PNAS
www.pnas.org

Supplementary Information for

Decline in climate resilience of European wheat

Helena Kahiluoto[1*], Janne Kaseva[2], Jan Balek[3,4], Jørgen E. Olesen[5], Margarita Ruiz-Ramos[6], Anne Gobin[7], Kurt-Christian Kersebaum[8], Jozef Takáč[9], Francoise Ruget[10], Roberto Ferrise[11], Pavol Bezak[9], Gemma Capellades[12], Camilla Dibari[11], Hanna Mäkinen[1], Claas Nendel[8], Domenico Ventrella[13], Alfredo Rodríguez[6,14], Marco Bindi[11], Mirek Trnka[3,4]

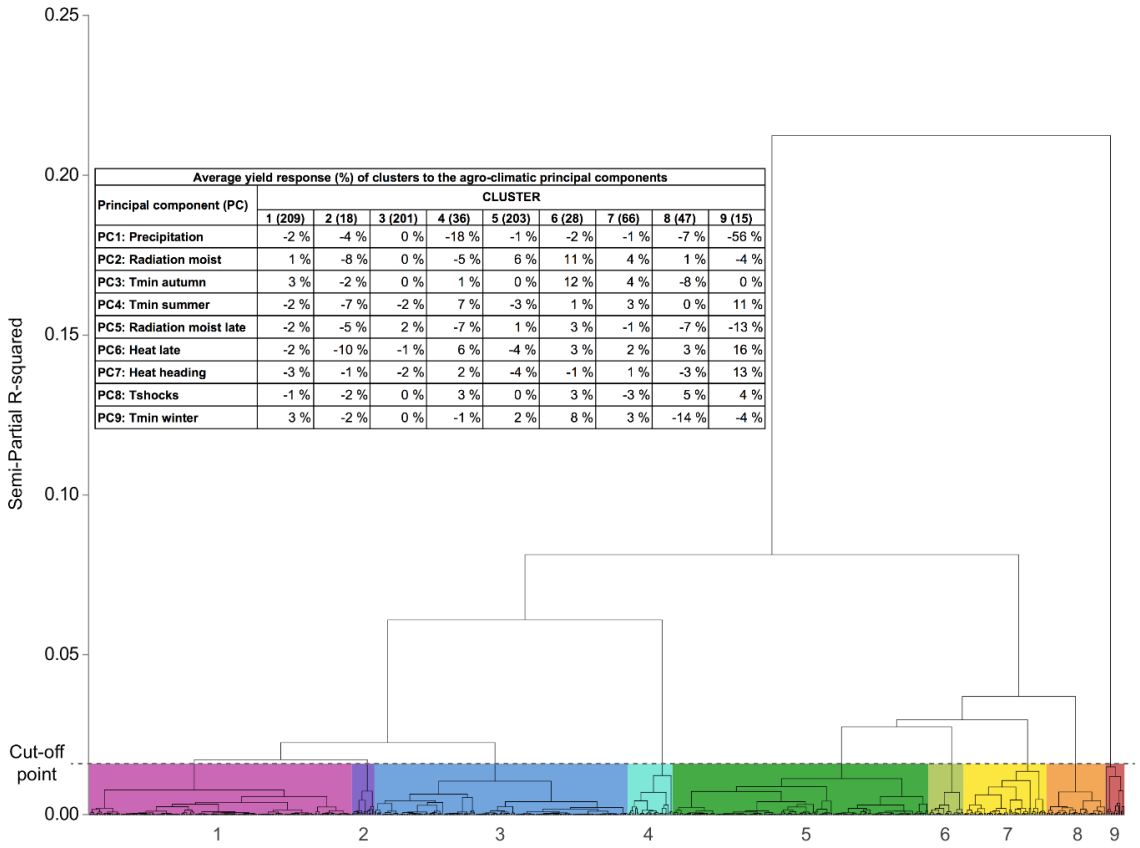
[1]LUT University, Sustainability Science, 53851 Lappeenranta, Finland
[2]Natural Resources Institute Finland, 31600 Jokioinen, Finland
[3]Global Change Research Institute, Academy of Sciences of the Czech Republic, 60300 Brno, Czech Republic
[4]Institute of Agriculture Systems and Bioclimatology Mendel University in Brno, 61300 Brno, Czech Republic
[5]Aarhus University, Department of Agroecology, Blichers Allé 20, 8830 Tjele, Denmark
[6]Universidad Politécnica de Madrid, CEIGRAM, 28040 Madrid, Spain
[7]Flemish Institute for Technological Research (VITO), Boeretang 200, 2400 Mol, Belgium
[8]Leibniz Centre for Agricultural Landscape Research, 15374 Müncheberg, Germany
[9]National Agricultural and Food Centre, Soil Science and Conservation Research Institute, Gagarinova 10, 827 13 Bratislava, Slovakia
[10]Mediterranean Environment and Modelling of Agroecosystems (EMMAH), Institut National de la Recherche Agronomique (INRA), Avignon Université, 84914 Avignon, France
[11]Department of Agri-food Production and Environmental Sciences, University of Florence, 50144 Florence, Italy
[12]GENVCE, Fundació Mas Badia, 17134 La Tallada d'Empordà, Spain
[13]Centro di Ricerca Agricoltura e Ambiente, Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria, Sede di Bari, 70125, Bari, Italy
[14]University of Castilla-La Mancha, Department of Economic A nalysis, 45071 Toledo, Spain

www.pnas.org/cgi/doi/10.1073/pnas.1804387115

Corresponding Author: Helena Kahiluoto
Email: helena.kahiluoto@lut.fi, tel +358 40 5118335

This PDF file includes:

Fig. S1
Tables S1 to S2
The list of data owners and organizers



Average yield response (%) of clusters to the agro-climatic principal components

Principal component (PC)	CLUSTER								
	1 (209)	2 (18)	3 (201)	4 (36)	5 (203)	6 (28)	7 (66)	8 (47)	9 (15)
PC1: Precipitation	-2 %	-4 %	0 %	-18 %	-1 %	-2 %	-1 %	-7 %	-56 %
PC2: Radiation moist	1 %	-8 %	0 %	-5 %	6 %	11 %	4 %	1 %	-4 %
PC3: Tmin autumn	3 %	-2 %	0 %	1 %	0 %	12 %	4 %	-8 %	0 %
PC4: Tmin summer	-2 %	-7 %	-2 %	7 %	-3 %	1 %	3 %	0 %	11 %
PC5: Radiation moist late	-2 %	-5 %	2 %	-7 %	1 %	3 %	-1 %	-7 %	-13 %
PC6: Heat late	-2 %	-10 %	-1 %	6 %	-4 %	3 %	2 %	3 %	16 %
PC7: Heat heading	-3 %	-1 %	-2 %	2 %	-4 %	-1 %	1 %	-3 %	13 %
PC8: Tshocks	-1 %	-2 %	0 %	3 %	0 %	3 %	-3 %	5 %	4 %
PC9: Tmin winter	3 %	-2 %	0 %	-1 %	2 %	8 %	3 %	-14 %	-4 %

Fig. S1. Yield responses of the cultivar clusters shown in the dendrogram to the agro-climatic principal components (PCs). The average yield responses (%) refer to the relative difference in yield between the extreme categories (the 40th and 60th percentiles) for the values of the agro-climatic variables (for more details see Methods, Step 2). Colours in the dendrogram refer to the colours for the clusters in Fig. 3. The number of cultivars per cluster is given in parentheses. For detailed PC characteristics, see Supplementary Table 1.

Table S1. Principal component (PC) loadings of the varimax rotated principal component analysis (PCA) matrix of the agro-climatic variables. Highly loaded variables (>|0.50|) are bolded. The numbers in parentheses refer to the agro-climatic variables in Supplementary Table 2. The proportions of the variance explained by the PCs (total 70.2%) are presented for each PC in the bottom row.

Agro-climatic variable	Precipi-tation	Radiation moist	Tmin autumn	Tmin summer	Radiation moist late	Heat late	Heat heading	Tshocks	Tmin winter
(16) RainDays_SM	**0.90**	0.00	0.04	-0.13	0.12	-0.07	-0.18	0.00	0.11
(18) Prec_SM	**0.89**	0.05	0.06	-0.11	0.22	-0.11	-0.19	-0.03	0.00
(37) SPEI3_M	**0.83**	0.04	-0.03	-0.13	0.15	-0.07	-0.07	0.09	0.14
(36) SPEI6_M	**0.76**	0.12	-0.01	-0.17	0.43	-0.13	-0.09	0.00	-0.01
(17) Prec_SH	**0.63**	0.19	0.00	-0.16	0.15	0.04	-0.27	-0.27	-0.11
(1) Prec_BefS	**0.52**	0.25	0.21	-0.31	-0.10	-0.12	-0.06	-0.03	-0.06
(38) SPEI3_H	0.47	0.28	-0.23	0.03	0.20	-0.30	-0.31	-0.02	-0.15
(8) DiffMainGS	0.43	0.19	0.38	-0.09	0.01	-0.22	-0.24	0.18	-0.05
(35) SPEI1_SH	**-0.70**	-0.33	0.13	0.15	-0.03	0.15	0.11	0.31	-0.08
(14) EGD_SH	0.13	**0.83**	0.13	0.06	-0.08	0.05	-0.14	0.23	0.03
(11) EGR_SH	-0.01	**0.80**	-0.07	0.00	0.05	-0.02	0.04	-0.04	0.20
(13) EGD_SM	0.13	**0.72**	0.21	-0.02	0.39	0.02	-0.06	0.17	0.04
(10) EGR_SM	0.24	**0.62**	-0.06	-0.02	**0.60**	0.00	0.03	-0.03	0.14
(20) SowDays	-0.16	-0.44	-0.11	0.41	-0.12	-0.08	0.02	0.32	0.38
(7) SevDrought040_SH	-0.28	**-0.71**	-0.06	0.09	-0.13	0.04	0.04	0.27	0.05
(32) Tmin_10	-0.10	0.04	**0.80**	0.04	0.04	-0.02	-0.11	0.06	0.03
(33) Tmin_11	0.14	0.03	**0.73**	0.16	0.02	0.25	-0.07	-0.19	0.26
(34) Tmin_12	0.12	0.05	**0.72**	0.05	0.08	-0.04	0.10	-0.11	0.16
(31) Tmin_9	-0.22	-0.03	**0.62**	0.38	0.05	-0.10	0.11	-0.08	0.15
(22) Temps_s_0	0.03	0.35	0.39	0.28	-0.01	0.20	-0.18	0.36	0.39
(28) Tmin_6	-0.07	-0.03	-0.04	**0.82**	-0.10	0.26	0.14	-0.11	-0.01
(30) Tmin_8	-0.40	-0.02	0.17	**0.71**	-0.20	0.12	-0.03	-0.09	-0.08
(27) Tmin_5	-0.26	0.00	0.29	**0.68**	0.08	0.26	0.23	-0.08	0.13
(29) Tmin_7	-0.30	-0.04	0.25	**0.66**	-0.14	0.38	0.15	0.05	-0.04
(26) Tmin_4	0.03	0.13	**0.56**	**0.60**	-0.06	0.13	0.08	0.11	-0.18
(15) EGD_HM	0.06	0.16	0.20	-0.12	**0.82**	0.09	-0.08	0.02	-0.12
(12) EGR_HM	0.36	0.22	-0.01	-0.14	**0.74**	-0.05	-0.11	-0.04	0.10
(19) Prec_HM	0.34	-0.05	-0.02	-0.04	**0.70**	-0.12	-0.10	0.08	0.12
(41) RainEvents_SM	**0.51**	0.16	0.04	-0.01	**0.53**	-0.11	0.13	-0.14	-0.05
(5) TempOver0_HM	-0.35	-0.13	0.16	0.18	0.45	0.34	-0.35	0.08	0.18
(40) HeatStress31_HM	-0.01	0.06	0.01	0.18	-0.07	**0.87**	0.11	-0.02	0.05
(39) HeatStress28_HM	-0.30	0.05	-0.05	0.24	-0.01	**0.78**	0.16	-0.06	0.04
(6) TempOver10_HM	-0.21	-0.09	0.01	0.40	0.05	**0.66**	-0.15	0.13	-0.04
(2) HeatStress25_H	-0.26	-0.09	0.05	0.05	-0.12	0.02	**0.82**	0.04	-0.01

(3) HeatStress28_H	-0.27	-0.02	-0.06	0.15	-0.14	0.15	**0.76**	0.21	-0.04
(4) Temp_BefH	-0.18	-0.04	-0.01	0.31	0.07	0.04	**0.64**	-0.33	0.21
(42) Temp5Shocks	-0.25	0.04	-0.20	0.11	0.13	-0.04	0.01	**0.69**	0.11
(43) Temp10Shocks	0.14	-0.06	-0.07	-0.11	0.03	-0.06	0.03	**0.67**	-0.14
(9) DiffLargeGS	-0.18	0.16	0.21	-0.22	-0.13	0.25	-0.01	**0.52**	-0.16
(25) Tmin_3	0.18	0.14	0.33	-0.07	0.03	0.07	0.15	-0.02	**0.70**
(24) Tmin_2	0.02	0.09	**0.55**	-0.10	0.21	-0.07	0.02	-0.11	**0.67**
(23) Tmin_1	-0.37	0.20	0.11	0.04	-0.22	0.17	-0.04	-0.17	0.43
(21) HarvDays	0.38	0.06	0.05	-0.01	0.21	-0.03	-0.08	-0.33	0.40
Variance explained (%)	**14.9**	**8.5**	**8.5**	**8.4**	**7.9**	**6.3**	**5.7**	**5.2**	**4.8**

Table S2. The agro-climatic variables critical to European wheat yield (units in parentheses). Low and High refer to the categories with the 40th (Low) and 60th (High) percentile limits of the observations, each category thus containing approximately 40% of observations for the agro-climatic variable.

Agro-climatic variable	Description	Low	High
(1) Prec_BefS	Precipitation during one month before sowing (mm)	0-44	60-1086
(2) HeatStress25_H	$T_{max} \geq 25$°C in the period 7 days before and 14 after start of the heading (d)	0-3	5-22
(3) HeatStress28_H	$T_{max} \geq 28$°C in the period 7 days before and 14 after start of the heading (d)	0	1-12
(4) Temp_BefH	T_{sum} above 10°C from T_{mean} from 14 days before heading till the start of heading (°C)	0-51.5	64.6-224
(5) TempOver0_HM	T_{sum} above 0°C from T_{mean} from heading until yellow ripeness (°C)	36-1090	1171-4932
(6) TempOver10_HM	T_{sum} above 10°C from T_{mean} from heading until yellow ripeness (°C)	1-469	511-2157
(7) SevDrought040_SH	Number of days from sowing to heading with $ET_a/ET_r < 0.40$ as the indicator of severe drought (d)	0-22	34-219
(8) DiffMainGS	Difference in days between start of the main growing season (T_{mean} continuously above 10°C) and T_{min} being below -2°C (d)	1-28	40-155
(9) DiffLargeGS	Difference in days between start of the large growing season (T_{mean} continuously above 5°C) and T_{min} being below -2°C (d)	0-3	12-114
(10) EGR_SM	Sum of effective global radiation from sowing to maturity (W/m2)	0-1818	2077-3442
(11) EGR_SH	Sum of effective global radiation from sowing to heading (W/m2)	0-1025	1159-3502
(12) EGR_HM	Sum of effective global radiation from heading to maturity (W/m2)	0-720	947-3203
(13) EGD_SM	Sum of effective growing days from sowing to maturity (d)	0-138	155-297
(14) EGD_SH	Sum of effective growing days from sowing to heading (d)	0-91	105-271
(15) EGD_HM	Sum of effective growing days from heading to maturity (d)	0-44	55-200
(16) RainDays_SM	Number of days from sowing to maturity with rain above 1 mm (d)	0-75	90-251
(17) Prec_SH	Seasonal precipitation from sowing to heading (mm)	0-280	360-2277
(18) Prec_SM	Seasonal precipitation from sowing to maturity (mm)	0-447	519-3807
(19) Prec_HM	Seasonal precipitation from heading to maturity (mm)	0-129	162-1827
(20) SowDays	Number of days when field is accessible during sowing window (d)	0-16	19-21
(21) HarvDays	Number of days when field is accessible during harvest window (d)	0-7	10-12
(22) Temps_s_0	Mean daily accumulation of temperature above 0 °C (°C)	0-2491	2615-5581
(23) Tmin_1	Minimum temperature in January (°C)	-17.2- -3.0	-0.9-12.6
(24) Tmin_2	Minimum temperature in February (°C)	-18.7- -2.4	-0.7-16.9
(25) Tmin_3	Minimum temperature in March (°C)	-15.5- 0.0	1.1-18.8
(26) Tmin_4	Minimum temperature in April (°C)	-4.7-3.7	4.5-20.8
(27) Tmin_5	Minimum temperature in May (°C)	1.1-7.6	8.5-27.5
(28) Tmin_6	Minimum temperature in June (°C)	6.1-10.8	11.7-32.6

(29) Tmin_7	Minimum temperature in July (°C)	8.1-12.9	13.9-34.5
(30) Tmin_8	Minimum temperature in August (°C)	7.4-12.7	13.6-34.5
(31) Tmin_9	Minimum temperature in September (°C)	1.1-9.5	10.5-28.7
(32) Tmin_10	Minimum temperature in October (°C)	-3.5-5.5	6.7-22.9
(33) Tmin_11	Minimum temperature in November (°C)	-7.3-2.0	3.2-17.5
(34) Tmin_12	Minimum temperature in December (°C)	-15.2- -1.7	-0.2-11.2
(35) SPEI1_SH	Number of months from sowing to heading with the standardized precipitation-evapotranspiration index (SPEI) below -1.0 threshold indicating drought.	0	2-5
(36) SPEI6_M	SPEI value for the month of maturity and the five previous months	-2.6- -0.20	0.15-4.9
(37) SPEI3_M	SPEI value for the month of maturity and the two previous months	-2.5- -0.12	0.25-6.2
(38) SPEI3_H	SPEI value for the month of heading and the two previous months	-2.8- -0.30	0.11-7.0
(39) HeatStress28_HM	$T_{max} \geq 28$°C in the period from heading to 10 days before the maturity (°C)	0-5	10-87
(40) HeatStress31_HM	$T_{max} \geq 31$°C in the period from heading to 10 days before the maturity (°C)	0-1	4-68
(41) RainEvents_SM	N of events with more than 20 mm of daily rainfall or more than 30 mm in 2 days from sowing to maturity (N)	0-3	5-118
(42) Temp5Shocks	N of temperature shocks when the mean daily temperature is above 5°C and T_{min} above 0°C consecutively for 10 days followed by T_{min} dropping below or equal to 0°C (N)	0-3	5-21
(43) Temp10Shocks	N of temperature shocks when the mean daily temperature is above 10°C and T_{min} above 0°C consecutively for 5 days followed by T_{min} dropping below or equal to 0°C (N)	0	2-8

Data owners

The data owners are as follows: Vladimíra Horáková from Central Institute for Supervising and Testing in Agriculture (for collecting and organizing the Czech wheat variety trials and consultations), Dr. Nicolina Staglianò from the University of Florence (for collecting and organizing the Italian dataset); Katarína Bučková from the Central Controlling and Testing Institute in Agriculture in Bratislava, Slovakia (for collecting the Slovak dataset); Fabien Masson and Marie-Hélène Bernicot, GEVES, France; Daniël Wittouck from the Agricultural Centre for Cereals, Belgium (for making available the reports on winter wheat variety trials); Luke variety trials, Finland; and SEGES, Denmark. The Spanish GNVCE database consisted of data from Centro de Transferencia Agroalimentaria – Gobierno de Aragón, Instituto Regional de Investigación y Desarrollo Agroalimentario y Forestal (RIAF, Junta de Comunidades de Castilla – La Mancha), Instituto Técnico Agronómico Provincial de Albacete (ITAP), Instituto Tecnológico Agrario de Castilla y León (ITACyL, ITAGRA), Centro de Investigaciones Científicas y Tecnológicas de Extremadura (CICYTEX), Centro de Investigaciones Agrarias de Mabegondo (CIAM, Galícia), Instituto Madrileño de Investigación y Desarrollo Rural, Agrario y Alimentario(IMIDRA), Instituto Navarro de Tecnologías e Infraestructuras Agroalimentarias (INTIA), and Instituto Vasco de Investigación y Desarrollo Agrario (NEIKER - Tecnalia). German variety trial data were provided by Landesforschungsanstalt für Landwirtschaft und Fischerei Mecklenburg-Vorpommern (Dr. A. Zenk, Ms G. Pienz), Bayerische Landesanstalt für Bodenkultur und Pflanzenbau (Dr. T. Felbermeir), Landesanstalt für Pflanzenbau Forchheim. Regional distribution of varieties were documented by Max-Rubner-Institute, Detmold/Germany. The German data was collected and compiled by Katrin Eisermann and Christopher Kersebaum.