Supplementary Information

Crop rotation sustains cereal yields under a changing climate

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Fig. S1. Time-series of observed yield across the experiments, separate for each crop. The fitted line indicated the long-term trend used to compute yield deviation. The trend was fitted after pooling the data from all treatments. We used a Gaussian GAM with k=5 to fit the year effect and to capture the non-linearity in the trend.

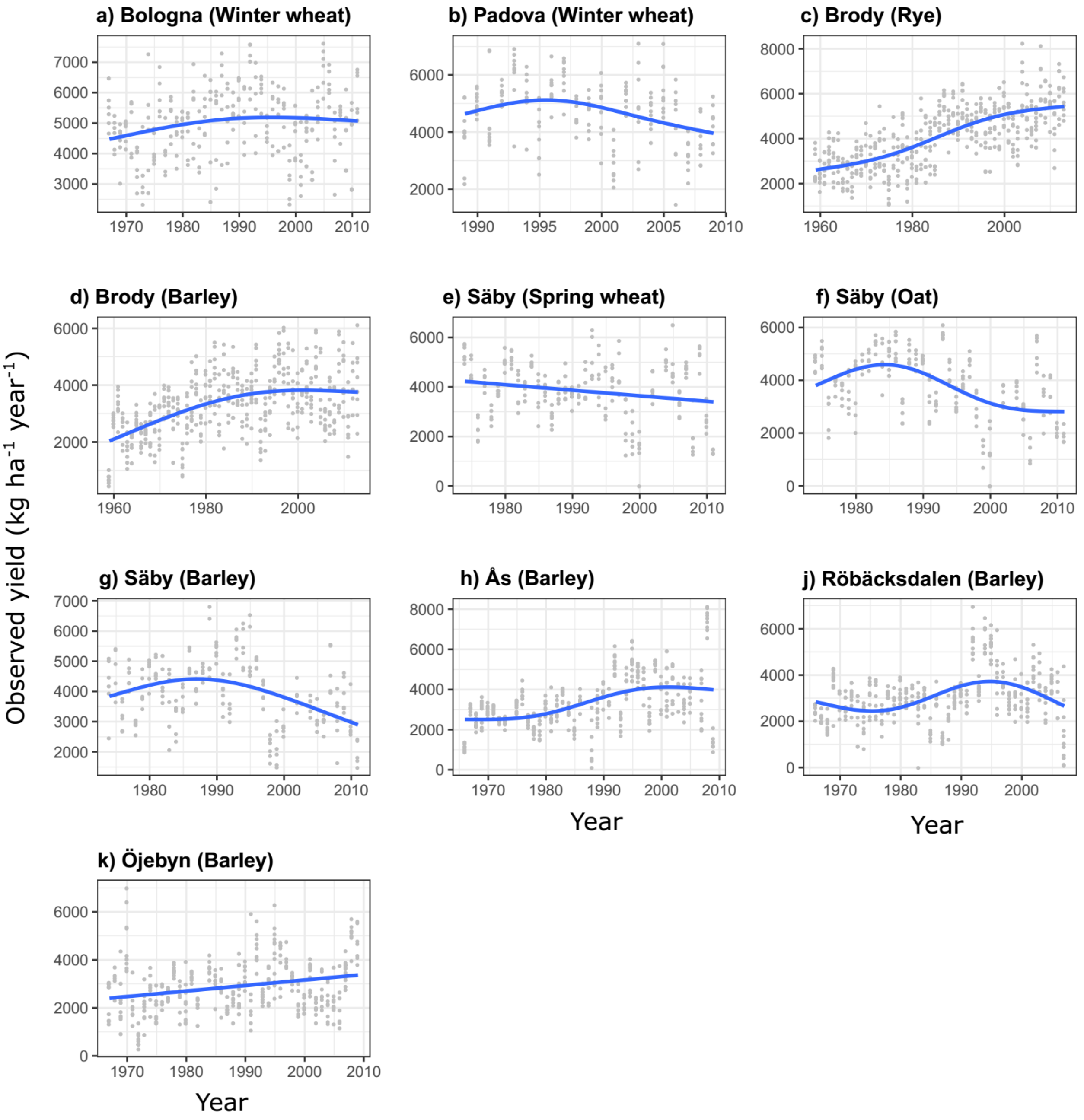

Table S1. Soil characteristics, NPK fertilization rate, and plot size and number of blocks for each experimental site.

Site	**Clay (%)**	**Silt (%)**	**Sand (%)**	**SOM (%)**	**N-P-K (kg ha^{-1})**	**Plot size (m^2)**	**Number of blocks**
Öjebyn	28	50	17	3.0	80-12-40	64	1
Röbäcksdalen	9	69	15	5.0	80-12-40	64	1
Ås	21	38	33	5.0	80-12-40	64	1
Säby	23	53	20	4.0	140-30-57	47.5	2
Brody	5	18	77	1.4	90-26-100	55	4
Padova	12.7	49.5	37.8	2.0	200-100-280	46.8	3
Bologna	27	15	58	1.3	180-110-100	56	2

Table S2. Characterization of the long-term experimental sites, including country, altitude above sea level, long-term mean temperature and precipitation over the growing season, and Pearson correlation between mean temperature and precipitation.

Site	**Country**	**Altitude (m a.s.l.)**	**Climate**	**Mean temperature (°C)**	**Precipitation (mm)**	**r_{pearson}**
Öjebyn	Sweden	5	Bordering subarctic and humid continental	14.2	196	-0.406
Röbäcksdalen	Sweden	13	Bordering subarctic and humid continental	13.8	209	-0.284
Ås	Sweden	392	Subarctic	12.1	255	-0.234
Säby	Sweden	15	Humid continental	14.4 (all cereals)	209 (spring barley) 201 (oat) 207 (spring wheat)	-0.133
Brody	Poland	92	Humid continental	11.9 (winter rye)	270 (winter rye)	0.037
				13.3 (spring barley)	203 (spring barley)	-0.213
Padova	Italy	6	Humid subtropical	12.3	339	-0.180
Bologna	Italy	32	Humid subtropical	13.3	302	-0.109

^Data Sources:

Öjebyn: data were obtained from Swedish Meteorological and Hydrological Institute (SMHI) and are relative to the Piteå meteorological station (location 65.32°N, 21.49°E until 1999, and 65.33°N, 21.49°E afterwards; elevation 6 m a.s.l.).

Röbäcksdalen: data were obtained from SMHI from the stations Umeå Flygplats (temperature data and precipitation until the end of 1995; location: 63.79°N, 20.29°E; elevation: 7 m a.s.l.) and Röbäcksdalen (precipitation after 1995; location 63.81°N, 20.24°E, elevation 10 m a.s.l.). A comparison for the period 1965-1987 for which precipitation data are available for both stations suggests that daily precipitation amounts are similar in the two locations.

Ås: data were obtained from SMHI and are relative to the Frösön meteorological station (location: 63.20°N, 14.49°E; elevation 376 m a.s.l.).

Säby: data were obtained from SMHI and are relative to the Uppsala Flygplats meteorological station (location: 59.90°N, 17.59°E; elevation: 21 m a.s.l.), except for the precipitation data from 1998 on, which refer to the Uppsala meteorological station (location: 59.86°N, 17.63°E, elevation: 13 m a.s.l.).

Brody: daily precipitation were collected at the Brody Experimental station of the Agronomy Department of the Poznań University of Life Sciences (location: 52.43°N, 16.30°E; elevation: 92 m a.s.l.). The temperature data were obtained from the E-Obs database, relative to the station Poznań (station ID 206; location: 52.20°N, 18.65°E, elevation 115 a.s.l.) (Klein Tank *et al* 2002).

Padova: all data were provided by the ARPAV Legnaro station located at the same site where the experiment was performed.

Bologna: all data were retrieved from the meteorological station located at the experimental site at the University of Bologna.

Reference

Klein Tank A M G, Wijngaard J B, Können G P, Böhm R, Demarée G, Gocheva A, Mileta M, Pashiardis S, Hejkrlik L, Kern-Hansen C, Heino R, Bessemoulin P, Müller-Westermeier G, Tzanakou M, Szalai S, Pálsdóttir T, Fitzgerald D, Rubin S, Capaldo M, Maugeri M, Leitass A, Bukantis A, Aberfeld R, van Engelen A F V., Forland E, Mietus M, Coelho F, Mares C, Razuvaev V, Nieplova E, Cegnar T, Antonio López J, Dahlström B, Moberg A, Kirchhofer W, Ceylan A, Pachaliuk O, Alexander L V. and Petrovic P 2002 Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment *Int. J. Climatol.* **22** 1441–53

Table S3. Average modelled or observed day of the year (and date) of sowing (spring crops) or beginning of spring growth (winter crops), full flowering, and maturity. Averages refer to the period covered by each data set of yield time series. Method refers to model used to predict the timing of the phenological stages.

Site	**Crop**	**Sowing (spring crops) or beginning of spring growth (winter crops)**	**Full flowering**	**Maturity**	**Method (reference)**
Öjebyn	Spring barley	142 (May 22nd)	201 (Jul 20th)	248 (Sep 5th)	(Olesen *et al* 2012, Juskiw *et al* 2001)
Röbäcksdalen	Spring barley	142 (May 22nd)	202 (Jul 21st)	248 (Sep 5th)	(Olesen *et al* 2012, Juskiw *et al* 2001)
Ås	Spring barley	139 (May 19th)	203 (Jul 22nd)	259 (Sep 19th)	(Olesen *et al* 2012, Juskiw *et al* 2001)
Säby	Spring barley	123 (May 3rd)	195 (Jul 15th)	239 (Aug 27th)	(Olesen et al 2012, Juskiw et al 2001)
Säby	Oat	121 (May 1st)	183 (Jul 2nd)	234 (Aug 22nd)	(Olesen et al 2012)
Säby	Spring wheat	123 (May 3rd)	184 (Jul 3rd)	238 (Aug 26th)	(Olesen *et al* 2012)
Brody	Spring barley	86 (Mar 27th)	163 (Jun 12th)	198 (Jul 17th)	(Olesen *et al* 2012, Juskiw *et al* 2001)
Brody	Winter rye	60 (Mar 1st)	149 (May 29th)	208 (Jul 27th)	(Blecharczyk *et al* 2016)*
Padova	Winter wheat	32 (Feb 1st)	122 (May 2nd)	181 (Jun 30th)	(Olesen *et al* 2012)*
Bologna	Winter wheat	32 (Feb 1st)	136 (May 16th)	190 (Jul 9th)	(Olesen *et al* 2012)*

* Beginning of the active growing season for winter crops determined on the basis of typical timings observed in the regions.

Table S4. We analyzed climate effects separately for the early and late season effects, but found that both winter and spring cereals responded more strongly to the climatic conditions during the entire growing season. The comparison is based on AIC of Model (2), fitting the same climate metrics within the three phenological periods for winter and spring cereals, separately. Models were fitted using maximum likelihood estimation. All models included site-crop combination and plot ID as random factors. ΔAIC indicated the difference in AIC from the best model identified by ΔAIC=0.

Phenological stage	**AIC**	**ΔAIC**
Winter cereals		
Spring growth-Flowering	14782.68	8.75
Flowering-Maturity	14778.96	5.03
Spring growth-Maturity	**14773.93**	**0**
Spring cereals		
Spring growth-Flowering	33912.09	71.53
Flowering-Maturity	34904.91	64.35
Spring growth-Maturity	**33840.56**	**0**