ORIGINAL ARTICLE

Continental lowlands face rising crop vulnerability: structural change in regional climate sensitivity of crop yields, Hungary (Central and Eastern Europe), 1921–2010

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Abstract

Central and Eastern Europe (CEE) is a pillar of global wheat and maize production. However, certain areas within the CEE region have become climate change hotspots, experiencing intensifying water deficits and drought pressure, rising mean and maximum temperatures. This study focuses on the long-term statistical relationships between climatic factors and rain-fed wheat and maize yields for different landscape types in Hungary over 30-year time windows between 1921 and 2010. The relationship between the variances of the detrended climatic parameters and crop yields was tested employing both simple and multifactorial linear models according to landscape types and periods. The sensitivity of wheat yields to spring–summer mean temperature shifted dynamically from the western part of the country to east (from cooler and wetter hilly landscapes to plains) between the periods 1921–1950 and 1981–2010. The cooling observed in summer temperature between the periods 1921–1950 and 1951–1980 supported an increase in wheat yields by an estimated 0.11–0.43 t ha^{-1} year^{-1}, while the 0.9–1.2 °C warming of May–July temperature may have cut wheat yields by an estimated 0.44–0.56 t ha^{-1} year^{-1} in various regions over 1981–2010. That being said, the regional sensitivity of wheat yields to May–July mean temperature did not display substantial differences between the periods 1921–1950 and 1981–2010. Besides negative effects, climate change had a positive impact on wheat yields, since increasing January–March mean temperatures mitigated the negative impact of warming summer temperatures on wheat yields by an estimated 16–34% over 1981–2010. In this 30-year period, increasing mean temperature together with decreasing precipitation explained 46–75% of the variances in maize yields reducing annual maize harvests by an estimated 11.1–12.4% year^{-1}.

Keywords Climate warming · Climate sensitivity · Food security · Maize and wheat yield · Moisture conservation · Water deficit · Yield loss

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Introduction

Globally, one of the areas where wheat and maize production has grown most dynamically over recent decades is Central and Eastern Europe (CEE) (FAO 2023; Tikhomirova 2023), and a major part of the European yield gap, i.e. growing potential, has been identified as being located in these regions (Schils et al. 2018). While the CEE group of countries is a pillar of global food security, it is in the southern part of this region that the zone of greatest sensitivity of cereal production to the warming climate and shrinking freshwater resources in Europe has been identified (Olesen et al. 2011; Pinke et al. 2022). Other studies also underline the high degree of climatic sensitivity of CEE countries with continental climate, where decreasing soil moisture and changing atmospheric circulation (Seneviratne et al. 2014) induce extremes of heat and severe droughts (Fischer et al. 2007; Bastos et al. 2021). As a result, while globally less than one-third of the variability in maize and wheat yield is explained by climate (Ray et al. 2015), in the southern part of CEE region, more than two-thirds of the fluctuation in maize yield is driven by combined climatic factors (Ray et al. 2012; Kern et al. 2018).

As a consequence of the fact that the transformation of regional climatic regimes and their impacts unfolds over the long-term, short data series allow only limited conclusions to be drawn (IPCC 2021). For instance, land use and landscape policy require long-term trends and predictions, as well as spatially explicit quantitative vulnerability assessments of environmental effects, including climate change (IPCC 2019; Pastor et al. 2022). The few long-term studies available highlight significant temporal differences in the pace of the transformation of the regional scale climate indices and of the relationship between climate and cereal yield (Trnka et al. 2016). Both past and predicted future impacts of climate change on grain yields have been researched along a scale ranging from individual parcels

(Hidy et al. 2012) to the global (Asseng et al. 2015). Certain pioneering studies focus on high resolution regional or landscape patterns of the climatic sensitivity of crop yields (Trnka et al. 2016; Mohammed et al. 2022), and successfully explore some hotspots in crop farming in relation to recent climate change, e.g. grain-growing in drylands (Huang et al. 2017; Leng and Huang 2017), maize cultivation in the US Midwest (Lobell et al. 2020) and wheat production in southern and eastern France (Ceglar et al. 2016). However, studies discussing long-term associations between climatic and cereal yield variables in a landscape context and especially analyses of the climate sensitivity of yields in different landscape types are scarce (Trnka et al. 2012). Yet landscape as a complex geographical and socioecological framework may well be key to an appropriate adaptation to the climate challenge (Harvey et al. 2014), as earlier confirmed in a qualitative risk assessment of European landscape characterisation (Delbaere and Nieto Serradilla 2004; Wascher 2005). In an attempt to address this scarcity, this examination aims to discover the long-term associations between, on the one hand, climatic factors as independent variables, and on the other, wheat and maize yields as dependent variables by landscape type in Hungary (CEE region) in 30-year time windows between 1921 and 2010.

Materials and methods

Study area

Situated in the southern part of CEE, in the Middle Danube Basin (Fig. 1), Hungary is in the temperate zone and may be characterised in the Köppen climate classification as a continental climate with cold winters, no dry seasons and hot and warm summers (Peel et al. 2007). Monthly mean temperature varies between -4 and 22 °C, and annual precipitation (594 ± 51 mm) is one of the lowest among the croplands of the European countries (Izsak et al. 2022).

Fig. 1 Bioclimatic regions of Hungary delineated along county borders. The background map shows the location of Hungary within Europe
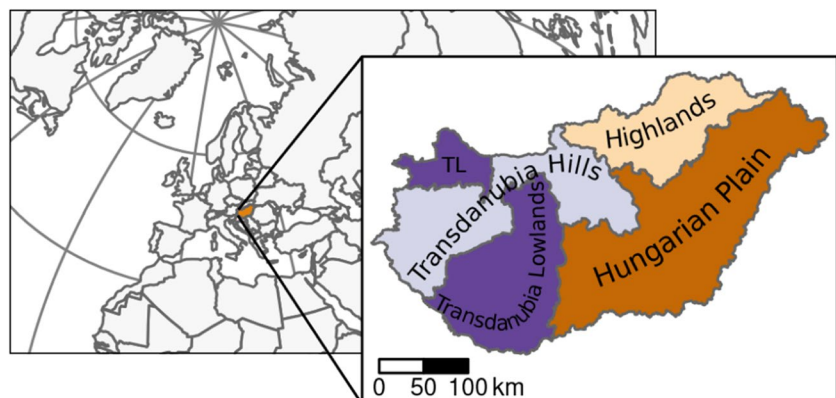
Despite this, cereal fields are mostly (> 95%) rainfed, and only 3% of the area given over to maize has been irrigated (Bozan et al. 2018a). As a result of agricultural modernisation in the nineteenth and twentieth centuries, an estimated 45% of the country was covered by arable lands in 2021 (KSH 2023). However, the abandonment rate of arable land is relatively high, with a mean of 0.44% year^{-1} over the last 50 years (KSH 2023). Almost half of the arable land of the country is thought to be prone to droughts (Fiala et al. 2014; Gulacsi and Kovacs 2015), and this sensitivity is characteristic of a wider region in South-Eastern Europe (Olesen et al. 2011). Looking at the years 1981–2010, in Hungary, 67% of wheat and 81% of maize yield fluctuation were driven by climate (Kern et al. 2018), while temperature has had a steadily growing negative impact on crop yields on the countrywide scale over the past century (SI Table S2).

To delineate bioclimatological regions, average cereal yields-by-county of the three 30-year periods studied (1921–1950, 1951–1980, 1981–2010) were clustered using Ward's method of hierarchical clustering with Euclidean distance. The threshold value at which to cut the dendrogram was determined on the basis of the topographical characteristics of the counties, derived from the EU-DEM v1.1 digital surface model (EEA 2016), so that the four selected regions represent the main landform types of the country (Table 1). The most characteristic landscape types are as follows:

continental lowland dominated by arable lands, continental hills dominated by arable lands and continental hills dominated by forests (Wascher 2005; Kocsis et al. 2018). The Hungarian Plain belongs to forest-steppe zone, but the other three regions are transitional areas between temperate broadleaf forest and forest-steppe zones (Kocsis et al. 2018). The climatic and cereal yield variables studied differed from each other significantly by region (SI Table S3, S4). Though a relative dominance of arable lands characterises the land use system in Hungary (arable lands 45%, forests 21%, meadows 8%) (KSH 2023), the Hungarian Plain has by far the most homogenous pattern of land use. Regional and depth averaged soil hydrologic and hydraulic parameters of the upper 2 m (Table 1; Toth et al. 2017) suggest rather homogeneous soil conditions throughout the country; however, the varying proportions of soil types comprising the topsoil reveal differences between the regions (Table 1). Excluding soil types unsuitable for cultivation (peat, gravel, non- or partly weathered rocks), loamy soils (sandy loam, loam and clay loam) dominate all regions; however, while their proportion exceeds 80% in the Transdanubian lowlands and Transdanubian hills and reaches almost 90% in the Highlands, only 63.5% of the Hungarian Plain is covered with loamy soils considered suitable for growing maize and wheat. On the other hand, sandy soils with poor water retention capacity and often low organic matter content and clay soils usually

Table 1 Basic statistics of selected topographical, land-use and land cover (LULC) and soil characteristics of the studied regions in Hungary

Descriptive environmental parameters, their quantifying indicators and dimensions		Region			
		Hungarian Plain	Transdanubian lowlands	Transdanubian hills	Highlands
Spatial extent:	Area km^2	36,067	22,733	20,801	13,425
LULC class ratio of:	Arable land (%)	65	58	45	43
	Forest and seminatural area (%)	12	18	26	31
Topography ($\bar{x} \pm$ SD)	Elevation (m.a.s.l.)	100 ± 18	151 ± 53	191 ± 86	215 ± 130
	Slope (%)	1.45 ± 1.35	4.46 ± 5.37	5.32 ± 6.8	8.83 ± 10.05
Crop Productivity Index ($\bar{x} \pm$ SD)		5.83 ± 1.31	6.39 ± 0.76	6.28 ± 0.81	6.21 ± 0.66
Soil hydraulic parameters of the top 2 m ($\bar{x} \pm$ SD)	Ks (cm day^{-1})	31.25 ± 14.51	24.86 ± 7.42	25.03 ± 9.27	28.06 ± 8.63
	Porosity (%)	46.48 ± 1.19	45.07 ± 1.12	45.29 ± 1.03	45.9 ± 0.9
	Plant available water content (%)	16.09 ± 0.82	16.73 ± 0.58	16.67 ± 0.68	16.97 ± 0.85
Soil types (%)	Sand	22.7	11.5	15.7	2.2
	Sandy loam	8.7	10.2	15.7	1.0
	Loam	30.8	64.9	48.7	32.5
	Clay loam	23.4	6.3	5.5	50.9
	Clay	13.3	0.0	0.5	7.2
	Other (not relevant in croplands)	1.0	7.1	13.9	6.2

LULC data: (EEA 2016; Copernicus 2019) soil productivity index: Soil Biomass Productivity maps of Croplands (Toth et al. 2013); soil hydraulic parameters: EU-SoilHydroGirds ver 1.0 (Toth et al. 2017); topsoil soil type: AGROTOPO database (Pasztor et al. 2015). Abbreviations: *LULC*, land use-land cover; *m.a.s.l.*, metres above sea level; $\bar{x}$, average; *SD*, standard deviation; *Ks*, saturated hydraulic conductivity

prone to waterlogging and compaction cover more than one-third of the Hungarian Plain, while their proportion remains below 20% in the Transdanubian hills and slightly exceeds 10% in the Transdanubian lowlands and the Highlands. A significantly lower average value for the soil productivity index is to be found in the Hungarian Plain than in other landscapes (Table 1). The lower index values represent lower biomass productivity potential based on climatic conditions, fertilisation practice and soil hydraulic parameters, while the higher ones represent a greater potential (Tóth et al. 2013).

No generalised evaluation or conclusion may be arrived at with regard to the regional differences in production factors of the Hungarian agriculture. Reviewing the most important factors, it was found that there are no significant differences between the regional averages of fertilisers used, agricultural labour, capital and education in agriculture (KSH 2008). Two indicators did, however, show significant regional differences: (i) the number of agricultural machines was higher in the Hungarian Plain than in Transdanubia and (ii) the greater share of irrigated areas (76%) was found in the Hungarian Plain (KSH 2008).

Data

The monthly averages of daily maximum (Tmax), mean (Tmean) temperatures (°C) and monthly precipitation sums (Prec) (mm month^{-1}) (quality controlled and amended for inhomogeneity by Izsák et al. 2022; Szentes et al. 2023) for six meteorological stations were obtained from the Hungarian Meteorological Service (OMSZ 2023). These provide an even spatial distribution across Hungary for the period 1921–2010. The gridded data of mean monthly potential evapotranspiration (PET) (mm month^{-1}) and the SPEI1 drought anomaly index at 0.5° resolution were extracted from the CRU TS 4.07 data series (Harris et al. 2020). PET was calculated using mean temperature, vapour pressure, cloud cover and static 1961–90 average wind field values in the Penman–Monteith equation (Harris et al. 2020). Using PET, the climatic water balance (Prec-PET) was calculated, that is, the difference between the precipitation and potential evapotranspiration sums. SPEI is a standardised precipitation evapotranspiration index based on normalised Prec-PET (Vicente-Serrano et al. 2010).

The county-scale (NUTS 3 statistical regions of the European Community) averages of annual wheat and maize yields (t ha^{-1}) and harvested areas (ha) were obtained from the Hungarian Central Statistical Office (KSH 2023). The time series of crop yields, however, had missing data for the years 1921, 1944–1946 and 1949. Additionally, there are no separate data on yields by different wheat types in the Hungarian agricultural statistics. However, given that the share of winter wheat was always predominant (e.g. 94–97%

during 2010–2018) (KSH 2023), data for wheat were considered to refer to winter wheat exclusively.

Data analysis

The 90-year time series provided a unique opportunity for the analysis of long-term spatial differences in climatic impacts on wheat and maize yields in three 30-year periods. Shapiro–Wilk and variance inflation tests showed that almost all data were distributed independently and identically (Supplementary Information [SI] Table S1). The life-cycle of winter wheat spans the period September/October–June/July overlapping the recharging phase of the annual hydrological cycle of the soils (mid-autumn–mid spring) when the soil hydrological balance is positive. In general terms, the plant's C3 metabolic mechanism is more efficient in cool environments. Shortly after seeding, in late autumn and winter, winter wheat requires a period of cold weather to start the dormant vegetative growth stage (Acevedo et al. 2002), in which the plant is very resistant to frost. During this period, the intensity of transpiration is low and the saturation of soils may negatively affect the plant (Mercau et al. 2016; Bozan et al. 2018b). The sensitive phase of winter wheat to freezing stress is the flowering stage over the late winter–early spring period. Later, between April and June, early droughts may cause significant harm to the plant but the probability of severe droughts in spring is low because of the dynamics of interannual hydrological cycle (Czibolya et al. 2020). The harvesting time of winter wheat falls between late June and mid-July in the region preceding the most drought prone late summer period. Therefore, the analysis focuses on the statistical associations between February–July Prec, and Prec-PET (hereinafter 'water deficit'), with the Tmean of May–July as independent variables, and annual wheat yields as dependent variables. An earlier investigation revealed that late winter and early spring temperature increase had a positive effect on yields of winter wheat in the CEE region. Consequently, the linear relationship between January–March Tmean and wheat yields is also examined.

In contrast to wheat, maize is sown between mid-April and early May in the CEE region. Maize has a C4 metabolism and the plant requires a hot and wet environment but its life cycle includes the hottest and driest months (July–September) when the evapotranspiration deficit (the difference between actual and potential evapotranspiration) is acute; therefore, the sensitivity of maize to water stress or drought is high (Marton et al. 2020; Kocsis et al. 2020). In the case of maize, the response of yield to the variables of Prec, Prec-PET, Tmax and Tmean was examined for the entire period of active root water uptake (May–August). The relationship between the variances of detrended climatic parameters (e.g. ΔPrec, Δ(Prec-PET), ΔTmax and ΔTmean) and crop yield

(ΔY) using the first difference method was tested employing simple and multifactorial linear models by region (r) and periods (p). For example:

$$\Delta Y_{r,p} = \beta_0 + \beta_1 \Delta Prec_{r,p} + \beta_2 \Delta Tmean_{r,p}$$

The adjusted bootstrap percentile (BCa) 95% confidence interval of the coefficients of determination (R^2) was estimated by non-parametric bootstrap resampling tests over 5000 replicates (Davison and Hinkley 1997) using the boot package in an R environment (Lobell and Field 2007; Canty and Ripley 2022). Besides independent variables, the linear combination of two climatic variables (e.g. Tmean + Prec, hereinafter 'combined climatic factors') and cereal yields was investigated, as suggested by Kronmal (1993). As PET is greatly influenced by temperature, consequently, neither Tmean nor Tmax was not examined using Prec-PET indices in a combined climatic factor since they cannot be considered independent variables. Although a linear regression test is only statistical association, the fact that changes in Prec, Prec-PET, Tmax and Tmean may have significant impact on cereal yields via plant physiology is justified (Lobell and Field 2007). Thus, we may reasonably presume that the results of the regression tests indicate the intensity of the relationship between the explanatory climatic variables and the response (yield) variables.

Results

Descriptive analyses

All regional averages of the explanatory variables studied differed from each other (SI Table S2), except for the hilly and lowland regions of Transdanubia where similar annual averages of mean temperature were recorded in 1951–1980 and 1981–2010 (SI Table S2). Maximum temperature showed the most spectacular changes over the 90 years studied, because Tmax regional averages declined significantly from 1921–1950 to 1951–1980 and increased, and significantly so, between 1951–1980 and 1981–2010 (Fig. 2; SI Table S1). The 30-year annual as well as summer and winter half year averages of mean temperature increased significantly in every region from 1951–1980 to 1981–2010. In contrast, mean temperature did not change significantly anywhere from 1921–1950 to 1951–1980 (Fig. 2, SI Table S1, S2). The increase in the summer mean temperatures was greater almost everywhere than in the winter ones (Fig. 2, SI Table S1, S2). The highest 30-year averages of the temperature and the lowest Prec-PET variables were observed in the Hungarian Plain. While the averages of temperature variables increased significantly, water deficit decrease proved significant only in the Transdanubian regions during

the 1981–2010 period, and precipitation sums did not show significant change over the 90-year period.

Chiefly due to agrotechnological development, the regional averages of wheat and maize yields were 3.3 and 3.2 times higher in 1980–2010 than in 1921–1950, respectively (Fig. 2; SI Table S1). Wheat and maize yields grew dynamically between the 1950s and the 1980s, and then, following a similar pattern to that of the European trends, slowed down from the mid-1980s. Moreover, wheat yields reached a plateau between the mid-1980s and late 2000s. The regional averages differed from each other significantly in every 30-year period, with only the yield averages of the Highlands region and the Hungarian Plain being the were same in 1921–1950 and 1951–1980 (SI Table S3). The highest yields appeared in the Transdanubian Lowlands region where climate was characterised by the mildest temperatures (Fig. 2; SI Table S1), with the smallest fluctuation and the highest sums of precipitation among the four regions. By way of contrast, farmers of the eastern lowlands, the Hungarian Plain, where continental climate conditions are characteristic, harvested significantly lower yields than on the Transdanubian Lowlands (Fig. 2; SI Table S1). Moreover, the wheat yield average of the Hungarian Plain had become the lowest within the four bioclimatological regions by 1981–2010.

Associations between climatic factors and cereal yields

Using non-parametric bootstrap resampling tests, we found that the spatiotemporal changes in the relationships of climatic and wheat yield variances resulted in a dynamic and diverse picture over the three 30-year periods under consideration. May–July mean temperature proved to be the dominant climatic driver of wheat yield fluctuations. Their association had a negative direction, i.e. the observed cooling from 1921–1950 to 1951–1980 bolstered wheat yields, then the significant May–July warming cut them back in every Hungarian region over 1981–2010. This negative relationship of Tmean and wheat yields displayed an important spatial transformation over 1921 and 2010 (Table 2). While Tmean$_{May–July}$ had a non-significant association with wheat yields in the Hungarian Plain ($p > 0.05$; df = 28) in 1921–1950, this association then became the most considerable in the Hungarian Plain over the third 30-year period ($p < 0.01$; df = 28) (Table 2). Simultaneously, in the Transdanubian Lowlands and hills, May–July Tmean ~ wheat yield associations proved to be the strongest in 1921–1950, but then the sensitivity of wheat yield had declined significantly by 1981–2010 (Fig. 3). The constantly increasing January–March Tmean had a much milder, and at the same time positive impact on wheat yields (SI Table S2), and their relationships had weakened significantly by 1981–2010.
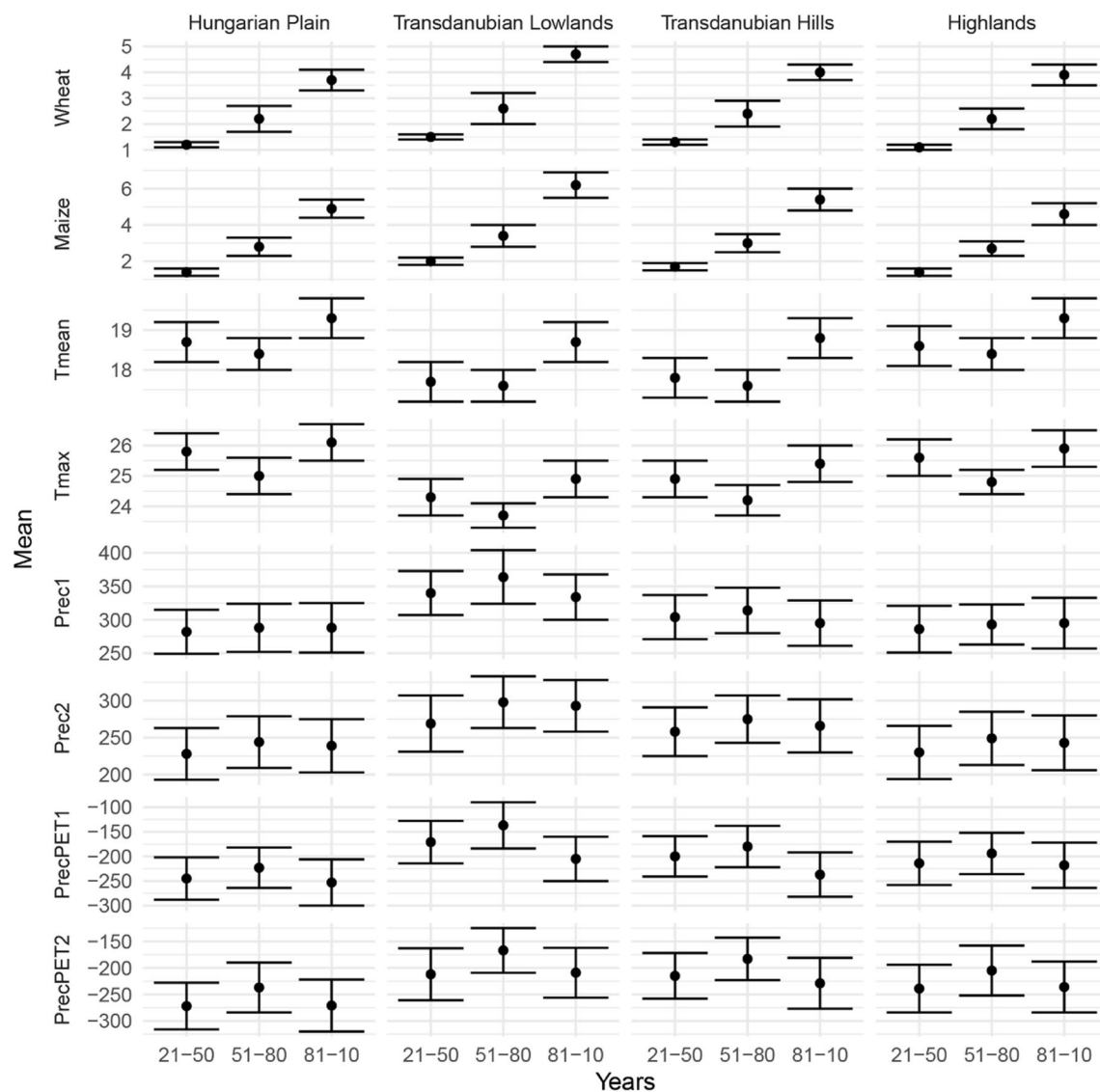
Fig. 2 Yield averages (t ha^{-1} ± SD) of wheat and maize, mean monthly temperatures, precipitation and climatic water balance in four agroecological regions of Hungary for three 30-year periods between 1921 and 2010. SD, standard deviation; Tmean, May–July mean temperature (°C); Tmax, May–August maximum temperature (°C); Prec1, February–July precipitation sum (mm); Prec2, May– August precipitation sum (mm); PrecPET1, February–July precipitation sum (mm) minus February–July sum of potential evapotranspiration (mm); PrecPET1, May–August precipitation sum (mm) minus May–August sum of potential evapotranspiration (mm); 21–50, 1921–1950; 51–80,1951–1980; 81–10, 1981–2010. Source: KSH 2023; OMSZ 2023, CRU TS 4.07

February–July precipitation and water deficit, as well as May–July drought indices, showed a positive impact on wheat yields but remained marginal even in 1981–2010 (Table 2).

The combined climatic factor composed of May–July mean temperature and February–July precipitation explained 54–66% of wheat yield variances in the Transdanubian Lowlands and Transdanubian Hills in 1981–2010, but this association was weak and non-significant in the Hungarian Plain between 1921 and 1950 (Table 2). Interestingly, in the Transdanubian Lowlands

and Transdanubian Hills, precipitation displayed a significant level of explanatory power in terms of a negative impact on wheat yields in the combined models over 1921–1950. In the case of the Highlands region, precipitation played a non-significant role in the multiple model during 1921–1950 ($p > 0.05$). In this period, Tmean$_{January–March}$ + Tmean$_{May–July}$ ~ wheat yield associations were mostly non-significant flowing from the non-significant level of explanatory power of either predictor, with the single exception of the Transdanubian Lowlands, where not only Tmean$_{January–March}$ + Tmean$_{May–July}$ ~ wheat yield ($p < 0.01$;

Table 2 Nonparametric bootstrap test results, coefficients of determination (R^2) and their 95% confidence intervals (CI) between climatic variables and wheat yields in the bioclimatic regions of Hungary for 30-year periods (1921–2010)

|	Wheat							
	Hungarian Plain		Transdanubian Lowlands		Transdanubian Hills		Highlands	
	R^2	CI	R^2	CI	R^2	CI	R^2	CI
1921–1950								
Prec	0.04	0.00–0.33	0.06	0.00–0.38	0.12	0.00–0.36	0.02	0.00–0.22
Prec-PET	0.02	0.00–0.16	0.02	0.00–0.22	0.02	0.00–0.21	0.00	0.00–0.01
SPEI1	0.01	0.00–0.06	0.01	0.00–0.10	0.01	0.00–0.09	0.00	0.00–0.01
$\text{Tmean}_{\text{May–July}}$	0.12	0.00–0.55	0.42	0.07–0.63	0.59	0.15–0.83	0.36	0.00–0.74
$\text{Tmean}_{\text{Jan–March}}$	0.39	0.08–0.67	0.24	0.01–0.53	0.12	0.00–0.43	0.20	0.01–0.48
$\text{Tmean}_{\text{May–July}} + \text{Prec}$	0.17	0.00–0.39	0.54	0.18–0.77	**0.66**	0.30–0.87	0.41	0.08–0.68
$\text{Tmean}_{\text{May–July}} + \text{Tmean}_{\text{Jan–March}}$	**0.45**	0.13–0.63	**0.56**	0.26–0.72	0.63	0.31–0.81	**0.47**	0.07–0.70
1951–1980								
Prec	0.01	0.00–0.11	0.07	0.00–0.25	0.03	0.00–0.16	0.00	0.00–0.00
Prec-PET	0.01	0.00–0.16	0.04	0.00–0.22	0.01	0.00–0.76	0.01	0.00–0.13
SPEI1	0.06	0.00–0.36	0.02	0.00–0.15	0.02	0.00–0.15	0.15	0.00–0.49
$\text{Tmean}_{\text{May–July}}$	0.17	0.00–0.51	0.20	0.00–0.52	0.25	0.01–0.55	0.41	0.05–0.72
$\text{Tmean}_{\text{Jan–March}}$	0.05	0.00–0.27	0.05	0.00–0.23	0.04	0.00–0.20	0.05	0.00–0.24
$\text{Tmean}_{\text{May–July}} + \text{Prec}$	**0.23**	0.01–0.44	**0.33**	0.04–0.62	**0.37**	0.09–0.60	**0.44**	0.08–0.71
$\text{Tmean}_{\text{May–July}} + \text{Tmean}_{\text{Jan–March}}$	0.20	0.01–0.44	0.22	0.02–0.47	0.37	0.09–0.60	0.43	0.10–0.70
1981–2010								
Prec	0.18	0.01–0.48	0.20	0.01–0.53	0.24	0.02–0.55	0.10	0.00–0.35
Prec-PET	0.22	0.03–0.54	0.18	0.01–0.51	0.26	0.03–0.56	0.15	0.01–0.43
SPEI1	0.22	0.03–0.48	0.17	0.01–0.44	0.21	0.03–0.48	0.13	0.01–0.40
$\text{Tmean}_{\text{May–July}}$	0.48	0.15–0.78	0.24	0.02–0.61	0.39	0.09–0.74	0.38	0.09–0.73
$\text{Tmean}_{\text{Jan–March}}$	0.14	0.00–0.38	0.13	0.00–0.45	0.09	0.00–0.37	0.14	0.00–0.39
$\text{Tmean}_{\text{May–July}} + \text{Prec}$	0.49	0.16–0.79	0.24	0.03–0.58	0.42	0.14–0.70	0.39	0.08–0.71
$\text{Tmean}_{\text{May–July}} + \text{Tmean}_{\text{Jan–March}}$	**0.66**	0.41–0.86	**0.49**	0.17–0.76	**0.63**	0.32–0.83	**0.59**	0.28–0.80

Prec, February–July precipitation sum (mm); *Prec-PET*, February–July precipitation sum (mm) minus February–July sum of potential evapotranspiration (mm); *SPEI1*, May–July drought index; *Tmean*, mean temperature (C°); *Tmax*, maximum temperature (C°); significant association (CI > 0.00). Data source: KSH, OMSZ and CRU TS 4.07

df = 28) (Table 2) but also $\text{Tmean}_{\text{January–March}} + \text{Tmean}_{\text{May–July}} + \text{Prec}_{\text{May–July}} \sim$ wheat yield association was significant ($p < 0.01$; df = 28; $R^2 = 0.62$). In the next two 30-year periods, the sensitivity of wheat yields to the combined $\text{Tmean}_{\text{May–July}} + \text{Prec}_{\text{May–July}}$ climatic factor grew at an unbroken pace in the Hungarian Plain and decreased continuously on the Transdanubian Lowlands. In contrast, $\text{Tmean}_{\text{January–March}} + \text{Tmean}_{\text{May–July}} \sim$ wheat yield relationships weakened in every region over 1951–1980. While the direction of change was up-down in the Transdanubian Hills, it was the opposite, down-up, in the Highlands. During 1981–2010, only the $\text{Tmean}_{\text{January–March}} + \text{Tmean}_{\text{May–July}}$ combined climatic factor showed a significant and a remarkably close relationship to wheat yields explaining an estimated 49 to 66% of wheat yield variances (Fig. 5, Table 2). The precipitation lost explanatory power (at the $p = 0.05$

level) in the $\text{Tmean}_{\text{May–July}} + \text{Prec}_{\text{May–July}} \sim$ wheat yield model in the last 30-year period.

Water deficit (Prec-PET) and drought indicated by the SPEI1 index clearly has the major impact on maize yields in 1921–1951 (Table 3), only to weaken with decreasing temperature in 1951–1980 and jump back to a very high level in 1981–2010, by which time the variances of water deficit explained 42–69% of maize yield variances (Fig. 4, Table 3). A different temporal pattern was observed concerning the associations of temperature indices and maize yields: Tmean and Tmax had neither linear relationship with maize nor a significant level of explanatory power in the combined climatic predictors over the first two 30-year periods. The coefficient of determination of temperature indices, however, jumped up by 1981–2010, and Tmax explained 49–64% and Tmean a 37–0.51% of maize variances (Fig. 3, Table 3).

Fig. 3 Coefficients of determination (R^2) between the first-differences of May–July mean temperature (Tmean) (°C) and wheat yields (t ha^{-1}), and May–August max temperature (Tmax) (°C) and maize yields (t ha^{-1}) for 1921–1950, 1951–1980 and 1981–2010 in the croplands of the bioclimatic regions of Hungary. Positive and negative directions indicate if deterministic relationship is positive or negative. Data source: KSH and OMSZ, software: QGIS 3.10
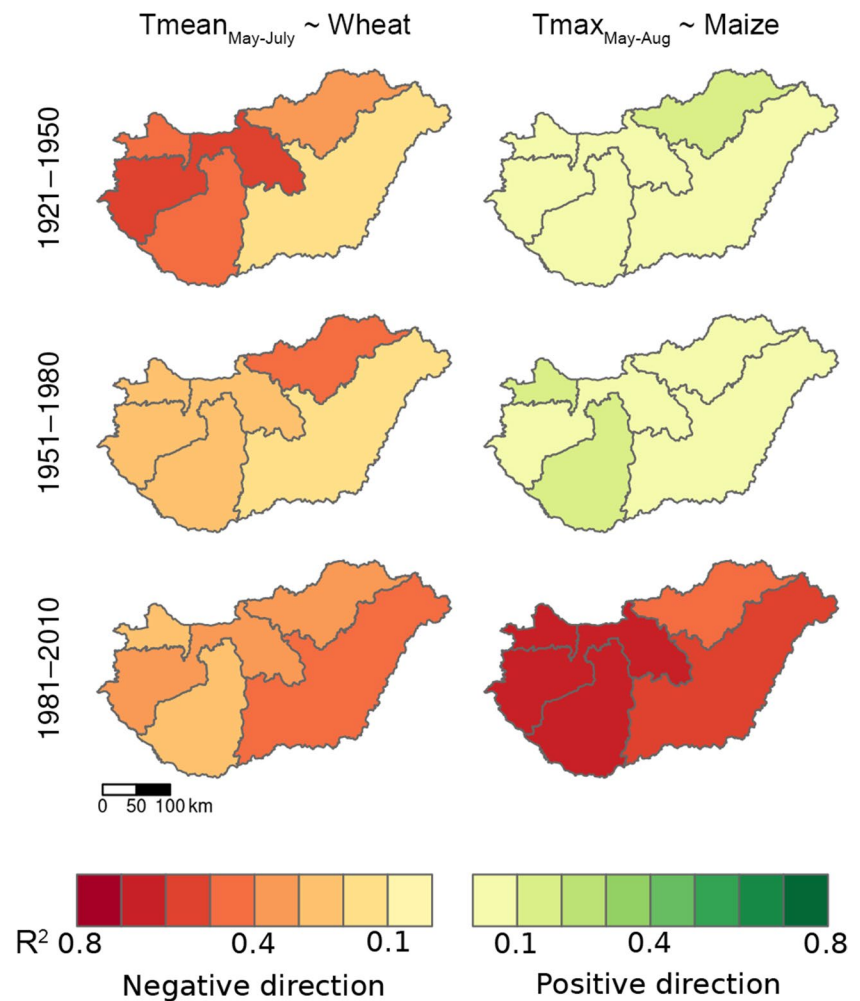
Precipitation was the dominant driver over the first two 30-year periods (Table 3), its variances explaining 35–66% of maize yield variances by region during 1921–1951. In this period, Highland maize seemed to be the most sensitive to precipitation (Table 3). Then the coefficients of determination indicated weaker precipitation ~ maize yield relationships in the period 1951–1980, then to return to a similarly strong level in 1981–2010 (Table 3). Interestingly, the R^2 of the last ('climate change affected') 30 years did not reach the values seen in 1921–1951 in the Hungarian Plain and the Highlands. Although May–July precipitation variables displayed a significant relationship to maize yields in all regions in 1981–2010, and Prec and Tmax indices did not show multicollinearity, Prec had a non-significant level of explanatory power within the Tmax + Prec ~ maize yield models in the Hungarian Plain and the Highlands only in the Transdanubian regions. In contrast, Prec was a significant component in Tmean + Prec ~ maize yields models over 1981–2010, when Tmean + Prec combined climatic predictors attained the status of a strong driver of maize yield variances explaining 46–75% of their variances (Fig. 5).

Estimating the contribution of climatic variables to yields

The results of point estimation using the regression equations suggest that rising May–July mean temperature may have reduced wheat yields by an estimated 0.44–0.56 t ha^{-1} year^{-1} in the bioclimatic regions examined here over the period 1981–2010 (Fig. 6, SI Table S5). However, the observed positive impact of increasing January–March mean temperatures on wheat yields mitigated this negative impact by an amount estimated to range between 16 and 34% (Fig. 6, SI Table S5). The lowest estimate of the positive impact of warming January–March mean temperature was obtained in the Hungarian Plain, while the highest ones occurred in the Transdanubian regions.

Using the regression equations of the association between the combined predictor of Tmean$_{May–Aug}$ + Prec$_{May–Aug}$ and maize yield our estimation is that rising May–August mean temperature together with decreasing precipitation (SI Table S1, S2) may have reduced maize yields seriously in the examined bioclimatic regions during 1981–2010

Table 3 Nonparametric bootstrap test results, coefficients of determination (R^2) and their 95% confidence intervals (CI) between climatic variables and maize yields (t ha^{-1}) in the bioclimatic regions of Hungary for 30-year periods (1921–2010)

	Maize							
	Hungarian Plain		Transdanubian Lowlands		Transdanubian Hills		Highlands	
	R^2	CI	R^2	CI	R^2	CI	R^2	CI
1921–1950								
Prec	**0.52**	0.16–0.73	**0.44**	0.15–0.67	**0.35**	0.04–0.63	**0.66**	0.22–0.87
Prec-PET	0.46	0.09–0.68	0.38	0.06–0.65	0.33	0.03–0.67	0.64	0.18–0.88
SPEI1	0.39	0.09–0.60	0.34	0.02–0.64	0.32	0.02–0.62	0.59	0.21–0.83
Tmean	0.00	0.00–0.04	0.00	0.00–0.00	0.00	0.00–0.00	0.03	0.00–0.24
Tmax	0.01	0.00–0.16	0.03	0.00–0.23	0.02	0.00–0.25	0.11	0.00–0.41
Tmean + Prec	0.57	0.18–0.74	0.57	0.28–0.71	0.39	0.03–0.62	0.67	0.22–0.86
Tmax + Prec	0.55	0.16–0.74	0.55	0.27–0.70	0.37	0.02–0.62	0.66	0.19–0.87
1951–1980								
Prec	0.31	0.02–0.62	0.14	0.01–0.45	0.21	0.01–0.42	0.21	0.01–0.52
Prec-PET	0.31	0.02–0.62	0.20	0.02–0.55	0.26	0.01–0.51	0.20	0.01–0.52
SPEI1	**0.37**	0.06–0.66	0.19	0.01–0.50	**0.41**	0.07–0.69	**0.29**	0.02–0.60
Tmean	0.01	0.00–0.06	0.06	0.00–0.26	0.02	0.00–0.18	0.00	0.00–0.05
Tmax	0.05	0.00–0.29	0.11	0.00–0.37	0.07	0.00–0.29	0.01	0.00–0.09
Tmean + Prec	0.34	0.04–0.62	0.16	0.01–0.47	0.22	0.02–0.41	0.28	0.04–0.55
Tmax + Prec	0.33	0.04–0.62	0.17	0.02–0.63	0.21	0.02–0.41	0.24	0.03–0.54
1981–2010								
Prec	0.44	0.14–0.66	0.62	0.39–0.78	0.62	0.29–0.79	0.37	0.08–0.62
Prec-PET	0.51	0.22–0.72	0.64	0.55–0.83	0.69	0.34–0.83	0.44	0.13–0.69
SPEI1	0.50	0.20–0.70	0.62	0.35–0.78	0.64	0.34–0.82	0.42	0.12–0.69
Tmean	0.48	0.17–0.73	0.50	0.26–0.66	0.51	0.26–0.70	0.38	0.07–0.61
Tmax	0.59	0.30–0.79	0.64	0.40–0.76	0.62	0.38–0.77	0.49	0.19–0.71
Tmean + Prec	0.55	0.23–0.76	**0.70**	0.46–0.81	**0.75**	0.47–0.87	0.46	0.14–0.68
Tmax + Prec	**0.60**	0.28–0.78	0.69	0.43–0.79	0.74	0.44–0.87	**0.50**	0.17–0.71

Prec, May–August precipitation sum (mm); *Prec-PET*, May–August precipitation sum minus May–August sum of potential evapotranspiration (mm); *SPEI1*, May–August drought index; *Tmean*, May–August mean temperature (C°); *Tmax*, May–August maximum temperature (C°); significant association: (CI > 0.00). Data source: KSH, OMSZ and CRU TS 4.07

(Fig. 6, SI Table S5). On the basis of the significant statistical relationship between Prec-PET and maize yields over 1951–1980, the decreasing water deficit from 1921–1950 to 1951–1980 (Fig. 2; SI Table S1) may have resulted a significant yield increase by region.

Discussion and conclusions

The long-term data analysed indicated a non-significant decrease in water deficit as well as an increase in spring and summer temperatures, and also in precipitation from 1921–1950 to 1951–1980. A subsequent combination of a significantly increasing water deficit, rising mean and maximum temperature from 1951–1980 to 1981–2010, and a non-significant increase in precipitation sums—taken together, these describe the main temporal processes of the climatic indices studied. Winter mean temperatures did not show a corresponding trend; they grew steadily over the 90 years studied (SI Table S2). As a result, temperature and water deficit had a decisive impact on wheat and maize yield variances, respectively (Tables 2 and 3), so much so that the $Tmean_{May–July} + Temp_{Jan–March}$ combined predictor explained 49 to 66% of wheat yield variances, while the $Tmean_{May–Aug} + Prec_{May–Aug}$ combined predictor and Prec-PET fluctuations accounted for 44 to 75% of interannual maize yield variance over the period 1981–2010 (Tables 2 and 3). During 1981–2010, warming May–August temperature, together with the decrease in precipitation, may have caused an estimated yield loss of 11.1–12.4% year^{-1} in maize, while warming may have reduced wheat yields an estimated 9.4–14.4% (Fig. 6, SI Table S1, S5). However, the observed positive impact of increasing January–March mean temperatures on wheat yields mitigated this negative impact by an estimated 16–34% (Fig. 6, SI Table S1, S5). This finding is in line with the results of recent studies underlining

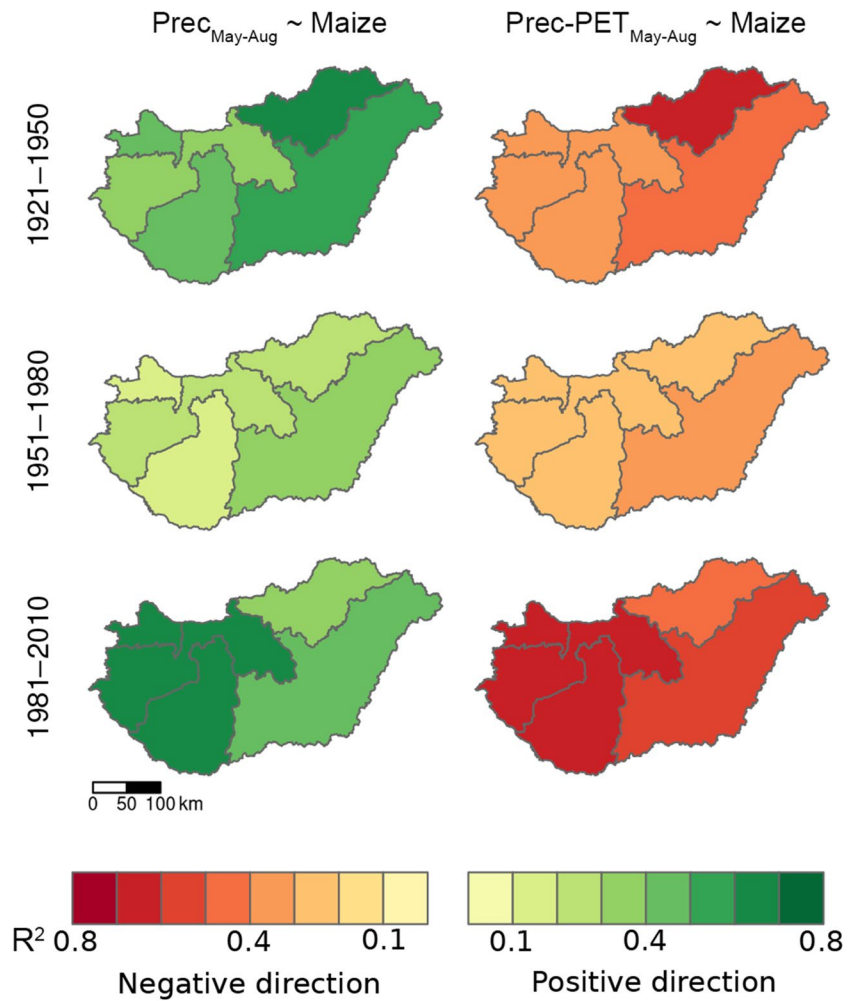**Fig. 4** Coefficients of determination (R^2) between the first-differences of climatic factors and maize yields (t ha^{-1}) in the croplands of the bioclimatic regions of Hungary for 1921–1950, 1951–1980 and 1981–2010. Prec, May–August precipitation sum (mm); Prec-PET, May–August precipitation sum (mm) minus May–August sum of potential evapotranspiration (mm). Positive and negative directions indicate if deterministic relationship is positive or negative. Data source: KSH, OMSZ and CRU TS 4.07, software: QGIS 3.10

Fig. 5 Coefficients of determination (R^2) between the first-differences of the combined climatic factors and wheat and maize yields (t ha^{-1}) in the bioclimatic regions of Hungary for 1981–2010. Tmean, mean temperature (C°); Prec, precipitation sum (mm). Bold letters indicate the dominant factor. Positive and negative directions indicate if deterministic relationship is positive or negative. Data source: KSH and OMSZ, software: QGIS 3.10
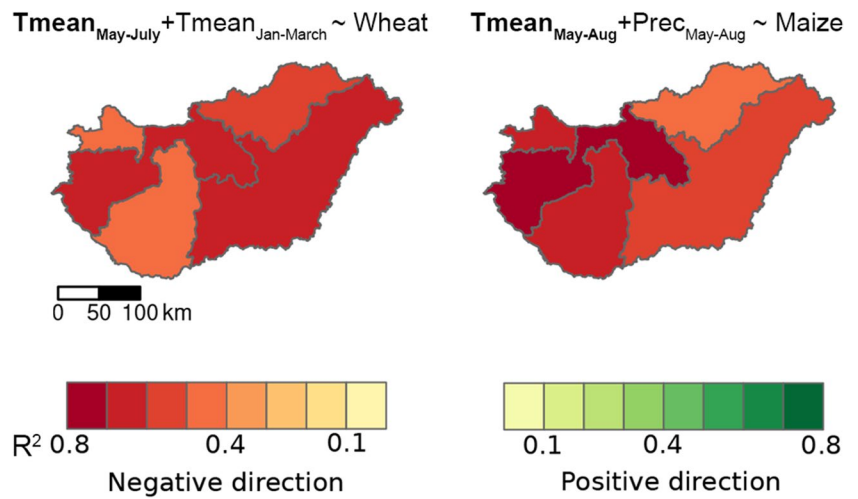
the prediction that frost-prone agricultural zones will benefit from a warming climate (Gaeva et al. 2023, Pavlova and Karachenkova 2023). Beyond these developments, we found that the range of regional sensitivity of wheat yields to

May–July mean temperature, the dominant climatic driver, did not display substantial differences between the first period (1921–1950) and the 'climate change affected' period (1981–2010) (Table 3). A similar pattern was observed in
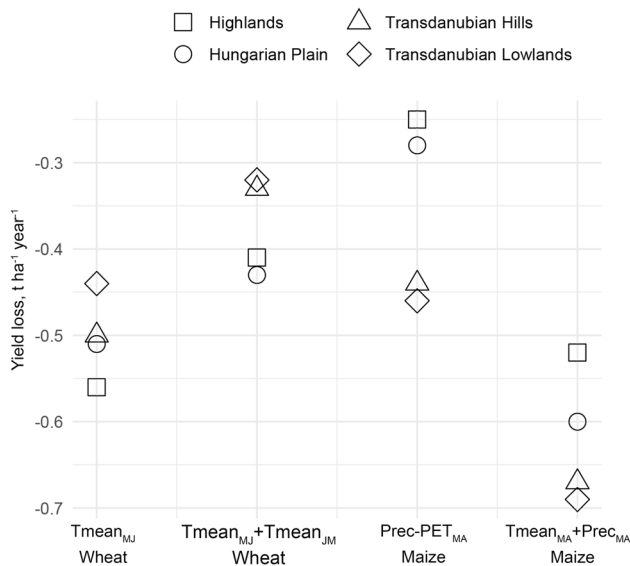
Fig. 6 Estimated impact of changing mean temperature ($\Delta°C$) and water deficit (Δmm) on wheat and maize yield from 1951–1980 to 1981–2010. $Tmean_{MJ}$, May–July mean temperature (C°); $Tmean_{JM}$, May–July mean temperature (C°); $Prec\text{-}PET_{MA}$, May–August precipitation sum minus May–August sum of potential evapotranspiration (mm); $Tmean_{MA}$, May–August mean temperature (C°); $Prec_{MA}$, May–August precipitation sum (mm). Data source: KSH, OMSZ and CRU TS 4.07

case of May–August precipitation, the dominant climatic driver of maize in 1921–1950 (Table 3).

The most suitable climate conditions for grain production, the mildest temperatures, the highest precipitation and the smallest water deficit were found in the Transdanubian Lowlands, and indeed the highest yields in the country were harvested in this region (Fig. 2; SI Table S1). In contrast, yields in the Hungarian Plain, where the warmest summer temperature, lowest precipitation sums and highest water deficit were observed, slid down the regional rank lists of wheat productivity (Fig. 2; SI Table S1). In the meantime, the sensitivity of wheat yield to May–July mean temperature shifted dynamically from the western part of the country to the Hungarian Plain (where a more continental climate prevails) from 1921–1950 to 1981–2010. Other studies also underline the higher climatic sensitivity of wheat production in drier landscapes situated in the steppe/prairie zone under continental climate conditions (Huang et al. 2017; IPCC 2019), especially due to rapid transformations in regional climate regimes in Europe (Liu et al. 2019; Bognar et al. 2022). Since a noticeable technological gap between the studied bioclimatic regions could not be presumed, only environmental conditions, e.g. the aggregate and interconnected impact of soil and (changing) soil water and climatic conditions could have caused the observed divergence in the regional wheat productivity. And indeed, the highest spring and summer values of temperature and Prec-PET variables, and relatively

low precipitation sums (Fig. 2; SI Table S1, S2), a dynamic lowering of the groundwater table (Garamhegyi et al. 2018) and the lowest soil productivity (Table 1), were observed in the Hungarian Plain. We also hypothesise that the changing agro-suitability of arable lands as a consequence of regionally different dynamics in land use change could be another explanatory factor in this changing yield rank position. Soil databases often have to grapple with uncertainties stemming from factors such as the spatial variability of soils, limited sampling density or methodology and diverse soil properties (Dai et al. 2019; Gupta et al. 2021). These uncertainties can challenge the accuracy and reliability of soil-related information, impacting research, practice and decision-making processes in agriculture, environmental management and land use planning. Addressing these uncertainties is essential to improve the accuracy of research founded on soil databases. These questions illuminate the limitation of this research and point to the necessity of more complex regional analyses. We also need to consider another limitation of the monthly averages of climatic parameters since a few days of extreme (hydro)climatic events frosts, droughts, heatwaves, etc. can explain a greater part of yield variances than the averages of the vegetation period or a major part of the vegetation period (Schauberger et al. 2021). Nonetheless, our results supplement previous findings on the regional pattern of crop yield-climate relationship, illuminating the increasing vulnerability of lowland landscapes to a warming climate, and especially the increasing frequency and severity of heatwaves and drought events of the kind seen in 2022.

Both the rapidly growing sensitivity of wheat and maize yields to warming and water limitation have become more dominant in recent years (Fiala et al. 2014; Fuzi and Ladanyi 2022), and may yet become more frequent according to climate model simulations (Toreti et al. 2019). The combination of landscape conditions and climate water deficit constitute a clear alarm signal, urging the implementation of a climate-smart land use system in Hungary, and especially in the lowlands. To mitigate further consequences of the climate crisis, there is a wide spectrum of adaptation options, e.g. moisture conservation measures, such as no-till cultivation (Jakab et al. 2017), mulching, increasing soil water storage capacity through improving soil porosity, infiltration and soil hydraulic conductivity (Madarasz et al. 2018), a change in crop-rotation (Brisson et al. 2010) and water harvesting (Reznik et al. 2017). Beyond these agroecological solutions, the direction of land use change needs to be turned back on the so-called marginal lands via combined land use solutions (e.g. agroforestry and cultivation of periodically inundated areas Opperman et al. 2009; Serra-Llobet et al. 2022), and restoration of reclaimed ecosystems (IPCC 2019; European Commission 2020), and degraded lands (Arneth et al. 2021)). In this context, one of the most critical ecosystems is wetlands, since the area loss of natural wetlands

is exceptionally large across CEE countries and wetlands were converted primarily to croplands (Fluet-Chouinard et al. 2023), especially in Hungary, where 97% of the wetlands, which covered an estimated one-third of the plains, were converted into agricultural areas (Schleupner and Schneider 2012; Nemeth et al. 2021). Wetlands are crucial ecosystems in supporting biochemical and hydrological cycles, as well as biodiversity (Tan et al. 2020), or in mitigating impacts from diffuse agricultural loads (Hatvani et al. 2022). Their restoration has benefits not only for biodiversity but via active interactions between surface waters and shallow groundwater for agriculture and forestry too (Levintal et al. 2023; Pepliński 2023). Thus, wetland restoration is increasingly being considered a key step towards the achievement of climate mitigation goals (Verhoeven 2014). Taking this avenue, the European Union is setting its sights on restoring 25,000 km of its rivers with their floodplains (European Commission 2020).

Declarations

Ethical approval Not applicable.

Competing interests The authors declare no competing interests.

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