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Agricultural Transformation and Crop-Specific Drought Sensitivity in Northwestern Türkiye: Climatic and Socioeconomic Perspectives

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Abstract

Agricultural sustainability and food security face increasing pressures from climatic variability, population growth, and industrialization. This study examined agricultural transformation and crop-specific drought sensitivity across ten provinces of the Marmara Region, Türkiye, alongside changes in demographic and industrial indicators. Drought and yield analyses covered 1991–2024, while structural agricultural changes were assessed for 2004–2024. Four strategic crops, wheat, sunflower, grain maize, and rice, were evaluated using cultivated area, production, yield, and crop area share data. Crop-diversity analyses were performed using both a primary three-crop dataset (wheat, sunflower, and grain maize) and a complementary four-crop dataset that included rice. Climatic moisture variability was represented by the Standardized Precipitation Evapotranspiration Index (SPEI) at five timescales (1–12 months). Trends were assessed using Mann–Kendall tests and Sen's slopes, crop diversity using the Shannon index, and relationships between drought and yield using standardized yield residuals, Spearman correlations, and province fixed effects panel models. No provincial SPEI trend remained significant after false discovery rate correction, whereas population increased significantly in all provinces and industrial share increased in seven. During 2004–2024, wheat area declined significantly in six provinces, while other crops exhibited spatially heterogeneous changes. Three-crop diversity increased significantly in four of nine evaluable provinces. Relationships between drought and yield were crop and timescale specific. Sunflower showed positive associations with short to medium term SPEI, strongest at SPEI-1 ($\rho = 0.324$), whereas wheat exhibited negative associations, strongest at SPEI-6 ($\rho = -0.283$). Grain maize showed no robust SPEI response, while rice was more closely associated with longer term moisture conditions, particularly SPEI-12. Overall, climatic moisture variability was more consistently associated with interannual yield anomalies than with structural changes in crop allocation. These findings highlight the importance of integrating crop specific drought monitoring, agricultural land use planning, and water management into sustainable agricultural strategies to support agricultural production stability under climatic and socioeconomic pressures. A supplementary crop calendar analysis identified four BH-FDR significant positive associations in 1991–2024 (three sunflower windows and one grain maize window); none remained significant in the 2004–2024 sensitivity period.

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1. Introduction

Food security depends on the availability, accessibility, utilization, and stability of sufficient, safe, and nutritious food [1]. These dimensions are increasingly challenged by climate change, population growth, urbanization, and competition for land and water. Rising food demand and urban expansion intensify pressure on productive agricultural resources, particularly in densely populated regions [2–4]. Climatic variability may simultaneously affect crop productivity and the stability of regional food supplies, highlighting the need to consider environmental and socioeconomic pressures together [5,6]. Accordingly, agricultural sustainability is increasingly shaped by the interaction of climatic and socioeconomic pressures rather than climate variability alone.

Climate change further increases these pressures by altering precipitation regimes, raising atmospheric evaporative demand, and intensifying drought and water scarcity. The Mediterranean Basin is particularly vulnerable because warming and declining water availability may constrain agricultural production [7,8]. Agricultural drought impacts nevertheless differ according to crop type, drought timing and duration, phenological stage, soil-water conditions, irrigation, and management [9–13]. Interactions between drought and heat may further increase crop losses [14,15], emphasizing the need for crop-specific and temporally differentiated assessments. Consequently, regional assessments based on a single crop, drought metric, or temporal scale may overlook substantial heterogeneity in agricultural drought responses. Evidence from comparisons of irrigated and rain-fed cereal production in Türkiye further indicates that water management can modify observed drought–yield relationships [13].

The Standardized Precipitation Evapotranspiration Index (SPEI) integrates precipitation and atmospheric evaporative demand across multiple accumulation periods [16,17]. Drought–yield relationships vary among crops, regions, and timescales [18–20]. Short accumulation periods may represent moisture deficits during sensitive phenological stages, whereas longer periods may reflect persistent soil-water and hydrological limitations. Multiscalar SPEI analysis can therefore provide a more differentiated assessment of agricultural drought sensitivity than a single temporal scale. However, meteorological drought does not necessarily translate directly into agricultural water stress. Reservoir storage and water-management infrastructure can modify surface-water availability during rainfall-deficit periods, while reservoir responses themselves depend on cumulative hydroclimatic conditions, water demand, and reservoir characteristics [21–23].

Agricultural transformation cannot, however, be attributed to hydroclimatic variability alone. Cultivated area and crop allocation are also influenced by irrigation, technology, profitability, production costs, markets, labor availability, and support policies [24–27]. Relationships among climate, land use, and agricultural production vary spatially across Türkiye [28], while farm-level land-use decisions reflect socioeconomic characteristics and production conditions [29]. In northwestern Türkiye, the adoption of climate-smart agriculture and soil- and water-conservation practices varies with education, farm size, agricultural income, and access to agricultural information [30,31]. Agricultural cooperatives may support adaptation, although differences in climate-change and renewable-energy awareness can limit this role [32]. More broadly, agricultural drought vulnerability in Türkiye reflects the combined influence of biophysical and socioeconomic conditions rather than climatic exposure alone [33]. Changes in relative profitability, input costs, market access,

and agricultural support policies may influence crop-allocation decisions, although their contributions can vary across provinces. Because comparable crop-specific economic data were not included in the models, these mechanisms are considered potential explanations rather than empirically established drivers of the observed land-use changes.

Long-term research has documented spatial and temporal differences in drought conditions across Türkiye [34–36], but meteorological drought monitoring has received greater attention than agricultural and hydrological impacts [37]. Crop modelling suggests that changing drought and temperature conditions may influence future production [38], while agricultural support policies in Türkiye have been associated with heterogeneous outcomes across agricultural production [25]. In this context, reservoir systems are also relevant because they influence the translation of hydroclimatic variability into water availability for agricultural and other regional demands [21–23,39–41]. This literature highlights the need to distinguish short-term hydroclimatic relationships with yield from longer-term changes in cultivated area and crop composition.

These interactions are particularly relevant to the Marmara Region of Türkiye, where intensive agricultural production coexists with rapid demographic growth, industrial development, and increasing competition for land and water resources. Previous studies have examined crop water stress, drought variability, and climate change impacts in Marmara and Thrace [42–45], as well as crop-specific drought–yield relationships elsewhere in Türkiye [46]. Regional reservoir systems also provide an important hydrological context for agricultural water availability [22,23]. However, relatively limited attention has been given to jointly examining multiscalar drought variability, crop-specific yield sensitivity, and long-term changes in cultivated area, crop composition, and agricultural diversity within regions experiencing simultaneous climatic and socioeconomic pressures. To address this gap, this study investigates agricultural transformation and drought sensitivity across ten provinces of the Marmara Region, focusing on wheat, sunflower, grain maize, and rice. Drought variability and crop-specific yield relationships are examined for 1991–2024, while structural agricultural changes are assessed for 2004–2024. Multiscalar Standardized Precipitation Evapotranspiration Index (SPEI) data are integrated with standardized yield residuals, agricultural land-use indicators, population, and industrialization data. Province fixed-effects panel models are employed to assess statistical associations between climatic moisture variability and agricultural responses while accounting for demographic and industrial indicators and unobserved time-invariant provincial characteristics. Reservoir distribution and primary uses are considered as regional hydrological context rather than explanatory variables in the statistical models, recognizing that reservoir storage and irrigation water availability can mediate the relationship between climatic variability and agricultural production [21]. Similarly, economic and policy factors influencing crop allocation are acknowledged but not directly estimated because consistent provincial data on crop prices, production costs, and agricultural support payments were unavailable.

By distinguishing interannual climatic moisture sensitivity from longer-term agricultural restructuring, this study provides an integrated perspective on agricultural sustainability under interacting climatic and socioeconomic pressures. The food-security implications concern agricultural production and its stability, not direct measurements of food access, utilization, or nutritional outcomes. The findings are intended to inform crop-specific drought monitoring, agricultural land-use planning, and water-resource management, while understanding of how climatic and socioeconomic pressures interact to shape agricultural sustainability.

2. Materials and Methods

2.1. Study Area

The study covered ten provinces of the Marmara Region in northwestern Türkiye: Balıkesir, Bilecik, Bursa, Çanakkale, Edirne, Kırklareli, Kocaeli, Sakarya, Tekirdağ, and Yalova (Figure 1). The region combines intensive agricultural production with high population density, urbanization, and industrial development and represents a transition between Mediterranean and temperate climatic conditions. Regional water availability is also supported by multipurpose reservoirs used for irrigation, drinking-water supply, and energy production, providing an important hydrological context for agricultural production [22,23]. Four strategic crops with contrasting production systems and water requirements were examined: wheat, sunflower, grain maize, and rice. İstanbul was excluded from the primary agricultural panel because a spatially consistent province-wide agricultural series was unavailable for the complete study period; Şile data were used only for sensitivity analysis. This exclusion was based on agricultural data comparability and spatial representativeness, rather than an assumed distortion of regional averages. The available Şile series was retained solely for a separate sensitivity assessment.



Figure 1. (**a**) Location of the Marmara Region within Türkiye and distribution of meteorological stations; (**b**) detailed map of the study area showing provincial boundaries, meteorological stations, and major reservoirs classified according to their primary use (irrigation or drinking water supply), providing hydrological context for agricultural production. The maps were prepared by the authors using a previously processed digital elevation model (DEM) supplied by the research team, meteorological station data from the Turkish State Meteorological Service (MGM), and reservoir data obtained within the scope of Project No. 4771, supported by the Scientific Research Projects Coordination Unit of Çanakkale Onsekiz Mart University (2024–2025).

2.2. Data Sources and Statistical Analysis

Agricultural, hydroclimatic, demographic, and economic data were integrated to evaluate agricultural transformation and crop-specific drought sensitivity across the Marmara Region. Annual cultivated area (decares, da; 1 da = 0.1 ha), production (t), and yield data for wheat, sunflower, grain maize, and rice, together with provincial population and industrial share of gross domestic product (GDP), were obtained from the Turkish Statistical Institute (TÜİK). Agricultural records for 1991–2003 were compiled from historical statistics and those from 2004 onward from the TÜİK online database. Monthly precipitation and temperature observations from the Turkish State Meteorological Service (MGM) were used to calculate the Standardized Precipitation Evapotranspiration Index (SPEI) at 1-, 3-, 6-, 9-, and 12-month scales. SPEI was selected for its multiscalar representation of climatic water balance and its applicability to crop-specific drought assessment [16,47,48]. Monthly climatic water balance was calculated as precipitation minus potential evapotranspiration (PET). The PET series were checked for numerical consistency with the Hargreaves–Samani formulation.

The station-level SPEI series were independently reproduced with the R package SPEI (version 1.8.1; https://CRAN.R-project.org/package=SPEI) using the three-parameter log-logistic distribution, unbiased probability-weighted moments (ub-pwm) parameter estimation, and a 1991–2024 calibration period, with separate distribution fitting for each calendar month. Recalculated values agreed with the stored series to numerical precision for all 13 stations and five accumulation scales. Reservoir locations and primary uses were additionally compiled to characterize the regional hydrological context; these data were used descriptively and were not included as explanatory variables in the statistical models. The agricultural statistics were retrieved from TurkStat MEDAS (Crop Production Statistics; accessed 10 October 2026) [49]. The 2004–2024 area-change calculations use the same five-year reference (2004–2008) and comparison (2020–2024) periods presented in Table 1. Meteorological station identifiers used in the data compilation are listed in Appendix A; the primary climatic series and İstanbul sensitivity stations are distinguished by their use in the analysis. Station coordinates, elevations, and the provenance of the reservoir layer are not inferred where original MGM or GIS metadata are unavailable. The verified station-level calculation dataset includes 13 monthly SPEI series (ten provincial stations plus Sarıyer, Florya, and Şile), each spanning 408 months in 1991–2024. Kadıköy Göztepe Rıhtım appears only in the supplied 14-station metadata inventory, not in the Station_SPEI calculation sheet (Appendix A). The 14-station metadata inventory is not the denominator for the SPEI sample: only the 13 stations present in the calculation worksheet contribute to the station-month total. Station identifiers, coordinates, elevations, and analytical roles are listed in Appendix A. Specifically, daily maximum and minimum air temperatures were used to estimate daily PET with the Hargreaves–Samani (1985) temperature-range method, including extraterrestrial radiation estimated from station latitude and day of year. Daily PET estimates were aggregated to monthly totals before calculation of the monthly precipitation-minus-PET climatic water balance [50].

Meteorological observations were assigned to the province represented by each corresponding provincial MGM station; station-level SPEI was not spatially interpolated or averaged across multiple stations to create province-wide estimates. The ten primary provincial series were linked to agricultural records by province and year. Given the regional scale of analysis and annual aggregation of crop statistics, a single long-term provincial station was considered an acceptable climatic proxy for each province The additional İstanbul-area stations (Sarıyer, Florya, and Şile) were not treated as independent provinces; Şile was considered only in the separate İstanbul sensitivity assessment. Accordingly, each provincial drought indicator represents the conditions at its assigned station rather than an area-weighted provincial climate average (Appendix A).

Table 1. Percentage changes in mean cultivated area between 2004 and 2008 and 2020–2024 and three-crop Shannon diversity trends during 2004–2024 (nine provinces with complete records).

Province	Wheat (%)	Sunflower (%)	Grain Maize (%)	Rice (%)	Shannon Trend (Sen Slope)
Balıkesir	−39.6	+20.6	−5.9	+57.9	**+0.0073** *
Bilecik	−14.2	+124.4	+30.7	—	+0.0028
Bursa	−53.2	−10.9	+11.9	+49.5	**+0.0137** *
Çanakkale	−32.2	+16.7	+235.6	+196.3	**+0.0134** *
Edirne	−25.7	+11.0	−45.3	+26.5	+0.0010
Kırklareli	−9.8	+38.7	+4.0	+58.3	**+0.0024** *
Kocaeli	−48.5	+36.4	−60.7	—	−0.0096
Sakarya	−61.9	+75.2	−28.1	—	+0.0008
Tekirdağ	+8.3	+20.8	−84.6	−16.2	−0.0004
Yalova	−10.8	+646.2	+75.5	—	NA †

Note: Cultivated-area change compares the 2004–2008 and 2020–2024 means; — indicates insufficient comparable data. The three-crop Shannon trend uses wheat, sunflower, and grain maize for nine provinces with complete annual records (2004–2024; $n = 21$ years per province). † indicates that Yalova was excluded from the Shannon trend comparison because grain-maize records were missing for 2013–2019 ($n = 14$ available years); missing entries were not treated as zero. Bold values indicate statistically significant trends after BH-FDR correction. An asterisk (*) indicates BH-FDR-adjusted $p < 0.05$ for the Shannon trend. The complementary four-crop analysis, including rice, covers six provinces with complete records and is reported separately in the text. Crop-specific observation coverage and the numbers of years contributing to the comparison periods are detailed in Supplementary Table S2.

All datasets were harmonized by province and year, with checks for units, crop names, duplicate records, and missing observations. Historical agricultural series (1991–2003) and the online TurkStat series (2004 onward) were evaluated separately because of potential discontinuities at the source transition. A dedicated diagnostic examined 40 province–crop combinations across wheat, sunflower, grain maize, and rice. For 2003–2004 comparisons, nine combinations lacked paired observations, leaving 31 evaluable pairs. Among the 31 combinations with paired observations, the diagnostic flagged large year-to-year differences in cultivated area for 30 and in production for all 31; for yield, three were classified as large, four as moderate, and 24 as small. These are diagnostic classifications, not proof of an undocumented change in units or definitions, nor evidence that every discontinuity is erroneous. Because a uniform correction could not be justified, no automatic rescaling or interpolation was applied. Structural analyses of cultivated area, production, crop-area share, and crop diversity were restricted to 2004–2024. The 1991–2024 hydroclimatic and yield-based analyses were retained with explicit period-sensitivity qualifications. Missing agricultural records remained missing. The complete diagnostic, provided as Supplementary Dataset S6, compares Mann–Kendall trends, Sen slopes, and BH-FDR-adjusted significance for 1991–2024, 1991–2003, and 2004–2024; it does not constitute a formal causal test of the data-source transition.

To address potential socioeconomic associations with wheat-area contraction, an additional exploratory province-level analysis was conducted for the ten study provinces. Percentage changes in wheat cultivated area and population were calculated from the 2004–2008 and 2020–2024 provincial means; industrial GDP-share change was expressed in percentage points between the same periods. Spearman rank correlations were calculated across provinces ($n = 10$), using available paired values. These cross-sectional associations are descriptive, do not identify land conversion, and cannot establish causal effects of demographic or industrial change. The calculations and province-level inputs are provided in Supplementary Dataset S7.

Temporal trends were evaluated using the Mann–Kendall test [51,52], with magnitude estimated by Sen's slope [53]. SPEI and population trends were assessed for 1991–2024 and industrial-share trends for 2000–2024. For Figure 2, Sen's slopes were normalized by the maximum absolute slope within each indicator. Structural agricultural change was additionally expressed as the percentage difference between the 2004–2008 and 2020–2024 means (1). Unnormalized Sen slopes are provided in Supplementary Table S1, while Figure 2 normalization is only a unitless display transformation and must not be interpreted as comparability of effect magnitudes across indicators. Here, $\bar{A}$ denotes the mean cultivated area in the indicated five-year period.

$$\Delta A\ (\%) = [(\bar{A}_{2020–2024} - \bar{A}_{2004–2008})/\bar{A}_{2004–2008}] \times 100 \quad (1)$$

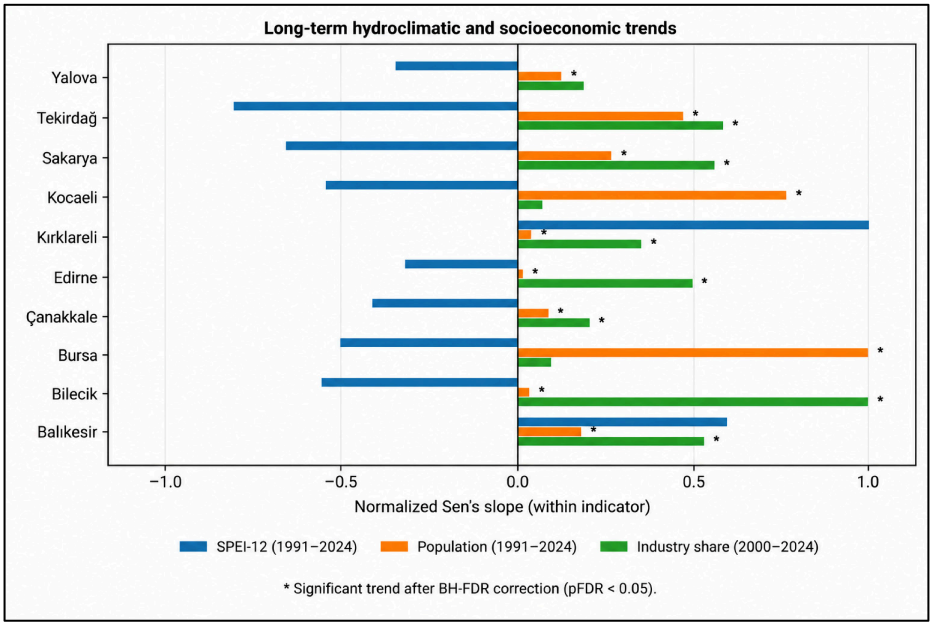


Figure 2. Long-term hydroclimatic and socioeconomic trends across the ten study provinces. Bars show normalized Sen's slopes for SPEI-12 and population (1991–2024) and industrial share (2000–2024). Asterisks indicate significant trends after BH-FDR correction (pFDR < 0.05).

Crop composition was evaluated using crop-area shares and the Shannon diversity index (2) [54]:

$$H' = -\Sigma_{i=1}{}^{s}\, p_i \ln(p_i) \quad (2)$$

where p_i is the proportion of cultivated area allocated to crop i within the selected crop set, and S is the number of crops included in the calculation. The primary analysis included wheat, sunflower, and grain maize across all ten provinces. A complementary analysis including rice was conducted for the six provinces with complete rice records during 2004–2024. Only complete province–year combinations were included. Recent evidence also supports the relevance of crop diversification when assessing agricultural responses to climatic variability [55].

For the primary three-crop Shannon trend comparison, complete annual records were available for nine provinces during 2004–2024. Yalova was excluded because grain-maize records were missing for 2013–2019; its 14 observed years were not treated as a complete time series. Missing crop-area entries were neither interpreted as zero cultivation nor imputed. The four-crop Shannon assessment was restricted to the six provinces with complete records and was interpreted separately because its crop composition differed from the three-crop index.

Crop-specific drought sensitivity was assessed using standardized yield residuals (SYRS) (3). Long-term temporal trends were removed separately from each province–crop yield series, and residuals were standardized as:

$$SYRS_{i,t} = e_{i,t}/s_{e,i} \quad (3)$$

where $e_{i,t}$ is the detrended yield residual for province–crop series i in year t, and $s_{e,i}$ is the standard deviation of residuals in that series. This approach emphasizes interannual yield departures while reducing the influence of long-term technological and management-related changes. Spearman correlations were calculated between SYRS and SPEI-1, SPEI-3, SPEI-6, SPEI-9, and SPEI-12 [56], consistent with recent multiscalar drought–yield assessments [49]. The primary analysis covered 1991–2024, with 2004–2024 examined as a sensitivity period. Crop-specific growing-season SPEI variables were constructed as arithmetic means of monthly SPEI within predefined calendar windows: November of the preceding year through June of the harvest year for wheat, April–August for sunflower, and April–September for grain maize and rice. This aggregation was applied separately to each SPEI accumulation scale and was independently reproduced from the monthly province-level series to numerical precision.

The primary fixed-effects panel models used available observations from 2000 to 2024, corresponding to the period for which provincial industrial GDP-share data were available. The resulting sample sizes were 250 observations for wheat and sunflower, 242 for grain maize, and 130 for rice. These panel-model sample periods differ from the 1991–2024 drought–yield correlation analyses and the 2004–2024 agricultural transformation analyses. Population and industrial share were treated as indicators of broader socioeconomic pressure rather than direct causal drivers. For the primary panel analysis, the Benjamini–Hochberg false discovery rate (BH-FDR) procedure [55] was applied jointly across 80 crop–response–SPEI-scale tests (four crops × four response variables × five accumulation scales). Statistical significance was defined as an FDR-adjusted *p*-value below 0.05. İstanbul was excluded from the primary analysis because the available Şile series was not representative of province-wide agricultural conditions and was retained only for sensitivity analysis. All statistical analyses and statistical modelling were performed using R (version 4.4.2; R Core Team, Vienna, Austria) within RStudio (version 2026.04.0+526; Posit Software, PBC, Boston, MA, USA). Cartographic processing and map production were performed using ArcMap (version 10.7; Esri, Redlands, CA, USA). Additional model diagnostics included variance inflation factors after accounting for province fixed effects (maximum observed VIF approximately 4.31), HC3 heteroskedasticity-consistent standard errors, clustering by province or year, and specifications with both province and year fixed effects. The significance of some SPEI coefficients depended on the variance estimator, and these sensitivity results were considered separately from the primary model estimates.

As a supplementary phenologically informed sensitivity assessment, six crop-specific calendar-based SPEI windows were considered for each of wheat, sunflower, grain maize, and rice (24 windows in total). Each window was defined by its SPEI accumulation scale and ending calendar month. Shorter windows approximated moisture conditions overlapping crop development, whereas longer windows represented antecedent or cumulative hydroclimatic conditions; none was treated as a direct observation of stage-specific crop water stress. Crop-specific standardized yield residuals were examined using province and year fixed-effects models for 1991–2024 and separately for 2004–2024. The Benjamini–Hochberg procedure was applied across the 24 crop–window tests within each period (pFDR < 0.05). These supplementary models were interpreted separately from the primary panel models that included socioeconomic controls. Crop-stage interpretation was informed by the FAO crop evapotranspiration guidelines [56]; the selected calendar windows remain approximate proxies rather than observed phenological dates.

3. Results

3.1. Changes in Crop Patterns and Agricultural Diversity

Cultivated area and crop composition changed substantially during 2004–2024, although the direction and magnitude varied among crops and provinces (Figures 3 and 4; Table 1). Wheat area declined significantly after BH-FDR correction in Balıkesir, Bursa, Çanakkale, Edirne, Kocaeli, and Sakarya. Between the 2004–2008 and 2020–2024 means, the reductions ranged from 25.7% in Edirne to 61.9% in Sakarya, with decreases of 53.2% in Bursa, 48.5% in Kocaeli, 39.6% in Balıkesir, and 32.2% in Çanakkale. The reported percentage differences describe changes between the 2004–2008 and 2020–2024 period means; the reported statistical significance refers to the separate temporal trend tests, not to a direct test of the difference between those two means.



Figure 3. Changes in strategic crop patterns and agricultural diversity (2004–2024). (**a**) Mean core-crop shares in nine complete-series provinces; (**b**) pooled cultivated-area change from the 2004–2008 to 2020–2024 period means (ten provinces for the three core crops; six for rice); (**c**) mean three-crop Shannon diversity in the same nine provinces, with a descriptive trend. Regional changes in panel (**b**) are calculated from sums of provincial period means, rather than the unweighted average of provincial percentage changes.

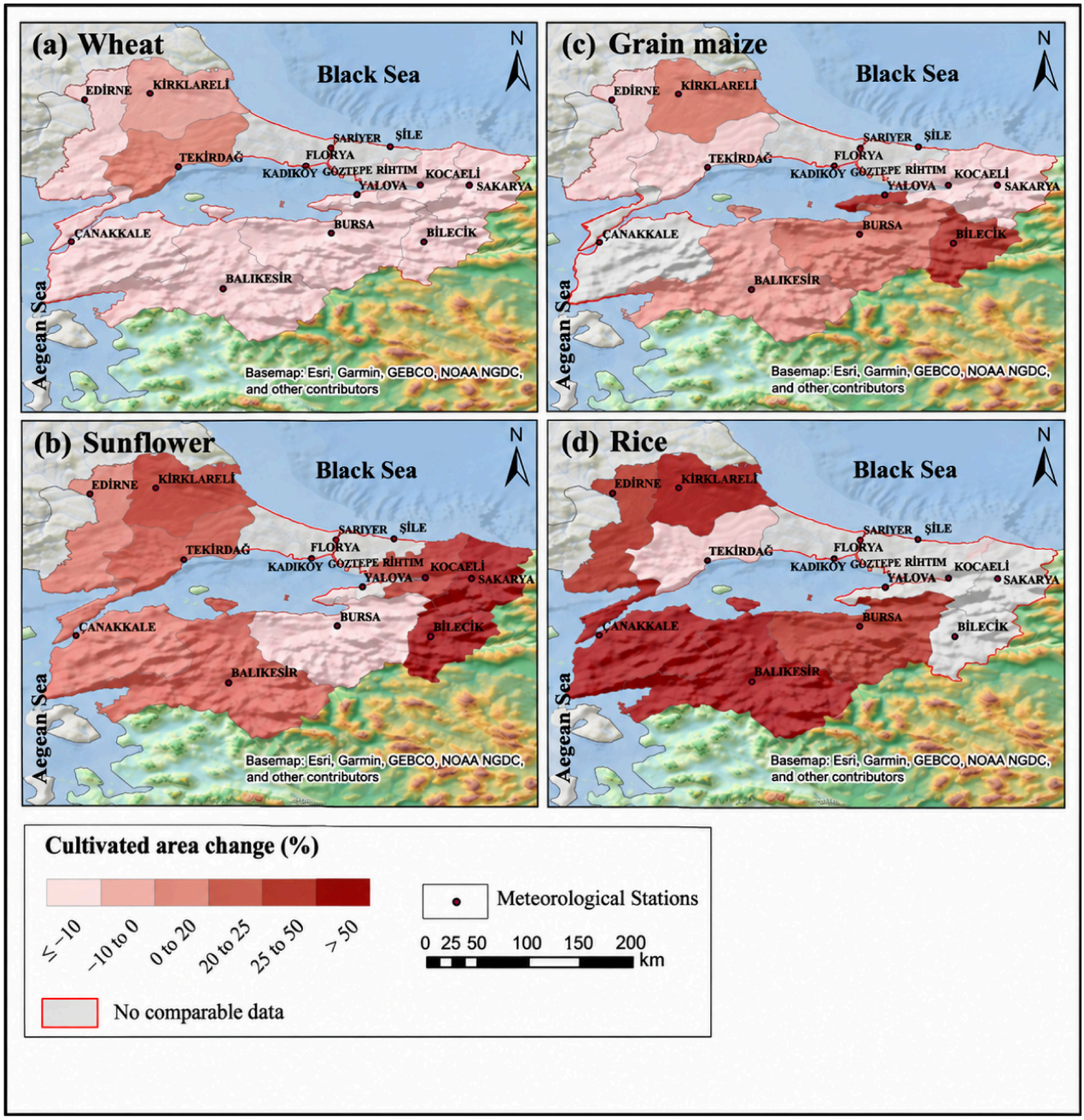


Figure 4. Spatial changes in cultivated area for (**a**) wheat, (**b**) sunflower, (**c**) grain maize, and (**d**) rice, calculated as the percentage difference between the 2004–2008 and 2020–2024 mean cultivated areas. The mapped values are unnormalized percentage changes; the same legend thresholds are used for the four crops. The color gradient from light pink to dark red represents changes in cultivated area, ranging from decreases to progressively greater increases. Gray areas outlined in red indicate areas with no comparable data, while red point symbols with black outlines represent meteorological stations. Source: Maps prepared by the authors using agricultural statistics obtained from the Turkish Statistical Institute (TurkStat, MEDAS database; accessed on 10 October 2026) and administrative boundary data provided by the General Directorate of Mapping (HGM), Türkiye.

Other crops showed more localized changes. Grain maize area increased significantly in Çanakkale but declined in Bilecik, Edirne, Kocaeli, Sakarya, and Tekirdağ. Sunflower area increased significantly in Kırklareli, Sakarya, Tekirdağ, and Yalova. Potential explanations include domestic vegetable-oil demand, processing capacity in Thrace, and agricultural support policies; these mechanisms were not directly tested in this study. Among provinces

with comparable rice records, rice area increased significantly in Balıkesir, Çanakkale, and Edirne, while trends in Bursa, Kırklareli, and Tekirdağ were not significant after BH-FDR correction (Figure 4). These results describe spatially heterogeneous crop allocation; possible contributions from irrigation availability, markets, and agricultural policy are discussed as untested mechanisms in the Discussion. Specifically, rice cultivated area increased by 26.5% in Edirne and 58.3% in Kırklareli between the two five-year means, although the Kırklareli temporal trend did not remain significant after BH-FDR correction (Figure 4d; Table 1). The magnitude of a two-period percentage change must not be equated with the significance of the full-series trend.

Crop-area shares also shifted (Figure 3a). Wheat share decreased and sunflower share increased significantly in Balıkesir, Bursa, Çanakkale, Edirne, Kırklareli, and Sakarya. Grain maize share increased significantly in Bursa, Çanakkale, and Sakarya but decreased in Bilecik, Edirne, and Tekirdağ. These results indicate spatial redistribution among the major crops rather than a uniform regional transition.

Three-crop Shannon diversity increased significantly in Balıkesir, Bursa, Çanakkale, and Kırklareli, while no significant trend was detected in the other evaluable provinces. Yalova was excluded because it did not meet the minimum number of complete observations. In the complementary four-crop analysis, diversity increased significantly in Balıkesir, Bursa, Çanakkale, Edirne, and Kırklareli but not in Tekirdağ (Figure 3c; Table 1). The change observed for Edirne after rice was included indicates that diversity estimates depended partly on the crops considered. The Shannon indices describe the distribution of cultivated area among the crops included in each calculation; they do not establish whether changes arose from intentional risk management or from shifts in profitability.

The three-crop Shannon analysis was based on nine complete provincial time series. Significant positive Sen's slopes were observed for Balıkesir (+0.0073 year^{-1}), Bursa (+0.0137 year^{-1}), Çanakkale (+0.0134 year^{-1}), and Kırklareli (+0.0024 year^{-1}). In the complementary four-crop analysis, positive trends were significant in Balıkesir, Bursa, Çanakkale, Edirne, and Kırklareli, but not in Tekirdağ. The two Shannon indices should not be compared as though they represented identical crop sets. The regional three-crop diversity curve in Figure 3c is calculated exclusively from the nine complete provincial series.

Additional 2003–2004 source-transition sensitivity results. Across the 40 province–crop combinations, paired 2003 and 2004 observations were available for 31; nine were missing. Of the 31 evaluable paired comparisons, 30 cultivated-area and 31 production comparisons were classified as large discontinuities, compared with three yield comparisons. For example, Balıkesir wheat cultivated area increased from 216,450 da in 2003 to 1,762,910 da in 2004 (+714.5%); the corresponding yield changed from approximately 204.8 to 277.0 kg da^{-1} (+35.3%). The substantial area discontinuity should not be interpreted as a confirmed expansion of agricultural land or corrected using an assumed conversion factor. In the period-specific trend comparison, seven cultivated-area, seven production, and six yield province–crop series were classified as sensitive to the period break. These results support the decision to interpret structural change using the internally comparable 2004–2024 period rather than treating full-period agricultural trends as homogeneous. The classification is descriptive and does not identify the cause of each discontinuity (Supplementary Dataset S6; separate 2003–2004 diagnostic workbook).

3.2. Crop-Specific Yield Sensitivity to Drought

Relationships between standardized yield residuals (SYRS) and SPEI differed by crop and accumulation scale (Figure 5; Table 2). Sunflower showed the strongest positive bivariate association at SPEI-1 (Spearman's $\rho = 0.324$, $n = 340$, BH-FDR $p < 0.05$), followed by SPEI-3 ($\rho = 0.302$, $n = 340$) and SPEI-6 ($\rho = 0.210$, $n = 340$); all three remained significant

after correction. SPEI-9 and SPEI-12 correlations were positive but not BH-FDR-significant. In the separate province fixed-effects panel analysis, the SPEI-3 coefficient (the lowest adjusted p-value across scales) was $\beta = 0.388$ (pFDR < 0.001).

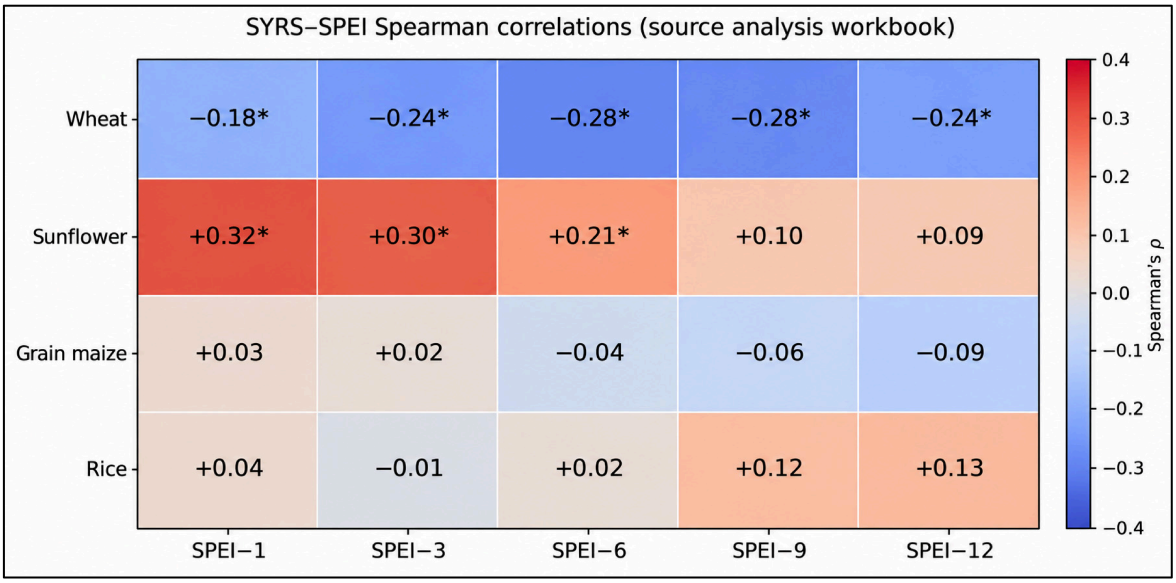


Figure 5. Spearman correlations (ρ) between standardized yield residuals (SYRS) and SPEI at 1-, 3-, 6-, 9-, and 12-month accumulation scales, using the pooled province–year records available for 1991–2024. Asterisks denote BH-FDR-adjusted $p < 0.05$ across the 20 crop × SPEI-scale tests. Values are rounded to two decimal places; sample sizes differ across crop and SPEI scale and are reported in Supplementary Table S3.

Wheat correlations were negative at all five SPEI scales and remained significant after BH-FDR adjustment in the source analysis workbook. The strongest bivariate association occurred at SPEI-6 ($\rho = -0.283$, $n = 340$), followed by SPEI-9 ($\rho = -0.278$, $n = 330$). The separate panel analysis had its lowest adjusted p-value at SPEI-6 with a coefficient ($\beta = -0.259$, pFDR $= 0.003$). These associations must not be interpreted as evidence that drought improves wheat yield; alternative seasonal and management-related explanations remain untested. The consistency of negative coefficients across multiple SPEI accumulation periods suggests that this pattern is not restricted to a single drought timescale, although the underlying mechanism remains unresolved.

Table 2. Crop-specific drought–yield associations from Spearman correlations and the primary province fixed-effects panel models (Spearman correlations: 1991–2024; panel models: 2000–2024).

Crop	Strongest Correlation Scale	Spearman ρ	Correlation FDR	Strongest SYRS Panel Scale	Panel β	Panel pFDR	Overall Response
Wheat	SPEI-6	−0.283	Yes	SPEI-6	−0.259	0.003	Negative
Sunflower	SPEI-1	+0.324	Yes	SPEI-3	+0.388	<0.001	Positive
Grain maize	—	—	No	SPEI-3	+0.181	0.178	No robust response
Rice	SPEI-12	+0.130	No	SPEI-12	+0.268	0.008	Positive association with SPEI-12

Note: ρ denotes Spearman's correlation coefficient, and β represents the primary panel model coefficient; these estimates are not interchangeable. FDR significance was assessed using the BH-FDR correction, with "No robust response" indicating no significant association. Supplementary Tables S3 and S4 provide detailed correlation and panel results, respectively, including sample sizes and adjusted p values. Table S4 reports approximate 95% confidence intervals ($\beta \pm 1.96$ SE), which are not cluster-adjusted. Correlation confidence intervals were not calculated. Supplementary crop calendar results are presented in Table 3.

Table 3. Significant crop–calendar SPEI associations in supplementary province- and year-fixed-effects models (1991–2024).

Crop	Calendar Window	Panel β	BH-FDR *p*	2004–2024 FDR Result
Sunflower	June SPEI-1	+0.180	0.019	Not significant
Sunflower	July SPEI-3	+0.254	0.003	Not significant
Sunflower	August SPEI-3	+0.253	0.011	Not significant
Grain maize	August SPEI-3	+0.227	0.019	Not significant

Note: Four of 24 prespecified crop–calendar windows were BH-FDR-significant in the 1991–2024 supplementary models. The remaining 20 windows were not significant. None of the 24 windows remained BH-FDR-significant in the 2004–2024 sensitivity analysis. Coefficients are from supplementary models with province and year fixed effects and two-way clustered standard errors, not from the primary panel specification. Calendar windows indicate cumulative climatic moisture and are not direct observations of phenological-stage water stress.

Grain maize exhibited weak correlations across all SPEI scales, with no significant relationship remaining after BH-FDR correction. Rice also showed weak bivariate relationships during 1991–2024, although the correlations became increasingly positive at SPEI-9 and SPEI-12. The panel analysis identified a significant positive coefficient for rice at SPEI-12 ($\beta = 0.268$, $p\text{FDR} = 0.008$), suggesting a closer association with longer-term climatic moisture conditions. The rice panel result is therefore interpreted as an association with sustained climatic moisture, not as direct evidence of changes in irrigation allocation or reservoir storage (Figure 6; Table 2).

The 2004–2024 sensitivity analysis broadly preserved these crop-specific patterns. Sunflower retained significant positive relationships, wheat maintained significant negative associations across all SPEI scales, and grain maize continued to show no robust SPEI relationship. For rice, significant positive correlations emerged at SPEI-9 ($\rho = 0.220$) and SPEI-12 ($\rho = 0.212$), consistent with the longer-timescale association identified in the panel analysis. These associations characterize yield anomalies rather than farm income or causal effects of water management. Crop-calendar timing and irrigation may influence their interpretation, but the corresponding mechanisms were not directly estimated.

3.3. Climatic and Socioeconomic Relationships with Agricultural Transformation

An exploratory cross-provincial assessment of socioeconomic change and wheat-area contraction yielded a Spearman association between wheat-area percentage change and population percentage change of $\rho = -0.030$, $p = 0.934$, $n = 10$, and between wheat-area percentage change and the change in industrial GDP share of $\rho = +0.152$, $p = 0.676$, $n = 10$ (Supplementary Dataset S7). These ecological associations are not evidence that population growth or industrial development caused wheat-area contraction.

Fixed-effects panel models revealed crop-specific differences in SPEI relationships after accounting for population, industrial share of provincial GDP, temporal change, and province-specific effects (Figure 6). Significant SPEI coefficients were most evident for standardized yield residuals (SYRS). For sunflower, the largest positive coefficient was at SPEI-1 ($\beta = 0.558$, $p\text{FDR} = 0.002$), whereas SPEI-3 had the lowest adjusted *p*-value ($\beta = 0.388$, $p\text{FDR} < 0.001$). For wheat, the largest absolute coefficient was at SPEI-1 ($\beta = -0.335$, $p\text{FDR} = 0.039$), whereas SPEI-6 had the lowest adjusted *p* value ($\beta = -0.259$, $p\text{FDR} = 0.003$). Wheat coefficients were negative and BH-FDR-significant at all five scales. Rice had significant positive coefficients at SPEI-9 ($\beta = 0.275$, $p\text{FDR} = 0.011$) and SPEI-12 ($\beta = 0.268$, $p\text{FDR} = 0.008$), the latter having the lowest adjusted *p*-value. No robust SPEI relationship was detected for grain maize SYRS. Coefficient magnitude and statistical significance are distinct criteria.

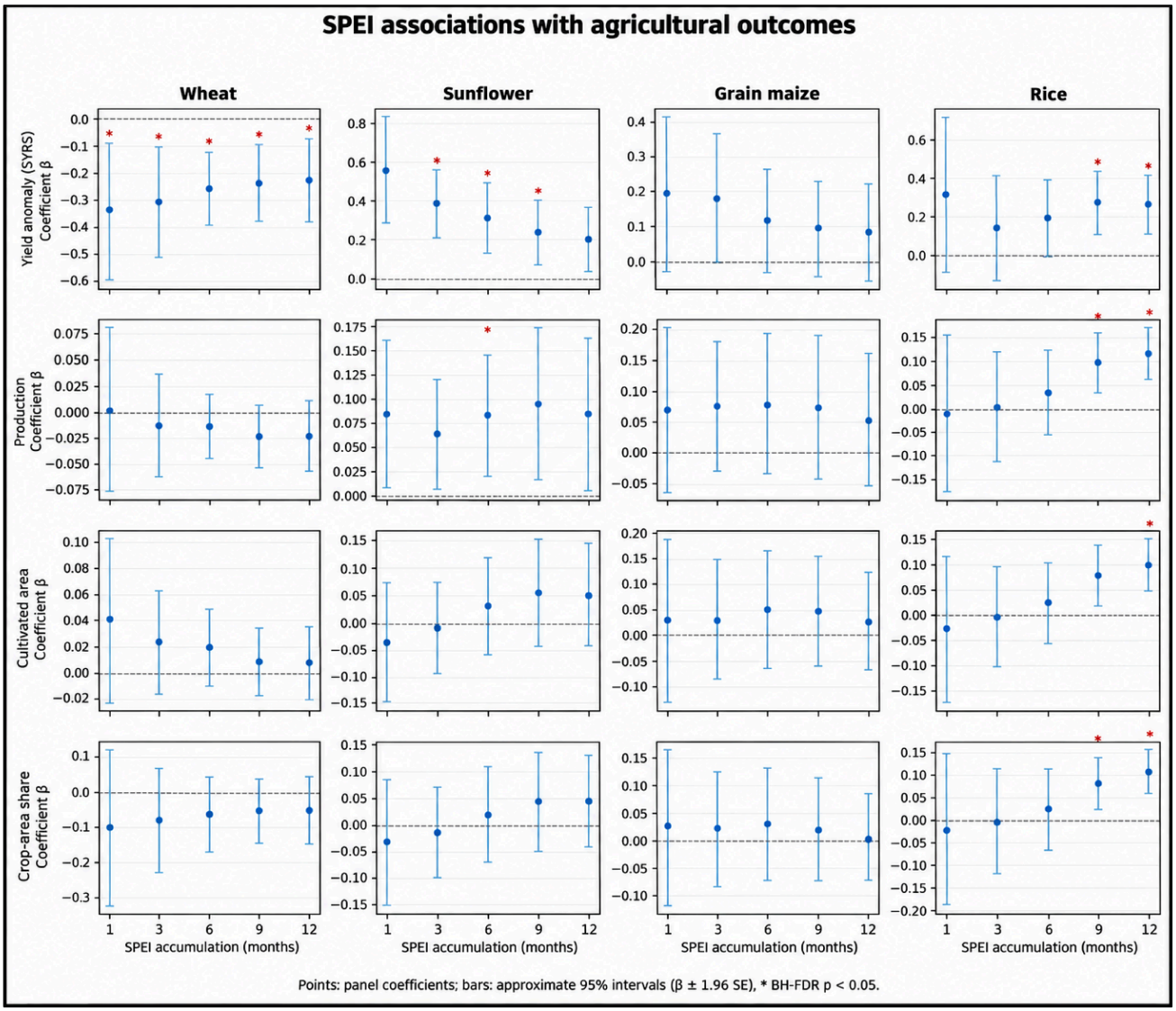


Figure 6. Associations between SPEI and agricultural responses estimated using separate province fixed effects panel models across five SPEI timescales (1, 3, 6, 9, and 12 months). Rows represent standardized yield residuals (SYRS), production, cultivated area, and crop area share; columns represent crops. Points show coefficients (β), and error bars indicate approximate 95% confidence intervals (β ± 1.96 SE) based on the original model standard errors. Asterisks indicate significance after Benjamini–Hochberg correction (pFDR < 0.05) across 80 models. Cluster-robust sensitivity results are reported separately in Supplementary Table S5.

SPEI relationships with production, cultivated area, and crop-area share during 2004–2024 were generally weaker and less consistent. No widespread BH-FDR-significant coefficients were detected for wheat, sunflower, or grain maize across these structural responses. Rice was a limited exception in the 2004–2024 structural-response models, with selected positive SPEI-12 associations for production, cultivated area, and crop-area share (Figure 6); these should be interpreted separately from the 1991–2024 SYRS panel result. This pattern was consistent with the positive SPEI-12 coefficient for rice SYRS and suggests a closer relationship between sustained moisture conditions and rice production than was detected for the other crops.

Overall, significant SPEI coefficients were concentrated in the SYRS models, while most estimates for the structural indicators overlapped zero. Thus, SPEI variability showed more consistent relationships with interannual yield anomalies than with production, cultivated

area, or crop-area share. The limited significant coefficients for cultivated area and crop share provide no statistical basis for attributing changes in crop composition to drought alone. Population and industrial share were included as contextual indicators rather than direct causal drivers, and their coefficients did not show a uniform regional pattern.

Including İstanbul through the available Şile agricultural series generally preserved the directions of the principal coefficients but weakened some estimates, particularly for wheat; sunflower coefficients were more stable. Because Şile does not represent province-wide agricultural conditions in İstanbul, interpretation was based on the primary ten-province analysis.

Supplementary crop-calendar SPEI results. In the 1991–2024 two-way fixed-effects analysis, four of the 24 crop–window associations remained significant after BH-FDR correction: sunflower June SPEI-1 ($\beta = 0.180$, $p\text{FDR} = 0.019$), sunflower July SPEI-3 ($\beta = 0.254$, $p\text{FDR} = 0.003$), sunflower August SPEI-3 ($\beta = 0.253$, $p\text{FDR} = 0.011$), and grain maize August SPEI-3 ($\beta = 0.227$, $p\text{FDR} = 0.019$). No wheat or rice calendar window remained significant. In the 2004–2024 sensitivity period, none of the 24 windows remained significant after BH-FDR correction. These supplementary findings concern calendar-specific moisture accumulation and are not interchangeable with the primary multiscalar panel estimates. The statistically significant windows are summarized in Table 3. The full 24-window coefficient comparison, including the 2004–2024 sensitivity period, is displayed in Figure 7.

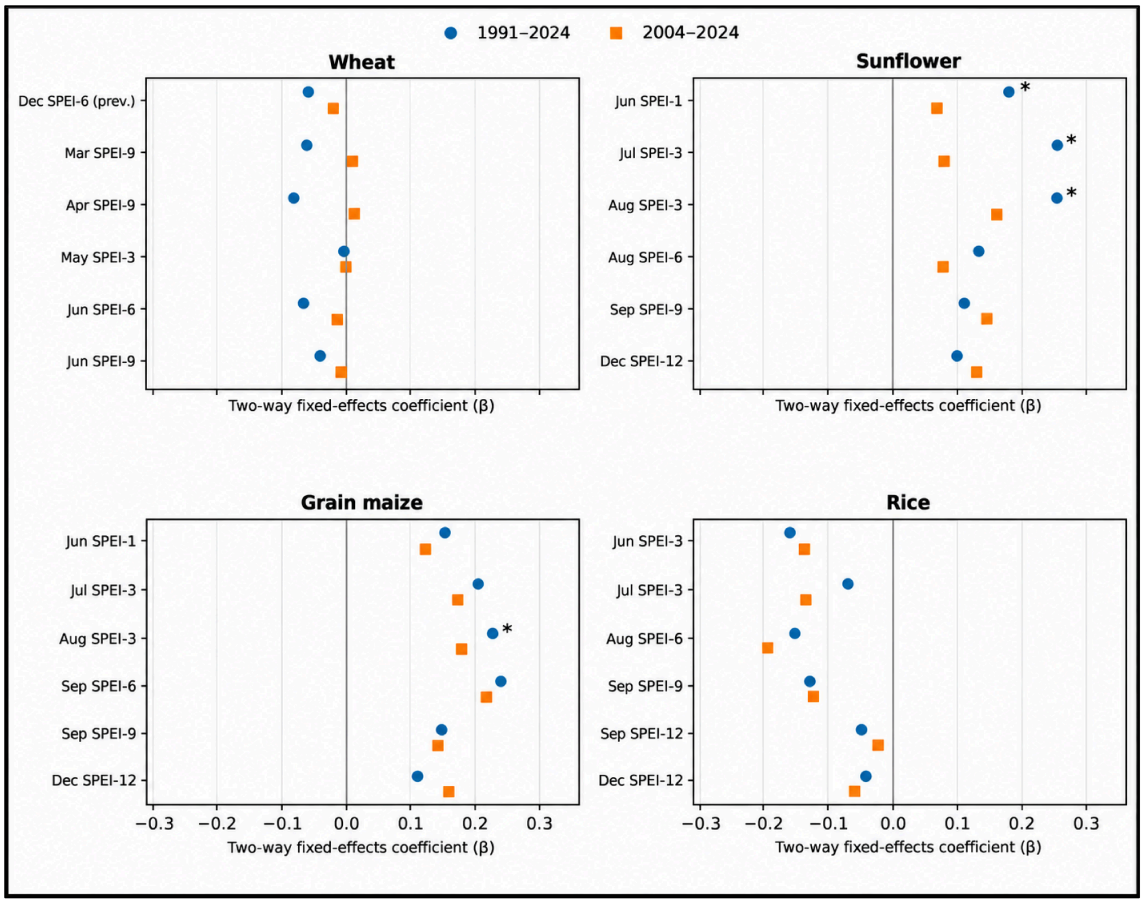


Figure 7. Supplementary crop-calendar SPEI associations with standardized yield residuals (1991–2024). The 24 prespecified windows were estimated using province and year fixed effects; significance was evaluated using BH-FDR correction across the 24 tests. None of the 24 windows remained significant in the 2004–2024 sensitivity analysis. Blue points represent 1991–2024 estimates and orange squares represent 2004–2024 estimates; asterisks denote BH-FDR-significant associations in the full period.

4. Discussion

The findings do not support a uniform increase in drought pressure as an explanation for agricultural transformation in the Marmara Region. No provincial SPEI trend remained significant after BH-FDR correction, whereas population increased significantly in all ten provinces and industrial share increased in seven (Figure 2). This pattern suggests that agricultural change occurred under heterogeneous climatic moisture conditions and rising socioeconomic pressure. However, the absence of significant long-term SPEI trends does not imply the absence of agricultural water stress, because meteorological drought can propagate differently through soil-water and hydrological systems, while reservoir storage and water management can modify the water ultimately available to agriculture [21–23,57]. The possible moderating roles of irrigation, soil-water availability, phenology, and management were not tested directly here, but this interpretation is consistent with reported differences between rainfed and irrigated systems and with broader evidence on interactions among drought, heat, crop physiology, and management [58–60]. At the same time, the weak relationships between SPEI and structural crop indicators suggest that long-term agricultural transformation should be considered within a broader sustainability framework encompassing climatic variability, demographic and industrial pressures, land-use competition, and agricultural policy.

The additional source-transition diagnostic strengthens this qualification. Marked differences between 2003 and 2004 in cultivated area and production, together with period-sensitive Sen slopes, indicate that apparent 1991–2024 structural trends could reflect both real agricultural change and differences between historical and online statistical series. Consequently, the main area-change results are based on 2004–2008 versus 2020–2024 averages, and no causal attribution is made for the 2003–2004 jumps. The diagnostic cannot distinguish statistical reclassification from actual changes in cropping without independent historical documentation.

Agricultural restructuring was more evident in crop-area and crop-composition indicators than in long-term drought trends. Wheat area declined significantly in six provinces, whereas sunflower, grain maize, and rice showed more spatially heterogeneous changes (Figures 3 and 4; Table 1). Crop diversity based on the three-crop analysis increased significantly in four of the nine evaluable provinces (Table 1), indicating that agricultural transformation did not follow a uniform regional pathway. These patterns are consistent with previous evidence that crop allocation and agricultural restructuring cannot be explained by climatic variability alone, but emerge from interactions among environmental and socioeconomic conditions [27,29,61]. This interpretation is also consistent with evidence that agricultural drought vulnerability reflects both biophysical and socioeconomic conditions rather than climatic exposure alone [33]. Such spatial heterogeneity may also reflect differences in economic incentives and production conditions. Crop allocation depends on expected net returns, which may vary across provinces according to market access, irrigation availability, land values, and support payments. For example, provinces located near major urban and industrial centers, such as Bursa, Kocaeli, and Sakarya, may experience greater competition for agricultural land, whereas agricultural production in Edirne and Kırklareli may be shaped by different land-use and production conditions. Although these mechanisms were not directly evaluated, they highlight the importance of considering regional socioeconomic differences when interpreting agricultural restructuring. The absence of a uniform regional transition may therefore reflect heterogeneous economic incentives alongside climatic and demographic pressures, rather than a single dominant driver. Nevertheless, the supplementary province-level socioeconomic correlations should be interpreted cautiously because only ten provinces were evaluated, the indicators share broad temporal trends, and no direct land-conversion, water-allocation, or crop-profitability

data were included. Accordingly, the observed reduction in wheat area cannot be causally attributed to urbanization or industrialization from these analyses.

Crop-specific analyses provided clearer evidence of climatic moisture sensitivity (Figures 5 and 6; Table 2). Sunflower responded positively to short- and medium-term SPEI, with the strongest bivariate association at SPEI-1 ($\rho = 0.324$) and the lowest panel adjusted p value at SPEI-3 ($\beta = 0.388$). This pattern suggests that sunflower yield variability may be associated with moisture conditions developing over relatively short periods, possibly during critical phenological stages. A supplementary crop-calendar analysis identified positive associations for selected June–August sunflower windows; these calendar-based indicators do not directly measure observed phenological-stage water stress, and none remained significant after BH-FDR adjustment in the restricted 2004–2024 period.

Wheat displayed BH-FDR-significant negative bivariate associations across all five SPEI scales. The strongest pooled correlation was observed at SPEI-6 ($\rho = -0.283$; $n = 340$), closely followed by SPEI-9 ($\rho = -0.278$; $n = 330$). In the fixed-effects panel, SPEI-1 had the largest absolute coefficient ($\beta = -0.335$), whereas SPEI-6 had the lowest adjusted p-value ($\beta = -0.259$, pFDR = 0.003). These negative associations should not be interpreted as evidence that drought improves wheat yield. A previous SPEI-based assessment in the Kızılırmak Basin also showed that wheat–drought relationships vary with drought characteristics and accumulation period [62]. Wheat responses may additionally reflect precipitation timing, temperature, cultivar selection, and management, as identified in previous research [12]. The November–June wheat moisture window encompasses preceding autumn and winter conditions as well as the spring growing season. The consistency of negative associations across multiple SPEI accumulation periods suggests that the pattern is not restricted to a single drought timescale, although the underlying mechanisms remain unresolved.

Grain maize showed no robust SPEI response, indicating an absence of a detectable signal in provincial yield anomalies rather than insensitivity to drought. Irrigation, soil-water storage, sowing dates, and technological improvements may weaken the relationship between meteorological drought and crop water stress, although these mechanisms were not directly tested in this study. Such buffering is plausible in irrigated systems, where irrigation management may partially decouple crop conditions from meteorological drought signals [63]. Rainfall reliability and timing may also be more important for maize than annual precipitation totals [64]. The weak SPEI signal for grain maize may also have an economic explanation. Irrigation practices and market-related factors, including feed demand, production contracts, and input costs, may contribute to agricultural decision-making and potentially modify the relationship between meteorological drought and maize production. However, these mechanisms were not directly evaluated in the present study. The absence of a robust province-level SPEI association does not establish climatic insensitivity, and the relative contributions of irrigation, management, and economic conditions were not quantified. The supplementary calendar-window model identified a positive grain-maize association for August SPEI-3 in 1991–2024, but this association did not retain BH-FDR significance in 2004–2024. Thus, this finding does not overturn the absence of a robust grain-maize signal in the primary multiscalar analysis; the results differ in their temporal definitions and model specifications. Rice showed a positive association between standardized yield residuals and the 12-month SPEI accumulation scale in the primary panel model ($\beta = 0.268$, pFDR = 0.008; Figure 6; Table 2), whereas the pooled bivariate rice correlation at SPEI-12 did not remain significant after BH-FDR correction (Figure 5). In the 2004–2024 structural-response analyses, selected rice associations with SPEI-12 were reported for production, cultivated area, and crop-area share; these are distinct response variables and do not establish a common causal mechanism (Figure 6). The observed rice-area increases

in Edirne (+26.5%) and Kırklareli (+58.3%) compare the 2004–2008 and 2020–2024 mean cultivated areas (Figure 4d) and are descriptive percentage changes, not SPEI coefficients. Reservoirs and irrigation infrastructure provide plausible hydrological context [22,23], and earlier research identifies economic influences on rice production in Çanakkale [65]. However, reservoir operations, irrigation allocation, and production costs were not evaluated as mediating mechanisms in this study. Consequently, the positive SPEI-12 coefficient indicates an association with sustained climatic moisture conditions rather than evidence of a direct reservoir or management effect. Significant SPEI associations were concentrated primarily in yield anomalies, whereas production, cultivated area, and crop-area share exhibited comparatively few significant relationships during 2004–2024 (Figure 6). This pattern supports a distinction between interannual climatic moisture sensitivity and long-term structural change. Crop allocation may also reflect economic, technological, irrigation, policy, and management considerations identified in the broader agricultural-policy literature [26]. However, these influences were not estimated directly in the present models.

Overall, drought variability was more clearly associated with interannual yield anomalies than with long-term crop allocation, with rice representing the main exception at longer SPEI timescales. These findings highlight substantial crop-specific drought sensitivity across the region, with responses differing according to both crop type and drought timescale. This crop-specific drought sensitivity is also relevant to the production dimension of food security because variations in crop responses to drought may influence the stability of regional agricultural output. Taken together, the results indicate that agricultural drought vulnerability emerges from interactions among meteorological moisture deficits, managed water availability, crop-specific sensitivity, and socioeconomic conditions rather than from meteorological drought alone. From a sustainable agricultural planning perspective, these findings support the consideration of crop- and timescale-specific drought monitoring alongside efficient irrigation, soil-water conservation, and protection of productive agricultural land. Such an integrated approach may help address climatic risks to crop productivity while accounting for longer-term pressures on agricultural land and water resources. Evidence from Balıkesir and Çanakkale also shows that the adoption of conservation measures depends on farmer awareness, information access, and farm characteristics [30]. These factors were not examined in the present study. Reservoir storage, releases, and crop-specific irrigation withdrawals were likewise not incorporated into the statistical models because comparable long-term data were not available for the full analysis period. Future research integrating meteorological drought, reservoir dynamics, irrigation withdrawals, and crop responses could more explicitly examine drought propagation from climatic water deficits through managed water availability to agricultural vulnerability.

The supplementary calendar-window findings suggest that moisture timing may contribute additional information for sunflower and grain-maize yield anomalies, particularly during summer development. However, these associations were not robust to the 2004–2024 period restriction. Province-level annual yield data could not establish actual phenological-stage dates, and differences in irrigation, cultivars, sowing dates, and soil-water conditions were not consistently observed. Consequently, the supplementary associations should be interpreted as exploratory seasonal proxies rather than causal estimates of stage-specific water stress. Incomplete crop-area records also restricted the geographical coverage of Shannon diversity comparisons. The interpretation of crop development stages follows the general FAO framework [56] and does not establish province-specific sowing or flowering dates. These findings are summarized in Table 3 and Figure 7.

5. Conclusions

The observed patterns of agricultural transformation in the Marmara Region were not consistently associated with meteorological drought variability, indicating that climatic indicators alone do not adequately characterize differences in agricultural restructuring. During 1991–2024, no provincial SPEI trend remained significant after multiple-testing correction, whereas population increased significantly in all ten provinces and industrial share increased in seven. During 2004–2024, agricultural restructuring was characterized by significant wheat-area contraction in six provinces, heterogeneous changes in sunflower, grain maize, and rice cultivation, and increased crop diversity in several provinces. These patterns highlight the importance of considering agricultural land-use change within a broader climatic and socioeconomic context.

A separate source-transition sensitivity assessment identified large 2003–2004 discontinuities in cultivated-area and production records for many province–crop combinations. Accordingly, conclusions about structural agricultural transformation are restricted to the 2004–2024 comparable series. The earlier agricultural records are retained for explicitly defined yield-related analyses, with period dependence acknowledged; the discontinuities are not treated as proven measurement errors.

Drought–yield relationships differed substantially among crops and accumulation timescales. Sunflower showed positive associations with short- to medium-term moisture conditions, whereas wheat exhibited negative associations across several SPEI scales, which should not be interpreted as evidence of beneficial drought effects and whose underlying mechanisms remain unresolved. Grain maize showed no robust SPEI response, while rice was more closely associated with longer-term moisture conditions. Importantly, significant SPEI relationships were concentrated primarily in interannual yield anomalies rather than structural indicators such as cultivated area and crop-area share. This distinction suggests that climatic moisture variability is more consistently associated with short-term yield fluctuations than with longer-term agricultural restructuring.

Supplementary crop-calendar models identified three significant positive sunflower associations and one grain-maize association in 1991–2024, but none remained significant after BH-FDR correction in 2004–2024. This period dependence underscores the need for cautious interpretation of calendar-specific drought–yield associations.

From a sustainability perspective, these findings emphasize the need to consider crop-specific climatic sensitivity alongside demographic and industrial pressures when developing regional agricultural strategies. Crop- and timescale-specific drought monitoring, efficient water management, and protection of productive agricultural land are potentially relevant planning considerations; their effectiveness was not evaluated in this study and should be regarded as implications for future assessment rather than interventions demonstrated by the statistical models. Economic and policy considerations, including agricultural support mechanisms and land-use regulations, should also be considered, although their effects were not directly estimated in this study. While our panel models account for unobserved time-invariant provincial characteristics, demographic pressures, and industrialization, the lack of spatially detailed information on production costs, market prices, and agricultural support policies remains an important limitation. Therefore, the estimated climatic relationships should be interpreted primarily as reflecting biophysical conditions, while farm-level land-use decisions are also shaped by economic considerations that are not fully captured in the analysis. Reservoir infrastructure provides an important hydrological context, but reservoir operations and irrigation withdrawals were not incorporated into the statistical models. Future research integrating irrigation, reservoir management, and farm-level economic data could help clarify the interacting climatic and

socioeconomic influences on agricultural transformation and inform more comprehensive sustainable agricultural planning.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su182211786/s1, Table S1: Unnormalized Sen's slope estimates, Mann–Kendall trend test results, and BH-FDR-adjusted significance levels for provincial SPEI-12, population, and industrial GDP share; Table S2: Province–crop agricultural data completeness, period means, and percentage changes in cultivated area during 2004–2024; Table S3: Spearman correlations between standardized yield residuals (SYRS) and SPEI at 1-, 3-, 6-, 9-, and 12-month accumulation scales, including sample sizes and BH-FDR-adjusted significance levels; Table S4: Primary province fixed-effects panel model coefficients, standard errors, approximate 95% confidence intervals, and BH-FDR-adjusted significance levels across 80 crop × response × SPEI-scale tests; Table S5: Robustness checks of SYRS panel models using alternative standard error estimators and two-way fixed-effects specifications; Dataset S6: Agricultural data source-transition diagnostics, period-specific trend comparisons, descriptive discontinuity classifications for 2003–2004, and data coverage assessment; Dataset S7: Province-level changes in wheat cultivated area, population, and industrial GDP share between the 2004–2008 and 2020–2024 periods, including exploratory Spearman correlation analyses.

Author Contributions: F.Y.Ö.: writing (original draft), visualization, validation, software, formal analysis, investigation, resources, data curation; E.Ö.: review and editing of the manuscript, conceptualization, methodology, validation, supervision, Project administration, resources; B.E.: review and editing of the manuscript, methodology, supervision. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Supplementary Tables S1–S5 and Supplementary Datasets S6 and S7 are available with the article. The original agricultural data were obtained from TurkStat MEDAS and meteorological observations from MGM.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Meteorological Station Inventory and SPEI Dataset Membership

Appendix A lists the metadata for 14 meteorological stations. The verified Station_SPEI worksheet contains 13 station-level SPEI series, each with 408 monthly records for January 1991–December 2024 (13 × 408 = 5304 station-month records). These comprise the ten stations representing the primary study provinces (Balıkesir, Bilecik, Bursa, Çanakkale, Edirne, Kırklareli, Kocaeli, Sakarya, Tekirdağ, and Yalova) and three additional İstanbul stations (Sarıyer, Florya, and Şile), present in the SPEI worksheet but not used as independent units in the ten-province agricultural panel. Kadıköy Göztepe Rıhtım (MGM code 17062) is included in the 14-station metadata inventory but is absent from the verified Station_SPEI worksheet and must not be counted among the 13 calculated station series. The İstanbul stations were not treated as independent province-level observations in the ten-province agricultural panel.

Data-scope reconciliation: the Station_SPEI worksheet contains 5304 station-month records (13 stations × 408 months), whereas the Province_SPEI worksheet contains 4488 province-month records (11 provinces × 408 months). The latter includes İstanbul

as a separate provincial climate series for contextual or sensitivity analyses; İstanbul is excluded from the ten-province primary agricultural panel. Thus, the difference of 816 records reflects distinct station-level and province-level datasets, not missing observations or an unexplained SPEI filtering step. Neither total represents the sample size of an individual regression, for which the model-specific *N* is reported.

Source traceability: the primary pooled correlations and main panel coefficients are recorded in MARMARA_GIDA_FINAL_TUM_ANALIZ_SONUCLARI(3).xlsx (SYRS_SPEI_CORR, PANEL_SPEI); meteorological time series and annual SPEI trends in Marmara_Drought_Analysis_FINAL_1991_2024(6).xlsx (Station_SPEI, Annual_Trends); and supplementary trends, data coverage, correlations, panel coefficients, and robustness checks in MARMARA_SUPPLEMENTARY_TABLES_S1_S5.xlsx (Tables S1–S5). The R verification package provides a separate processing-stage coverage count and crop-calendar analyses.

Appendix B. Descriptive 2003–2004 Agricultural-Series Discontinuity Audit

Across 40 province–crop combinations per variable, 31 had paired 2003–2004 observations and nine lacked paired values. The diagnostic classifications and their counts are reported in the Materials and Methods and Results sections; full province–crop results are provided in the accompanying source-transition workbook.

Supplementary Dataset S6, the accompanying 2003–2004 source-transition diagnostic workbook (MARMARA_2004_BREAK_SENSITIVITY_RESULTS) contains period-specific trend comparisons, paired-year discontinuity flags, robustness classifications, and missing-data coverage. The thresholds used for the descriptive break flags are defined by the original diagnostic procedure; they should not be interpreted as a formal structural-break hypothesis test. The workbook is an additional reproducibility artifact and does not replace the 2004–2024 structural analysis.

Station membership and monthly record counts were verified against the Station_SPEI and Input_QC worksheets of Marmara_Drought_Analysis_FINAL_1991_2024. The distinction between the 14-station metadata inventory and the 13-station SPEI dataset is intentional; the inventory alone does not establish use in SPEI computation.

MGM Station Code	Station Name	Longitude (°E)	Latitude (°N)	Elevation (m)	Role in Analysis
17119	YALOVA	29.2796	40.6589	4	Primary province SPEI series
17120	BİLECİK	29.9772	40.1414	539	Primary province SPEI series
17116	BURSA	29.0133	40.2308	100	Primary province SPEI series
17069	SAKARYA	30.3934	40.7676	30	Primary province SPEI series
17056	TEKİRDAĞ	27.4965	40.9585	4	Primary province SPEI series
17066	KOCAELİ	29.9173	40.7663	74	Primary province SPEI series
17052	KIRKLARELİ	27.2178	41.7382	232	Primary province SPEI series
17050	EDİRNE	26.5508	41.6767	51	Primary province SPEI series
17112	ÇANAKKALE	26.3993	40.1410	6	Primary province SPEI series
17150	BALIKESİR	27.9201	39.6323	102	Primary province SPEI series
17061	SARIYER	29.0502	41.1464	59	Additional İstanbul SPEI series; not a primary province-panel unit
17610	ŞİLE	29.6007	41.1688	83	Additional İstanbul SPEI series; not a primary province-panel unit
17636	FLORYA	28.7865	40.9758	37	Additional İstanbul SPEI series; not a primary province-panel unit
17062	KADIKÖY GÖZTEPE RIHTIM	29.0190	40.9883	5	Metadata inventory only; absent from Station_SPEI

Data availability and reproducibility: Source traceability is reported at the provider and dataset level where original table-level query identifiers are unavailable; the study does not claim to have independently verified missing MEDAS query IDs or an original reservoir GIS layer vintage.

Agricultural data were obtained from TurkStat MEDAS (accessed 10 October 2026), and meteorological observations from MGM. The accompanying Supplementary Tables S1–S5 summarize trend, coverage, correlation, panel, and robustness results; Supplementary Dataset S6 contains the province–crop-level 2003–2004 discontinuity flags, full- and sub-period trend estimates, and data-coverage diagnostics; these identify a source-transition sensitivity, not a formally established causal break. Reservoir locations provide descriptive context and are not model covariates.

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