrigation access, farm management, input availability, and adaptation capacity. Within the statistical framework employed in this study, smaller drought-associated yield penalties reflect greater yield stability under comparable climatic stress.

The results demonstrate three principal empirical patterns. First, worsening drought conditions were consistently associated with lower cash-crop yields, regardless of whether drought was measured by the Standardized Precipitation Index (SPI), SPEI, or soil moisture. Second, drought sensitivity varied substantially among crops, with sugarcane exhibiting the largest estimated yield response. Third, the effects were predominantly contemporaneous, as the independent one-period lagged association was not statistically significant. Collectively, these findings indicate that drought-related agricultural instability in Sindh is both climatically significant and crop specific, underscoring the importance of accounting for heterogeneity in evaluations of agricultural resilience.

Discussion

The results indicate a consistent negative association between drought intensity and crop yield across Sindh. Pooled fixed-effects models showed that higher drought intensity, as measured by SPI, SPEI, and soil-moisture conditions, was significantly associated with reduced crop productivity. Among these indicators, the SPEI model produced the largest estimated yield decline and the highest explanatory power. This finding suggests that combining precipitation deficit with atmospheric evaporative demand offers a more comprehensive representation of agricultural drought than precipitation alone. Previous research has also demonstrated that the explanatory capacity of drought indices for crop losses depends on their temporal scale and their ability to capture moisture stress during critical crop-growth stages (Wang et al., 2017; Santini et al., 2022).

The principal SPEI coefficient indicated an estimated 9.25% reduction in crop yield for

JOURNAL FOR SOCIAL SCIENCE STUDIES
An International Peer-Reviewed Open Access Journal
ISSN (Online): 3006-2071 | ISSN (Print): 3006-2063
Volume 4 • Issue 5 • September 2026

each one-unit increase in standardized drought intensity, compared with 8.37% for SPI and 7.59% for soil-moisture-based drought. These differences do not establish the universal superiority of any single index, as each captures a distinct dimension of drought. Soil moisture directly represents water availability to crops, SPI primarily reflects precipitation deficits, and SPEI incorporates both precipitation and atmospheric water demand. Modanesi et al. (2020) demonstrated that soil-moisture indicators provide valuable information on agricultural drought and crop-yield variability. The consistent negative association across all three measures reinforces the conclusion that drought contributed to yield instability in the study area.

Substantial differences in drought response were observed among crops. Sugarcane exhibited the largest estimated yield decline at approximately 12.47%, followed by cotton at 8.34% and rice at 6.84%. These findings support the application of crop-specific models, as drought exposure does not result in uniform agricultural effects. The heightened sensitivity of sugarcane is plausible given its long growth duration and high water requirements, making it dependent on consistent water supply throughout the growing period. Previous research in Sindh has highlighted the importance of irrigation scheduling and water availability for sugarcane productivity (Qureshi et al., 2002). Similarly, Singels et al. (2019) demonstrated that the allocation of limited irrigation water during drought can significantly affect sugarcane survival and yield.

Cotton demonstrated an intermediate level of drought sensitivity. Although cotton is generally regarded as relatively adapted to semi-arid environments, water stress during critical developmental stages can still substantially reduce productivity. Riaz et al. (2019) reported significant yield reductions under water-deficit conditions among cotton genotypes in Pakistan and identified notable differences in drought stability among genotypes. The current findings align with this evidence and indicate that cotton production in Sindh remains vulnerable to increasing moisture stress, despite its relative adaptation to arid conditions.

Rice exhibited the smallest proportional drought response among the three crops, although the association remained statistically significant. This result does not imply that rice is inherently drought-resistant. District-level productivity is influenced by crop physiology, irrigation access, cultivar selection, management practices, and spatial variation in production environments. Torres and Henry (2018) demonstrated that rice yields can decline significantly under mild to moderate drought, with considerable variation in drought stability among breeding lines. The smaller coefficient observed in this study therefore reflects lower relative sensitivity within the specific agricultural context, rather than an absence of drought vulnerability.

The categorical drought analysis revealed that significant production losses occurred even before drought reached the most extreme classification. Moderate drought was associated with a coefficient of −0.107, indicating that substantial yield penalties can arise under drought conditions that are more frequent than severe or extreme events. Santini et al. (2022) also demonstrated that crop losses increase with both the magnitude and duration of drought. This finding is practically significant, as agricultural drought management should not focus solely on rare extreme events. Recurrent moderate drought can generate considerable cumulative losses and therefore requires early intervention.

The lagged analysis produced a different pattern. The previous-period SPEI term was not statistically significant ($p = .525$) after accounting for contemporaneous drought exposure. This result suggests that the most pronounced yield effect occurred during the same production period as the drought event. However, this should not be interpreted as evidence that drought lacks longer-term agricultural consequences. Drought can influence groundwater availability, irrigation infrastructure, farm income, soil conditions, and subsequent management decisions in ways not captured by a single one-period lag. Wang et

JOURNAL FOR SOCIAL SCIENCE STUDIES
An International Peer-Reviewed Open Access Journal
ISSN (Online): 3006-2071 | ISSN (Print): 3006-2063
Volume 4 • Issue 5 • September 2026

al. (2017) emphasized that drought impacts are highly dependent on timing and crop-development stage, which may explain why contemporaneous growing-season exposure was more strongly associated with yield than the previous year's climatic conditions.

The robustness analyses further confirmed the stability of the main findings. The principal SPEI coefficient remained statistically significant when using two-way clustered standard errors, and a longer drought-accumulation specification also yielded a significant negative coefficient of −0.062. Comparable negative relationships were observed across alternative drought indicators and crop-specific models. Consistency across these specifications reduces the likelihood that a particular drought definition drove the main results or model assumptions.

From a resilience perspective, the findings indicate that drought resistance varied among crops. In this study, agricultural resilience was assessed based on relative yield stability under drought exposure, rather than through a multidimensional socioeconomic resilience index. Smaller proportional yield reductions were interpreted as evidence of greater resistance to drought within the observed production system. Turner et al. (2014) emphasized that agricultural drought resilience is closely linked to maintaining yield stability and enhancing water-use efficiency under limited moisture conditions. Rey et al. (2017) similarly argued that resilience in irrigated agriculture depends on both water availability and adaptive management.

The findings have important implications for irrigation management in Sindh. While irrigation can buffer the effects of climatic drought, it cannot fully eliminate exposure to water stress when overall water availability is limited. Troy et al. (2015) demonstrated that irrigation can reduce crop sensitivity to climatic extremes, although the level of protection varies by crop and environmental context. In Sindh, drought adaptation should prioritize efficient irrigation scheduling, enhanced water productivity, reduced conveyance losses, drought-responsive crop management, and the allocation of water during critical growth stages. The pronounced response observed for sugarcane indicates that water-intensive crops may require more targeted management under recurrent drought conditions.

Several limitations warrant consideration. District-level data do not capture farm-level variation in irrigation access, cultivar selection, soil management, fertilizer application, pest pressures, or farmer adaptation strategies. While fixed-effects models control for persistent unobserved differences between district–crop units, they cannot eliminate bias from all time-varying factors. Additionally, the resilience assessment in this study reflects yield sensitivity rather than encompassing broader socioeconomic resilience. Future research could incorporate irrigation volumes, groundwater conditions, farm-level adaptation, production costs, household responses, and post-drought recovery.

In summary, the results demonstrate that drought is significantly associated with cash-crop yield instability in Sindh, with effects varying by crop and drought measure. Sugarcane showed the highest sensitivity, cotton an intermediate response, and rice e the smallest proportional decline. The significant losses observed under moderate drought conditions suggest that adaptation efforts should begin before drought reaches extreme levels. These findings support implementing crop-specific, spatially targeted drought-management strategies rather than a uniform provincial approach.

Conclusion

The results indicate that drought intensity is significantly associated with cash-crop yield instability across Sindh, Pakistan. Consistent findings across the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and soil-moisture indicators confirm that worsening moisture conditions correspond with reduced agricultural productivity. SPEI exhibited the strongest association, underscoring the importance of accounting for both precipitation deficits and atmospheric

ISSN (Online): 3006-2071 | ISSN (Print): 3006-2063
Volume 4 • Issue 5 • September 2026

evaporative demand in agricultural drought assessment.

Drought sensitivity varied considerably among crops. Sugarcane experienced the largest proportional yield decline, followed by cotton and rice, demonstrating that agricultural resilience is crop specific rather than uniform across Sindh. Notably, significant yield losses occurred even under moderate drought, indicating that interventions should be implemented before drought conditions intensify. The absence of a significant lagged SPEI effect suggests that the most pronounced yield response occurs within the same production period.

The results support the formulation of crop-specific and spatially targeted drought-management strategies in Sindh. Enhanced drought monitoring, efficient irrigation scheduling, improved water-use efficiency, adoption of drought-tolerant crop varieties, and early intervention during emerging moisture deficits may contribute to stabilizing agricultural production. Future research should incorporate irrigation availability, groundwater conditions, farm-level adaptation, and socioeconomic factors to provide a more comprehensive assessment of agricultural resilience under escalating climatic stress.

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Volume 4 • Issue 5 • September 2026

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