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# Impact of Agricultural Drought on Sunflower Production across Hungary

**Endre Harsányi [1], Bashar Bashir [2], Firas Alsilibe [3], Karam Alsafadi [4], Abdullah Alsalman [2], Adrienn Széles [1], Muhammad Habib ur Rahman [5,6], István Bácskai [1], Csaba Juhász [1], Tamás Ratonyi [1] and Safwan Mohammed [1,*]**

[1] Faculty of Agricultural and Food Sciences and Environmental Management, Institute of Land Utilization, Technology and Regional Development, University of Debrecen, 4032 Debrecen, Hungary; harsanyie@agr.unideb.hu (E.H.); szelesa@agr.unideb.hu (A.S.); bacskai.istvan@agr.unideb.hu (I.B.); juhasz@agr.unideb.hu (C.J.); ratonyi@agr.unideb.hu (T.R.)
[2] Department of Civil Engineering, College of Engineering, King Saud University, Riyadh 11421, Saudi Arabia; bbashir@ksu.edu.sa (B.B.); asalman@ksu.edu.sa (A.A.)
[3] Department of Transport Infrastructure and Water Resources Engineering, Széchenyi István University, 9026 Győr, Hungary; firas.alsilibe@hallgato.sze.hu
[4] School of Geographical Sciences, Nanjing University of Information Science and Technology, Nanjing 210044, China; karam.alsafadi@alexu.edu.eg
[5] Institute of Crop Science and Resource Conservation (INRES), University of Bonn, 53115 Bonn, Germany; mhabibur@uni-bonn.de
[6] Department of Agronomy, MNS-University of Agriculture, Multan 60000, Pakistan
* Correspondence: safwan@agr.unideb.hu



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**Abstract:** In the last few decades, agricultural drought (Ag.D) has seriously affected crop production and food security worldwide. In Hungary, little research has been carried out to assess the impacts of climate change, particularly regarding droughts and crop production, and especially on regional scales. Thus, the main aim of this study was to evaluate the impact of agricultural drought on sunflower production across Hungary. Drought data for the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI) were collected from the CARBATCLIM database (1961–2010), whereas sunflower production was collected from the Hungarian national statistical center (KSH) on regional and national scales. To address the impact of Ag.D on sunflower production, the sequence of standardized yield residuals (SSYR) and yield losses $Y_{lossAD}$ was applied. Additionally, sunflower resilience to Ag.D (SRAg.D) was assessed on a regional scale. The results showed that Ag.D is more severe in the western regions of Hungary, with a significantly positive trend. Interestingly, drought events were more frequent between 1990 and 2010. Moreover, the lowest SSYR values were reported as −3.20 in the Hajdu-Bihar region (2010). In this sense, during the sunflower growing cycle, the relationship between SSYR and Ag.D revealed that the highest correlations were recorded in the central and western regions of Hungary. However, 75% of the regions showed that the plantation of sunflower is not resilient to drought where $SRAg.D_x < 1$. To cope with climate change in Hungary, an urgent mitigation plan should be implemented.

**Keywords:** crop resilience; food security; poverty; SPI; SPEI; SSYR; Hungary

## 1. Introduction

Climate change is one of the most challenging and complex issues facing the world today [1]. Over the last few centuries, the burning of fossil fuels and widespread deforestation have resulted in increased atmospheric greenhouse gas (GHG) concentrations, which have led to significant climate shifts across the planet [2]. Since 1750, the concentrations of GHGs such as methane ($CH_4$), carbon dioxide ($CO_2$), and nitrous oxide ($N_2O$) have risen by 156%, 47%, and 23%, respectively [1,3]. Due to anthropogenic activities, the average temperature rose by 0.99 °C, in the first two decades of the 21st century (2001–2020), and according to predictions, by 2050, the temperature increase is expected to reach 1.5 °C, or perhaps even higher than the average temperature in the preindustrial period (1850–1900) [1]. This accelerated rise in temperature has caused a spike in droughts, floods, irregular precipitation patterns, heat waves, and other extreme climate events around the world [4,5].

According to the annual report of Weather, Climate, and Catastrophe Insight [6], natural disasters alone caused direct losses and damage totaling over USD 268 billion worldwide in 2020; on average, losses due to natural disasters and emergencies have exceeded USD 200 billion per year since 2016. Approximately 95% of these losses are linked to weather-related events, where hurricanes, floods and droughts are the major contributors and have a direct link to climate change [6]. Overall, the impact of climate change is extensive, but its effects are now clearly visible on the agricultural sector [7], on which the world's food production and economy relies. It is also important to highlight that the world population is predicted to hit 9.7 billion by 2050 [8], which would increase the pressure on the agricultural sector to fulfill the growing food demands already impacted by climate change.

Among natural disasters caused by weather and climate change, drought is a unique issue; the global trend towards more or less frequent drought episodes is still a highly discussed topic [9–14]. This is attributed to the complicated characteristics of droughts, which usually develop slowly but can extend for months or even years [15,16]. Furthermore, the consequences can have a variety of effects on several sectors [17–20]. Additionally, the lack of a unified universal definition [21,22] and the wide range of indicators used to assess meteorological, agricultural, hydrological, and socioeconomic droughts [23] enhance the complexity.

Drought impacts all socioeconomic and environmental systems [24], with significant effects on anthropogenic fields including agriculture, forestry, water resource management, energy generation, and health [25]. Drought impacts can be divided into two categories: direct and indirect [25]. Direct effects include decreased crop production [26], increased numbers of forest fires [27], decreased water levels [28], and increased livestock mortality rates [29]. Indirect effects of drought include highly unstable food prices, which may be exacerbated by market effects in the agricultural sector [30]. As a result, estimating total costs and losses at the regional and national levels is difficult. Indirect losses are mostly greater than direct losses [31], although they are more difficult to link to a specific event.

In order to detect, monitor, and characterize drought events, many drought indices have been developed, such as the Palmer Drought Severity Index Standardized (PDSI) [32], Precipitation Index (SPI) [33], and the Standardized Precipitation Evapotranspiration Index (SPEI) [34]. Table 1 presents more details about the most commonly used drought indices in the literature.

**Table 1.** Common drought indices.

| Index | Definition | Factor | Calculation Time Scale |
|---|---|---|---|
| PDSI [32] | Palmer Drought Severity Index | Precipitation, temperature, soil moisture and evapotranspiration | Monthly |
| CMI [35] | Crop Moisture Index | Mean temperature and precipitation | Weekly |
| CSDI [36] | Crop Specific Drought Index | Evapotranspiration | Seasonal |
| RI [37] | National Rainfall Index | Precipitation | Annually and every century |
| RDI [38] | Reclamation Drought Index | Level of river water, snowfall, stream flows, reservoirs level and temperature | Monthly |
| EPI [39] | Effective Precipitation Index | Precipitation | Daily |

**Table 1.** *Cont.*

| Index | Definition | Factor | Calculation Time Scale |
|---|---|---|---|
| BMDI [40] | Bhalme and Mooley Drought Index | Precipitation | Monthly, annually |
| SPI [33] | Standardized Precipitation Index | Precipitation | 3-, 6-, 12-, 24- and 48-month periods. |
| SPEI [34] | Standardized Precipitation Evapotranspiration Index | Precipitation, evapotranspiration | Monthly |
| SRI [41] | Standardized Runoff Index | Precipitation | 3-, 6-, 12-, 24- and 48-month periods. |

In Europe, the accelerated warming in this region [42], in comparison with many other parts of the world, has intensified drought events for prolonged periods, accompanied by rising temperatures and low rainfall, particularly in the center of the continent (i.e., Hungary) [43,44].

Hungary, similarly to other European countries in the Carpathians, is affected by droughts and climate change [45,46]. Droughts have been common in Hungarian history, leading to reduced crops, animal devastation, and the risk of hunger and illnesses [47]. The frequency of drought events has also increased significantly in Hungary [47]. Generally, every two years, Hungary experiences a moderate drought, and every three years, it experiences a severe drought [48]; these drought conditions are projected to continue for the rest of the 21st century [45,49]. In this sense, little research has been conducted in Hungary to assess the impact of climate change on crop production, especially on a regional scale. Hence, our understanding of the direct impacts of different drought cycles on crop production is still limited. Thus, the main aims of this research were: (1) to track agricultural drought (Ag.D) evolution across Hungarian counties between 1960 and 2010 by using the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI); (2) to analyze the dynamic interaction between sunflower yield and drought cycles; and (3) to identify the counties most prone to drought. In this study, sunflower crops were chosen due to their economic importance, where it is considered one of the most important oil crops (550,000 ha) across Hungary.

## 2. Materials and Methods

### *2.1. Data Collection and Trend Analysis*

Agricultural drought (Ag.D) data were collected from the CARBATCLIM database [50]. The CARBATCLIM platform provides researchers with necessary climate data between 1960 and 2010 for the whole Carpathian Region (44° N and 50° N, 17° E and 27° E). This project was supported by the European Commission, and the output is a climate atlas with spatial resolution 0.1° × 0.1° [51,52]. Within the CARBATCLIM database, Hungary is covered by 1045 grid points (Figure 1), where each point contains all climate variables. In this study, we downloaded the data for both the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI) for six months (i.e., SPI-6, SPEI-6), as a proxy of Ag.D. Notably, homogeneity of the data and their quality were assessed by the CARBATCLIM team. Later on, gridded points were sorted into groups according to their Hungarian counties; then, the average of each group was calculated and adopted as a representative value of Ag.D (Figure 1).

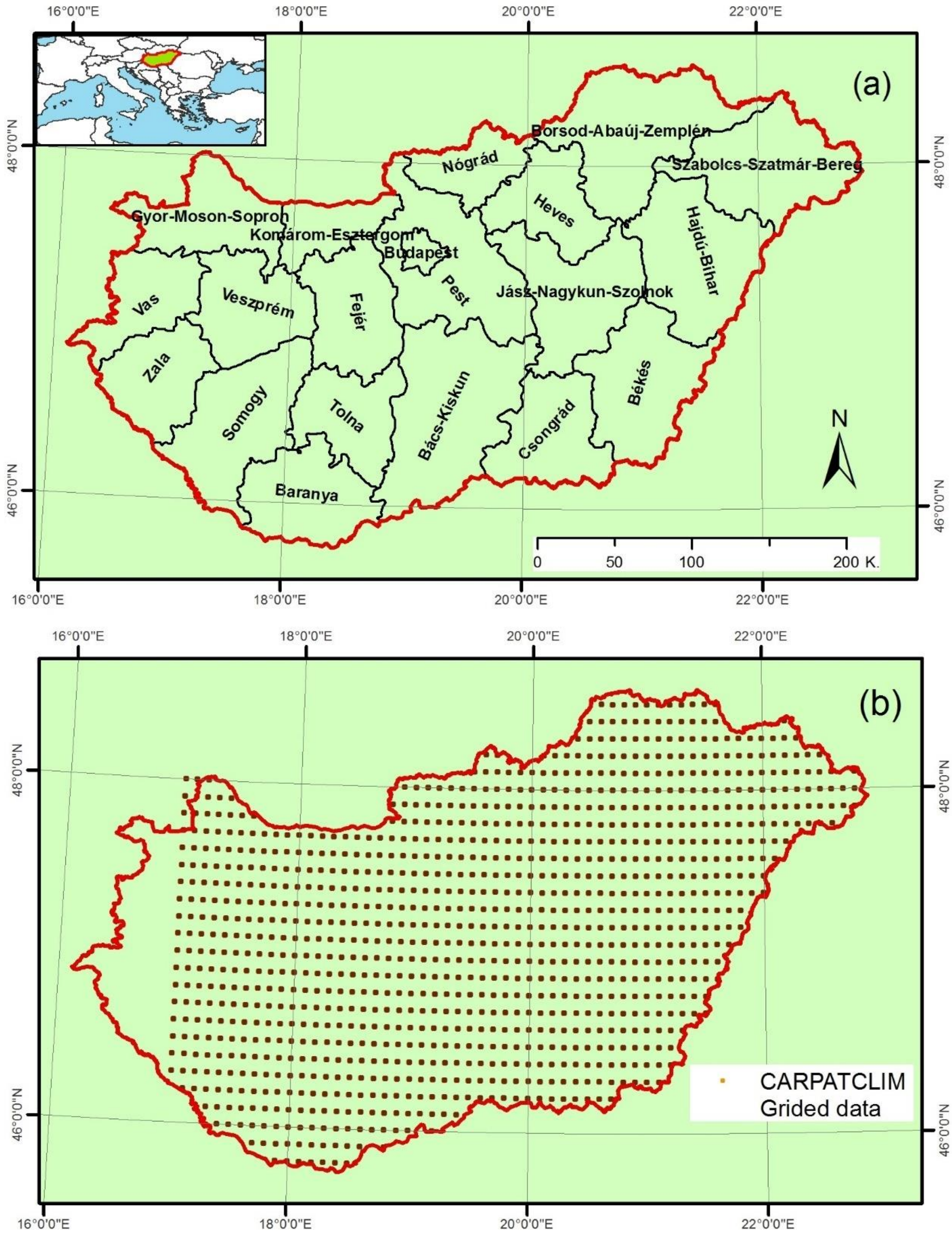



**Figure 1.** Map of Hungary: (**a**) Hungarian counties, and (**b**) distribution of 1045 gridded points across Hungary.

The sunflower database was built using information from the Hungarian national statistical center (KSH) (https://www.ksh.hu/stadat_eng accessed on 6 May 2020). This database contains the planted area (ha), production (thousand tons) and yield (kg/ha), at a national scale (1990–2019), as represented in Figure 2. However, to address the specific study goals, available sunflower yield data were collected on a county scale from 2000 to 2019.

For trend analysis, Mann–Kendall (MK) [53] tests were performed and Sen slopes (β) [54] were calculated for the studied variables. Both the MK test and Sen slope (β) are non-parametric tests; MK is used to indicate trends (i.e., increase or decrease) in the studied time series, whereas the Sen slope computes the value of the change (slope).

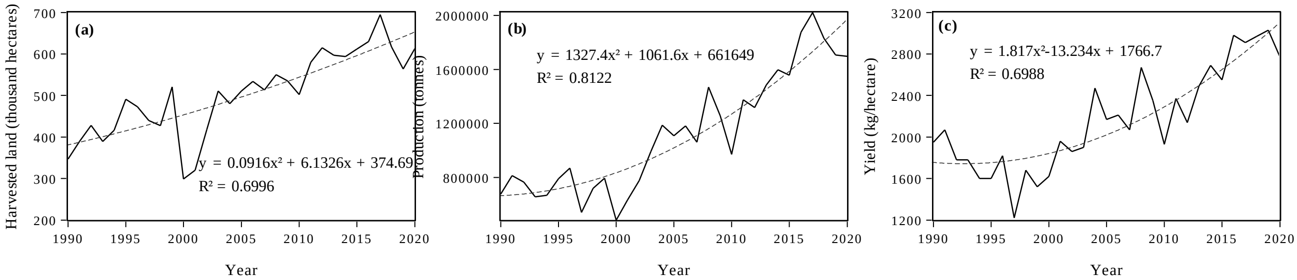



**Figure 2.** Evolution of sunflower cultivation across Hungary at a national scale (1990–2019): (**a**) harvested sunflower land between 1990 and 2019 (left graph); (**b**) production in tons across Hungary (middle graph); and (**c**) sunflower yield between 1990 and 2019 (right graph).

### 2.2. *Agricultural Drought Indices*

To quantify drought characteristics (severity, spatial extent, duration, and frequency), several drought indices could be employed, which mainly depend on the research questions and data availability [55–57]. Many ecosystem elements such as rainfall, evapotranspiration, temperature, river discharge, soil moisture, and change in vegetation cover could be used as inputs for modeling and monitoring drought [58–60]. Scientifically, the Ag.D indicates a shortage in soil moisture, which inhibits soil from providing necessary amounts of water to attain optimal crop production requirements [56,61]. In this study, the SPI and SPEI in a six-month time scale were adopted as a proxy for Ag.D (1961–2010).

#### 2.2.1. Standardized Precipitation Index (SPI)

The SPI [33] is one of the most common indices used for tracking and monitoring drought episodes [62], and is recommended by the World Meteorological Organization [55,63]. Monthly rainfall data are the only input for calculating drought in several time scales [33]. Through different transformations, from gamma distribution to normal distribution, the final equations for SPI can be drawn as follows:

$$\mathrm{SPI} = -\left(\mathrm{t} - \frac{2.515517 + 0.802853\mathrm{t} + 0.010328\mathrm{t}^2}{1 + 1.432788\mathrm{t} + 0.189269\mathrm{t}^2 + 0.001308\mathrm{t}^3}\right) for\ 0 < H(x) \leq 0.5 \quad (1)$$

$$\mathrm{SPI} = +\left(\mathrm{t} - \frac{2.515517 + 0.802853\mathrm{t} + 0.010328\mathrm{t}^2}{1 + 1.432788\mathrm{t} + 0.189269\mathrm{t}^2 + 0.001308\mathrm{t}^3}\right) for\ 0 < H(x) < 1 \quad (2)$$

where:

$$H(x) = \mathrm{q} + (1 - \mathrm{q})G(x) \quad (3)$$

More details about SPI calculation, (t, q, $G(x)$), was presented in detail by McKee et al. [33]. Drought classifications according to SPI values are presented in Table 2.

**Table 2.** Drought classes based on SPI and SPEI values.

| SPI Value | SPEI Value | Ag.D Class |
|---|---|---|
| >0 | >0 | NA |
| −0.84–0 | −0.84–0 | Moderate Ag.D |
| −1.28–−0.84 | −1.28–−0.84 | Severe Ag.D |
| −1.65–−1.28 | −1.65–−1.28 | Extreme Ag.D |
| >−1.65 | >−1.65 | Very extreme Ag.D |

2.2.2. SPEI

The SPEI [34] is a developed indicator from the same background as SPI [52]. Monthly rainfall and potential evapotranspiration are the main inputs for calculating the SPEI [34]. The final equation of SPEI could be drawn as follows:

$$\text{SPEI} = W - \frac{C_0 + C_1 W + C_2 W}{1 + d_1 W + d_2 W^2 + d_3 W^3} \tag{4}$$

$$\text{where } W = \begin{cases} \sqrt{-2ln\ (P)} & when\ P \leq 0.5 \\ \sqrt{-2ln\ (1-P)} & when\ P > 0.5 \end{cases} \tag{5}$$

The equation constant ($C_0$, $C_1 \ldots$ ); and other mathematical approaches was presented in detail by Vicente-Serrano et al. [34]. Drought classifications according to SPEI values are presented in Table 2.

Despite the fact that both indices have the same background, the SPEI has been proven to be superior to SPI in drought monitoring and climate change assessments [33,52].

*2.3. Impact of Agricultural Drought*

2.3.1. Sequence of Standardized Yield Residuals (SSYR)

To address the impact of Ag.D on crop yield, the bias attributed to technological factors (i.e., pest control, fertilization, and high-yield varieties) should be removed. To do so, polynomial regression was calculated for observed yield ($Y_{R\ (x)}$) on the county scale (2000–2019); then, the data were detrended ($Y_{P\ (x)}$), and the residuals were calculated (i.e., $Y_{R\ (x)} - Y_{P\ (x)}$). Finally, the SSYR was computed using the following equation [64,65]:

$$\text{SSYR} = \frac{Y_{P\ (x)} - \forall_{P\ (x)}}{\partial_{P\ (x)}} \tag{6}$$

where $Y_{P\ (x)}$ is the potential yield (detrended), $\forall_{P\ (x)}$ is the mean of $Y_{P\ (x)}$, and $\partial_{P\ (x)}$ is the standard deviation $Y_{P\ (x)}$. The classifications of SSYR values are presented in Table 3. Additionally, the correlation coefficients (*r*) between SSYR and both the SPI and SPEI were calculated (2000–2010) on a monthly scale.

**Table 3.** Classification of the sequence of standardized yield residual (SSYR) values which ranged from normal conditions to extreme drought impacts.

| SSYR Value | Impacts of Ag.D |
|---|---|
| $-0.5 <$ SSYR $\leq 0.5$ | Normal |
| $-1.0 <$ SSYR $\leq -0.5$ | Mild |
| $-1.5 <$ SSYR $\leq -1.0$ | Moderate |
| $-2.0 <$ SSYR $< -1.5$ | High |
| SSYR $\leq -2.0$ | Extreme |

2.3.2. Yield Losses, $Y_{\text{loss Ag.D}}$

The direct impacts of Ag.D on sunflower production and yield losses across the Hungarian counties were calculated using the approach suggested by Tigkas et al. [66]:

$$Y_{lossAg.D\ (x)} = \frac{Y_{R\ (x)} - Y_{P\ (x)}}{Y_{P\ (x)}} \times 100 \tag{7}$$

where $Y_{lossAg.D\ (x)}$ is the yield loss due to agricultural drought, $Y_{R\ (x)}$ is the recorded yield (observed), $Y_{P\ (x)}$ is the potential yield (detrended), and *x* is the year. $Y_{P\ (x)}$ refers to the development of crop production without any environmental constraints such as water shortages, heat waves, or other environmental factors [66].

2.3.3. Sunflower Resilience to Ag.D (SRAg.D):

The SRAg.D was calculated for each county in Hungary using the equation suggested by Sharma and Goyal [67]:

$$\text{SRAg.D}_x = \frac{Y^d_{R\ (x)}}{Y^d_{P\ (x)}} \quad (8)$$

where $\text{SRAg.D}_x$ is the sunflower resilience to Ag.D in each county, $Y^d_{R\ (x)}$ is the recorded yield in the driest year (2000–2010), and $Y^d_{P\ (x)}$ is the potential yield. The SRAg.D ranged from >1 (resilient) to <0.8 (severely non-resilient). The classification of SRAg.D values are presented in Table 4.

**Table 4.** Classification of sunflower resilience to Ag.D (SRAg.D) values, which ranged from resilient to severely non-resilient.

| SRAg.D Value | SRAg.D |
|---|---|
| SRAg.D > 1 | Resilient |
| 0.9 < SRAg.D < 1 | Slightly non-SRAg.D |
| 0.8 < SRAg.D < 0.9 | Moderately non-SRAg.D |
| SRAg.D < 0.8 | Severely non-SRAg.D |

For simplification, Figure 3 depicts a flowchart of the study steps.

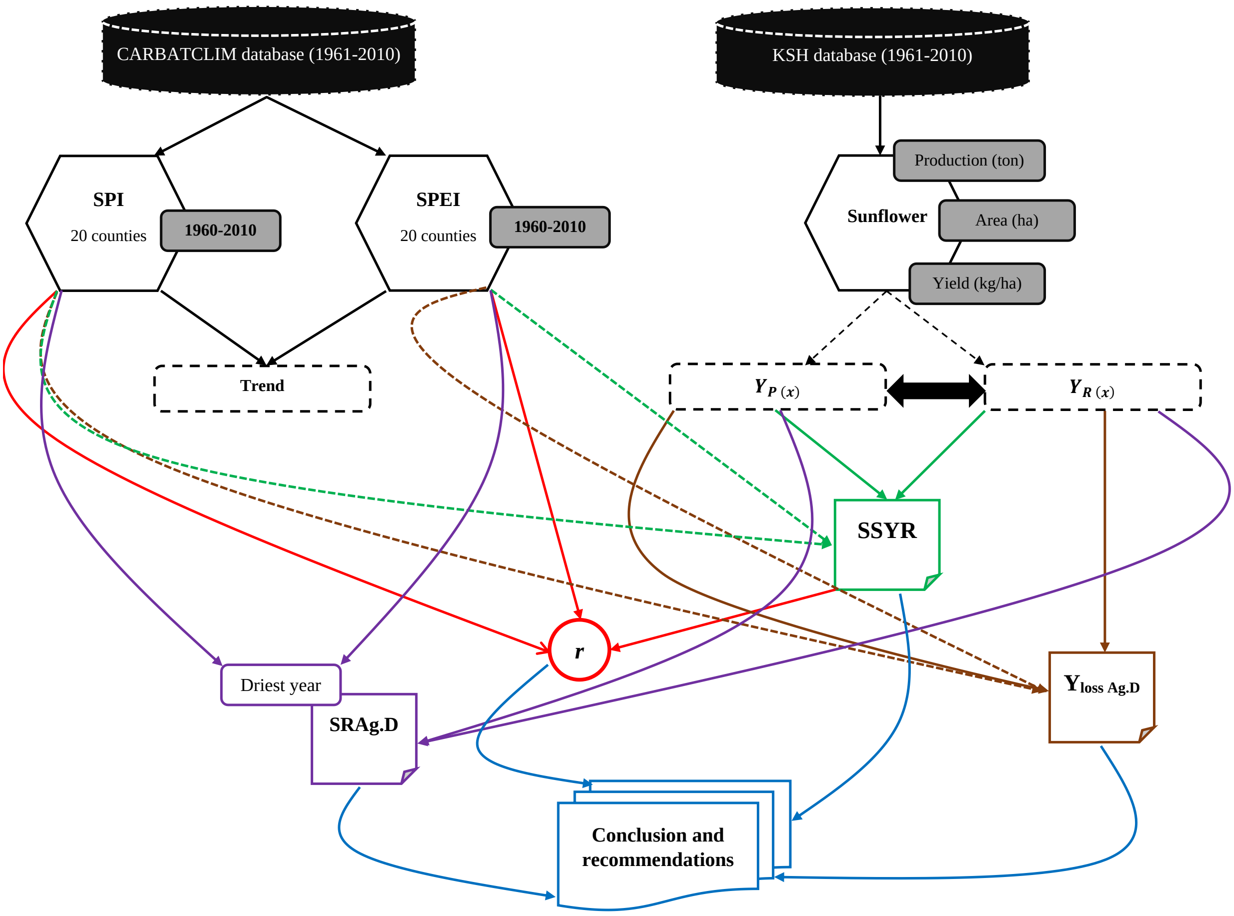



**Figure 3.** Flowchart of the study process from obtaining the data through to providing conclusions and recommendations. SPI, SPEI: drought indices. Trend: MK test. $Y_{R\ (x)}$ : observed yield (2000–2019), $Y_{P\ (x)}$: potential yield (detrended). SSYR: sequence of standardized yield residuals, $Y_{loss\ Ag.D}$: yield losses, $\text{SRAg.D}_x$: sunflower resilience to Ag.D.

## 3. Results

### 3.1. Trend in Ag.D across Hungarian Counties:

Hungary experienced Ag.D cycles several times, as can be seen in Figure 4. Figure 4a,d demonstrate that Ag.D episodes were more intense in western and central Hungary (i.e., ZA, VE, VA, and GY) compared with the eastern region of the country (i.e., HB, HE, JN, and SS). Notably, Ag.D cycles have become more frequent since 1990, when more negative values were recorded (Figure 4a,d).

Trend analyses by MK test and Sen slope also indicate that western Hungarian counties are more prone to Ag.D compared with other country regions (Table 5). In terms of SPI-6 (1960–2010), the majority of the counties (14 out of 20) exhibited a positive trend, which indicate less susceptibility to Ag.D. In fact, only four counties, HB, HE, JN, and SS, which are located in eastern Hungary, exhibited a significantly positive trend ($p < 0.05$) (Table 5).

For SPEI, most of counties exhibited a negative trend for SPEI-6 (1960–2010), except for HB, HE, JN, and SS. Nonetheless, significantly negative ($p < 0.05$) trends in SPEI-6 (1960–2010) were recorded in GY, SO, VA, VE, and ZA (western regions) (Table 5). Notably, both drought indices agreed on negative trends in each of the following counties: GY, SO, TO, VA, VE, and ZA, as shown in Figure 4b.

**Table 5.** Trends in Ag.D indices (SPI-6, SPEI-6) and sunflower production (kg/ha) across Hungary.

| County | Code | SPI-6 | | SPEI-6 | | Sunflower | |
|---|---|---|---|---|---|---|---|
| | | MK and β | $p$ | MK and β | $p$ | MK and β | $p$ |
| **Bács-Kiskun** | BC | 0.0005 | 0.05 | $-5 \times 10^{-5}$ | 0.83 | +55.83 | **0** |
| Baranya | BA | 0.0002 | 0.32 | $-2 \times 10^{-4}$ | 0.40 | +48.04 | **0** |
| Békés | BE | 0.0005 | 0.05 | $6 \times 10^{-5}$ | 0.79 | +59.03 | **<0.0001** |
| Borsod-Abaúj-Zemplén | BO | 0.0005 | 0.06 | $7 \times 10^{-5}$ | 0.75 | +75.19 | **<0.0001** |
| Budapest | BU | 0.0003 | 0.28 | $-3 \times 10^{-4}$ | 0.27 | +70.28 | **0** |
| Csongrád-Csanád | CS | 0.0003 | 0.21 | $-1 \times 10^{-4}$ | 0.55 | +32.18 | **0.01** |
| Fejér | FE | 0.0001 | 0.67 | $-4 \times 10^{-4}$ | 0.06 | +47.99 | **0.01** |
| Győr-Moson-Sopron | GY | 0.0001 | 0.74 | $-5 \times 10^{-4}$ | **0.03** | +38.33 | **0.01** |
| Hajdú-Bihar | HB | 0.0006 | **0.01** | $2 \times 10^{-4}$ | 0.46 | +71.6 | **<0.0001** |
| Heves | HE | 0.0005 | **0.02** | $1 \times 10^{-4}$ | 0.60 | +71.34 | **0** |
| Jász-Nagykun-Szolnok | JN | 0.0007 | **0.00** | $2 \times 10^{-4}$ | 0.44 | +60 | **<0.0001** |
| Komárom-Esztergom | KE | 0.0003 | 0.21 | $-2 \times 10^{-4}$ | 0.26 | +58.06 | **<0.0001** |
| Nógrád | NO | 0.0003 | 0.24 | $-1 \times 10^{-4}$ | 0.65 | +65 | **0.01** |
| Pest | PE | 0.0003 | 0.16 | $-2 \times 10^{-4}$ | 0.48 | +65.15 | **0** |
| Somogy | SO | −0.0004 | 0.07 | $-8 \times 10^{-4}$ | **0.00** | +61.46 | **0** |
| Szabolcs-Szatmár-Bereg | SS | 0.0008 | **0.00** | $3 \times 10^{-4}$ | 0.15 | +72.58 | **0** |
| Tolna | TO | 0.0000 | 0.94 | $-4 \times 10^{-4}$ | 0.06 | +53.54 | **0** |
| Vas | VA | −0.0008 | **0.00** | $-1 \times 10^{-3}$ | **<0.0001** | +44.77 | **0** |
| Veszprém | VE | −0.0001 | 0.69 | $-6 \times 10^{-4}$ | **0.01** | +56.57 | **0** |
| Zala | ZA | −0.0007 | **0.01** | $-1 \times 10^{-3}$ | **<0.0001** | +50 | **<0.0001** |

* Gray and bold values indicate a significance level of 0.05 ($p < 0.05$). MK, trend; β, Sen slope.

Despite the differences in identifying drought events between SPI-6 and SPEI-6 due to different inputs and mathematical equations, both indices highlighted the following years: 1962, 1968, 1972, 1983, 1986, 1990, 1992–1993, 2000–2003, and 2007 as drastic periods (SPI-6 and SPEI-6 values of less than −1.28) in terms of Ag.D (Figure 4a,d).

The lowest recorded values of SPI-6 and SPEI-6 (i.e., the highest recorded levels of drought) in each county are presented in Figure 4c. For SPI-6, the lowest values were recorded in CS (−3.33), GY (−2.96), VA (−2.95), and TO (−2.8). Unexpectedly, the lowest values of SPEI-6 were recorded in central and southern counties. For instance, the lowest value of SPEI-6 was recorded in Csongrád-Csanád (CS) (−4.71), which is located in southern Hungary, followed by BU (−4.21) (central), then GY (−4.04) (western) (Figure 4c).

As depicted in Figure 4c, the SPEI-6 (red line) represents higher Ag.D values than the SPI-6 (blue line); this can mainly be explained by the fact that the SPEI-6 employs both evapotranspiration and rainfall for drought computation, whereas the SPI-6 depends only on the monthly changes in rainfall. Notably, the conjunction of evapotranspiration and rainfall inflated the drought values in the study area.

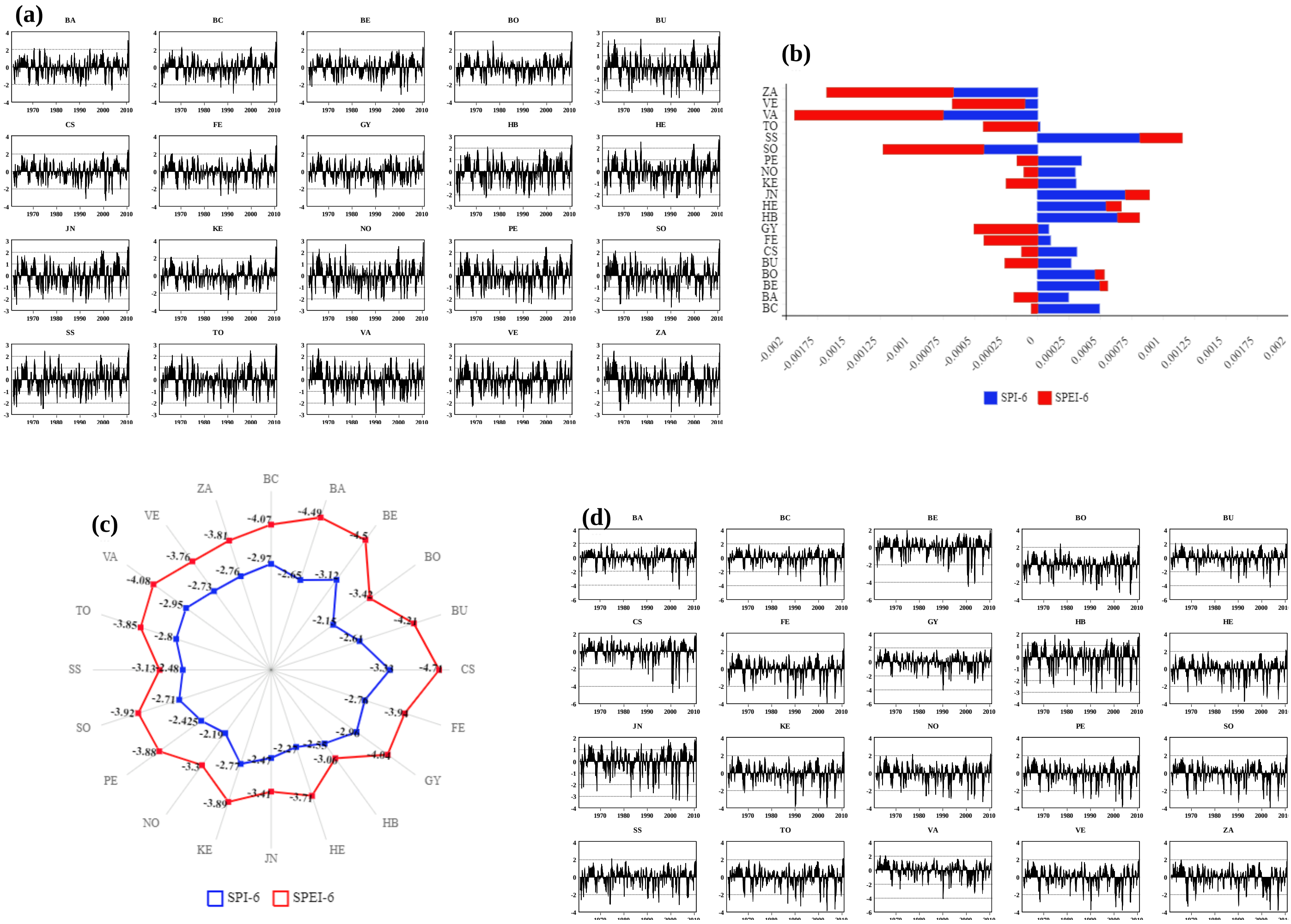



**Figure 4.** Ag.D evolution across Hungary (1960–2010): (**a**) Evolution of SPI-6 across Hungarian counties (1960–2010); (**b**) trends in SPI-6 and SPEI-6 based on MK tests and Sen slopes; (**c**) lowest recorded values of SPI-6 and SPEI-6 across Hungarian counties (1960–2010); (**d**) Evolution of SPEI-6 across Hungarian counties (1960–2010).

### *3.2. Sequence of Standardized Yield Residuals (SSYR)*

According to the MK tests and Sen slopes, sunflower yield (kg/ha) exhibited a positive trend across Hungarian counties between 2000 and 2019 (Table 5, Figure 5). The greatest increase in sunflower yield was observed in BO (+75.19 kg/ha, $p < 0.05$), followed by SS (+72.58 kg/ha, $p < 0.05$), then HB (+71.6 kg/ha, $p < 0.05$). Notably, these counties are located in eastern Hungary, and experienced positive but non-significant trends for both SPI-6 and SPEI-6 (Table 5, Figure 5).

Thus, to isolate the positive impact of human intervention which include, but are not limited to, the selection of new varieties, pest control, advance field irrigation technology, and precision agriculture, the sequence of standardized yield residuals (SSYRs) was applied.

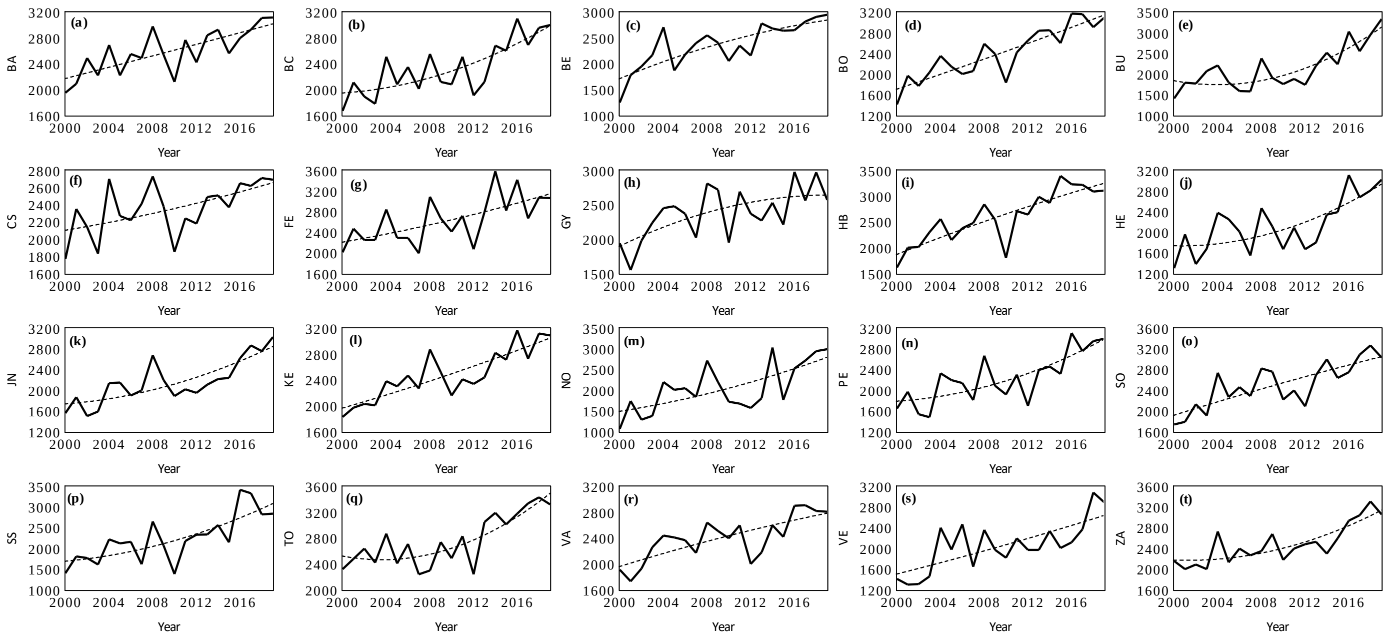


**Figure 5.** Sunflower yield in the studied Hungarian counties (2000–2019). (**a**) BA, (**b**) BC, (**c**) BE, (**d**) BO, (**e**) BU, (**f**) CS, (**g**) FE, (**h**) GY, (**i**) HB, (**j**) HE, (**k**) JN, (**l**) KE, (**m**) NO, (**n**) PE, (**o**) SO, (**p**) SS, (**q**) TO, (**r**) VA, (**s**) VE, (**t**) ZA.

The output of the SSYR analysis highlighted the yeEars 2000, 2010, and 2012 as the years most affected by Ag.D (SSYR ≤ −1) in terms of sunflower production, as shown in Figure 6. The lowest SSYR was recorded in HB (−3.2, extreme impact in 2010), followed by TO (−2.41, extreme impact in 2012), and VA (−2.34, extreme impact in 2010) (Figure 6).

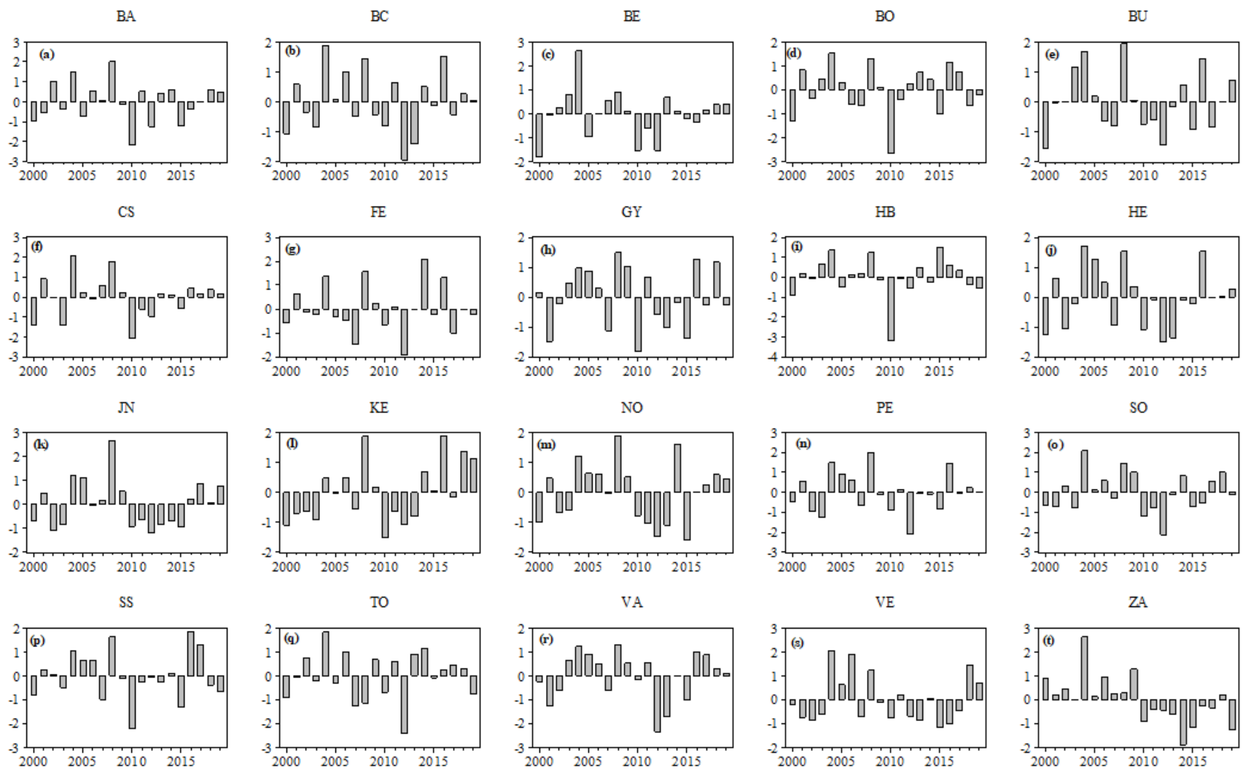
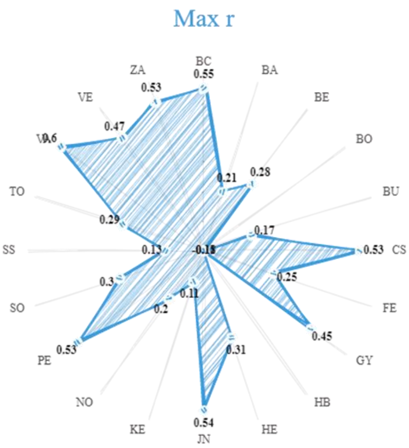


**Figure 6.** Evolution of *SSYR* in the studied Hungarian counties (2000–2019). (**a**) BA, (**b**) BC, (**c**) BE, (**d**) BO, (**e**) BU, (**f**) CS, (**g**) FE, (**h**) GY, (**i**) HB, (**j**) HE, (**k**) JN, (**l**) KE, (**m**) NO, (**n**) PE, (**o**) SO, (**p**) SS, (**q**) TO, (**r**) VA, (**s**) VE, (**t**) ZA.

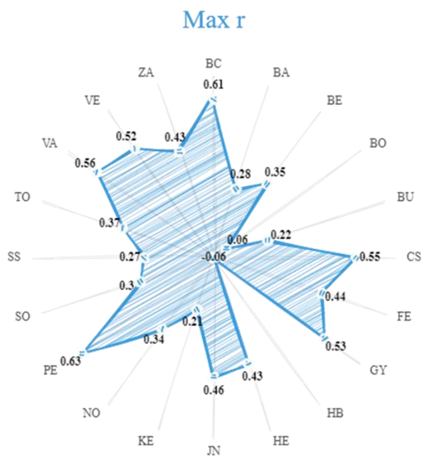
During the growing cycle (April–October), a high correlation between SSYR and Ag.D was observed, especially in summer seasons (Figures 7 and 8). For SPI-6, the highest correlation (Max. $r_{\text{SSYR vs. SPI-6}}$) was recorded in VA ($r_{\text{SSYR vs. SPI-6}}$ = 0.6, July, western Hungary) and BC ($r_{\text{SSYR vs. SPI-6}}$ = 0.55, August, central Hungary) (Figure 7). Similarly, central and western counties exhibited the highest $r$ values between SSYR and SPEI-6. For instance, the Max. $r_{\text{SSYR vs. SPEI-6}}$ was obtained in PE ($r_{\text{SSYR vs. SPEI-6}}$ = 0.63, July, central Hungary), BC ($r_{\text{SSYR vs. SPEI-6}}$ = 0.59, July, central Hungary), and VE ($r_{\text{SSYR vs. SPEI-6}}$ = 0.51, July, western Hungary) (Figure 8). However, both Ag.D indices indicate that drought cycles affected the sunflower yield during the summer months, where the western counties were classified as the most affected by drought.




| County | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BC | -0.14 | -0.16 | 0.07 | 0.09 | 0.15 | 0.47 | 0.54 | 0.55 | 0.43 | 0.34 | 0.43 | 0.03 |
| BA | 0.21 | -0.03 | -0.26 | -0.26 | -0.36 | -0.22 | -0.15 | -0.10 | -0.21 | -0.29 | -0.20 | -0.25 |
| BE | -0.42 | -0.33 | -0.36 | -0.51 | -0.36 | 0.04 | 0.04 | -0.04 | -0.02 | 0.15 | 0.28 | 0.14 |
| BO | -0.18 | -0.12 | -0.17 | -0.31 | -0.40 | -0.28 | -0.27 | -0.18 | -0.31 | -0.25 | -0.11 | -0.17 |
| BU | -0.27 | -0.14 | -0.09 | -0.28 | -0.28 | -0.03 | 0.08 | -0.04 | -0.09 | 0.06 | 0.17 | 0.05 |
| CS | 0.26 | 0.21 | 0.34 | 0.10 | 0.43 | 0.53 | 0.38 | 0.35 | 0.34 | 0.52 | 0.47 | 0.51 |
| FE | 0.06 | 0.20 | 0.25 | 0.18 | -0.11 | 0.10 | 0.19 | -0.01 | -0.11 | -0.16 | -0.03 | -0.19 |
| GY | 0.25 | 0.45 | 0.24 | -0.03 | -0.20 | 0.03 | 0.12 | 0.01 | -0.30 | -0.34 | -0.28 | -0.37 |
| HB | -0.27 | -0.37 | -0.39 | -0.50 | -0.55 | -0.36 | -0.33 | -0.30 | -0.39 | -0.30 | -0.18 | -0.36 |
| HE | 0.10 | 0.17 | 0.25 | 0.16 | 0.15 | 0.22 | 0.25 | 0.31 | 0.12 | 0.06 | 0.09 | -0.01 |
| JN | -0.33 | -0.41 | 0.03 | 0.17 | 0.16 | 0.28 | 0.38 | 0.54 | 0.41 | 0.22 | 0.10 | 0.09 |
| KE | 0.11 | -0.06 | 0.05 | -0.05 | -0.20 | 0.04 | 0.08 | 0.02 | -0.11 | -0.13 | -0.07 | -0.17 |
| NO | -0.19 | -0.09 | 0.06 | 0.03 | 0.04 | 0.20 | 0.11 | 0.11 | 0.03 | 0.02 | -0.03 | -0.11 |
| PE | -0.10 | -0.04 | 0.27 | 0.28 | 0.20 | 0.41 | 0.53 | 0.49 | 0.30 | 0.15 | 0.22 | 0.04 |
| SO | 0.30 | 0.22 | 0.07 | 0.18 | 0.00 | 0.16 | 0.19 | 0.07 | -0.22 | -0.29 | -0.26 | -0.40 |
| SS | -0.17 | -0.10 | -0.20 | -0.11 | -0.24 | -0.07 | -0.04 | 0.13 | -0.09 | -0.18 | -0.12 | -0.34 |
| TO | -0.04 | 0.20 | -0.09 | 0.17 | 0.22 | 0.29 | 0.26 | 0.20 | 0.08 | 0.00 | 0.06 | -0.22 |
| VA | 0.43 | 0.50 | 0.20 | 0.02 | 0.15 | 0.41 | 0.60 | 0.53 | 0.22 | 0.21 | 0.14 | -0.15 |
| VE | 0.47 | 0.33 | 0.41 | 0.40 | 0.22 | 0.37 | 0.41 | 0.29 | 0.02 | -0.11 | -0.14 | -0.44 |
| ZA | 0.03 | 0.22 | 0.39 | 0.53 | 0.25 | 0.10 | -0.24 | -0.30 | -0.78 | -0.54 | -0.35 | -0.01 |

| | | | | | | |
|---|---|---|---|---|---|---|
| -0.60 | -0.40 | -0.20 | 0.00 | 0.20 | 0.40 | 0.60 |

**Figure 7.** Correlation values between SSYR and SPI during the sunflower growing cycle (2000–2010) (**right** table), and max correlation (Max. r) between the SSYR and SPI (**left** figure).




| County | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BC | -0.06 | 0.04 | 0.13 | 0.15 | 0.24 | 0.56 | 0.61 | 0.59 | 0.53 | 0.45 | 0.47 | 0.12 |
| BA | 0.28 | 0.08 | -0.19 | -0.21 | -0.27 | -0.10 | -0.04 | 0.01 | -0.04 | -0.07 | -0.01 | -0.11 |
| BE | -0.24 | -0.18 | -0.27 | -0.44 | -0.25 | 0.15 | 0.01 | -0.06 | 0.01 | 0.26 | 0.35 | 0.29 |
| BO | -0.05 | 0.06 | -0.07 | -0.22 | -0.22 | -0.11 | -0.10 | -0.06 | -0.19 | -0.08 | 0.02 | -0.04 |
| BU | -0.12 | 0.13 | 0.03 | -0.11 | -0.13 | -0.04 | 0.03 | -0.10 | -0.13 | 0.15 | 0.22 | 0.07 |
| CS | 0.29 | 0.13 | 0.31 | 0.02 | 0.39 | 0.55 | 0.40 | 0.33 | 0.36 | 0.52 | 0.48 | 0.50 |
| FE | 0.22 | 0.44 | 0.31 | 0.31 | 0.01 | 0.19 | 0.29 | 0.10 | 0.02 | 0.00 | 0.09 | -0.12 |
| GY | 0.31 | 0.53 | 0.42 | 0.11 | -0.07 | 0.11 | 0.16 | 0.05 | -0.27 | -0.21 | -0.24 | -0.36 |
| HB | -0.16 | -0.18 | -0.28 | -0.37 | -0.39 | -0.23 | -0.23 | -0.24 | -0.26 | -0.14 | -0.06 | -0.22 |
| HE | 0.20 | 0.32 | 0.35 | 0.28 | 0.31 | 0.39 | 0.43 | 0.43 | 0.22 | 0.25 | 0.25 | -0.03 |
| JN | -0.03 | -0.03 | 0.18 | 0.03 | 0.18 | 0.38 | 0.46 | 0.45 | 0.35 | 0.34 | 0.41 | 0.31 |
| KE | 0.15 | 0.11 | 0.14 | 0.00 | -0.11 | 0.19 | 0.21 | 0.18 | 0.06 | 0.09 | 0.08 | -0.19 |
| NO | -0.10 | 0.04 | 0.14 | 0.06 | 0.17 | 0.34 | 0.24 | 0.26 | 0.18 | 0.23 | 0.14 | -0.12 |
| PE | -0.01 | 0.14 | 0.33 | 0.31 | 0.33 | 0.54 | 0.63 | 0.57 | 0.45 | 0.30 | 0.31 | 0.03 |
| SO | 0.30 | 0.22 | 0.07 | 0.18 | 0.00 | 0.16 | 0.19 | 0.07 | -0.22 | -0.29 | -0.26 | -0.40 |
| SS | -0.03 | 0.12 | -0.08 | 0.00 | -0.07 | 0.12 | 0.15 | 0.27 | 0.09 | 0.00 | 0.00 | -0.28 |
| TO | 0.04 | 0.33 | 0.01 | 0.27 | 0.33 | 0.37 | 0.35 | 0.22 | 0.11 | 0.11 | 0.13 | -0.24 |
| VA | 0.48 | 0.56 | 0.46 | 0.18 | 0.29 | 0.40 | 0.50 | 0.42 | 0.15 | 0.32 | 0.14 | -0.16 |
| VE | 0.45 | 0.39 | 0.52 | 0.49 | 0.34 | 0.46 | 0.51 | 0.40 | 0.18 | 0.05 | -0.02 | -0.50 |
| ZA | 0.19 | 0.24 | 0.36 | 0.43 | 0.29 | 0.25 | 0.24 | 0.08 | -0.19 | -0.31 | -0.40 | -0.51 |

| | | | | | | |
|---|---|---|---|---|---|---|
| -0.60 | -0.40 | -0.20 | 0.00 | 0.20 | 0.40 | 0.60 |

**Figure 8.** Correlation values between the SSYR and SPEI during the sunflower growing cycle (2000–2010) (**right** table), and max correlation (Max. r) between the SSYR and SPEI (**left** figure).

### 3.3. Yield Losses $Y_{loss\ Ag.D}$

Between 2000 and 2010, the loss of sunflower yield was distinguished in two different years, as depicted in Figure 9. In 2004, the highest $Y_{loss\ Ag.D}$ was recorded in VE ($Y_{loss\ Ag.D} = -38.32\%$, western Hungary), followed by HE ($Y_{loss\ Ag.D} = -33.95\%$, eastern Hungary) and then BE ($Y_{loss\ Ag.D} = -32.89\%$, central Hungary) (Figure 9). However, in 2008, all counties across Hungary experienced yield losses, where the highest losses were observed in NO ($Y_{loss\ Ag.D}$ = −42.03%, northern Hungary), JN ($Y_{loss\ Ag.D}$ = −33.49%, central Hungary), and SS ($Y_{loss\ Ag.D}$ = −29.37%, eastern Hungary).

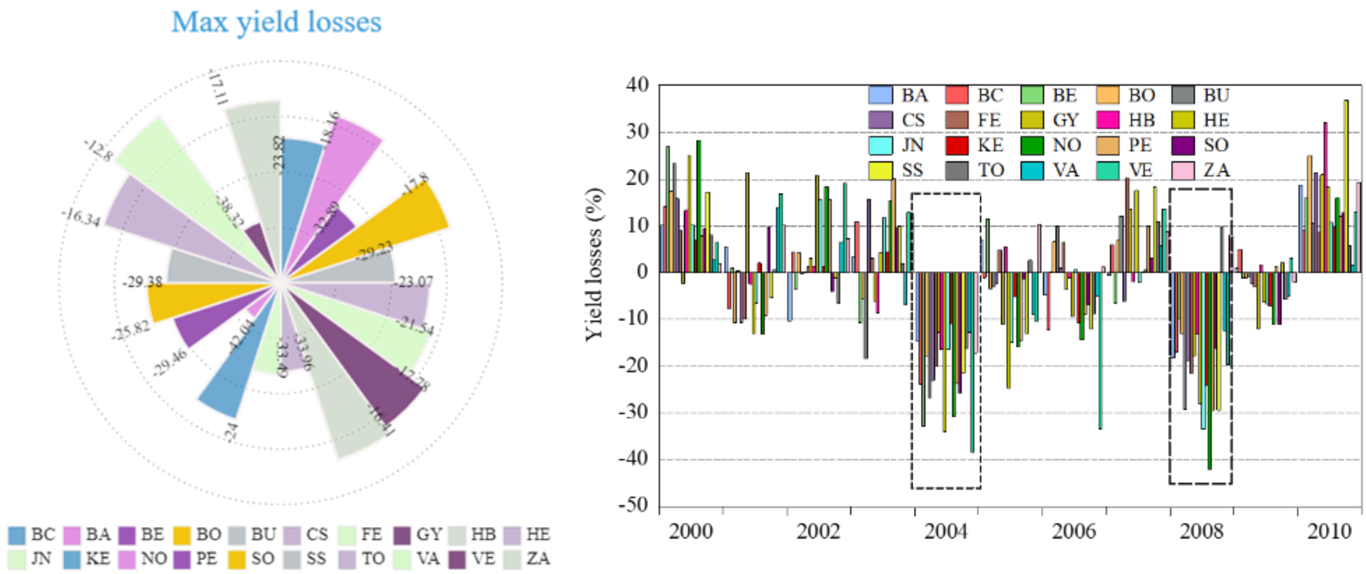



**Figure 9.** Sunflower resilience to Ag.D (SRAg.D) (**right**), and max yield losses (**left**).

By calculating the SRAg.D, the resistance of sunflower crops to drought events could be distinguished across Hungarian counties (Figure 10). The results showed that the crop yields in central and western regions were more prone to loss due to drought events. The SRAg.D value reached 0.74 (severely non-SRAg.D) in HE, and 0.79 (also severely non-SRAg.D) in PE. In contrast, the highest value was recorded in eastern Hungary (BE; 1.11).

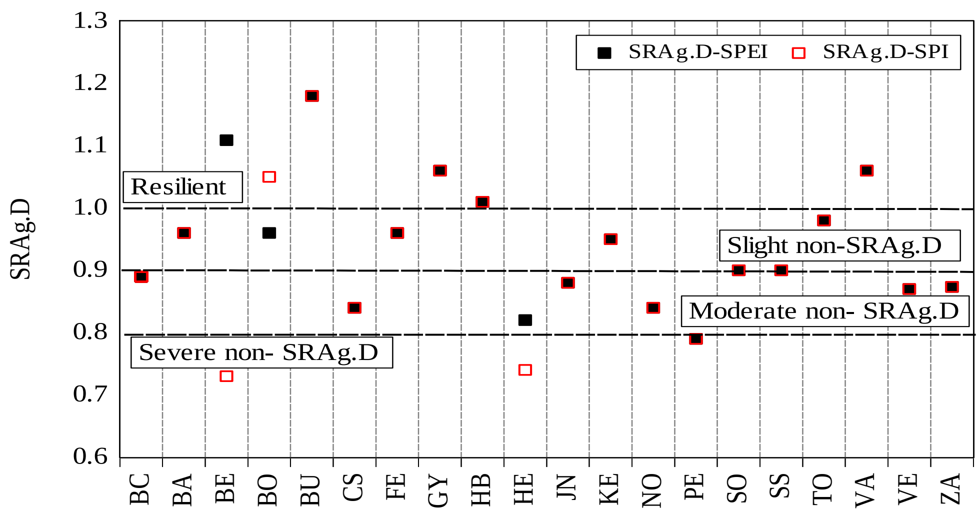



**Figure 10.** Resilience of sunflower production to Ag.D across Hungarian counties (2000–2010).

## 4. Discussion

In the last few decades, drought cycles have become more intense and frequent all over the world due to rapid climate change [9,68–70]; for instance, in Brazil [71], Syria [63], Hungary [52], China [72], and southern Europe [73]. Subsequently, many industries have been affected either directly or indirectly, such as the agricultural sector [74–79], hydrology [80–83], the economy [76,84], human health [85–87], and tourism [88–90]. In this sense, our research shows a negative trend in agricultural drought episodes across Hungarian counties (Figure 4; Table 5). Additionally, the results emphasize the direct impact of Ag.D on sunflower production (Figure 6), where the yield losses reached 40% in some counties (Figure 9).

Many studies have been carried out across Europe for monitoring and assessing drought evolution, identifying a positive trend, especially in southern and central regions [73,91–93]. Hungary, which is in the center of the Pannonian basin (central Europe), suffers from drought episodes. For instance, Alsafadi et al. [52] reported an increase in drought trends in western Hungary comparing with the east; however, drought frequency was more intense in central Hungary. Mohammed et al. [49] indicated a positive strong correlation between Ag.D (SPI-3, SPI-6) and NDVI (Normalized Difference Vegetation Index). However, future climate projections indicate an increase in drought cycles due to changing future rainfall patterns (2071–2100) [45]. At the regional scale (county scale), drought evolution has been more intense in central and western Hungary than the east. Similar results were reported by Szabó et al. [94], where western Hungary was identified as being more susceptible to climate change. This issue could be explained by the fact that the central region receives less rainfall than other areas [52]; thus, the SPI and SPEI values are decreased, which directly lead to the evolution of drought. In this case, soil moisture will be decreased, and less water will be available for use on agricultural crops (i.e., sunflowers), which will lead to water stress and yield losses (Figures 6, 9 and 10) due to the inhibition of physiological functioning in some crops [69]. Interestingly, this phenomenon could affect all crops, especially maize, which is very sensitive [79]. In this sense, Adrienn and Janos [95] reported that agricultural drought is the main constraint for crop production across Hungary.

Both SPI and SPEI have drawbacks, which generates some uncertainty in the results. For SPI, using only monthly rainfall data without considering their temporal distribution could affect the interpretation of results, along with failure in predicting the exact times of the drought evolution cycle (i.e., start and end) [34,96]. For SPEI, heat waves can be misinterpreted as droughts in some areas [97]. Additionally, calculating evapotranspiration based only on temperature is not sufficient [98]. However, both indices are widely used all over the world, and their outputs can be used for monitoring drought [72,99–101].

The interaction between crop yield and drought indices during the growing cycle (April–October) could be linked to increasing crop evapotranspiration (crop-ET0) and temperature. In this sense, Stagge et al. [73] reported an increase in crop-ET0 and temperature. However, the resistance of sunflower to drought was tracked across Hungarian counties. The results also showed that crop yield in central and eastern Hungary was less resilient to drought, where the SRAg.D value reached 0.74 (severely non-SRAg.D) in Heves and 0.79 (severely non-SRAg.D) in Pest. However, the highest value was recorded in eastern Hungary (Bekes, 1.11). In fact, climate change has affected crop production for both irrigated and rainfed agricultural systems, where drought has significantly reduced crop yield [79,102,103]. Globally, temperature and rainfall directly influence crop production, where they behave nonlinearly [103–106]. Thus, any changes in these climate variables or even the interaction between them will affect agricultural production, not only for sunflowers, but for all crop types. Shortage of rainfall is linked to abnormal atmospheric circulation (at high pressure) that prevents clouds and precipitation from forming [68,107], or a change in the rain belt [68]. However, less cloud and precipitation lead to drier conditions, increased temperature, decreased humidity, and increased evapotranspiration demand, which amplify drought conditions [68]. Scientifically, drought causes a shortage in soil water content and leads to a water deficit which directly affects crop yields [65,79,108]. Unfortunately, most agricultural land across Hungary is cultivated as a rainfed agricultural system; thus, climate change (precipitation patterns), and especially drought, will negatively affect the agricultural sector and crop production [49].

There were some limitations to this study, such as drought trends being assessed based on the average of gridded point data that represent each county, instead of using the whole gridded points. Additionally, only 10 years were available as a record of sunflower yield across Hungarian counties, which used to calculate the direct impact of Ag.D on sunflower yields; more years would have been better for interpreting the relationship between drought and crop production. On the other hand, both SPI and SPEI have their own limitations in identifying drought cycles. In this context, for calculating drought by using SPI, we only need monthly rainfall data; other climate variables are neglected, which could affect the credibility of the SPI [52]. Even though SPEI involves more climate variables (rainfall and potential evapotranspiration (PET)), and is based on the Thorn Thwaite equation, other climate variables are not considered [52]. However, the output from our analysis is enough to draw the attention of decision makers to the evolution of drought and climate change in central Europe.

## 5. Conclusions

Drought is a multifaceted and complicated natural hazard, which slowly evolves in the ecosystem and is affected by a multitude of physical and biological factors. Hungary, which is located in central Europe (Pannonian basin), frequently suffers from drought events and climate change. However, little research has been conducted in Hungary to assess the impacts of climate change on crop production, especially on a regional scale. In this context, this study was designed to track the evolution of agricultural drought (SPI-6, SPEI-6) across Hungary (1960–2010), and to investigate the dynamic interactions between sunflower yield and drought cycles. The results showed that agricultural drought episodes were more intense in western and central Hungary (i.e., ZA, VE, VA, and GY) compared with the eastern region of the country. Nonetheless, the Ag.D cycles had become more frequent since 1990, where more negative values of Ag.D were recorded.

Sunflower production was badly affected by agricultural drought in 2000, 2010, and 2012, where SSYR $\leq -1$. The lowest SSYR values were recorded in HB ($-3.2$, extreme impact in 2010), followed by TO ($-2.41$, extreme impact in 2012), and VA ($-2.34$, extreme impact in 2010). Notably, yield losses (Yloss Ag.D) were experienced in all Hungarian counties in 2004 and 2008 due to agricultural drought. The results also reveal that crop yield in central and western Hungary were more prone to yield loss due to drought events.

The outputs of this study will be of great interest to stakeholders and decision makers for formulating climate mitigation and adaptation plans for the agricultural sector in Hungary. However, more research to develop new varieties of sunflowers, which are tolerant to drought and other extreme climate events, is highly recommended. In our future research, we will involve other drought indices such as the Crop Moisture Index and Crop Specific Drought Index to highlight the impacts of drought on sunflowers and other strategic crops in Hungary.

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