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Supplementary Materials for

Spatial variations in crop growing seasons pivotal to reproduce global fluctuations in maize and wheat yields

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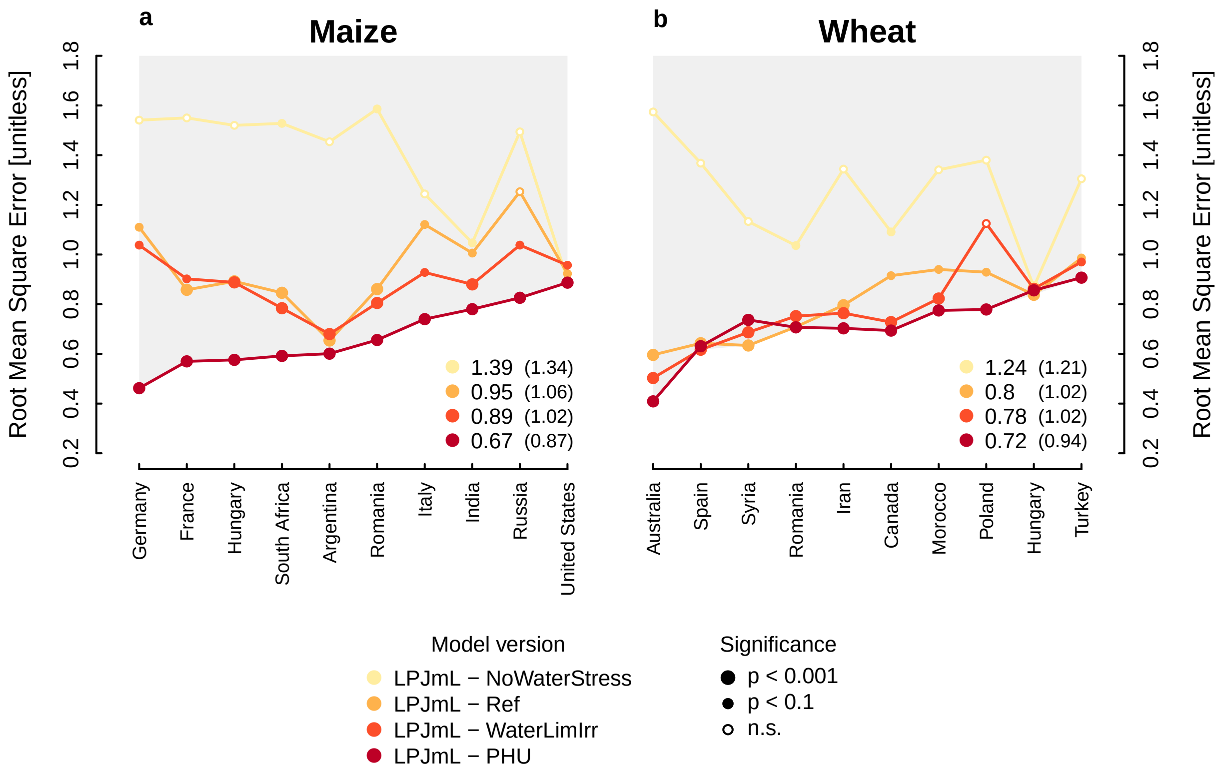

Fig. S1. Root mean square error of standardized country-level yield anomalies for maize (a) and wheat (b). RMSE values between four different LPJmL simulations (see Table 1) and observed FAO yield anomaly time series (1980 – 2010) are highlighted for the 10 main producer countries showing highest weather sensitivity (see Table S1, S2 for all main producer countries). Statistical significance of the explained variance is indicated through chart symbols (large dots if p-value < 0.001; small dots if p-value < 0.1; circle if not significant, i.e. p-value ≥ 0.1). Mean RMSE values across displayed most weather-sensitive main producers (and across all main producers in brackets) are shown in the bottom-right corner.

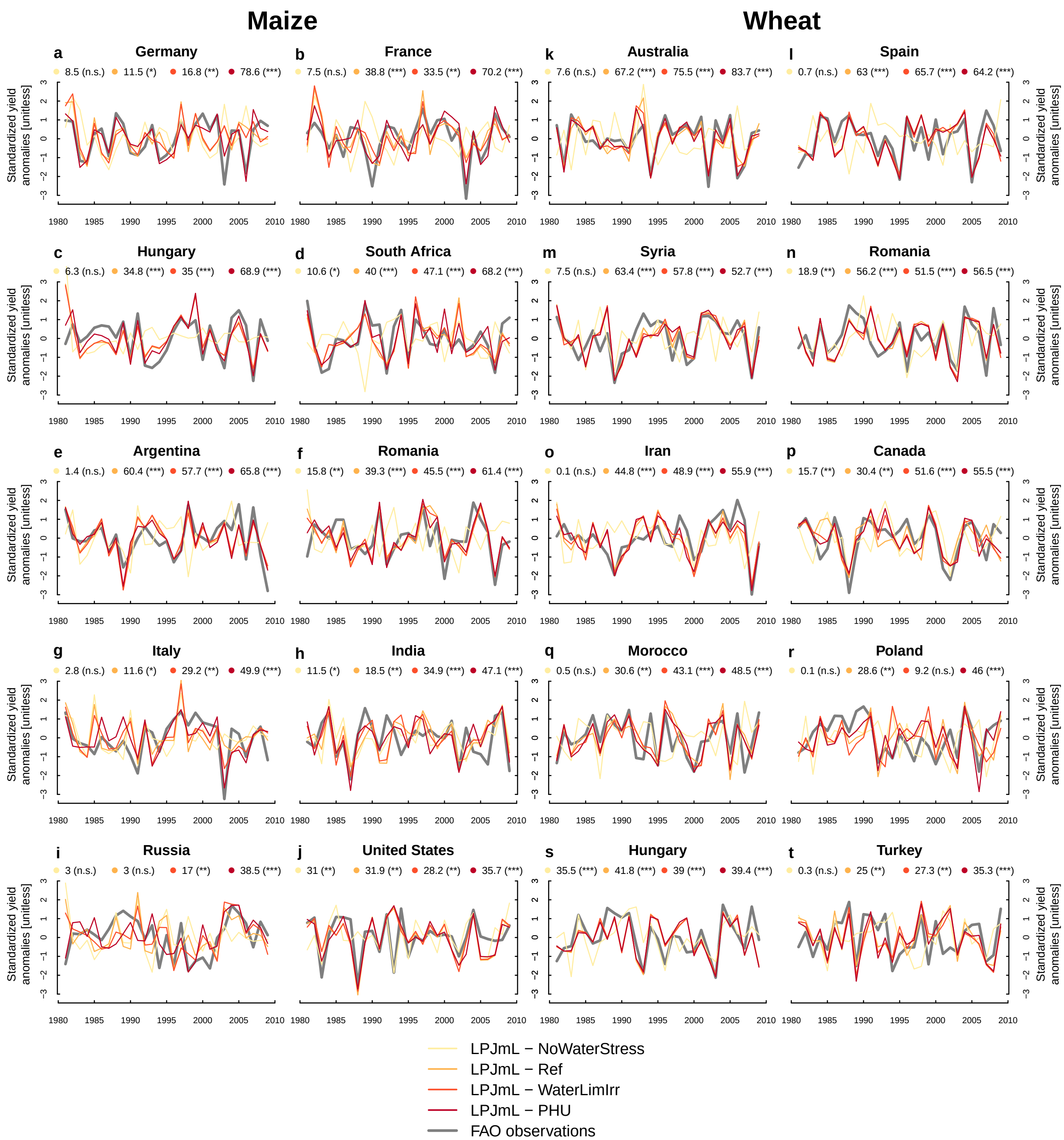

Fig. S2. Observed and simulated historical maize and wheat yield anomaly time series. Simulated (yellow – red) and observed (gray) standardized yield anomalies from 1980 – 2010 for maize (left column) and wheat (right column) are shown for the most weather-sensitive main producers in Figure 1. Colored dots in each panel indicate the R^2 value between FAO observations and the respective LPJmL simulation with statistical significance in brackets (”***” if $p < 0.001$; ”**” if $p < 0.05$; ”*” $p < 0.1$; ”n.s.” if $p \geq 0.1$).

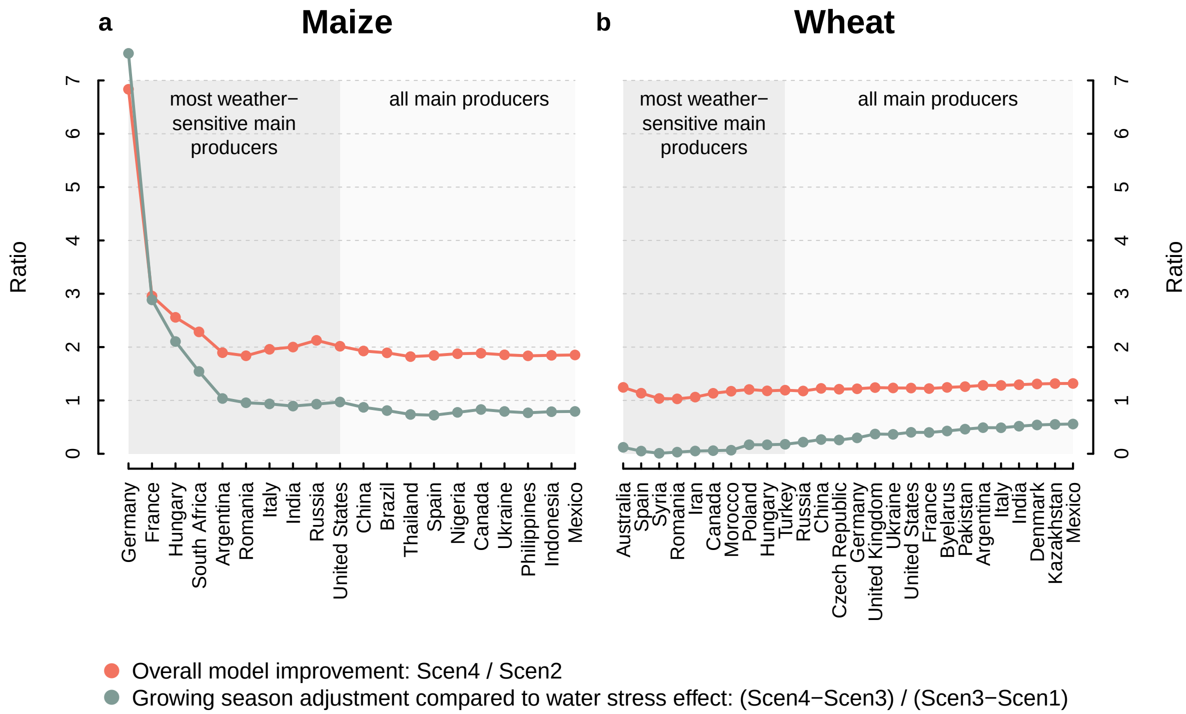

Fig. S3. Sensitivity of mean explained variance to number of countries considered. Scen1 (LPJmL–NoWaterStress), Scen2 (LPJmL–Ref), Scen3 (LPJmL–WaterLimIrr), and Scen4 (LPJml–PHU) represent R^2 values between observed and simulated maize (**a**) and wheat (**b**) yield anomalies achieved by the respective model as in Figure 1, but here shown as cumulative ratios across an increasing number of countries, starting from the single most weather-sensitive country to all main producers. Red lines illustrates the overall model improvement realized in this study (i.e. LPJmL–Ref to LPJmL–PHU), shown as the ratio of Scen4 and Scen2. This underpins the statement in the main text that the explained variance in maize simulations roughly doubles across all main producer countries. The green line illustrates the increase in explained variance due to the growing season adjustment (i.e. LPJmL–WaterLimIrr to LPJmL–PHU) compared to the increase due to considering water stress (i.e. LPJmL–NoWaterStress to LPJmL–WaterLimIrr), shown as $(Scen4 - Scen3)/(Scen3 - Scen1)$. This supports the statement in the main text that the growing season adjustment improves the explained variance for maize to about the same degree as the representation of water stress. For wheat, panel **b** highlights that the growing season adjustment becomes more important toward the lower end of weather sensitivity.

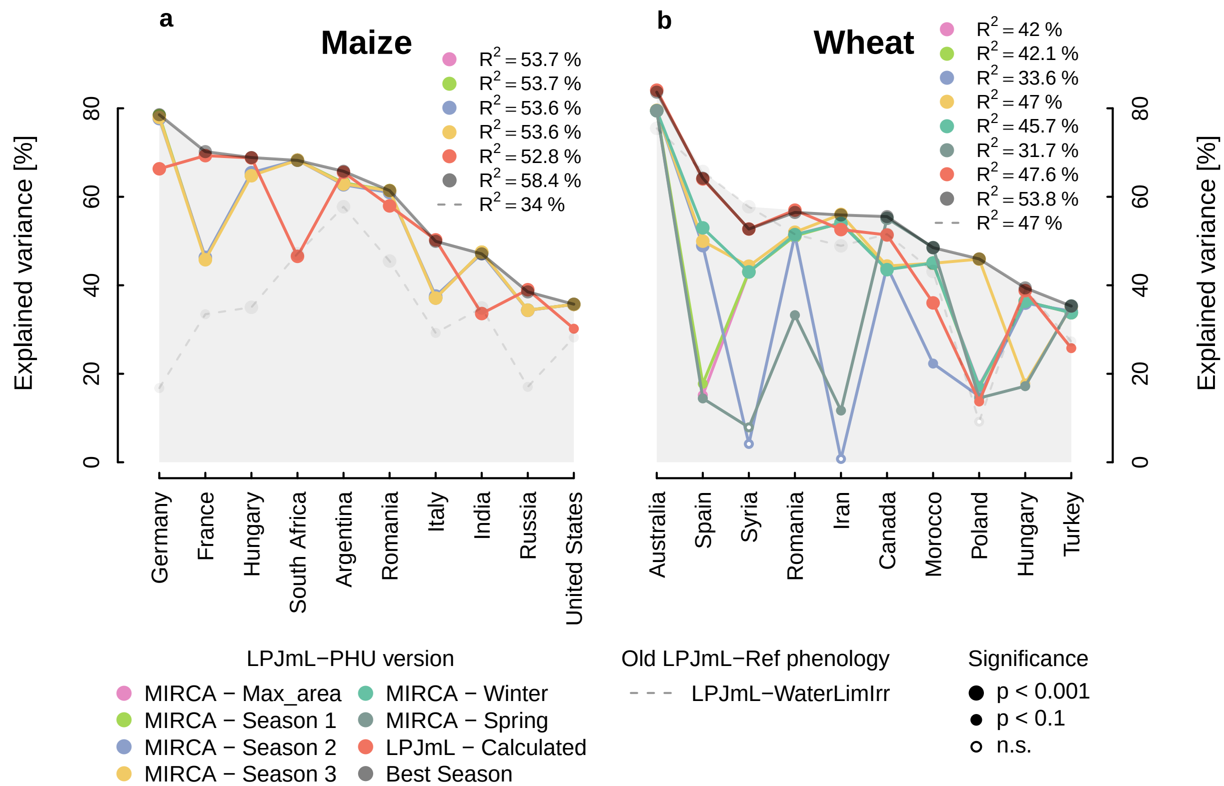

Fig. S4. Evaluation of available growing season inputs. This figure shows the explained variance of country-level yield anomalies simulated with the LPJmL–PHU model, similar to Figure 1, but differentiating available growing season inputs, for maize (**a**) and wheat (**b**), respectively. "MIRCA maxarea" refers to the MIRCA growing season with the largest cropland area associated, "MIRCA winter" and "MIRCA spring" refer to winter or spring crops (only wheat), "MIRCA season 1 – 3" refer to the first, second, or third season listed. "LPJmL – Calculated" refers to growing seasons calculated by the LPJmL–Ref model used as input in LPJmL–PHU, and the "Best season" refers to the per-country selection of the season that leads to the highest correlation between simulated and observed yield anomalies across the seven previous options (the default setup for LPJmL–PHU in this paper as described in Table 1). The dashed line represents LPJmL–WaterLimIrr (LPJmL–Ref phenology but water constraints as in LPJmL–PHU) as shown in Figure 1. The difference between the red and the dashed line thus illustrates the model improvement solely due to spatially-resolved PHUs (i.e. without contributions from MIRCA2000 crop calendar dates). R^2 values in the top-right corner indicate the mean value across displayed countries.

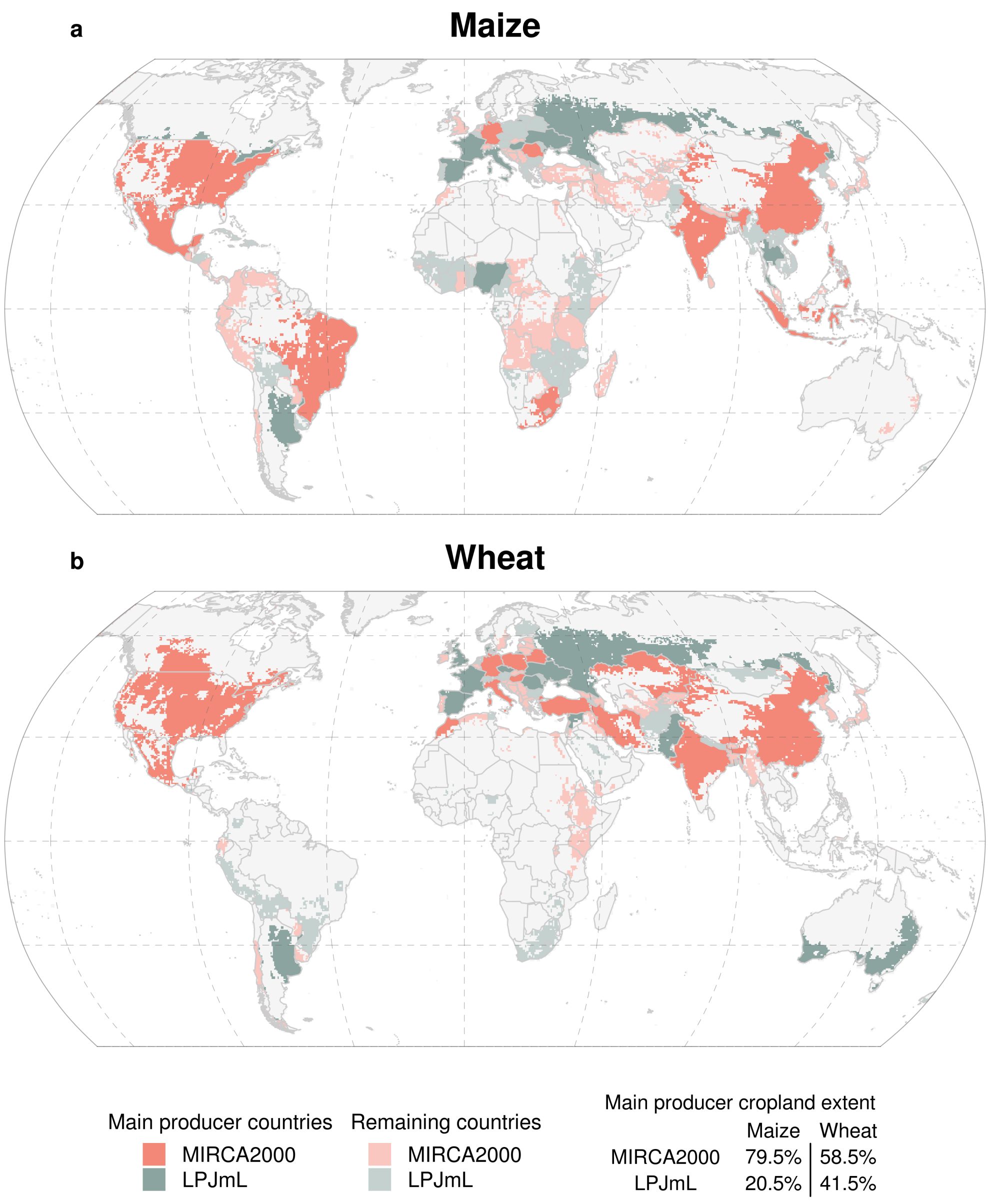

Fig. S5. Best-performing crop calendar per country. For maize (**a**) and wheat (**b**), countries are associated with the crop calendar – i.e. MIRCA2000 or LPJmL-calculated – that leads to the highest correlation between simulated and observed yield anomalies when used as input in the LPJmL–PHU model (see Material and Methods). Main producer countries, that collectively provide $\geq$90% of the respective global production, are highlighted through more saturated hues. Grid cells in which the respective crop is not simulated are masked. The legend table differentiates for both crops the main producer countries' cropland extent with respect to the best-performing crop calendar. Note that the MIRCA2000 dataset is compiled at subnational resolution in countries such as the USA, India, China, and Brazil, and provides national-level information in Russia, Spain, France, Ukraine, Pakistan, and Argentina among others *(27)*.

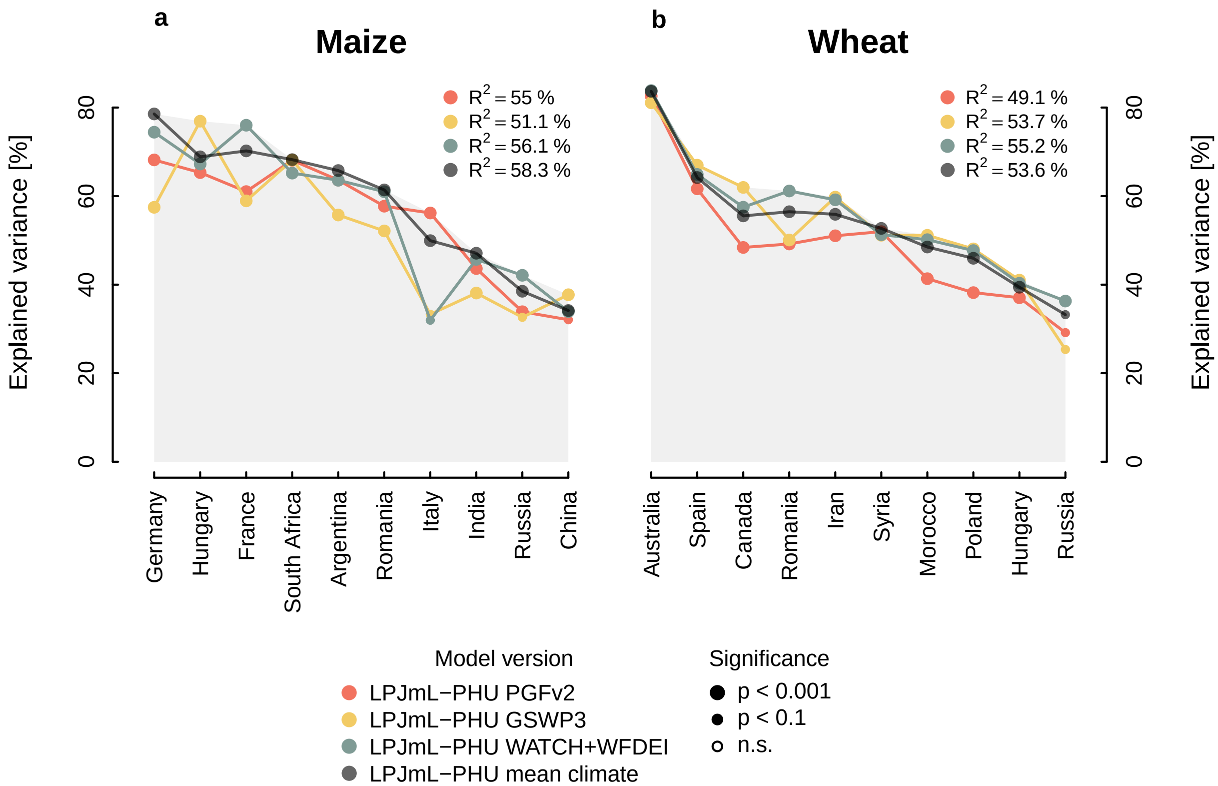

Fig. S6. Evaluation of different climate inputs. The figure shows the explained variance of country-level yield anomalies, similar to Figure 1, but for LPJmL–PHU simulations based on three climate inputs (PGFv2.1, GSWP3, and WATCH+WFDEI), for maize (**a**) and wheat (**b**), respectively. The simulation ”mean climate” refers to the mean of individual LPJmL–PHU simulations forced by the respective climate input. R^2 values in the top-right corner indicate the mean value across displayed countries.

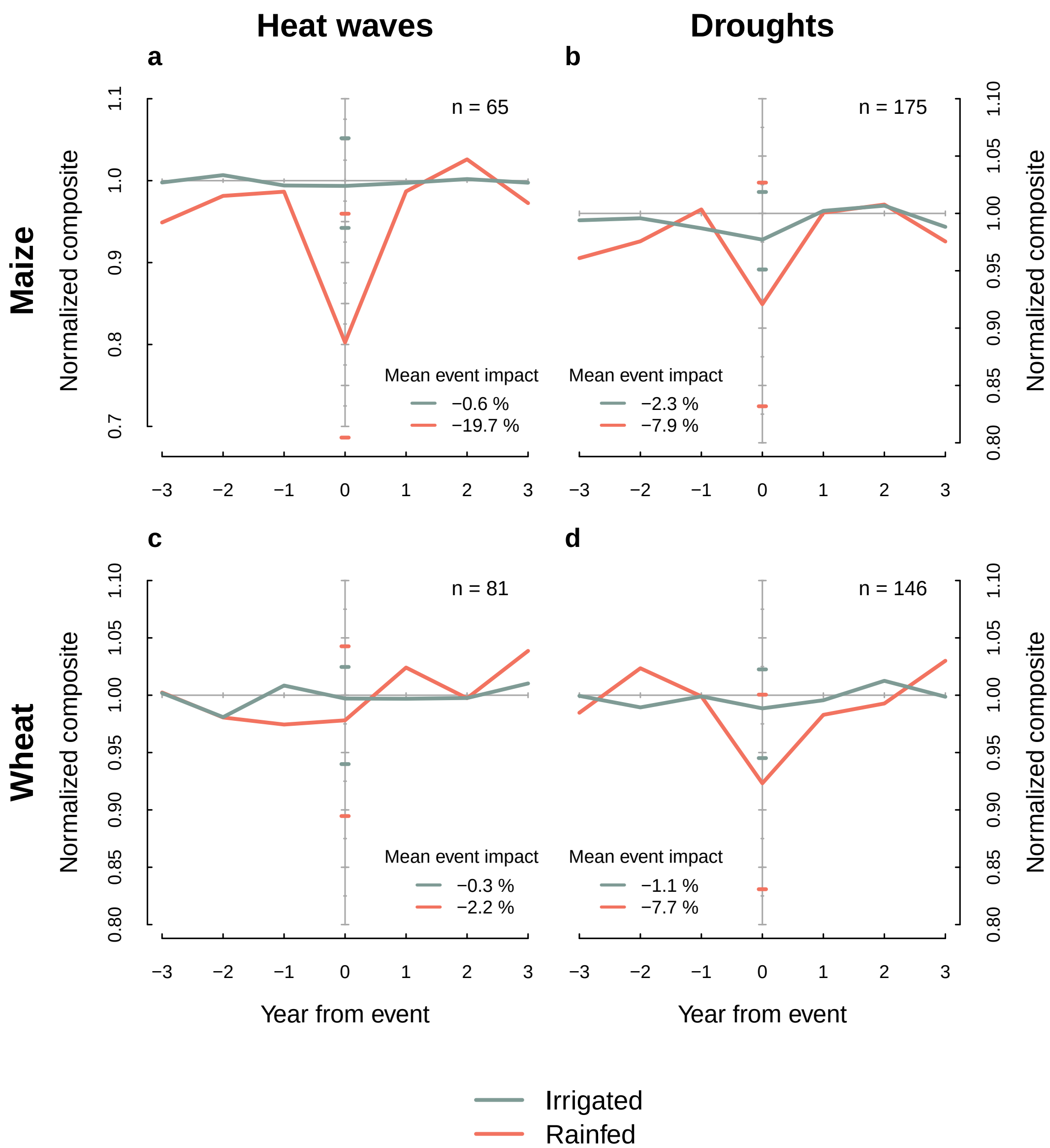

Fig. S7. Influences of heat waves and droughts on rainfed and irrigated yields. Similar to Figure 2, but separated for rainfed and irrigated systems, this composite plot illustrates average yield influences (maize top row, wheat bottom row) of worldwide heat waves (first column) and droughts (second column) recorded in EM-DAT *(13)* (1964 – 2007), simulated with the LPJmL–PHU model. Note the different y-axis scale in panel **a**.

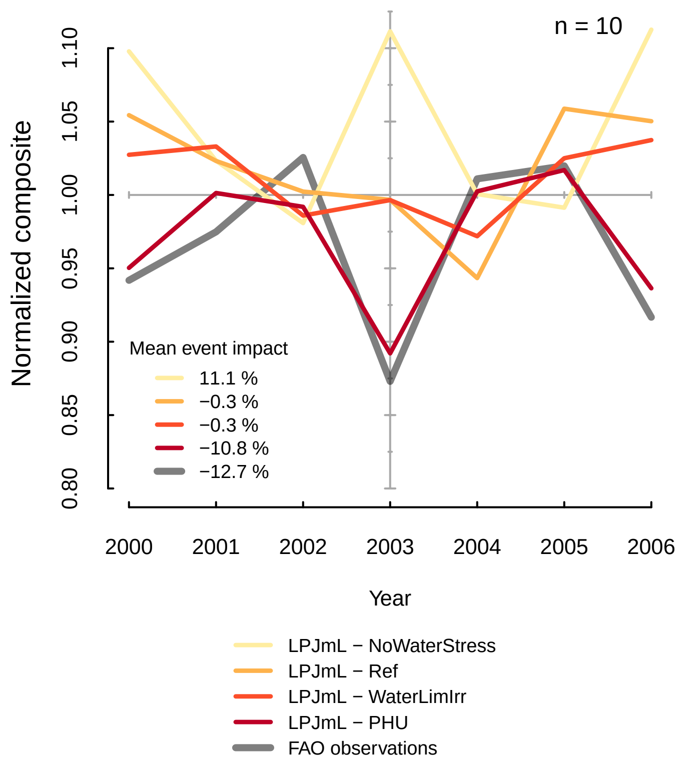

Fig. S8. Observed and simulated influences of the 2003 European heat wave on maize yields. Similar to Figure 2a, this plot shows a composite of maize yield impacts induced by heat waves, but here for countries affected by the European heat wave in 2003 only (10 countries listed in EM-DAT *(13)*: Austria, Belgium, Croatia, France, Germany, Italy, Netherlands, Portugal, Slovakia, Spain).

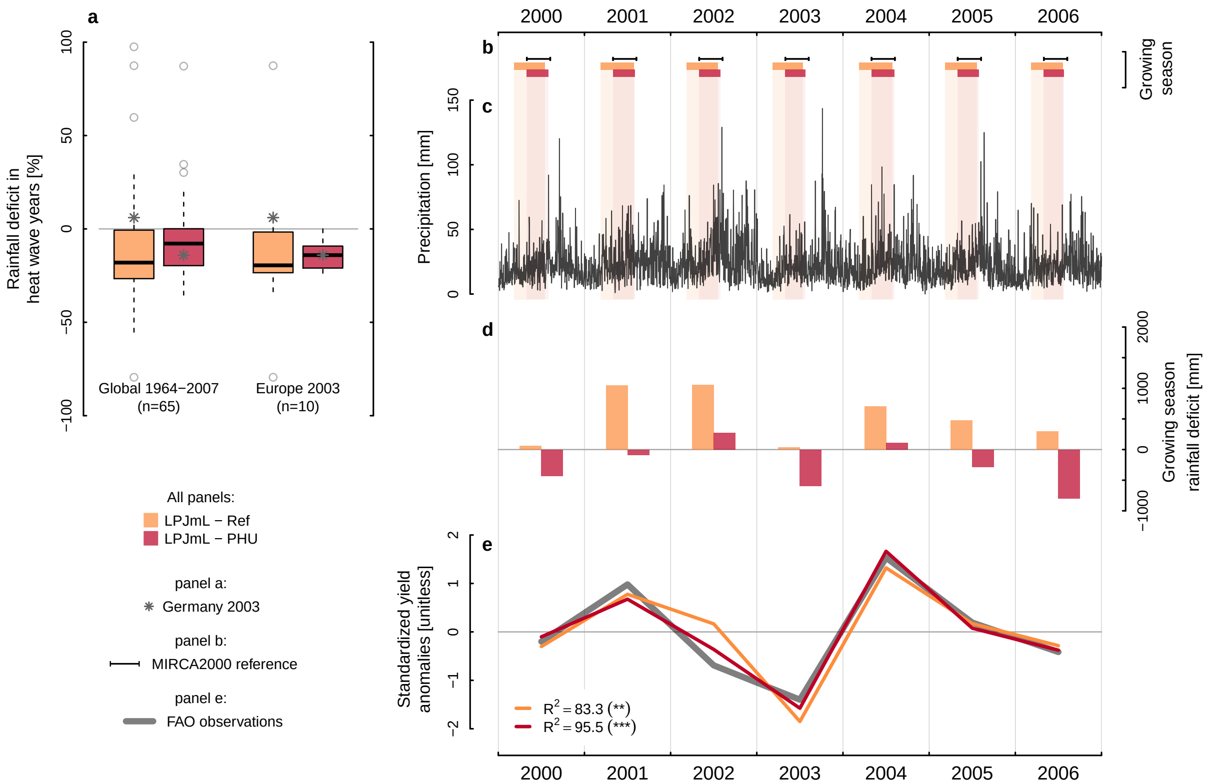

Fig. S9. Effects of growing season adjustment on wheat rainfall deficit. Same as Figure 3 but for spring wheat.

Table S1. Explained variances and RMSE of maize country-level yield anomalies. This table details data for Figure 1 and S1. Simulated yield anomalies are evaluated at country level aggregation against FAO statistics for the four simulations LPJmL–NoWaterStress, LPJmL–Ref, LPJmL–WaterLimIrr, and LPJmL–PHU (details in Table 1), based on the coefficient of determination (R^2, in percent) and Root Mean Square Error (RMSE, unitless). The table lists the main producer countries (accounting for 90% of global maize production, as of the 2000 – 2011 mean) and is ordered by best R^2 performance across LPJmL–Ref, LPJmL–WaterLimIrr, and LPJmL–PHU (separating the most weather-sensitive main producers, in accordance with Fig. 1 and S1). Statistical significance of the explained variance is indicated through (*) if p-value < 0.1 and (n.s.) otherwise.

		LPJmL–NoWaterStress		**LPJmL–Ref**		**LPJmL–WaterLimIrr**		**LPJmL–PHU**	
	Country	R^2 [%]	$RMSE$ [unitless]	R^2 [%]	$RMSE$ [unitless]	R^2 [%]	$RMSE$ [unitless]	R^2 [%]	$RMSE$ [unitless]
1	Germany	8.5 (n.s.)	1.54	11.5 (*)	1.11	16.8 (*)	1.04	78.6 (*)	0.46
2	France	7.5 (n.s.)	1.55	38.8 (*)	0.86	33.5 (*)	0.9	70.2 (*)	0.57
3	Hungary	6.3 (n.s.)	1.52	34.8 (*)	0.89	35 (*)	0.89	68.9 (*)	0.58
4	South Africa	10.6 (*)	1.53	40 (*)	0.85	47.1 (*)	0.78	68.2 (*)	0.59
5	Argentina	1.4 (n.s.)	1.45	60.4 (*)	0.65	57.7 (*)	0.68	65.8 (*)	0.6
6	Romania	15.8 (*)	1.59	39.3 (*)	0.86	45.5 (*)	0.8	61.4 (*)	0.66
7	Italy	2.8 (n.s.)	1.24	11.6 (*)	1.12	29.2 (*)	0.93	49.9 (*)	0.74
8	India	11.5 (*)	1.05	18.5 (*)	1.01	34.9 (*)	0.88	47.1 (*)	0.78
9	Russia	3 (n.s.)	1.49	3 (n.s.)	1.25	17 (*)	1.04	38.5 (*)	0.83
10	United States	31 (*)	0.9	31.9 (*)	0.92	28.2 (*)	0.96	35.7 (*)	0.89
11	China	0.7 (n.s.)	1.41	31.1 (*)	0.94	31.8 (*)	0.94	34.2 (*)	0.92
12	Brazil	3 (n.s.)	1.28	23.6 (*)	1	29.2 (*)	0.94	33.7 (*)	0.81
13	Thailand	1.6 (n.s.)	1.22	27.3 (*)	0.94	28 (*)	0.94	25.3 (*)	0.96
14	Spain	3.2 (n.s.)	1.24	8 (n.s.)	1.14	17.3 (*)	1.07	22.8 (*)	1.02
15	Nigeria	2.7 (n.s.)	1.46	2.1 (n.s.)	1.42	0 (n.s.)	1.33	16.4 (*)	1.4
16	Canada	10.9 (*)	1.1	4.6 (n.s.)	1.2	1.5 (n.s.)	1.3	12.1 (*)	1.01
17	Ukraine	0.6 (n.s.)	1.37	6.2 (n.s.)	1.22	7.2 (n.s.)	1.21	0.2 (n.s.)	1.16
18	Philippines	0.1 (n.s.)	1.35	4.6 (n.s.)	1.21	5.5 (n.s.)	1.2	1 (n.s.)	1.04
19	Indonesia	3.5 (n.s.)	1.09	0.7 (n.s.)	1.21	0.3 (n.s.)	1.24	5 (n.s.)	1.2
20	Mexico	2.8 (n.s.)	1.5	0 (n.s.)	1.38	1.9 (n.s.)	1.29	2.7 (n.s.)	1.27
	mean of most weather-sensitive main producers (1–10)	9.84	1.39	28.98	0.95	34.49	0.89	58.43	0.67
	mean of all main producers (1–20)	6.38	1.34	19.9	1.06	23.38	1.02	36.88	0.87

Table S2. Explained variances and RMSE of wheat country-level yield anomalies. Same as Table S1, but for wheat.

	Country	LPJmL–NoWaterStress R^2 [%]	LPJmL–NoWaterStress $RMSE$ [unitless]	LPJmL–Ref R^2 [%]	LPJmL–Ref $RMSE$ [unitless]	LPJmL–WaterLimIrr R^2 [%]	LPJmL–WaterLimIrr $RMSE$ [unitless]	LPJmL–PHU R^2 [%]	LPJmL–PHU $RMSE$ [unitless]
1	Australia	7.6 (n.s.)	1.57	67.2 (*)	0.6	75.5 (*)	0.5	83.7 (*)	0.41
2	Spain	0.7 (n.s.)	1.37	63 (*)	0.64	65.7 (*)	0.62	64.2 (*)	0.63
3	Syria	7.5 (n.s.)	1.13	63.4 (*)	0.63	57.8 (*)	0.69	52.7 (*)	0.74
4	Romania	18.9 (*)	1.04	56.2 (*)	0.71	51.5 (*)	0.75	56.5 (*)	0.71
5	Iran	0.1 (n.s.)	1.34	44.8 (*)	0.8	48.9 (*)	0.76	55.9 (*)	0.7
6	Canada	15.7 (*)	1.09	30.4 (*)	0.92	51.6 (*)	0.73	55.5 (*)	0.69
7	Morocco	0.5 (n.s.)	1.34	30.6 (*)	0.94	43.1 (*)	0.82	48.5 (*)	0.78
8	Poland	0.1 (n.s.)	1.38	28.6 (*)	0.93	9.2 (n.s.)	1.12	46 (*)	0.78
9	Hungary	35.5 (*)	0.87	41.8 (*)	0.84	39 (*)	0.86	39.4 (*)	0.86
10	Turkey	0.3 (n.s.)	1.3	25 (*)	0.99	27.3 (*)	0.97	35.3 (*)	0.91
11	Russia	27.2 (*)	0.96	34.1 (*)	0.89	19.4 (*)	1.02	33.2 (*)	0.9
12	China	0.4 (n.s.)	1.28	7.7 (n.s.)	1.16	11.9 (*)	1.11	33.1 (*)	0.87
13	Czech Republic	9.2 (n.s.)	1.14	31.1 (*)	0.94	28.3 (*)	0.96	30 (*)	0.95
14	Germany	5.3 (n.s.)	1.21	21.6 (*)	1.04	12.4 (*)	1.12	30.5 (*)	0.93
15	United Kingdom	2.6 (n.s.)	1.27	13.8 (*)	1.63	0.6 (n.s.)	1.33	29.6 (*)	0.94
16	Ukraine	15.6 (*)	1.07	25.5 (*)	1	26 (*)	0.99	27.5 (*)	0.98
17	United States	52.7 (*)	0.72	22.6 (*)	1.01	22.9 (*)	1.01	26.7 (*)	0.98
18	France	4.4 (n.s.)	1.24	22.9 (*)	1	17.8 (*)	1.05	22.1 (*)	1.01
19	Byelarus	9.5 (n.s.)	1.13	7.1 (n.s.)	1.17	10.8 (*)	1.14	22.4 (*)	1
20	Pakistan	7.8 (n.s.)	1.18	8.3 (n.s.)	1.17	6.6 (n.s.)	1.2	19.9 (*)	1.68
21	Argentina	4.3 (n.s.)	1.37	0.8 (n.s.)	1.21	4.7 (n.s.)	1.16	16.4 (*)	0.99
22	Italy	6 (n.s.)	1.19	12.2 (*)	1.11	12.6 (*)	1.1	15.1 (*)	1.09
23	India	2.8 (n.s.)	1.25	1.5 (n.s.)	1.3	0 (n.s.)	1.4	10.6 (*)	1.6
24	Denmark	0.1 (n.s.)	1.37	0 (n.s.)	1.36	0 (n.s.)	1.37	9.4 (n.s.)	1.14
25	Kazakhstan	0.2 (n.s.)	1.35	1.5 (n.s.)	1.3	1.6 (n.s.)	1.3	6.9 (n.s.)	1.16
26	Mexico	2.4 (n.s.)	1.27	0 (n.s.)	1.37	0.1 (n.s.)	1.4	1.3 (n.s.)	1.13
	mean of most weather-sensitive main producers (1–10)	8.69	1.24	45.1	0.8	46.96	0.78	53.77	0.72
	mean of all main producers (1–26)	9.13	1.21	25.45	1.03	24.82	1.02	33.55	0.94

Table S3. List of extreme events considered in this study. Heat wave and drought events between 1964 – 2007 recorded at country level in EM-DAT *(13)* are included in the analysis of maize and wheat simulations (Figure 2) if the respective crop contributes at least 5% to the total country cropland area. Country names are shown as ISO3 codes.

	Maize				Wheat			
	Heat waves (n=65)	**Droughts** (n=175)			**Heat waves** (n=81)		**Droughts** (n=146)		
1	1966 USA	1964 ECU	1985 CHN	1999 USA	1965 IND	2005 IND	1964 IND	1989 FRA	2003 HUN
2	1968 MEX	1964 NPL	1986 HUN	1999 URY	1966 USA	2005 PAK	1964 IRN	1990 BOL	2003 RUS
3	1972 ARG	1964 SOM	1986 IDN	2000 BOL	1968 MEX	2005 PRT	1964 NPL	1990 GRC	2004 BOL
4	1972 USA	1964 ZAF	1986 ZAF	2000 BIH	1972 ARG	2005 USA	1964 ZAF	1990 PER	2004 PER
5	1980 USA	1965 CHN	1987 ETH	2000 BGR	1972 USA	2006 FRA	1965 CHN	1990 ESP	2004 PRT
6	1983 PER	1965 ETH	1987 SOM	2000 GEO	1975 PAK	2006 ESP	1965 ETH	1990 MKD	2004 ZAF
7	1983 USA	1965 KEN	1987 VNM	2000 MDA	1978 IND	2007 ALB	1966 MAR	1991 AUS	2005 CHN
8	1985 GRC	1966 BFA	1988 BOL	2000 ROU	1979 PAK	2007 AUT	1966 PER	1991 CHL	2005 ZMB
9	1986 USA	1966 IDN	1988 BFA	2000 SOM	1980 USA	2007 BGR	1967 AUS	1991 CHN	2006 AFG
10	1987 GRC	1966 PER	1988 CAN	2001 BFA	1983 PER	2007 GRC	1967 NPL	1991 FRA	2006 AUS
11	1987 NPL	1966 SEN	1988 CHN	2001 CMR	1983 USA	2007 HUN	1968 CHL	1991 ZAF	2006 NPL
12	1988 MKD	1967 NPL	1988 MEX	2001 NAM	1985 GRC	2007 ITA	1968 LSO	1991 USA	2006 PER
13	1990 FRA	1967 TZA	1988 ZAF	2001 SWZ	1985 IND	2007 JPN	1969 AFG	1991 ZMB	2007 LSO
14	1990 MEX	1968 HTI	1988 TZA	2001 ZWE	1986 USA	2007 MKD	1969 ETH	1991 ZWE	2007 MDA
15	1990 USA	1969 BFA	1988 USA	2002 ITA	1987 GRC	2007 SVK	1969 IRQ	1992 DNK	2007 USA
16	1993 USA	1969 ETH	1989 ALB	2002 MEX	1987 IND	2007 TUR	1969 PER	1992 HUN	2007 ZWE
17	1994 CHN	1969 PER	1989 ETH	2002 PER	1987 NPL		1969 YMN	1992 LSO	
18	1994 ROU	1969 SEN	1989 FRA	2002 SEN	1988 MKD		1971 AFG	1992 PER	
19	1995 RUS	1969 SOM	1990 BOL	2002 VNM	1990 FRA		1971 MAR	1993 IND	
20	1995 ESP	1969 YMN	1990 BFA	2003 ARG	1990 MEX		1972 IND	1993 MKD	
21	1995 USA	1971 CMR	1990 CMR	2003 BIH	1990 USA		1972 NPL	1993 RUS	
22	1996 ROU	1971 KEN	1990 GRC	2003 HRV	1991 PAK		1973 ETH	1994 BOL	
23	1997 CHN	1972 IDN	1990 PER	2003 ETH	1993 AUS		1974 AUS	1995 MEX	
24	1998 ITA	1972 NPL	1990 ESP	2003 HTI	1993 USA		1977 BOL	1995 ZAF	
25	1998 ROU	1973 ETH	1990 SWZ	2003 HUN	1994 CHN		1977 CAN	1995 ZMB	
26	1998 USA	1974 HTI	1990 MKD	2003 IDN	1994 IND		1977 JPN	1996 IND	
27	2000 BGR	1974 SOM	1991 CHN	2003 RUS	1994 ROU		1977 TUN	1997 CHN	
28	2000 HRV	1976 BEL	1991 FRA	2003 TZA	1995 EGY		1977 YMN	1997 ETH	
29	2000 GRC	1977 BOL	1991 KEN	2004 BOL	1995 RUS		1978 AUS	1997 FRA	
30	2000 ROU	1977 BFA	1991 NAM	2004 KEN	1995 ESP		1978 CHN	1997 ITA	
31	2001 NZL	1977 CAN	1991 ZAF	2004 PER	1995 USA		1978 MEX	1997 PRT	
32	2001 RUS	1977 HTI	1991 TZA	2004 PRT	1996 PAK		1979 IND	1998 IRQ	
33	2002 CHN	1977 SEN	1991 USA	2004 SOM	1996 ROU		1979 NPL	1998 RUS	
34	2002 NGA	1977 TZA	1991 ZMB	2004 ZAF	1997 CHN		1980 ZAF	1998 ZWE	
35	2003 AUT	1977 YMN	1991 ZWE	2005 CMR	1998 IND		1980 ESP	1999 CHN	
36	2003 BEL	1978 CHN	1992 HTI	2005 CHN	1998 ITA		1981 DZA	1999 IRN	
37	2003 HRV	1978 IDN	1992 HUN	2005 VNM	1998 ROU		1981 AUS	1999 ISR	
38	2003 FRA	1978 MEX	1992 PER	2005 ZMB	1998 USA		1982 FRA	1999 JOR	
39	2003 DEU	1979 KEN	1993 MKD	2006 NPL	1999 PAK		1982 IND	1999 MEX	
40	2003 ITA	1979 NPL	1993 RUS	2006 PER	2000 BGR		1982 ZAF	1999 MAR	
41	2003 NLD	1980 BFA	1994 BOL	2006 TZA	2000 HRV		1982 ZMB	1999 PAK	
42	2003 PRT	1980 HTI	1994 KEN	2007 MDA	2000 GRC		1982 ZWE	1999 ESP	
43	2003 SVK	1980 SOM	1994 NZL	2007 SWZ	2000 ISR		1983 BOL	1999 SYR	
44	2003 ESP	1980 ZAF	1995 BFA	2007 USA	2000 JOR		1983 BGR	1999 USA	
45	2004 ALB	1980 ESP	1995 MEX	2007 ZWE	2000 MAR		1983 ETH	2000 AFG	
46	2004 CHN	1982 FRA	1995 NAM		2000 ROU		1983 LSO	2000 ARM	
47	2004 MKD	1982 IDN	1995 ZAF		2000 TUR		1983 MAR	2000 AZE	
48	2004 ROU	1982 NAM	1995 ZMB		2001 RUS		1983 PER	2000 BOL	
49	2005 PRT	1982 SEN	1996 TZA		2002 CHN		1983 PRT	2000 BGR	
50	2005 USA	1982 ZAF	1997 CHN		2002 IND		1983 ROU	2000 GEO	
51	2006 BEL	1982 ZMB	1997 ECU		2002 PAK		1984 CAN	2000 IND	
52	2006 FRA	1982 ZWE	1997 ETH		2003 DZA		1985 CHN	2000 MDA	
53	2006 DEU	1983 BOL	1997 FRA		2003 AUT		1986 HUN	2000 MNG	
54	2006 NLD	1983 BGR	1997 IDN		2003 HRV		1986 ZAF	2000 ROU	
55	2006 ESP	1983 ETH	1997 ITA		2003 FRA		1987 ETH	2000 TJK	
56	2007 ALB	1983 NGA	1997 KEN		2003 ITA		1987 IND	2000 UZB	
57	2007 AUT	1983 PER	1997 PRT		2003 PRT		1988 BOL	2001 ZWE	
58	2007 BIH	1983 PRT	1997 VNM		2003 SVK		1988 CAN	2002 AUS	
59	2007 BGR	1983 ROU	1998 BFA		2003 ESP		1988 CHN	2002 ITA	
60	2007 GRC	1983 SOM	1998 NAM		2003 GBR		1988 MEX	2002 LSO	
61	2007 HUN	1983 SWZ	1998 RUS		2004 ALB		1988 ZAF	2002 MEX	
62	2007 ITA	1984 CAN	1998 ZWE		2004 CHN		1988 TUN	2002 PER	
63	2007 MKD	1984 IDN	1999 CHN		2004 JPN		1988 USA	2003 ARG	
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65	2007 SVK	1984 TZA	1999 ESP		2004 ROU		1989 ETH	2003 ETH	