

Supplementary Materials:

Supplementary S1. Long-term trends of weather characteristics in the Great Hungarian Plain based on 120 years of meteorological data

We analyzed 120 years of data collected from two meteorological stations (Budapest and Szeged) using simple linear regression models (sources of data: https://odp.met.hu/climate/station_data_series/daily/from_1901/mean_temperature/, https://odp.met.hu/climate/station_data_series/daily/from_1901/precipitation_sum/).

In the case of precipitation, the data of both stations showed a decrease in the amount of annual precipitation; however, the regressions were significant only on the station's data in Budapest (Figures S1ab). At our stations in Budapest, precipitation decreased while temperature increased.

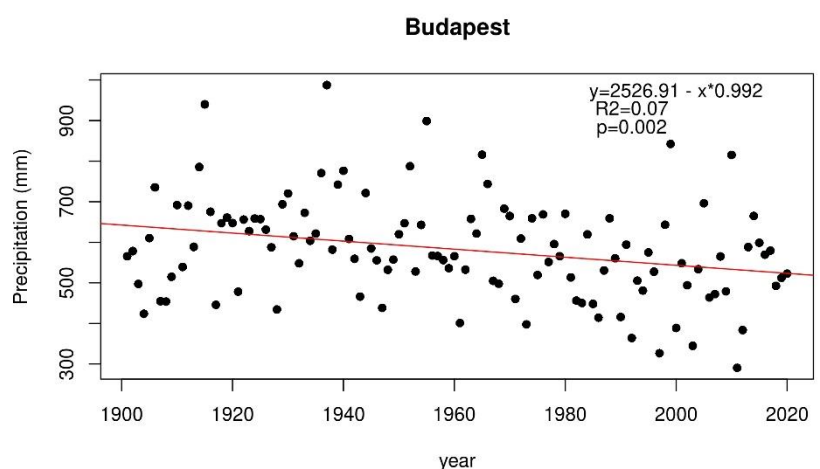


Figure S1a. Regression of the 120 years annual precipitation data in Budapest meteorological station.

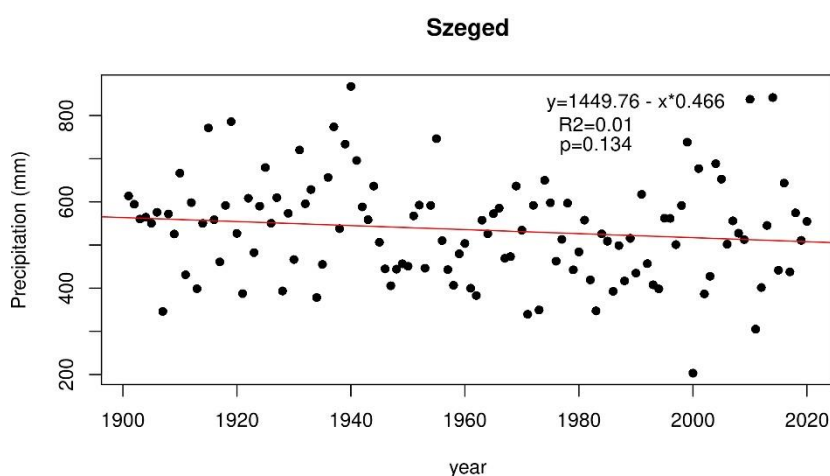


Figure S1b – Regression of the 120 years annual precipitation data in Szeged meteorological station.

The mean annual temperature data showed an increase in the mean annual temperature in both stations however, only the regression of Budapest station data was significant Budapest (Figures S1cd). The rise of the temperature was striking, especially since 2000.

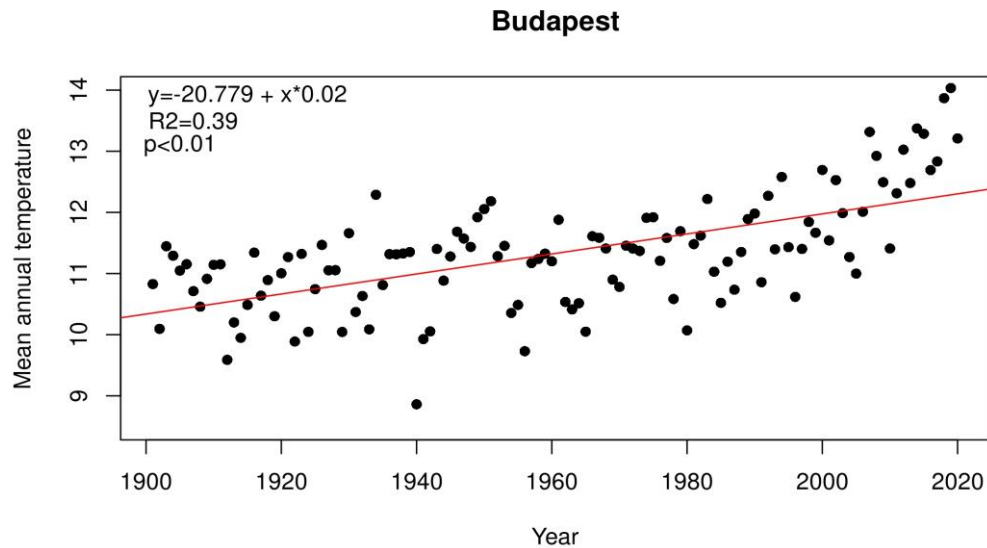


Figure S1c – Regression of the 120 years mean annual temperature data in Budapest meteorological station.

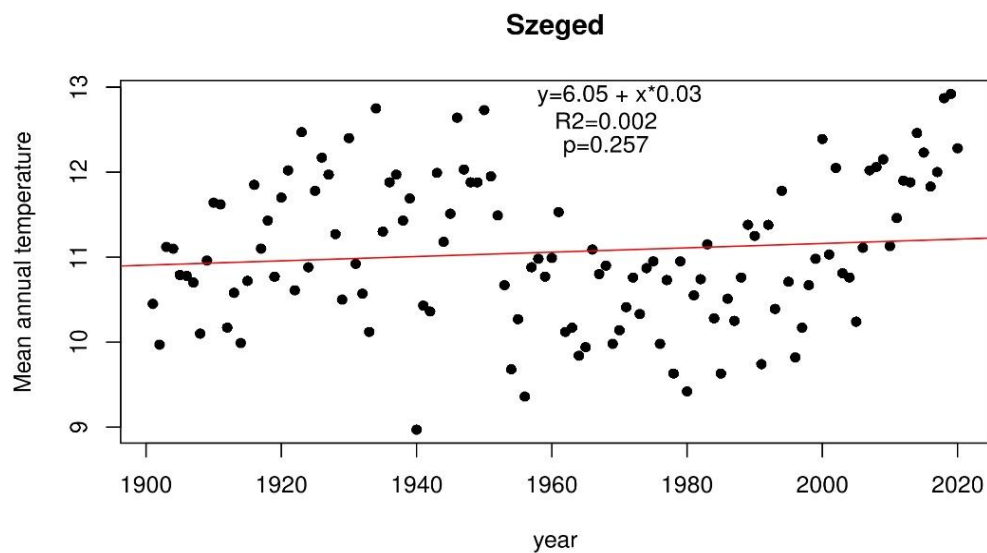


Figure S1d – Regression of the 120 years mean annual temperature data in Szeged meteorological station.

We divided the 120-year dataset into two parts: from 1901 to 1979 and from 1980 to 2020, and we calculated regression for both datasets separately.

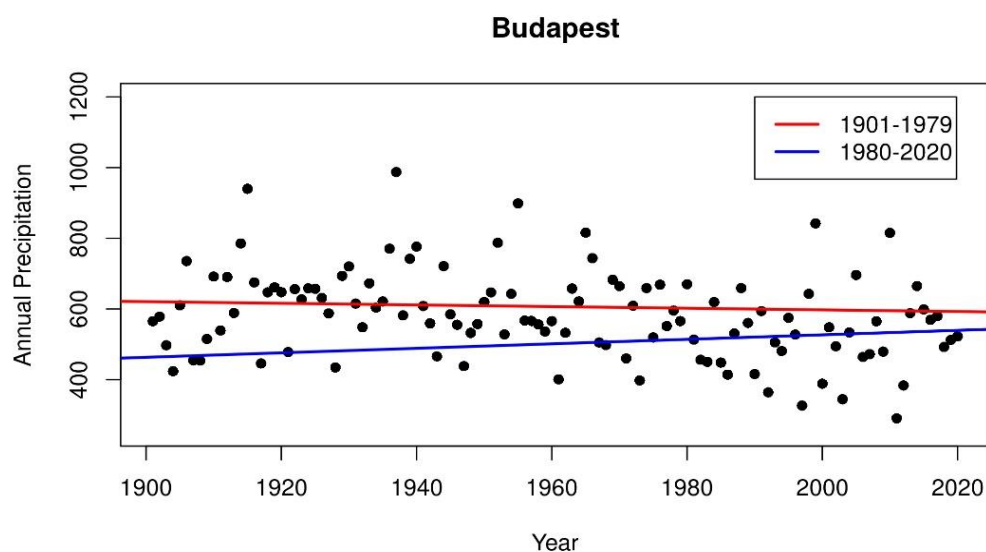


Figure S1e – Regression of the annual precipitation data in Budapest meteorological station. The red line shows the regression line for the 1901–1979 period ($y=1063.52 - 0.22x$, $R^2=-0.01$, $p=0.688$) and the blue line shows the 1980–2020 period ($y=-745.15 + 0.64x$, $R^2=-0.021$, $p=0.69$).

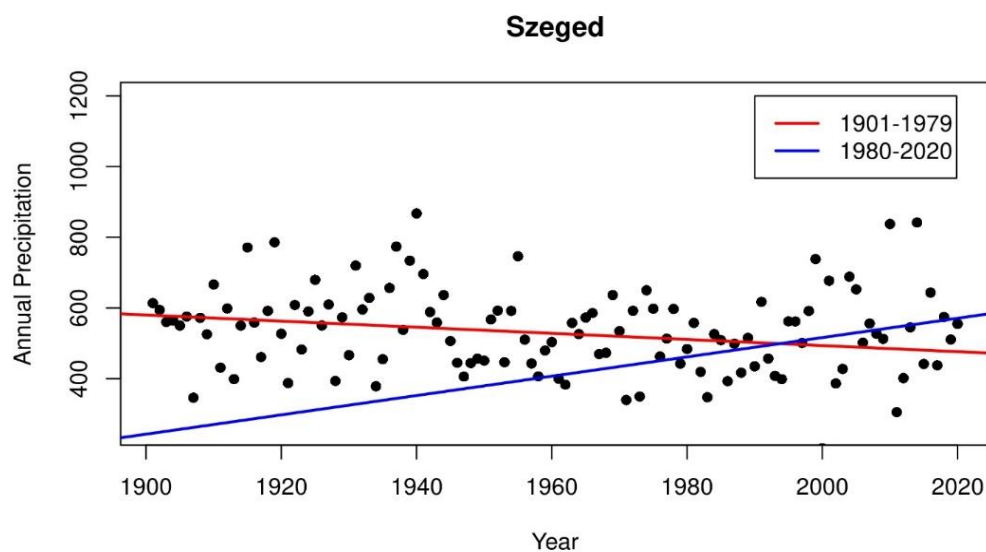


Figure S1f – Regression of the annual precipitation data in Szeged meteorological station. The red line shows the regression line for the 1901–1979 period ($y=2222.84 - 0.865x$, $R^2=0.02$, $p=0.114$) and the blue line shows the 1980–2020 period ($y=-4949.86 + 2.73x$, $R^2=0.04$, $p=0.11$).

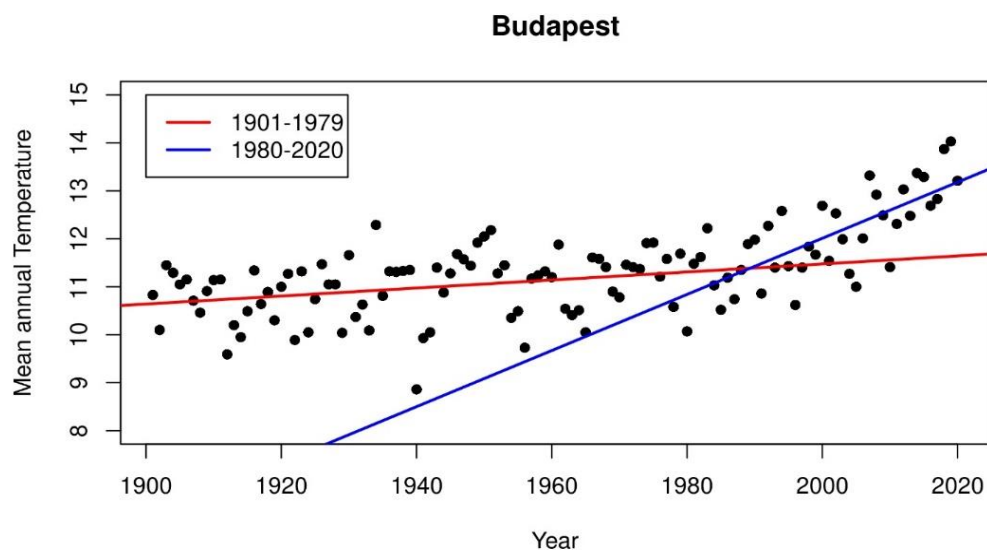


Figure S1g – Regression of the mean annual temperature data in Budapest meteorological station. The red line shows the regression line for the 1901-1979 period ($y = -5.24 + 0.008x$, $R^2 = 0.072$, $p = 0.0097$) and the blue line shows the 1980-2020 period ($y = -105 + 0.0585x$, $R^2 = 0.539$, $p < 0.0001$).

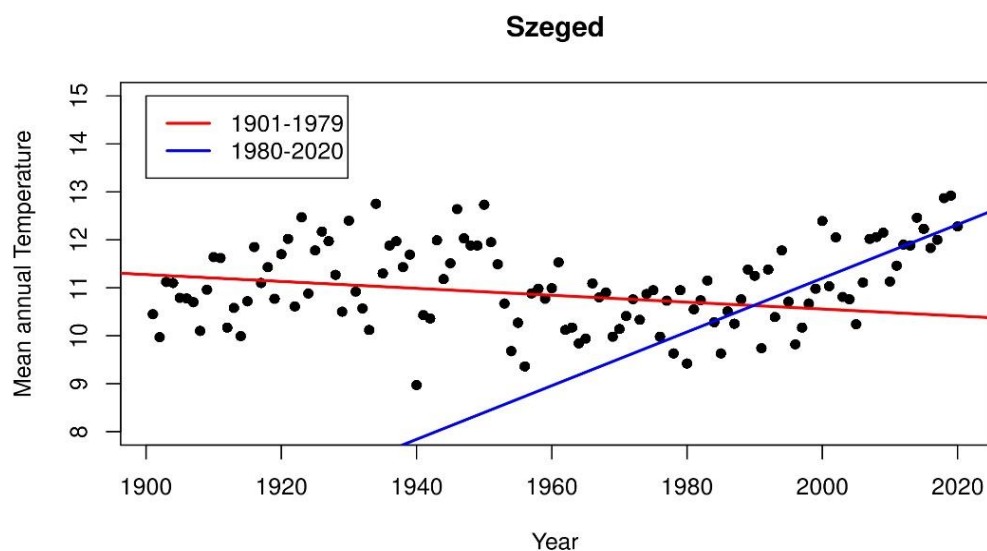


Figure S1h – Regression of the mean annual temperature data in Szeged meteorological station. The red line shows the regression line for the 1901-1979 period ($y = 24.94 - 0.007x$, $R^2 = 0.028$, $p = 0.075$) and the blue line shows the 1980-2020 period ($y = -100.8 + 0.056x$, $R^2 = 0.537$, $p < 0.0001$).

In Budapest, there were significantly increasing mean annual temperature trends for both periods (S1g). There was a slight and non-significant decrease in the first period and a steep and significant increase in the second one in Szeged (S1h).

We calculated the coefficient of variation (CV%) of both parameters (mean annual temperature and precipitation) by dividing the 120 years into 20 years periods. The results are shown in Table S1.

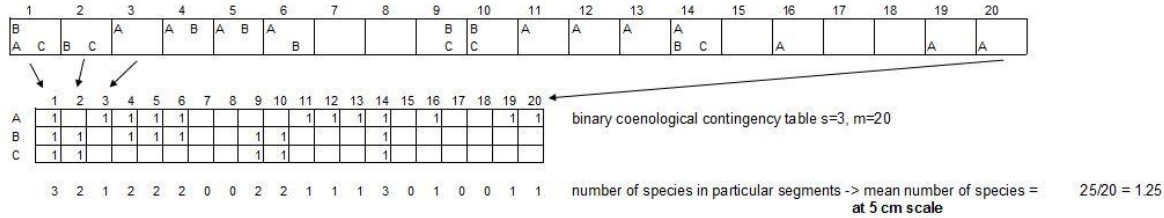
Table S1. Coefficient of variation (CV%) of the two meteorological stations' mean annual temperature and precipitation.

years	Budapest		Szeged	
	Mean Annual Precipitation CV%	Mean Annual Temperature CV%	Mean Annual Precipitation CV%	Mean Annual Temperature CV%
1901–1920	21.32	4.73	18.9	5.29
1921–1940	17.92	7.19	22.76	8.12
1941–1960	17.72	6.22	18.27	8.18
1961–1980	18.53	5.48	18.27	5.31
1981–2000	23.33	5.38	23.58	6.48
2001–2020	22.35	6.74	25.55	6.08

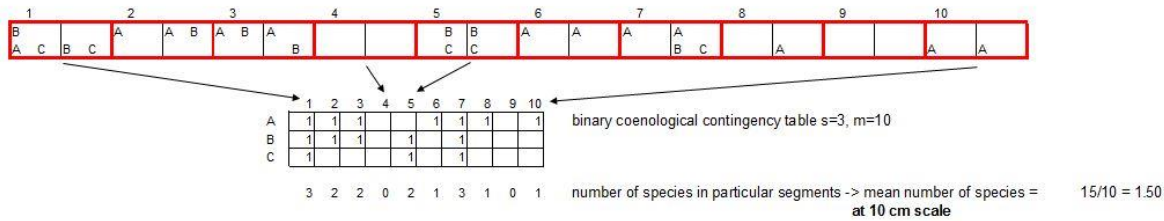
Supplementary S2. Estimating species richness from transect data at different scales

Baseline transect: Presence of three species (A, B, C) recorded in micro-quadrats (20 contiguous 5 cm x 5cm units)

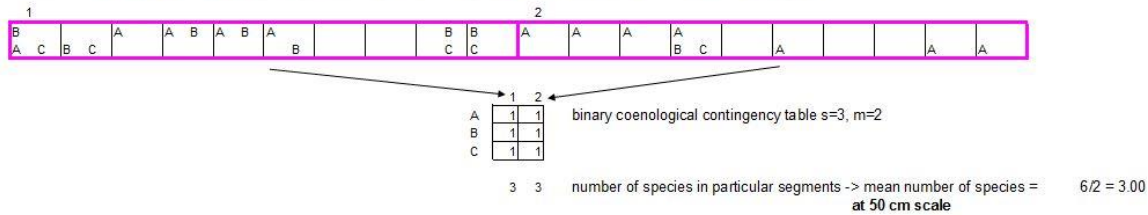
Example 1: Sampling the baseline transect with the (original) 5cm long segments, resulting in 20 plots



Example 2: Sampling (re-scaling) the baseline transect with 10 cm long segments (merging 2 adjacent units), resulting in 10 plots



Example 3: Sampling (re-scaling) the baseline transect with 50 cm long segments (merging 10 adjacent units), resulting in 2 plots



Supplementary S3. Definition and calculation of the Pálfai aridity index

We calculated the modified Pálfai Drought Index (PaDI₀) with the following formula:

$$PaDI_o = \frac{\left[\sum_{i=apr}^{aug} T_i \right] / 5 * 100}{c + \sum_{i=oct}^{sept} (P_i * w_i)}$$

where:

PaDI₀ – Pálfai Drought Index, °C/100 mm

T_i – average monthly temperature from April to August (°C)

P_i – monthly precipitation from October to September (mm)

w_i – weighting parameter (Table S2)

c – constant (10 mm)

Table S2. Weighting parameters for PaDI₀ index

Month	w _i weighting parameter
October	0.1
November, December	0.4
January–April	0.5
May	0.8
June	1.2
July	1.6
August	0.9
September	0.1

Supplementary S4 Calculation and testing the synchrony index

We calculated the synchrony index (A_{ij}) between species richness time series of sites with the following formula:

$$A_{ij} = \frac{\sum D_{ij}}{(T-1)}$$

where;

A_{ij} – synchrony index

D_{ij} – number of times series i and j move in same direction

T – number of observations

direction of species richness changes between years												number of changes to the same direction	
pair of sites	dates	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020		
Battonya	mean S	15,35	12,5	15,8	16,3	11,3	13	13,9	13,4	14,8	15,7	7	synchrony index= 7/9 =0.78
Csévharaszt	mean S	7,2	3,45	7,5	6,2	4,3	6,75	7,05	5,65	4,9	6,2		
Battonya	mean S	15,35	12,5	15,8	16,3	11,3	13	13,9	13,4	14,8	15,7	6	synchrony index= 6/9 =0.67
Fülöpháza	mean S	5,05	3	4,95	3,55	3,5	3,65	3,7	3,85	3,8	4,75		
Csévharaszt	mean S	7,2	3,45	7,5	6,2	4,3	6,75	7,05	5,65	4,9	6,2	8	synchrony index= 8/9 =0.89
Fülöpháza	mean S	5,05	3	4,95	3,55	3,5	3,65	3,7	3,85	3,8	4,75		
												mean synchrony index=	0.78

Figure S4a. Example for the calculation of synchrony index between species richness (mean S) time series of sites (observed at 2 m scale).

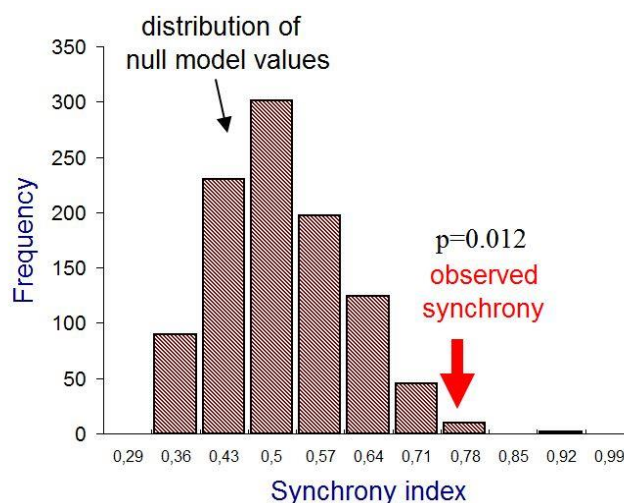
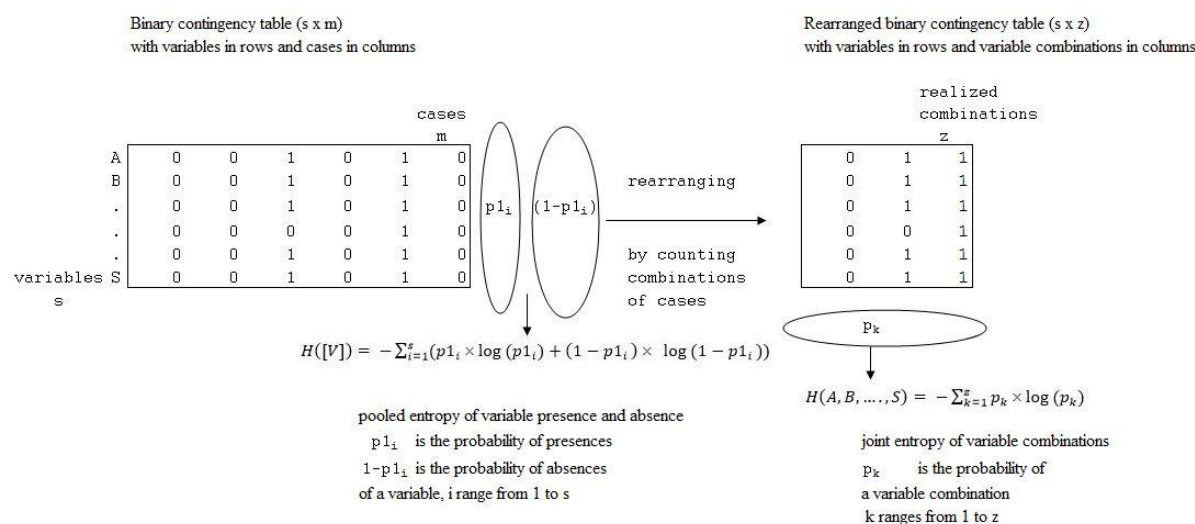


Figure S4b. Example for testing significance of observed mean synchrony index against a null model. Null model = expected synchrony using the same species richness values but randomizing these values among dates (999 complete randomizations over time).

Supplementary S5 Calculation of temporal associations between peaks (extrema) of weather events and species richness

We used information theory models (Juhász-Nagy and Podani 1983, Juhász-Nagy 1984) for calculating temporal association (coincidence) between extrema of weather (drought events) and minima of species richness. First, we created a variables – dates binary contingency table where the presence of droughts and richness minima were marked by “1” while the absence of these events were marked by “0”.



Multiple Association among variables = Pooled Entropy - Joint Entropy

$$I(V) = H([V]) - H(A, B, \dots, S)$$

Here we present a real example with detailed calculations:

Example for the binary contingency table
 Example with annual species richness and the minima of early season precipitation
 (i.e. minima of cumulative 4 months precipitation 4 months before vegetation sampling)

2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020

0	0	1	0	1	1	0	0	1	0	1	0	0	0
0	0	1	0	1	1	0	0	1	0	0	0	0	0
0	0	1	0	1	1	0	0	1	0	0	0	0	0
0	0	0	0	0	1	0	0	1	0	0	1	0	0
0	0	1	0	0	1	0	0	1	0	0	0	1	0
0	0	1	0	0	1	0	0	0	0	0	1	0	0

presence of PPT minimum at Battonya
 presence of PPT minimum at Csevharszt
 presence of PPT minimum at Fülöpháza
 presence of minimum species richness at Battonya
 presence of minimum species richness at Csevharszt
 presence of minimum species richness at Fülöpháza

dates with extreme data

We test whether the presences of variables were associated (were different from random) by calculating the contingency information of this table compared with null models where presences within each of the variables were randomized.

Contingency Information is expressed as the difference between the Pooled Entropy and the Joint Entropy of the binary table.

First, we calculate the pooled entropy (by summing up the entropy of each variable):

2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	sum of presences	sum of absences	probability of presences p(1)	probability of absences p(0)
0	0	1	0	1	1	0	0	1	0	1	0	0	0	5	9	0,3571	0,6429
0	0	1	0	1	1	0	0	1	0	0	0	0	0	4	10	0,2857	0,7143
0	0	1	0	1	1	0	0	1	0	0	0	0	0	4	10	0,2857	0,7143
0	0	0	0	0	1	0	0	1	0	0	1	0	0	3	11	0,2143	0,7857
0	0	1	0	0	1	0	0	1	0	0	0	1	0	4	10	0,2857	0,7143
0	0	1	0	0	1	0	0	0	0	0	1	0	0	3	11	0,2143	0,7857

probability of presences p(1)	probability of absences p(0)	entropy of presences $-p1*\log(p1)$	entropy of absences $-p0*\log(p0)$
0,3571	0,6429	0,5305	0,4098
0,2857	0,7143	0,5164	0,3467
0,2857	0,7143	0,5164	0,3467
0,2143	0,7857	0,4762	0,2734
0,2857	0,7143	0,5164	0,3467
0,2143	0,7857	0,4762	0,2734
		3,0321	+ 1,9967 = 5,0288
		pooled entropy of presences	pooled entropy of absences
		total pooled entropy	

Then we calculate the joint entropy (the entropy of variable combinations): We rearranged the original binary table according to the variable combinations and counted the frequency of each combination. Joint entropy is the sum of entropies of these combinations.

Rearranged binary table:								
Combinations:	<1>	<2>	<3>	<4>	<5>	<6>	<7>	<9>
	0	1	1	1	0	1	0	1
	0	1	1	1	0	1	0	0
	0	1	1	1	0	1	0	0
	0	1	0	1	1	0	0	0
	0	1	1	1	0	0	1	0
	0	1	1	0	1	0	0	0
Frequency:	7	1	1	1	1	1	1	1
Probability of combinations:	0,5000	0,0714	0,0714	0,0714	0,0714	0,0714	0,0714	0,0714
								summa: 1,0000
Entropy of combinations:	0,500	0,272	0,272	0,272	0,272	0,272	0,272	0,272
								2,4037
Joint entropy of combinations								

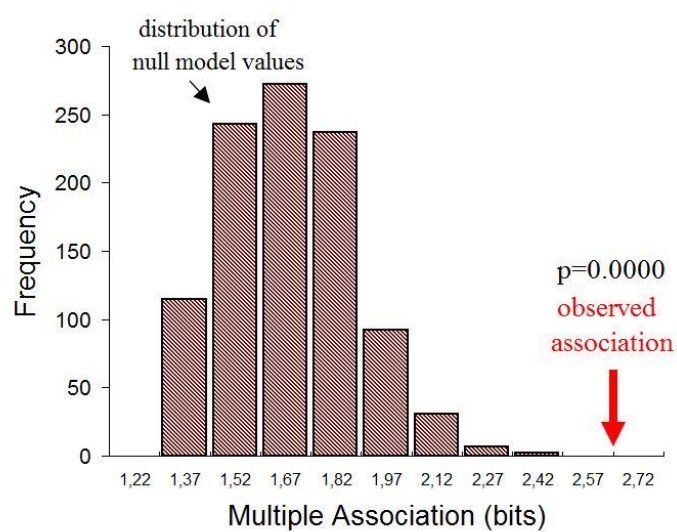
Multiple associations of variables (i.e. the contingency information of binary table) is expressed as the difference between the Pooled Entropy and the Joint Entropy:

$$\text{Multiple Association} = \text{Pooled Entropy} - \text{Joint Entropy}$$

$$2.625 = 5.0288 - 2.4037$$

Testing significance of observed multiple association by null model.

Null model = expected association using the same number of peaks but randomizing these peaks among dates (999 complete randomizations over time).



The related calculations have been performed by the comspat R package (comspat; see Tsakalos 2022; Tsakalos et al. 2022).

Supplementary S6. Temporal trends of weather characteristics and species richness

S6.1. Temporal trends of weather characteristics

We checked the temporal trends of the climate variables (precipitation, mean annual temperature and Pálfai Drought Index) using a linear mixed-effect model (LME). Specifically, the fitted model used year as the predictor and all climatic variables as the response variables. Because we were interested in searching for overall climatic trends, we included the site as a random factor. We calculated two measures of precipitation (mm); the first was taken as the total precipitation falling 4 months before the sampling (Prec_4m), and the second measure included 12 months before the sampling (Prec_12m). Pálfai Drought Index and MAT. We calculated all of the values climatic values at each site (i.e. Battonya, Csévharaszt and Fülöpháza) and sampling year. We tested for normality of the climate data using the Shapiro-Wilk test. Then we used Pinheiro and Bates (2000) ‘nlme’ R package and the ‘corAR1’ function to check for first-order autocorrelation between the predictors. Lastly, we used Barton’s (2020) ‘MuMIn’ R package and the ‘r.squaredGLMM’ function to calculate the models R^2 values; hence providing different measures of the variability explained by the fixed effects (R^2 marginal) and the variability explained by the random entire model (R^2 conditional). There were no significant trends in either site ($R^2 = 0.0004$). However, we found a very strong positive first-order autocorrelation ($\Phi = 0.99$); closer inspection of the data revealed that the variables MAT and Pálfai were highly positively correlated through time and across study sites.

All of the analyses were conducted in R version 3.6.3. (R Core Team 2020).

Table S6.1. Parameters of the linear mixed effect model for climate variables (Prec_4m = sum of precipitation [mm] 4 months before sampling; Prec_12m = sum of precipitation [mm] 12 months before sampling; Pálfai = Pálfai Drought Index; MAT = mean annual temperature [$^{\circ}$ C]).

Source	Value	Std. Error	DF	t value	p value	R^2m	R^2c
intercept	2013.88	5.99	31.00	336.24	0.00	0.0004	0.0004
Prec_4m	0.00	0.00	31.00	-0.53	0.60		
Prec_12m	0.00	0.00	31.00	-0.03	0.98		
Pálfai	-0.10	0.11	31.00	-0.87	0.39		
MAT	0.08	0.34	31.00	0.22	0.83		

S6.2. Temporal trend in species richness

We checked the temporal trend of species richness using LMEs. Specifically, we prepared three separate LMEs (one for each site); each model used years as the predictor and species richness as the response variable and included scale (0.1 m, 2 m and 40 m) as a random factor. Normality and autocorrelation assumptions were checked following the method described above. One dataset (40 m data in Fülöpháza site) was $\log(1+x)$ transformed because of non-normal distribution. There were no significant trends in species richness in either sites. There was a strong positive first-order autocorrelation in case of the Battonya site ($\Phi = 0.71$), while a weak negative autocorrelation was detected in Csévharaszt ($\Phi = -0.2$) and in Fülöpháza ($\Phi = -0.18$).

Table S6.2. Parameters of the linear mixed effect model for species richness

Site	Source	Value	Std. Error	DF	t value	p value	R ² m	R ² c
Battonya	intercept	262.10	740.33	26.00	0.35	0.73	0.00036	0.9472
	year	-0.12	0.37	26.00	-0.33	0.75		
Csévharaszt	intercept	112.96	93.04	38.00	1.21	0.23	0.00067	0.9694
	year	-0.05	0.05	38.00	-1.13	0.27		
Fülöpháza	intercept	13.39	9.09	38.00	1.47	0.15	0.0017	0.9584
	year	-0.01	0.00	38.00	-1.35	0.18		

Supplementary S7. Relationships species richness and weather characteristics

We tested the relationship between species richness values, precipitation and mean annual temperature data with linear mixed effect models. We calculated the regression for the three spatial scales separately with site as a random variable. The normality assumption of the data was tested by Shapiro-Wilk test. First-order autocorrelation was checked with „corAR1” function (Pinheiro and Bates 2000). P-values of multiple tests was adjusted by Bonferroni-Holm method (Holm 1979). R^2 values were obtained by “r.squaredGLMM” function in the “MuMIn” package (Barton 2020).

Only Pálfai index and species richness showed a significant relationship at 2m spatial scale ($p=0.025$) but the adjusted p value was not significant. There was a strong positive first-order autocorrelation in case of 10 cm spatial scale ($\Phi=0.53$) and in 40 m spatial scale ($\Phi=0.58$), while no autocorrelation was detected in 2 m spatial scale ($\Phi=0.04$).

Analyses were conducted in R version 3.6.3. (R Core Team 2020) by using the ‘nlme’ package (Pinheiro et al. 2020).

Table S7.1. Parameters of the linear mixed effect model for species richness and climate variables (s10cm = species richness in 10 cm spatial scale; s2m = species richness in 2 m spatial scale; s4m = species richness in 4 m spatial scale; Prec_4m = sum of precipitation 4 months back from the date of sampling; Prec_12m = sum of precipitation 12 months back from the date of sampling; Pálfai = Pálfai Drought Index- PADI; MAT = mean annual temperature)

Scale	Source	Value	Std. Error	DF	t value	p value	Corrected p value	R ² m	R ² c
s10cm	intercept	40.18	66.33	30.00	0.61	0.55		0.01	0.94
	year	-0.02	0.03	30.00	-0.54	0.59	1.00		
	Prec_4m	0.00	0.00	30.00	0.14	0.89	1.00		
	Prec_12m	0.00	0.00	30.00	0.81	0.42	1.00		
	Pálfai	-0.11	0.06	30.00	-1.94	0.06	0.86		
	MAT	-0.14	0.16	30.00	-0.85	0.40	1.00		
s2m	intercept	218.32	129.31	30.00	1.69	0.10		0.02	0.95
	year	-0.10	0.07	30.00	-1.53	0.10	1.00		
	Prec_4m	0.00	0.00	30.00	0.98	0.34	1.00		
	Prec_12m	0.00	0.00	30.00	-0.88	0.38	1.00		
	Pálfai	-0.40	0.17	30.00	-2.36	0.0247*	0.37		
	MAT	-0.34	0.44	30.00	-2.36	0.44	1.00		
s40m	intercept	211.79	531.10	30.00	0.40	0.69		0.02	0.91
	year	-0.08	0.27	30.00	-0.30	0.76	1.00		
	Prec_4m	0.00	0.01	30.00	0.28	0.78	1.00		
	Prec_12m	0.00	0.00	30.00	-0.79	0.44	1.00		
	Pálfai	-0.75	0.42	30.00	-1.76	0.09	1.00		
	MAT	-1.59	1.22	30.00	-1.31	0.20	1.00		