Supplementary material to Pinke et al. (2024) Continental lowlands face rising crop vulnerability: structural change in regional climate sensitivity of crop yields, Hungary (Central and Eastern Europe), 1921–2010. Regional Environmental Change

To identify and delimit the geographical regions for a comparative investigation, cluster analysis using Ward's method and squared Euclidean distance was carried out with the 5-y average of wheat and maize yields of the counties between 1921 and 2010 as variables. Calculation was carried out using SPSS 23 (REF). The results were visualised on dendrograms to identify the composition of groups properly (Figure S5, S9). In order to trace the temporal stability of the clusters, the time series were split, and the investigation was repeated for the three 30-y intervals (1921–1950; 1951–1980; 1981–2010) defined previously (Fig. S2–S4 and S6–S8).

The results show, that:

1. The cluster analysis resulted in different territorial sub-groups in the case of wheat and maize referring to different ecological characters of wheat and maize (Figure S5, S9).

2. Clusters did not display temporal stability for the three 30-y periods; this refers to differentiation in technical advance and changing climatic conditions (Figure S1 and Figures S2–S4 / S6–S8).

We therefore concluded that stable and homogeneous regions of wheat and maize production couldn't be delimited based solely on one variable, i.e. the yield, as its spatial pattern showed great variance over time. For this reason, other indicators were also included in the investigation to delimit regions (shown on Table S1).

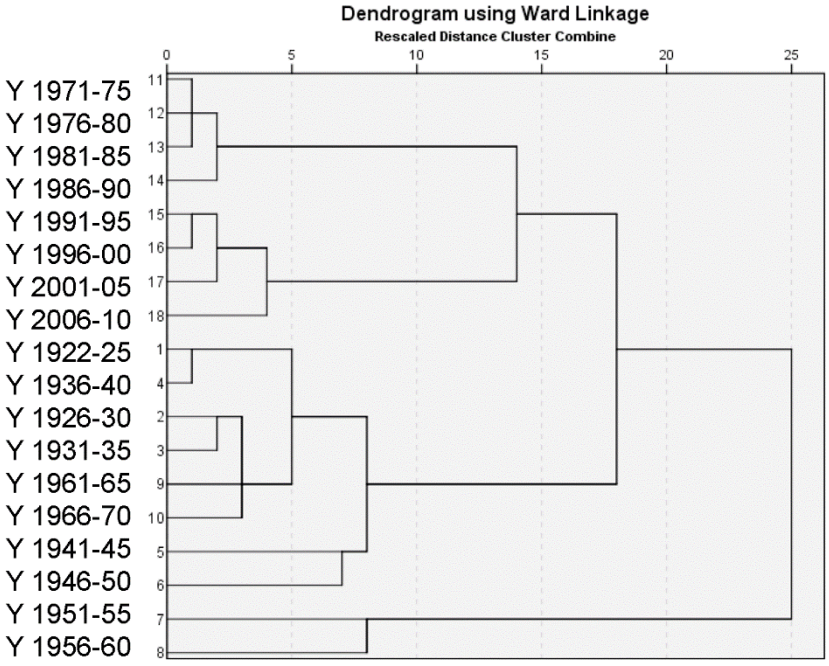

Fig. S1 Similarities and differences of 5-year intervals based on the wheat production of the counties for 1921–2010

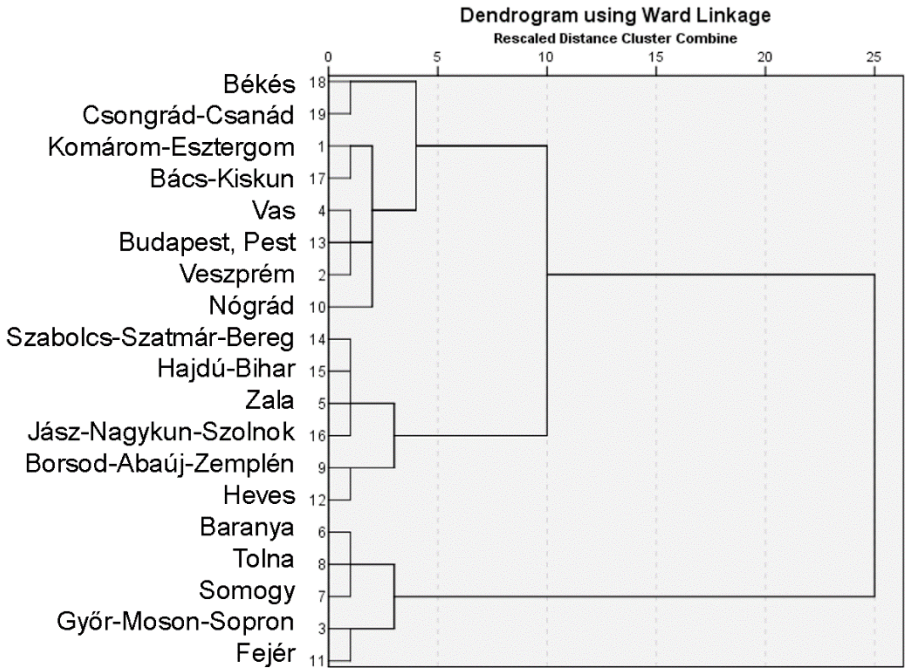

Fig. S2 Dendrogram indicating similarities and differences between the counties of Hungary for wheat yields based on the 5-year averages for 1921–1950

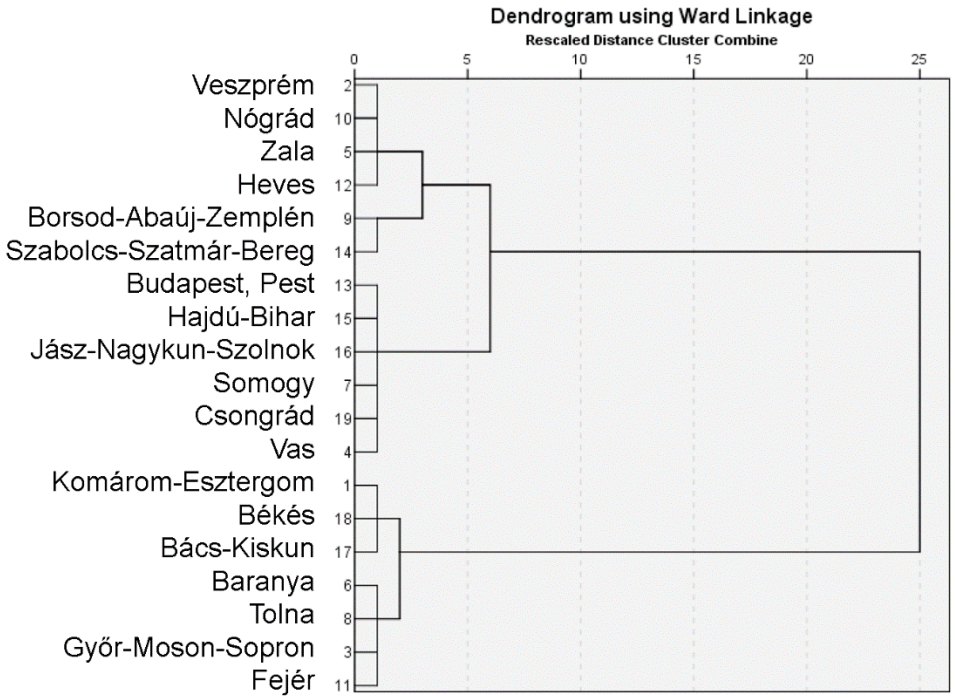

Fig. S3 Dendrogram indicating similarities and differences between the counties of Hungary for wheat yields based on the 5-year averages for 1951–1980

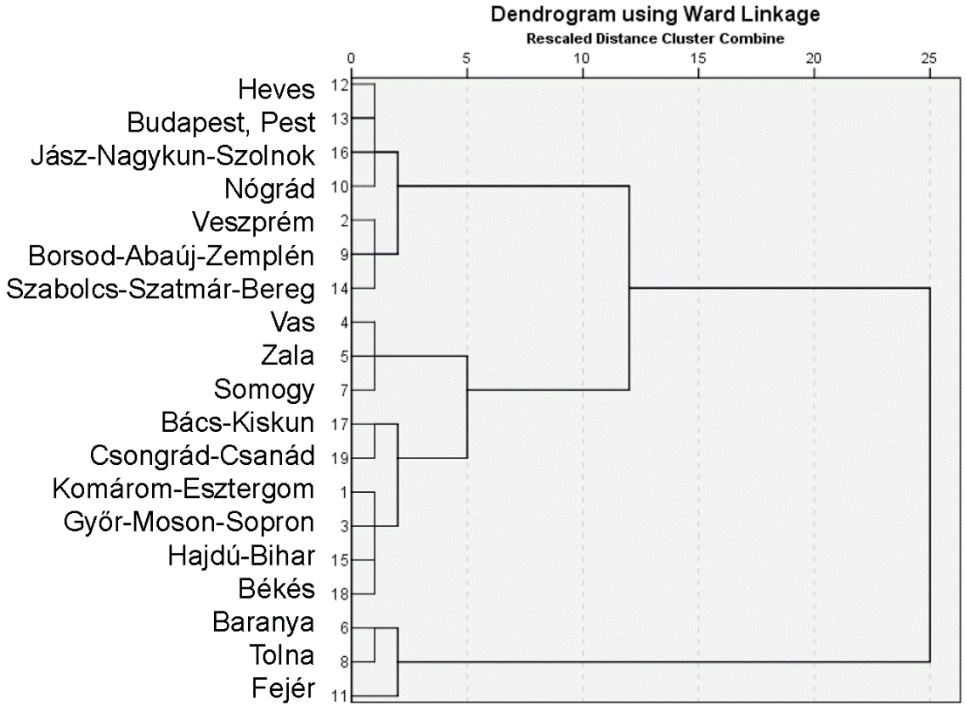

Fig. S4 Dendrogram indicating similarities and differences between the counties of Hungary for wheat yields based on the 5-year averages of 1981–2010

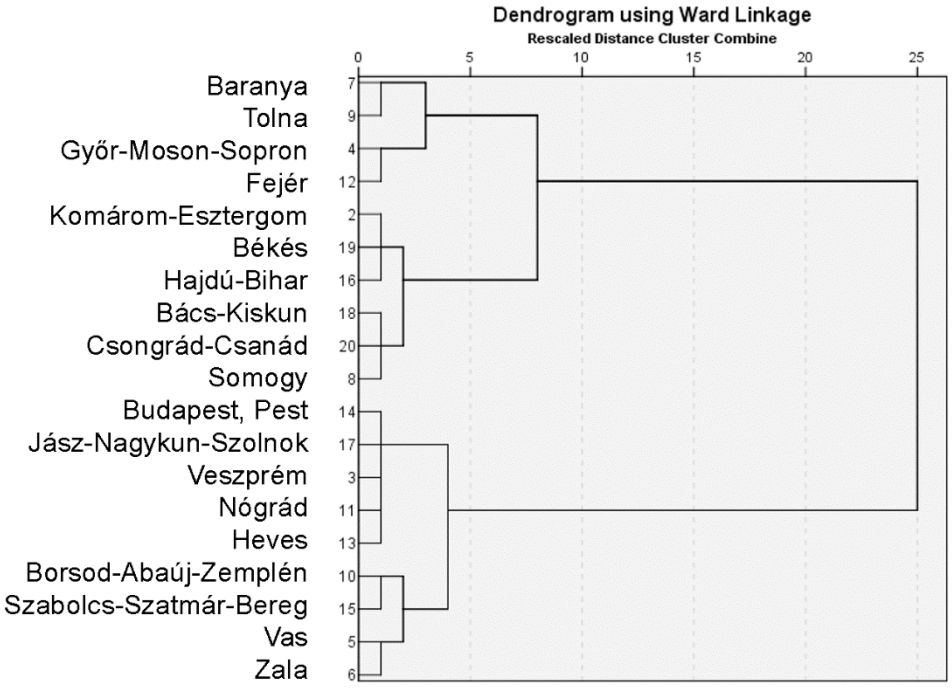

Fig. S5 Dendrogram indicating similarities and differences between the counties of Hungary for wheat yields based on the 5-year averages for 1921–2010

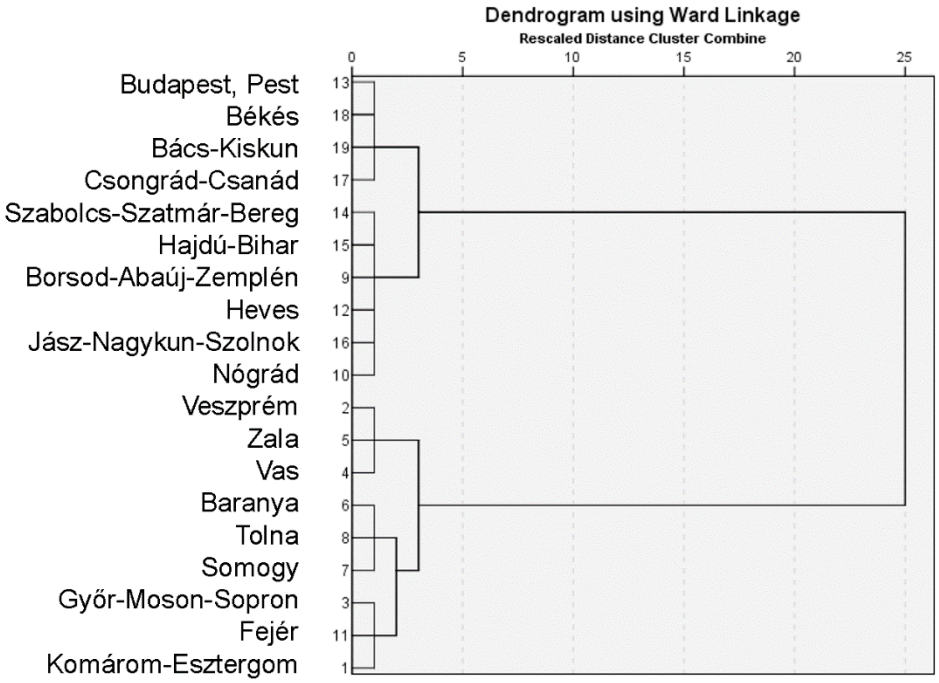

Fig. S6 Dendrogram indicating similarities and differences between the counties of Hungary for maize yields based on the 5-year averages for 1921–1950

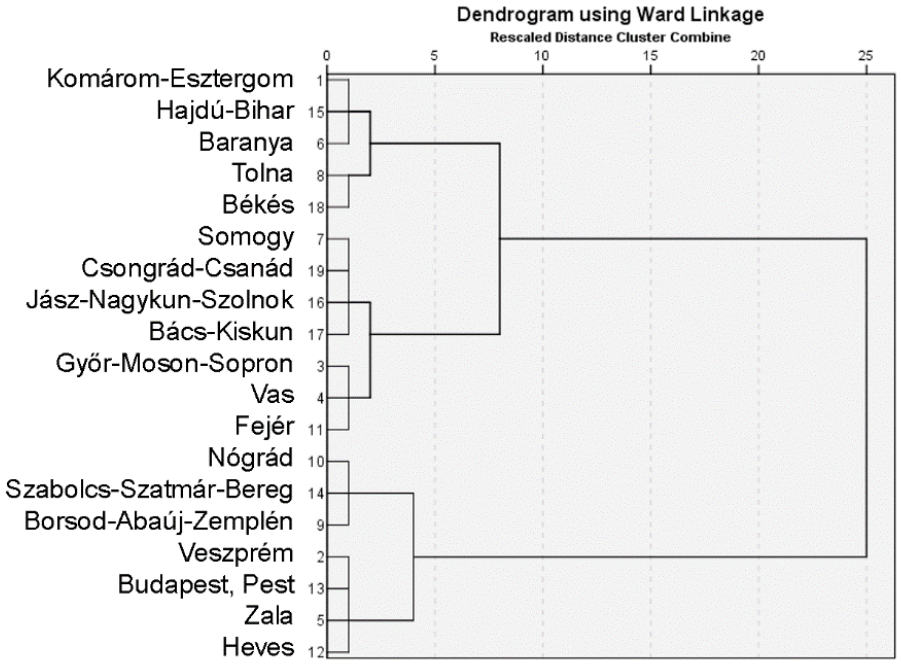

Fig. S7 Dendrogram indicating similarities and differences between the counties of Hungary for maize yields based on the 5-year averages for 1951–1980

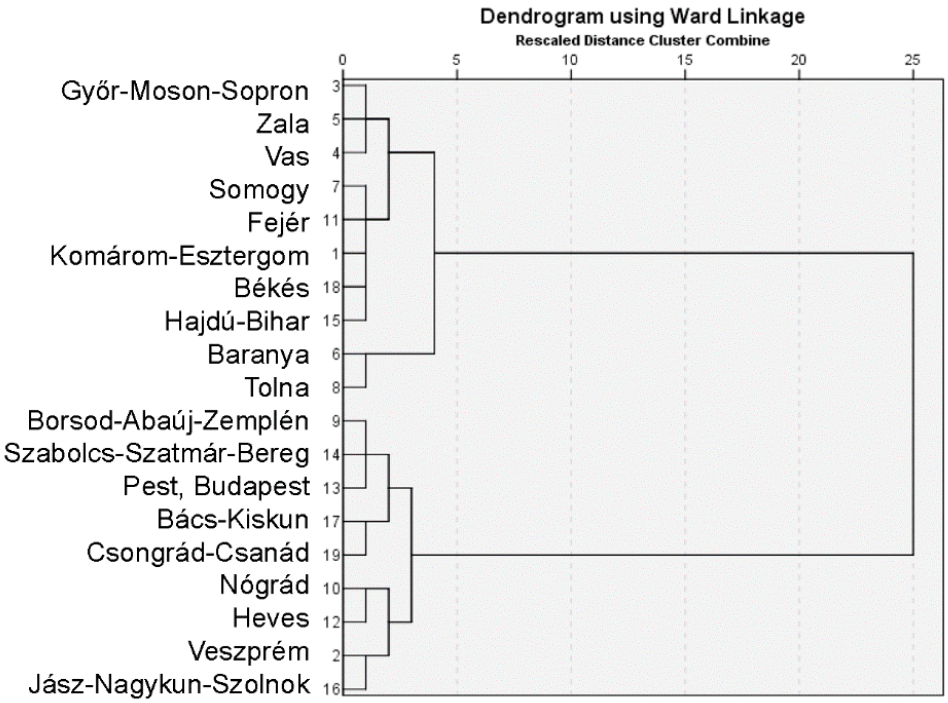

Fig. S8 Dendrogram indicating similarities and differences between the counties of Hungary for maize yields based on the 5-year averages for 1981–2010

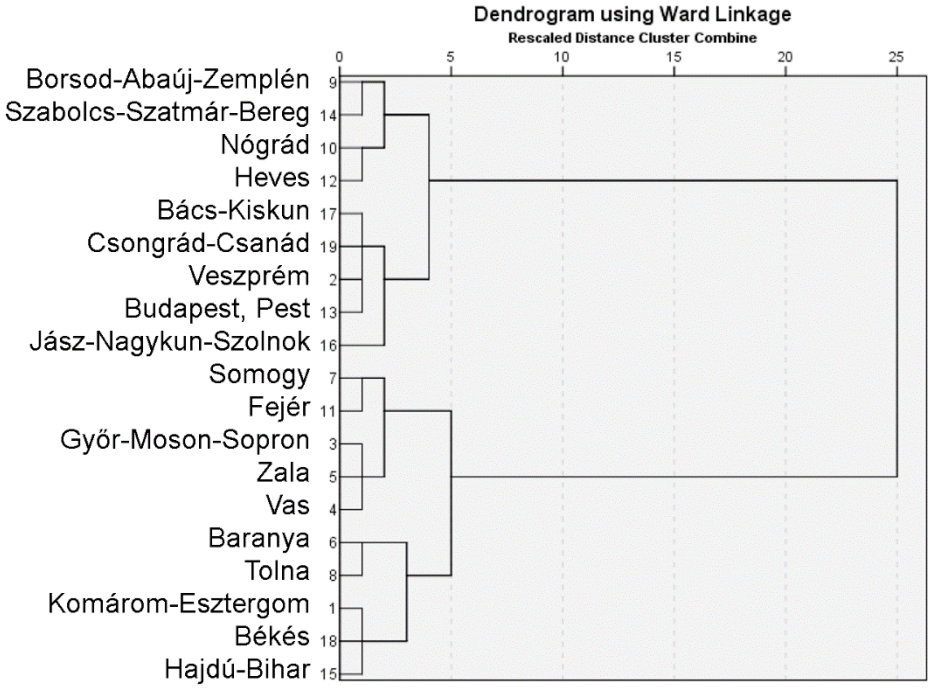

Fig. S9 Dendrogram indicating similarities between the counties of Hungary for maize yields based on the 5-year averages for 1921–2010

Table S1 Yield averages (t ha^{-1} ± SD) of wheat and maize, mean monthly temperatures during January–March and May–August and precipitation during February–July and May–August in four agroecological regions of Hungary for three 30-y periods between 1921 and 2010.

	1921–1950	1951–1980	1981–2010	1921–1950	1951–1980	1981–2010
	Wheat, t ha^{-1}			Maize, t ha^{-1}		
Hungarian Plain	1.2 ± 0.1	2.2 ± 0.5*	3.7 ± 0.4*	1.4 ± 0.2	2.8 ± 0.5*	4.9 ± 0.5*
Transdanubian Lowlands	1.5 ± 0.1	2.6 ± 0.6*	4.7 ± 0.3*	2.0 ± 0.2	3.4 ± 0.6*	6.2 ± 0.7*
Transdanubian Hills	1.3 ± 0.1	2.4 ± 0.5*	4.0 ± 0.3*	1.7 ± 0.2	3.0 ± 0.5*	5.4 ± 0.6*
Highlands	1.1 ± 0.1	2.2 ± 0.4*	3.9 ± 0.4*	1.4 ± 0.2	2.7 ± 0.4*	4.6 ± 0.6*
	Mean temperature$_{May–July}$, °C			Maximum temperature$_{May–August}$, °C		
Hungarian Plain	18.7 ± 0.5	18.4 ± 0.4	19.3 ± 0.5*	25.8 ± 0.6	25.0 ± 0.6*	26.1 ± 0.6*
Transdanubian Lowlands	17.7 ± 0.5	17.6 ± 0.4	18.7 ± 0.5*	24.3 ± 0.6	23.7 ± 0.4*	24.9 ± 0.6*
Transdanubian Hills	17.8 ± 0.5	17.6 ± 0.4	18.8 ± 0.5*	24.9 ± 0.6	24.2 ± 0.5*	25.4 ± 0.6*
Highlands	18.6 ± 0.5	18.4 ± 0.4	19.3 ± 0.5*	25.6 ± 0.6	24.8 ± 0.4*	25.9 ± 0.6*
	Precipitation$_{February–July}$, mm			Precipitation$_{May–August}$, mm		
Hungarian Plain	282 ± 33	288 ± 36	288 ± 37	228 ± 35	244 ± 35	239 ± 36
Transdanubian Lowlands	340 ± 33	364 ± 40	334 ± 34	269 ± 38	298 ± 35	293 ± 35
Transdanubian Hills	304 ± 33	314 ± 34	295 ± 34	258 ± 33	275 ± 32	266 ± 36
Highlands	286 ± 35	293 ± 30	295 ± 38	230 ± 36	249 ± 36	243 ± 37
	Precipitation−PET$_{February–July}$, mm			Precipitation−PET$_{May–August}$, mm		
Hungarian Plain	−245±43	−223±41	−253±47	−272±44	−237±47	−271±49
Transdanubian Lowlands	−171±43	−137±47	−205±45*	−212±49	−167±42	−209±47*
Transdanubian Hills	−200±41	−180±42	−237±45*	−215±43	−183±40	−229±48*
Highlands	−214±44	−194±42	−218±46	−239±45	−205±47	−236±48

SD: standard deviation; PET: potential evapotranspiration; *Significant difference from the previous period ($p < .05$) using Welch t-test. Source: KSH 2023, OMSZ 2022, CRU TS 4.07.

Table S2 Winter (October–March) and summer (April–September) half years, as well as annual averages of mean monthly temperature (± S.D.) and sums of precipitation in four agroecological regions of Hungary for three 30-y periods between 1921 and 2010

Regions	1921–1950	1951–1980	1981–2010
	Mean temperature, °C		
	Year		
Hungarian Plain	10.2 ± 0.4	10.2 ± 0.3	10.8* ± 0.4
Transdanubian Lowlands	9.7 ± 0.4	9.7 ± 0.3	10.5* ± 0.4
Transdanubian Hills	9.6 ± 0.4	9.7 ± 0.3	10.5* ± 0.4
Highlands	9.9 ± 0.4	10.1 ± 0.3	10.7* ± 0.4
	October–March		
Hungarian Plain	3.1 ± 0.7	3.4 ± 0.5	3.7 ± 0.6
Transdanubian Lowlands	2.7 ± 0.6	3.1 ± 0.5	3.7* ± 0.6
Transdanubia, hills	2.9 ± 0.7	3.3 ± 0.5	3.8* ± 0.6
Highlands	2.7 ± 0.7	3.2 ± 0.5	3.6 *± 0.6
	April–September		
Hungarian Plain	17.3 ± 0.4	17.1 ± 0.4	17.9* ± 0.4
Transdanubian Lowlands	16.3 ± 0.4	16.3 ± 0.3	17.1 *± 0.4
Transdanubia, hills	16.3 ± 0.4	16.4 ± 0.3	17.3* ± 0.4
Highlands	17.0 ± 0.4	17.1 ± 0.3	17.7* ± 0.4
	May–August		
Hungarian Plain	19.1 ± 0.5	18.8 ± 0.3	19.8* ± 0.5
Transdanubian Lowlands	18.2 ± 0.5	18.1 ± 0.3	19.2* ± 0.5
Transdanubia, hills	18.2 ± 0.4	18.0 ± 0.3	19.2* ± 0.5
Highlands	18.9 ± 0.5	18.8 ± 0.4	19.8* ± 0.5
	January–March		
Hungarian Plain	0.9 ± 1.1	1.2 ± 1.0	1.9 ± 1.0
Transdanubian Lowlands	1.2 ± 1.1	1.6 ± 0.9	2.4 ± 1.0
Transdanubia, hills	0.9 ± 1.0	1.2 ± 0.9	2.1 ± 1.0
Highlands	0.6 ± 1.1	1.1 ± 1.0	1.9 ± 1.0
	Precipitation, mm		
	Year		
Hungarian Plain	544 ± 49	537 ± 44	536 ± 48
Transdanubian Lowlands	654 ± 53	632 ± 44	623 ± 44
Transdanubia, hills	587 ± 51	581 ± 44	569 ± 46
Highlands	549 ± 47	549 ± 49	548 ± 53
	October–March		
Hungarian Plain	179 ± 23	171 ± 20	163 ± 18
Transdanubian Lowlands	283 ± 38	255 ± 32	240 ± 23
Transdanubia, hills	155 ± 21	149 ± 16	145 ± 16
Highlands	155 ± 20	152 ± 17	146 ± 17
	April–September		
Hungarian Plain	263 ± 27	262 ± 27	263 ± 32
Transdanubian Lowlands	369 ± 40	379 ± 38	377 ± 38
Transdanubia, hills	294 ± 26	289 ± 27	278 ± 25
Highlands	256 ± 28	250 ± 29	255 ± 27

*Significant difference from the previous period ($p < .05$) using Welch t-test. SD = standard deviation.
Source: OMSZ

Table S3 Differences between annual mean temperature and precipitation sums in four agroecological regions of Hungary for three 30-y periods between 1921 and 2010, Welch t values/p-values (df = 29)

	Hungarian Plain	Transdanubia Lowlands	Transdanubia Hills	Highlands
	Annual precipitation sums, mm			
	1921–1950			
Hungarian Plain	1	<0.01	<0.01	0.48
Transdanubia Lowlands	8.71	1	<0.01	<0.01
Transdanubia Hills	3.24	-6.22	1	<0.01
Highlands	0.71	-10.93	3.12	1
	1951–1980			
Hungarian Plain	1	<0.01	<0.01	0.37
Transdanubia Lowlands	6.24	1	<0.01	<0.01
Transdanubia Hills	2.28	-5.11	1	0.03
Highlands	0.90	-7.96	2.6	1
	1981–2010			
Hungarian Plain	1	<0.01	<0.01	0.02
Transdanubia Lowlands	5.89	1	<0.01	<0.01
Transdanubia Hills	2.47	-5.24	1	<0.01
Highlands	2.47	-5.02	2.3	1
	Annual average of mean temperature, °C			
	1921-1950			
Hungarian Plain	1	<0.01	<0.01	<0.01
Transdanubia Lowlands	15.35	1	<0.01	<0.01
Transdanubia Hills	19.71	-3.75	1	<0.01
Highlands	23.16	6.05	9.82	1
	1951–1980			
Hungarian Plain	1	<0.01	<0.01	<0.01
Transdanubia Lowlands	13.63	1	0.45	<0.01
Transdanubia Hills	12.84	-0.77	1	<0.01
Highlands	11.02	11.16	10.86	1
	1981–2010			
Hungarian Plain	1	<0.01	<0.01	<0.01
Transdanubia Lowlands	5.43	1	0.51	<0.01
Transdanubia Hills	7.28	0.67	1	<0.01
Highlands	4.78	11.795	5.51	1

Source: OMSZ

Table S4 Differences between regional wheat and maize yield averages in four agroecological regions of Hungary for three 30-y periods between 1921 and 2010, Welch t values/p-values (df = 29)

	Hungarian Plain	Transdanubia Lowlands	Transdanubia Hills	Highlands
	Wheat, t ha^{-1}			
	1921–1950			
Hungarian Plain	1	<0.01	0.03	0.13
Transdanubia Lowlands	-6.54	1	<0.01	<0.01
Transdanubia Hills	-2.26	-10.87	1	<0.01
Highlands	1.55	-8.55	-4.17	1
	1951–1980			
Hungarian Plain	1	<0.01	<0.01	0.37
Transdanubia Lowlands	-8.86	1	<0.01	<0.01
Transdanubia Hills	-5.15	-6.01	1	<0.01
Highlands	0.90	-7.96	6.76	1
	1981–2010			
Hungarian Plain	1	<0.01	<0.01	<0.01
Transdanubia Lowlands	-16.26	1	<0.01	<0.01
Transdanubia Hills	13.78	-6.85	1	<0.01
Highlands	-3.64	11.795	9.34	1
	Maize, t ha^{-1}			
	1921-1950			
Hungarian Plain	1	<0.01	<0.01	0.06
Transdanubia Lowlands	-13.87	1	<0.01	<0.01
Transdanubia Hills	-10.22	-11.71	1	<0.01
Highlands	-1.94	-12.61	-8.60	1
	1951–1980			
Hungarian Plain	1	<0.01	<0.01	0.13
Transdanubia Lowlands	-10.83	1	<0.01	<0.01
Transdanubia Hills	-7.08	-7.18	1	<0.01
Highlands	1.55	-6.58	-5.32	1
	1981–2010			
Hungarian Plain	1	<0.01	<0.00	<0.01
Transdanubia Lowlands	-10.24	1	<0.01	<0.01
Transdanubia Hills	-5.09	-4.94	1	<0.01
Highlands	4.25	-12.13	-7.42	1

Source: KSH

Table S5 Estimated yield impact ($\Delta t\ ha^{-1}\ year^{-1}$) of changing mean temperature ($\Delta°C$) and water deficit (Δmm) from 1951–1980 to 1981–2010

	Wheat		
Region	Equation, $Tmean_{May\text{-}July}$~wheat yield	$x_1 = Tmean_{May\text{-}July}$, $\Delta°C$	Yield impact, $\Delta t\ ha^{-1}\ y^{-1}$
Hungarian Plain	$y=-0.5703x_1-0.0004$	0.9	-0.51
Transdanubian Lowlands	$y=-0.418x_1+0.0234$	1.1	-0.44
Transdanubian Hills	$y=-0.3297x_1+0.0085$	1.2	-0.50
Highlands	$y=-0.5703x_1-0.0004$	0.9	-0.56
	Equation, $Tmean_{May\text{-}July}+Tmean_{Jan\text{-}March}$ ~ wheat yield	$x_2 = Tmean_{Jan\text{-}March}$, $\Delta°C$	Yield impact, $\Delta t\ ha^{-1}\ y^{-1}$
Hungarian Plain	$y=0.00003+(-0.60097x_1)+(0.14167x_2)$	0.8	-0.43
Transdanubian Lowlands	$y=0.01794+(-0.42641x_1)+(0.16135x_2)$	0.8	-0.32
Transdanubian Hills	$y=0.03027+(-0.42641x_1)+(0.16465x_2)$	0.9	-0.33
Highlands	$y=0.02245+(-0.62839x_1)+(0.1718x_2)$	0.8	-0.41
	Maize		
	Equation, $Prec\text{-}PET_{May\text{-}Aug}$~ maize yield	$x = Prec\text{-}PET_{May\text{-}Aug}$, Δmm	Yield impact, $\Delta t\ ha^{-1}\ y^{-1}$
Hungarian Plain	$y=-0.8388x+0.0192$	-34	-0.28
Transdanubian Lowlands	$y=-0.418x+0.0234$	-42	-0.46
Transdanubian Hills	$y=0.0216x+0.0079$	-46	-0.44
Highlands	$y=-0.667x+0.0361$	-31	-0.25
	Equation, $Tmean_{May\text{-}Aug}+Prec_{May\text{-}Aug}$ ~ maize yield	$x_1 = Tmean_{May\text{-}Aug}$, $\Delta°C$; $x_2 = Prec_{May\text{-}Aug}$, Δmm	Yield impact, $\Delta t\ ha^{-1}\ y^{-1}$
Hungarian Plain	$y=-0.004760+(-0.567326x_1)+(0.005117x_2)$	1.0; -5	-0.60
Transdanubian Lowlands	$y=-0.010707+(-0.575951x_1)+(0.00904x_2)$	1.1; -5	-0.69
Transdanubian Hills	$y=0.002869+(-0.497103x_1)+(0.008771x_2)$	1.2; -9	-0.67
Highlands	$y=-0.009075+(-0.479266x_1)+(0.005074x_2)$	1.0; -6	-0.52

Tmean: mean temperature; Prec-PET: precipitation sum minus potential evapotranspiration sum; Prec: precipitation sum; y: yield change.