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Climate change in the Debrecen area in the last 50 years and its impact on maize production

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Abstract— The average yield of maize is significantly dependent on the meteorological conditions of the growing year. Both the most favorable weather conditions and the weather anomalies that tend to cause damage depend on the given phenophase. The aim of this research is to analyze the climatic changes that are important in maize production in the Hajdúság region.

For the climatological study of the area, homogenized temperature and precipitation data from the Hungarian Meteorological Service was used for the Debrecen region, which are freely available for download from the data repository of the institution. Trend analysis was performed for the last 50-year (1973–2022) and 30-year (1993–2022) periods. In total, 40 meteorological data series matching the study objective were analyzed. Linear regression calculations were performed using the SPSS 27 statistical software. For the non-parametric procedure, the MAKESENS Excel application was used, based on the Mann-Kendall (MK) test and Sen's slope estimation.

This research shows that the choice of the length of the study period affects the results of trend analysis. The numerical values of the trend slope for the 30-year vs. 50-year period differ, and for some parameters there are also substantial differences (e.g., trend sign). The results of the parametric and non-parametric trend analyses differed only marginally for the temperature variables included. Also, for precipitation data that do not follow a normal distribution (e.g., monthly), there were only a few significant differences. The trend in mean annual temperature shows an increase of 0.39 and 0.52 °C in 10 years, and an increase of around 2 °C in 50 years and 1.5 °C in 30 years. There is a significant warming in both the summer and winter half-years, with the summer half-year showing a steeper upward trend in the 50-year data series and the winter half-year in the 30-year data series. There is a clear pattern of large, highly significant warming in the summer months and less significant changes in the two spring and two autumn months that were observed. A negative, non-significant trend in annual precipitation is observed. The decreases of 17 mm and 24 mm/10 years obtained for the 50- and 30-year time series are not negligible from a practical point of view. For the summer half-year, the precipitation amount is decreasing, with a slope of -27 mm/10 years for the last 30 years, but even this value is not significant due to the high variability. There is no significant change in the amount of precipitation in the winter half-year over the last decades. Significant trends cannot be detected from monthly or even semi-annual or annual precipitation data. The Mann-Kendall test showed a trend decrease only in the 30-year April data series at the p=0.1 significance level. Overall, the changes are negative for maize production. It should be highlighted that the obvious warming, combined with a slight decrease in precipitation, is leading to a deterioration in crop water availability and a reduction in crop yields. The impact of the identified adverse climatic changes can be compensated to a significant extent by the proposed agrotechnical responses.

Key-words: temperature, precipitation, trend, Mann-Kendall test, linear regression, maize production

1. Introduction

Climate change has been one of the most important global environmental challenges of recent decades, with significant environmental, economic, and social impacts in complex ways. The exposure of crop production is obvious, but its extent varies depending on the climatic, soil, and hydrological conditions of the region and the crop species.

Maize is known to be a heat- and water-intensive crop. In Hungary, rainfall is the most important meteorological factor determining crop yields. In 2021, and especially in 2022, very severe drought affected most of the country, including the Debrecen area (*Gombos* and *Nagy,* 2022, 2023). Data from a maize yield experiment in Debrecen show a strong positive correlation between the amount of rainfall during the growing season and the average yield (*Nagy,* 2012). According to *Márton* (2004), the relationship is not linear, the optimal amount of rainfall depends on the nutrient supply, and in the wettest years yield depression may occur. According to *Szalóki* (1989), the total water requirement of maize is 420–550 mm measured with lysimeter. The water requirement of the crop is significantly higher than the average rainfall of the growing season, with 100–150 mm in the main production areas, and in some places with 200 mm, with only a smaller water deficit (40–80 mm) in the southwestern part of the Transdanubian region (*Nagy,* 2007). The yield security of maize is improved if the deeper layers of the soil are saturated with water in the preceding winter half-year. This effect has been statistically demonstrated in some production areas (*Nagy*, 2012).

Adequate soil moisture is required for germination and initial development, but the water consumption of the plant is not yet significant. Heavy rainfalls in March and April hamper soil preparation and sowing. This can lead to a delay in sowing, especially on compacted soils. Even during the period of intensive vegetative development, maize is not very sensitive to precipitation deficits (*Cheng et al.*, 2021, *Széles et al.*, 2019). This is indicated by the fact that very dry (essentially rainless) weather in June did not in itself reduce the average yield below the average (*Gombos* and *Nagy*, 2019), however, using machine learning methods to study maize yield and its determinants, it was found that May precipitation is one of the most influential parameters (*Nyéki et al.*, 2021).

Precipitation in July and August is particularly important, as the plant's water requirements are greatest during silking, grain setting, and early crop development (*Antal et al.*, 1992). Other studies have also found these phenophases to be essentially the most sensitive to water deficit, with only minor differences in the delimitation of the period (*Westgate* and *Boyer*, 1986; *Smith et al.*, 2004; *Nielsen et al.*, 2010). Thereafter, the water need of maize gradually decreases. Precipitation after physiological maturation has an adverse effect. In September-October, dry, moderately warm weather is optimal, because it accelerates grain dehydration and drying and, consequently, does not hinder harvesting.

Several studies have demonstrated the yield reducing effects of high temperatures (*Schlenker* and *Roberts*, 2009; *Lobell et al.*, 2013; *Ben-Ari et al.*, 2016; *Carter et al.*, 2016), a phenomenon that is becoming increasingly common in Hungary. Maize is most sensitive to heat stress during the reproductive phenophase, especially during silking The viability of pollen is impaired by temperatures above 35 °C, which is further exacerbated when coupled with low humidity (*Fonseca* and *Westgate*, 2005). A french research has shown that the number of days with maximum temperatures above 32 °C explains the interannual variability of the average yield to a degree essentially equal to that of precipitation (*Hawkins et al.,* 2013). Studies by *Schlenker* and *Roberts* (2009) showed a negative effect of temperatures above 29 °C on US county-level yield averages.

Low temperatures do not usually cause irreversible damage. Frost damage is rare if sowing is timed correctly. Major damage to maize occurs only at -2 to -3 °C (*Dhillon et al.*, 1988). At the beginning of the growing season, it is not uncommon for temperatures to be below or just above the base temperature of maize. At this time, plant development is arrested or very slow. Low mean temperatures in April and May result in a prolongation of the phenophases and ultimately the ripening period (this may be partially compensated by later warm weather). Harvesting is either done at higher grain moisture (high drying costs) or later, when the risk of adverse weather is significantly higher, making the harvesting workflow more difficult and increasing harvest losses.

The global average temperature shows a clear and increasing trend. The most recent 10-year period of 2013–2022 shows an average surface temperature 1.15 °C above the average for the period 1851–1900, with a warming rate of

1.65 °C for land (IPCC, 2023). The global average (land) precipitation has shown a weak upward trend over the 20th century, with large inter-decadal variability. The trend has not been significantly decreasing since 1950 (IPCC, 2007). However, the pattern of changes in precipitation patterns shows a high degree of geographical variability. Some areas have become drier than in the past (Southern Europe, Soutwest USA, Sahel, South Africa), while other areas have shown an increasing trend in precipitation (most of the USA, Northern Europe, Northern Asia, Central Asia) (IPCC, 2007; EEA, 2014; USGCRP, 2017).

The change in the national mean temperature in Hungary over the 120-year period 1901–2020 is 1.2 °C, while over the period 1981–2020 it is 1.7 °C. There has been significant warming in all seasons, with the largest increase in the summer temperatures (OMSZ, 2019a). The spring precipitation is the one that shows a clear change, with a 17% decrease. There are differences in the trend of the annual amount between the different parts of the country. There is a decrease in the western part of the country and a slight increase in most of the Great Hungarian Plain. For the period 1981–2020, an upward trend in annual precipitation can already be observed on a national average (OMSZ, 2019b).

Several studies have been carried out to investigate the climatic changes that have taken place in some municipalities and smaller regions of the country. In Keszthely, the trend of annual precipitation decrease in the period 1871–2014 is not significant (*Kocsis* and *Anda*, 2017). Precipitation decrease trends in the spring (-32 mm/100 year), April (-14 mm/100 year), and October (-24 mm/100 year) were found to be significant. *Füzi* and *Ladányi* (2020) investigated various parameters related to frost in the Sopron region (NW-Hungary). All trends show decreasing number of days with different frost level and increasing duration of frost free periods. These results are in agreement with the general warming tendencies. Another study of *Füzi* and *Ladányi* (2022) dealing with various temperature and precipitation indicators describes an increasing frequency of extreme weather events (especially which are related to heat stress) in the Moson Plain.

The main meteorological features of the period 1901–2010 in Debrecen are summarized by *Juhász et al.* (2018). The analysis of the 110-year trends includes, in addition to the classical annual and seasonal mean temperature and precipitation totals, a number of indicators derived from daily data.

The aim of this research is to analyze the climatic changes that have occurred in one of the most important regions, the Hajdúság maize production region in Hungary, which has excellent soil conditions for this crop. The authors consider it important to include data from the most recent years in the trend analysis, and the processed data series should be sufficiently long.

2. Material and methods

2.1. Study area and data

The majority of the Hajdúság, one of the main maize growing areas in Hungary, is located in Hajdú-Bihar county (Hungary), geographically comprising the Hajdúhát and the southern pasrt of Hajdúság. The dominant soil type of the area is loess chernozem with lime deposits, which is a lowland calcareous loess soil with excellent fertility and water management. The area was climatologically analyzed using homogenized temperature and precipitation data from Debrecen, provided by the Hungarian Meteorological Service. The daily resolution database for the period 1901–2020 is freely available for download on the website of the organization (Meteorological Data Repository, OMSZ):

- daily amount of precipitation,
- daily minimum temperature,
- daily maximum temperature,
- daily mean temperature.

The post-1973 part of the series was included in the analysis, supplemented with data for the years 2021–2022. During this period, measurements were taken at the airport located south of the city (47°30' N, 21°38' E, 107 above sea level) (*Fig. 1*).

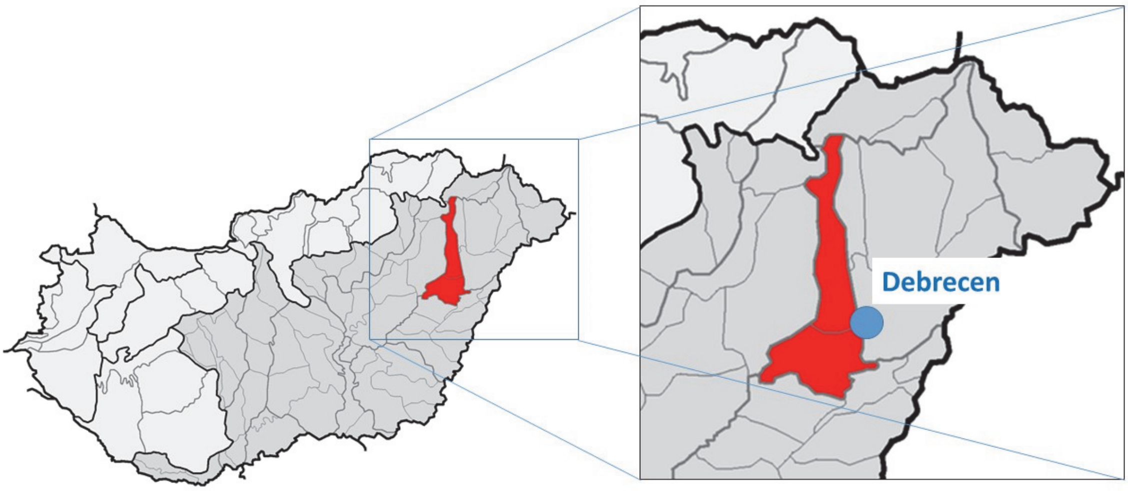

Fig. 1. Geographical position of the study area (Hajdúság area (red), Debrecen-Airport meteorological station)

At the Debrecen-Airport station, the mean annual temperature is 11.0 °C and the mean annual precipitation is 543 mm averaged over the period 1991–2020.

The coldest month is January (-0.8 °C), the warmest is July (21.9 °C). The lowest precipitation is in January-March, the highest in May-July (24 mm in January, 68 mm in July) (*Table 1*).

Table 1. Average monthly temperature and precipitation in Debrecen (1991-2020)

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
T (°C)	-0.8	0.9	5.8	11.9	16.8	20.3	21.9	21.8	16.5	11.0	5.6	0.5
P (mm)	24	32	30	45	59	67	68	46	47	41	41	42

The quality of the database used is fully in line with the research objectives. The data series are homogenized to the current situation, and inhomogeneities due to changes in measurement conditions have been filtered out. In Debrecen, there have been only minor changes in the environment of the measurement site during the 50-year period under study, with one relocation of the station within the airport in 1995. However, the measurement technology changed in 2000 with the automation of the station. The traditional mercury station and maximum and minimum alcohol thermometers have been replaced by a platinum Pt100 resistance thermometer which continuously measures the temperature. A prerequisite for reliable change detection is the use of controlled, homogenized data series. Trend analyses based on raw, non-homogenized data are often misleading and may erroneously detect changes that are the opposite of real changes (*Izsák* and *Szentimrey,* 2020).

2.2. Methods

Trend analysis was used to investigate the climate changes in Debrecen over the past decades until today. Analyses were performed for the last 50-year period (1973–2022) and the last 30-year period (1993–2022). These are long enough periods to identify trends, but do not go back to years irrelevant to current crop production skills. On the basis of the international literature and the authors' own previous research results, the meteorological parameters of importance for maize production were identified and trend analysis was performed on them:

- monthly mean temperatures (April, May, June, July, August, September, October),
- monthly averages of daily minimum temperatures (April, May, June, July, August, September, October),
- monthly averages of daily maximum temperatures (April, May, June, July, August, September, October),

- mean temperatures for winter and summer half-year,
- average daily minimum temperatures in the winter and summer half-year,
- average daily maximum temperatures in the winter and summer half-year,
- annual mean temperature,
- annual average daily minimum temperatures,
- annual average daily maximum temperatures,
- monthly rainfall totals (April, May, June, July, August, September, October),
- total precipitation for the winter half-year (October-March),
- rainfall totals for the summer half-year (April-September),
- annual rainfall amount.

2.3. Trend analysis

Both parametric and non-parametric methods are available for time series trend analysis.

The usual parametric tests require normality and independence of the data. For the non-parametric tests, normality is not a prerequisite, i.e., for many meteorological data sets (e.g., precipitation data or various derived parameters are usually included), the use of the latter is justified. Other arguments in favor of non-parametric methods are that they are less sensitive to outliers and can be applied to both linear and non-linear trends.

The non-parametric Mann-Kendall (rank-based) statistical test (*Mann*, 1945; *Kendall*, 1975) has been widely used in trend analysis of meteorological time series, both for precipitation and temperature (*Wang et al.,* 2013; *Khalili et al.,* 2016; *Skowera et al.,* 2016; *Krebs et al,.* 2021; *Makungo* and *Mashinye*, 2022; *Kubiak-Wójcicka et al.,* 2023). The only prerequisite for this robust method is the independence of data. The associated Sen's slope estimator calculates the slope value (m_{ij}) for each pair of data, and the median of these gives the estimate of the slope (Q) of the linear trend:

$$m_{ij} = (Y - Y_{ji})/(j-i), \quad (1)$$

$$Q = \text{median}\,(m)_{ij}, \quad (2)$$

where Y_j and Y_i are the values of the meteorological variables at time $t=j$ and $t=i$ ($j>i$), respectively, and i=1, ..., n-1, j=2, ..., n, n is the number of elements in the sample.

The use of linear regression analysis on climate time series is also common in studying trends in terms of temperature and precipitation (*Kocsis* and *Anda*, 2017; *Juhász et al.*, 2018; *Humphries et al.,* 2018; *Karimi et al.,* 2021; *Barna et* *al.,* 2022). There are several studies where, in addition to linear regression analysis, non-parametric methods are used to investigate climate trends (*Kocsis* and *Anda*, 2018). The equation of the linear regression model is

$$Y = a + b\text{-}X\,, \tag{3}$$

where Y is the dependent variable (e.g., temperature), X is the independent variable (for time series, time, e.g., year), b is the slope of the trend line (e.g., °C/year), and a is the intercept (trend value at time "0").

The coefficients, i.e., the fit of the line, are determined using the least-squares method, which provides the sensitivity of the model to outliers. A positive m value indicates an increasing trend and a negative m value indicates a decreasing trend.

As a first step of data processing, an Excel spreadsheet was used to produce the monthly, semi-annual, and annual data series for the period 1973–2022 based on the daily resolution database.

This was followed by a normality test using the SPSS 27 statistical software. For testing normality, the Shapiro-Wilk test was chosen, which is the most recommended and widely used method for small (n<50) samples (*Razali* and *Wah*, 2011; *King* and *Eckersley*, 2019).

Regardless of normality, both parametric and non-parametric trend analyses were performed for each data series. The results were interpreted taking into account the results of the SW test, and if normality was met, the comparison of the two trends provided additional information.

Linear regression calculations with significance testing based on the related two-sided t-test method were also performed using the SPSS 27 statistical software. For the non-parametric procedure, the Excel macro MAKESENS (FMI) developed by the Finnish Meteorological Institute was used. The application determines the significance and slope of the trend based on the Mann-Kendall (MK) test and Sen's slope estimation (*Salmi et al*., 2002). The slope, as the change in trend value per unit time, is presented in units of °C/10 years for temperature values and mm/10 years for precipitation data for ease of interpretation. MAKESENS tests for four levels of significance using the Z-test statistic (α: 0.1, 0.05, 0.01, and 0.001, with two-sided tests). When the aforementioned significance levels are detected, the time series is likely to exhibit a monotonic increasing trend (Z sign positive) or decreasing trend (Z sign negative). Even with α=0.1, there is only a 10% probability of error by rejecting H0 (no trend) (*Salmi et al,* 2002).

2.4. Examination of yields

The performed average yield analyses were based on the results of the maize yield trials conducted at the Debrecen-Látókép experiment site over a 32-year period from 1991 to 2022. The yield averages of the treatments most representative of farm conditions were included in the analysis.

Trend analysis was performed using the same non-parametric method applied to meteorological data (MAKESENS, *Salmi et al*., 2002). The monthly temperature and precipitation patterns for the 8–8 years falling in the lower and upper quartile were then analyzed based on the yield averages. The comparison of the averages gave an overview of the importance of each monthly meteorological parameter in the evolution of the yield average. A more detailed quantitative analysis of the relationship between the average yield and the weather conditions was not the subject of this research.

3. Results

The normality test on the 50-year data series yielded results in line with the authors' expectations. The normal distribution of the temperature parameters is confirmed in almost all cases by the Shapira-Wilk test with $p > 0.05$ (the only exception is the minimum temperature in October). The monthly precipitation data are not normally distributed, but for longer periods (annual, semi-annual), the test showed normality. Independence is met for all sample elements. Therefore, the performed parametric trend test is relevant for most of the meteorological parameters under study, but should be treated with reservations for monthly precipitation. Non-parametric trend tests do not require a normal distribution, but their use is appropriate in such cases, as they are not sensitive to outliers. In evaluating the changes, the authors relied primarily on the results of the Mann-Kendall test and Sen's slope estimator, which was complemented and compared with the information provided by the parametric method.

3.1. Temperature trends

3.1.1. Monthly temperature

In the period 1973–2022, the monthly mean temperature, the monthly mean of the maximum values, and the monthly mean of the minimum values show an increasing trend in all months considered (*Table 2*). In May and September, the changes are not significant, and the increase is typically only 0.1–0.2 °C/10 years. In April, maximum values increased the most and minimum values the least, and the trend of the mean increase was also close to 0.5 °C/10 years. In the summer months, an upward trend was confirmed for all parameters at the p=0.001 significance level. Maximum temperatures increased most, with a 10-year increase of 0.95 °C in August, and slightly less in June and July (0.78 °C and 0.75 °C, respectively). This is also the order of the months for mean temperatures. The 10-year increases in trend values are 0.73 °C in August, 0.65 °C in June, and 0.56 °C in July. The positive trend for minimum values is 0.5–0.6 °C/10 years for all three summer months. The warming observed in October is smaller (0.2–0.3 °C/10 years) and shows significance only for the average minimum and maximum values.

Table 2. Trend parameters for monthly temperature data, calculated by non-parametric (Mann-Kendall test and Sen's estimator) and parametric (linear regression) methods. Significance levels are *** : p<0.001, **: p<0.01, *: p<0.05, $^{+}$: p<0.1.

Indicator	Month	1973–2022 (50 years) Trend (°C/10 years)^{significance}		1993–2022 (30 years) Trend (°C/10 years)^{significance}	
		MK + Sen's slope	LR	MK + Sen's slope	LR
Average temperature	April	0.46**	0.40***	0.30	0.19
	May	0.11	0.17	-0.44	-0.40
	June	0.65***	0.66***	0.81***	0.80***
	July	0.56***	0.57***	0.63^{+}	0.58***
	August	0.73***	0.68***	0.82*	0.78***
	September	0.14	0.15	0.66^{+}	0.63^{+}
	October	0.20	0.19	0.20	0.23
Minimum temperature	April	0.35*	0.26	0.07	-0.03
	May	0.10	0.13	-0.34	-0.27
	June	0.59***	0.55***	0.73***	0.78***
	July	0.50***	0.51***	0.48^{+}	0.52***
	August	0.55***	0.54***	0.58**	0.61***
	September	0.22	0.19	0.55	0.36
	October	0.26^{+}	0.23	0.20	0.20
Maximum temperature	April	0.74***	0.69***	0.74	0.63
	May	0.28	0.34^{+}	-0.26	-0.25
	June	0.78***	0.79***	0.96**	0.97***
	July	0.75***	0.78***	0.86*	0.77***
	August	0.95***	0.89***	1.00**	1.01***
	September	0.18	0.22	1.07^{+}	0.96^{+}
	October	0.31^{+}	0.35	0.39	0.39

Looking at the 30-year period of 1993–2022, there is a significant difference in May, September, and part of April compared to the previous period. Instead of a slight warming over the 50-year period, the mean temperature in May has decreased by 0.44 °C/10 years (slightly less for the minimum and maximum values) over the last 30 years. Although the change is not significant, it is noteworthy, because this is the only month with a negative temperature trend, and it is also an important month for maize production. In September, instead of the 50-year non-significant positive trend in mean temperature, significant warming (0.66 °C/10 years) is already observed at the p=0.1 level over the last 30 years. The increase in September maximum values is the largest (1.07 °C/10 years). The April mean temperature still shows an upward trend, but it is smaller and no longer significant. The variation in maximum and minimum temperatures is very different. While maximum values show an increasing trend of 0.74 °C/10 years (although not significant), the April mean minimum temperatures show essentially no trend change. For the summer months, the temperature trend over the last 30 years shows a larger 10-year change than over the 50-year period (there was no intense warming in the 70s and 80s). In particular, June and August have seen an increase in temperature, with mean temperatures rising by 0.81 and 0.82 °C/10 years, monthly average minimum values by 0.73 and 0.58 °C/10 years, and maximum values by 0.96 and 1.00°C/10 years.

The trend values obtained by linear regression with least squares fitting for the 50-year data series are in good agreement with the results of the non-parametric trend analysis. In all cases the differences are below 0.1 °C/10 years, but mostly below 0.05 °C/10 years, which is negligible from a practical point of view. For the April minimum values and the October minimum and maximum values, only the MK test showed significance (p=0.05 and p=0.1, respectively). For the May maximum values, the trend was confirmed as significant by the parametric procedure (p=0.1), but not by the MK test. For the 30-year data series, there were differences in the strength of significance. In particular, the significance level of the July and August trends was found to be weaker by the MK test, but there was no significant difference in the magnitude of the increase (< 0.1 °C/10 years).

3.1.2. Annual and semi-annual temperature

The 10-year increase in the annual mean temperature trend over the period 1973–2022 is 0.39 °C. Similar warming (0.41 °C) was observed in the summer half-year, and a slightly smaller warming (0.29 °C) in the winter half-year. The average of the minimum temperatures showed a nearly equal increase on all three time scales (0.33-0.36 °C/10 years). The maximum temperature showed larger warming, with a 10-year trend increase of 0.40 °C in the winter half-year, 0.61 °C in the summer half-year, and 0.52 °C per year (*Table 3*).

The trends over the last 30 years show a more intense warming than that observed in the period 1973–2022, with the exception of the mean summer half-year temperature and the averages of the minimum values. The annual mean temperature is increasing at a rate of 0.52 °C/10 years. The winter half-year mean temperature trend has become about twice as steep (0.62 °C/10 years) as the trend over the 50-year period. The most intense change is detected in the mean maximum temperatures. Here, the trend increases by 0.71 °C, 0.72 °C, and 0.85 °C every 10 years for the annual, summer half-year and winter half-year, periods, respectively.

The rates of change obtained from parametric and non-parametric trend analyses are essentially the same over the 50-year period. Even for the shorter study period, only small differences arise from methodological differences, generally not exceeding 0.05 °C/10 years. For the annual and semi-annual data, all temperature parameters investigated showed a significant trend.

Table 3. Trend parameters for yearly and half-year (h-y) temperature data, calculated by non-parametric (Mann-Kendall test and Sen's estimator) and parametric (linear regression) methods. Significance levels are ***: p<0.001, **: p<0.01, *: p<0.05, $^{+}$: p<0.1

Indicator	Time period	1973-2022 (50 years) Trend (°C/10 years)^{significance}		1993-2022 (30 years) Trend (°C/10 years)^{significance}	
		MK + Sen's slope	LR	MK + Sen's slope	LR
Average temperature	Year	0.39^{***}	0.39^{***}	0.52^{**}	0.53^{***}
	Summer h-y	0.41^{***}	0.44^{***}	0.41^{*}	0.43^{***}
	Winter h-y	0.29^{*}	0.33^{***}	0.62^{*}	0.63^{***}
Minimum temperature	Year	0.35^{***}	0.35^{***}	0.52^{***}	0.47^{***}
	Summer h-y	0.36^{***}	0.36^{***}	0.33^{**}	0.33^{***}
	Winter h-y	0.33^{*}	0.33^{***}	0.63^{*}	0.58^{***}
Maximum temperature	Year	0.52^{***}	0.52^{***}	0.71^{***}	0.72^{***}
	Summer h-y	0.61^{***}	0.62^{***}	0.72^{**}	0.69^{***}
	Winter h-y	0.40^{**}	$0,41^{***}$	0.85^{*}	0.78^{***}

3.2. Precipitation trends

Precipitation shows significantly greater variability than temperature, both on monthly and annual bases. This partly explains why the trends obtained are mostly not significant at the p=0.05 level, or even at the p=0.1 level, which provides a wider range (*Table 4*).

Over the longer period, only September showed an increasing (+3.6 mm/10 years) but not significant trend of the examined months. The other months show a non-significant decrease, with October showing the smallest decrease (<1 mm/10 years, practically no change), June the largest (-6.2 mm/10 years), followed by July (-4.5 mm/10 years). The annual precipitation total is also decreasing, with a trend of -17.2 mm/10 years. The decrease has basically taken place in the summer half-year (-15.8 mm/10 years). The trend of 3.2 mm/10 years in the winter is negligible and not significant. The parametric test showed a significant decreasing trend at the p=0.1 level in June (-7.4 mm/10 years) and in the summer half-year values (-15 mm/10 years).

In the period 1993–2022, the two methods show a decreasing precipitation in April (-11.5 mm/half year, *p*=0.1) in complete agreement. Of the examined months, only October shows an increase in precipitation, but it is not significant and of very small value. From May to September, a slight decrease is observed in all months, but even in May, it is only 4.5 mm/10 years. Decreases in June and July that are more significant in the 50-year base have not been observed for the last 30 years. The trend in precipitation decline in the summer half-year is 27 mm/10 years, while precipitation in the winter half-year hardly changes (+3 mm/10 years is practically negligible). Consistent with these findings, the trend in annual precipitation is also decreasing (non-significant) at a rate of 24 mm/10 years.

Table 4. Trend parameters for monthy, yearly, and half-year (h-y) precipitation data, calculated by non-parametric (Mann-Kendall test and Sen's estimator) and parametric (linear regression) methods. Significance levels are ***: $p<0.001$, **: $p<0.01$, *: $p<0.05$, $^{+}$: $p<0.1$

Indicator	**Time period**	**1973-2022 (50 years)** Trend (mm/10 years)^{significance}		**1993-2022 (30 years)** Trend (mm/10 years)^{significance}	
		MK + Sen's slope	**LR**	**MK + Sen's slope**	**LR**
Precipitation	April	-2.1	-1.9	-11.5^{+}	-11.6^{+}
	May	-2.0	-3.5	-4.5	-3.6
	June	-6.2	-7.4^{*}	-0.9	-1.4
	July	-4.5	-3.6	-1.7	-3.0
	August	-2.1	-2.7	-2.6	-6.1
	September	3.6	4.0	-0.6	-1.6
	October	-0.8	-1.2	2.3	3.1
	Year	-17.3	-11.6	-24.0	-18.3
	Summer h-y	-15.8	-15.0^{+}	-26.8	-27.2
	Winter h-y	3.2	3.8	3.0	4.9

3.3. *Maize yield*

In the period 1993–2022, the average yield was 10.4 t/ha in the long-term maize experiment at the Debrecen-Látókép experiment site, under agrotechnologically typical of farm conditions. The value, which is significantly above the national average and the moderate differences between years, is due to the excellent soil conditions (structure, water management properties) (*Fig. 2*). A slightly decreasing but not significant trend can be observed, with a value of 0.20 t/ha.

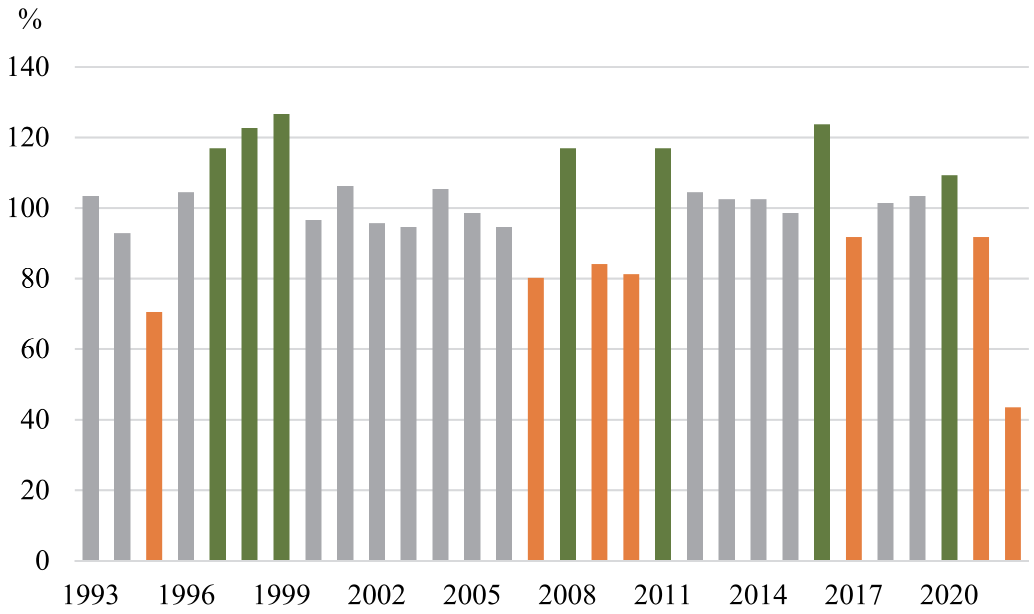

Fig. 2. Annual average yields of the Debrecen-Látókép long-term maize experiments as a percentage of the average yield for the period 1993–2022.

Based on the yield average, weather conditions in the lower and upper quartile years differ most in July. The 8 years with the lowest yields (low yield years) have an average July precipitation of only 36 mm and a mean temperature of 23.1 °C, while the high yield years have average precipitation of 100 mm and 21.3 °C, respectively (*Table 5*). Of the high yield years, there was only one in which the July rainfall total was below the multi-year average, but then the weather was cold, and June and August were both wetter than average.

Table 5. Monthly precipitation sum (ps) and mean temperature (m) values averaged over low yield years (LYY) and high yield years (HYY).

	April	**May**	**June**	**July**	**August**	**September**	**October**
LYY-ps (mm)	38	51	62	36	37	64	43
HYY-ps (mm)	40	63	77	100	50	37	45
LYY-m (°C)	11.2	16.6	21.0	23.1	22.6	16.0	10.5
HYY-m (°C)	11.4	15.8	20.3	21.3	21.1	17.2	10.4

The months of May, June, and August are also shown to be cooler on average and slightly wetter in high yield years. However, these months alone do not tend to have a decisive effect on yields. For example, in half of the low yield years, June was particularly wet.

In April, the average precipitation and temperatures for low and high yield years were almost the same, slightly lower than the 30-year average. The weather in September no longer affects the yield average, as maize has typically reached physiological maturity by this time. However, it is an interesting correlation that, on average over the 8 low yield years, this month is wetter and cooler than the average of the 8 high yield years.

4. Discussion and conclusions

The performed research shows that the trend analysis results and the conclusions that can be drawn from them are influenced by the choice of the length of the study period. The numerical values of the slope of the trend differ, and for some parameters there are also substantial differences (e.g., trend sign), a phenomenon that can be encountered even in the case of the 30- and the 50-year period. Several studies analyze trends of 100 years or more (*Juhász et al.*, 2018; *Kocsis* and *Anda,* 2017), with which comparisons of trends over shorter periods should be treated with caution. The results of the parametric and non-parametric trend analyses for the temperature variables that were included differed only marginally (the choice of period has a much more pronounced effect). There were also only few cases of substantial differences for precipitation data that do not follow a normal distribution (e.g., monthly). In the study by *Kocsis* and *Anda* (2018), the results obtained with the non-parametric method showed better agreement with the results from other studies.

The annual mean temperature increase trends of 0.39 and 0.52 °C/10 years show an increase of around 2 °C over 50 years and 1.5 °C over 30 years, in line with the national average increase over the 1981–2020 period (OMSZ, 2019a).

Juhász et al. (2018) show a warming of 1.4 °C for Debrecen over the 1971–2010 period, but this does not include the most recent warmest years.

There is a significant warming in both the summer and winter half-years, with the summer half-year showing a steeper upward trend in the 50-year series and the winter half-year in the 30-year series. No seasonal analysis clearly comparable to the literature sources has been carried out, but the data clearly show a high, highly significant warming in the summer months and less intense changes in the 2 spring and 2 autumn months. On average in Hungary, the transitional seasons also showed less warming, with winter and summer showing greater warming (OMSZ, 2019a).

The annual and semi-annual maximum values showed a larger increase than the minimum values. The larger daily temperature variation may be related to stronger radiation effects. No studies have been carried out in this respect, but there has been a significant increase in the domestic solar irradiance values (about 200 hours) for the period 1991–2020 compared to the period 1971–2000.

The challenge in analyzing precipitation data series is the high variability that masks trends. Significant trends (p=0.05) are not typically found in monthly or even semi-annual or annual data. No significant change was detected in any of the 50-year data series by the Mann-Kendall test. Only the 30-year April data series showed a trend-like change at the p=0.1 significance level. Nevertheless, the analysis of change provides useful information.

There is a negative, non-significant trend in annual precipitation. The decreases of 17 mm and 24 mm/10 years obtained for the 50- and 30-year time series, respectively, are not negligible from a practical point of view. Previous declining trends in precipitation have been described by other sources (*Szalai*, 2011). Climate change scenarios, with greater uncertainty, have also suggested a continuation of this trend (*Bartholy et al.*, 2011). In contrast, a significant increase is already observed on a national average over the period 1981–2020 (OMSZ, 2019b). Looking at the annual data series separately for the same period in this research, it was found that there is no change in Debrecen, with a non-significant trend of 2.2 mm/10 year decrease.

In the summer half-year, precipitation is decreasing, with a slope of -27 mm/10 years for the last 30 years, but even this is not significant due to its high variability. There is no significant change in the amount of precipitation in the winter half-year over the last decades.

Altogether, the changes are negative for maize production. The clear annual warming tends to increase evaporation, which is accompanied by a slight decrease in precipitation. The two phenomena together lead to a deterioration in the water availability of the crop, which is a key factor for the yield. There are two viewpoints for the decreasing precipitation in April in terms of crop production. On the one hand, it is favorable for seedbed preparation and sowing. On the other hand, especially on soils with more extreme water management (clay, sand), post-sowing rainfall may be necessary for proper emergence. The analysis of the yield data series also points to this duality. A drier than average April can lead to low or high average yields. Temperatures in April-May have not increased compared to the previous period, i.e., no faster initial development should be expected. In recent years, it has been repeatedly observed that the plant develops slowly and is more exposed to various pests, especially animal pests, during this period. The high yield averages tend to occur in years when the summer months (July in particular) are cooler and wetter than usual. This tendency suggests a markedly unfavorable warming trend in the summer months, which is more pronounced for maximum temperatures. Precipitation also tends to show a downward trend, which is clearly unfavorable. The risk of soil and atmospheric droughts is increasing, especially during the wider interval of the silking-yield formation period, which is critical for maize. Although maize is a heat-sensitive crop, the statement (*Varga-Haszonits* and *Varga,* 2004) that the warmer summer areas of the country are the most favourable from a temperature point of view is no longer true. Rather, the negative impact of heat stress due to excessively high daytime temperatures is becoming a more important factor from a practical aspect. The weather in September and October has become slightly more favorable for the final stages of ripening, watering, drying, and harvesting.

Precision maize farming offers the possibility to at least partially compensate for negative changes by using modern techniques and agrotechnical elements adapted to the changed climatic conditions. Based on the obtained results, the following can be proposed:

- the use of water conservation techniques in soil and seedbed preparation due to lower rainfall in April;
- choosing the appropriate sowing date earlier than usual for a more secure emergence;
- cultivation of a genotype with relatively rapid initial development even at lower temperatures;
- emphasis on agrotechnical methods to reduce the stress and impact of summer water stress.

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