The following supplement accompanies the article

Yield gap of winter wheat in Europe and sensitivity of potential yield to climate factors

Shaoxiu Ma*, Galina Churkina, Arthur Gessler, Ralf Wieland, Gianni Bellocchi

*Corresponding author: shaoxiuma@gmail.com

Climate Research 67: 179–190 (2016)

S1. Trend and correlation analyses

The trend and correlation analysis for climate variables and the estimated potential yields was used to both corroborate the climate dataset used in the present study and identify the climatic limiting factors of winter wheat yield in Europe. The non-parametric sign test (Cox-Stuart) was used to examine the trends in the climate variables and the estimated potential yields during the 1976-2005 period. Then these trends were compared with previous studies (Supit et al. 2010a, b). The advantage of the Cox-Stuart test is that it is not sensitive to extreme values (Cox and Stuart 1955; Supit et al. 2010a, b), a fact that is important since the temperature trend might be non-linear due to extreme weather conditions (Makowski et al. 2008). The year 1976 was chosen as starting point to coincide with the initiation of the most recent period of sustained warming in the 20th century (following the period from the late 1940s through the early 1970s, which exhibited a cooling trend, IPCC 2001). The monthly and seasonal average values as well as the average of different combinations of months during the growth period of winter wheat were used in the trend analysis**.** The average values of the climate variables were calculated according to the daily resolution used to drive the ANTHRO-BGC model.

The correlation analysis between the average value of the climate variables and the estimated potential yield was performed to identify the climate variable and the time period with the strongest impact on yield in each grid cell. Indeed, both intra-seasonal and inter-seasonal changes of climate variables have an impact on crop yield (Rowhani et al. 2011). Spearman's correlation coefficient was calculated using IDL V7.0. The average coefficient across Europe was computed using the cultivated area of winter wheat as weighting factor.

S2.1 Trends in climate variables

Between 1976 and 2005, the daily mean temperature displayed a statistically significant trend to increase in large areas of Europe. However, trends had strong seasonal differences among regions (Fig. S1). In spring, daily mean temperature showed a statistically significant upward trend in large parts of Germany, France, Great Britain, Ireland and Spain (Fig. S1). In summer, this upward trend shifted to Central and Eastern Europe (Fig. S1). In contrast, in autumn and winter there only a few small areas were associated with a significant temperature increase. A comparable seasonal difference in the trends of daily mean temperatures in different parts of Europe was previously found by Supit et al. (2010a), who used interpolated station data (Micale & Genovese 2004) for their analysis. The annual temperature change within the 1976-2005 period is not statistically significant in large parts of Europe mainly because temperature variability has increased mainly owing to a higher frequency of warm extremes (Moberg & Jones 2005, Moberg et al. 2006).

A seasonal and location-dependent upward trend in global solar radiation was found by Supit et al. (2010a) whereas the radiation trends estimated in the present study were mostly not significant. We estimated global solar radiation by applying an algorithm based on the existing climate variables from the MCRU dataset, such as temperature and cloudiness (Chen et al. 2009). The radiation data used by Supit et al. (2010a) were computed as a function of either sunshine duration, a combination of cloudiness and temperature range or only the temperature range (Supit et al., 2010a). Consequently, they were not based on observations, but calculated using rather simple models. Thus the trends found require confirmation against independent observations.

S2.2 Trends in potential yield

The potential yields had a statistically significant upward trend between 1976 and 2005 in northern and north-eastern Europe and the Alpine Mountain region, and a significant downward trend in Spain (extending to northern Africa) and southern Europe (Fig. S2). Significant decreases in rain-fed potential yield were observed in parts of Central Europe and France and a significant increase in Ireland, parts of United Kingdom, Western France and parts of the Alps (Fig. S2).

The potential yield thus showed a positive trend in relatively cool regions of Europe. This finding can be mainly attributed to the warming trend because crop yields in northern Europe are mainly limited by cool temperatures (Holmer 2008), whereas in contrast yields in southern Europe are rather restricted by high temperatures and low rainfall (Reidsma & Ewert 2008). As discussed above, the general global warming trend also occurred in Europe (Fig. S3) even though it was statistically significant only in a few regions (right panel). Contrasting the insignificant trend of temperature changes from 1976 to 2005 in the northern and north-eastern parts of Europe, the significantly increasing yield trends indicate that the potential yield is sensitive to even very small increases in temperature in the cool temperate climate.

The negative trend in water-limited yields in parts of Central Europe occurred mainly in regions where irrigation is already required and implemented (Wriedt et al. 2009). The area with a decreasing yield trend identified here is smaller than the one estimated by Supit et al. (2010b). This difference might be partially attributed to the different models and climatic driver datasets (Supit et al. 2010b) used in the two studies. The yields estimated by different models can strongly vary and have considerable uncertainties (Palosuo et al. 2011, Asseng et al. 2013). Moreover, the study of Supit et al. (2010b) was executed on a different resolution and the results were subsequently aggregated to the sub-regional level, which may also explain part of the differences.

S2.3 The correlation between the potential yield and climate variables

We explored the sensitivity of potential yield to climate variables for different periods of the growing season as well as for different regions in Europe. Different climate variables averaged over different periods of the year showed different correlations with potential and rain-fed potential yield (Fig. S4). On the temporal scale, mean radiation from April to July had the strongest correlation with potential yield (Fig. S4.a). On the spatial scale, radiation in spring and summer had positive correlations in most areas of Europe, while a few grids in the south of western and central Europe showed negative correlations (Fig. S5). Mean temperature was negatively correlated with the potential yield in spring in the south-west of Europe (Spain, southern France, north of Italy), and positively in central and northern Europe (Fig. S5). The negative correlation with temperature was extended from southern to south-eastern and eastern Europe in summer (Fig. S5).

The positive correlation between radiation and potential yield points to radiation as a major yield-limiting factor in large parts of Europe. One potential reason is that the earlier start of the growing season in response to global warming (Chmielewski et al. 2004, Menzel 2006, Ma et al. 2011) leads to less available radiation at that time (Supit et al. 2010b). The changed phenology of crops was also observed to impact yield, evapotranspiration and energy balance in the USA (Sacks and Kucharik 2011). The duration of the growing season and the solar radiation intensity are typical climatic constraints for plant growth in the northern parts Europe (Olesen & Bindi 2002, Olesen et al. 2011). The negative correlations between precipitation and potential yield as displayed in Fig. S4.a are not realistic since water limitation was removed when estimating the potential yield.

Precipitation during the growing season, however, showed a positive correlation with the rain-fed potential yield (Fig. S4.b) in most regions of Europe, with the exception of the United Kingdom and a few points scattered in the Alpine Mountain region in spring and summer (Fig. S6). On the contrary, radiation and temperature in spring and summer had negative correlations with the water-limited yield in various regions of Europe (Fig. S6).

The positive correlation between the precipitation and the water-limited yield observed here clearly indicates the importance of water as a limiting factors for crop growth in Europe. This finding is in agreement with a previous study, where it was shown that the intensive drought in 2003 was a major contributor to the reduction of gross primary production of terrestrial ecosystems including crops over large areas of Europe (Ciais et al. 2005).

The negative correlations between temperatures and water-limited yield in parts of southern Europe might be partially explained by the temperature rise in spring for the period between 1976 and 2005. This leads to an earlier leaf onset and, in turn, has the consequence that less radiation is available for crops at the start of growing season (Supit et al. 2010b). Moreover, the temperature rise in summer can shorten the growing stage and intensify plant respiration (Supit et al. 2010b), which will also reduce yield.

As a consequence, the climate dataset, which was used in present study, is comparable to the climate datasets used in previous studies so that we can consider the estimated potential in the present study sufficiently reliable. At the same time, we confirmed that precipitation and radiation are the most important climatic limiting factors for winter wheat yield in Europe.

Asseng S, Ewert F, Rosenzweig C, Jones JW, Hatfield JL, Ruane AC, Boote KJ, Thorburn PJ, Rötter RP, Cammarano D, Brisson N, Basso B, Martre P, Aggarwal PK, Angulo C, Bertuzzi P, Biernath C, Challinor AJ, Doltra J, Gayler S, Goldberg R, Grant R, Heng L, Hooker J, Hunt LA, Ingwersen J, Izaurralde RC, Kersebaum KC, Müller C, Naresh Kumar S, Nendel C, O'Leary G, Olesen JE, Osborne TM, Palosuo T, Priesack E, Ripoche D, Semenov MA, Shcherbak I, Steduto P, Stöckle C, Stratonovitch P, Streck T, Supit I, Tao F, Travasso M, Waha K, Wallach D, White JW, Williams JR, Wolf J (2013) Uncertainty in simulating wheat yields under climate change. Nat Clim Change 3:827-832

Chmielewski F-M, Mueler A, Bruns E (2004) Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961-2000. Agr Forest Meteorol 121:69-78

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon W-T, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen J, Rinke A, Sarr A, Whetton P (2007) Regional climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate Change 2007: The physical science basis. Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York, NY

Ciais P, Reichstein M, Viovy N, Granier A, Ogee J, Allard V, Aubinet M, Buchmann N, Bernhofer C, Carrara A, Chevallier F, De Noblet N, Friend AD, Friedlingstein P, Grunwald T, Heinesch B, Keronen P, Knohl A, Krinner G, Loustau D, Manca G, Matteucci G, Miglietta F, Ourcival JM, Papale D, Pilegaard K, Rambal S, Seufert G, Soussana JF, Sanz MJ, Schulze ED, Vesala T, Valentini R (2005) Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437:529-533

Cox DR, Stuart A (1955) Some quick sign tests for trend in location and dispersion Biometrika 42:80-95

Holmer B (2008) Fluctuations of winter wheat yields in relation to length of winter in Sweden 1866 to 2006. Clim Res 36:241-252

Ma S, Churkina G, Trusilova K (2011) Investigating the impact of climate change on crop phenological events in Europe with a phenology model. Int J Biometeorol 56:749-763

Makowski K, Wild M, Ohmura A (2008) Diurnal temperature range over Europe between 1950 and 2005. Atmos Chem Phys 8:6483-6498

Menzel A (2006) European phenological response to climate change matches the warming pattern. Global Change Biol 12:1969-1976

Micale F, Genovese G (2004) Methodology of the MARS Crop Yield Forecasting System. . Publication EUR 21291 EN of the Office for Official Publications of the EU, Luxembourg Vol. 1. Meteorological Data Collection, Processing and Analysis.

Moberg A, Jones PD (2005) Trends in indices for extremes in daily temperature and precipitation in central and western Europe, 1901–99. Int J Climatol 25:1149-1171

Moberg A, Jones PD, Lister D, Walther A, Brunet M, Jacobeit J, Alexander LV, Della-Marta PM, Luterbacher J, Yiou P, Chen D, Klein Tank AMG, Saladi O, Sigr J, Aguilar E, Alexandersson H, Almarza C, Auer I, Barriendos M, Begert M, Bergstroem H, Boehm R, Butler CJ, Caesar J, Drebs

A, Founda D, Gerstengarbe F-W, Micela G, Maugeri M, Oesterle H, Pandzic K, Petrakis M, Srnec L, Tolasz R, Tuomenvirta H, Werner PC, Linderholm H, Philipp A, Wanner H, Xoplaki E (2006) Indices for daily temperature and precipitation extremes in Europe analyzed for the period 1901-2000. J Geophys Res 111:D22106

Nakićenović N, 2000. Greenhouse gas emissions scenarios. Technol Forecast Soc 65:149-166.

Olesen JE, Bindi M (2002) Consequences of climate change for European agricultural productivity, land use and policy. Eur J Agron 16:239-262

Olesen JE, Trnka M, Kersebaum KC, Skjelvag AO, Seguin B, Peltonen-Sainio P, Rossi F, Kozyra J, Micale F (2011) Impacts and adaptation of European crop production systems to climate change. Eur J Agron 34:96-112

Palosuo T, Kersebaum KC, Angulo C, Hlavinka P, Moriondo M, Olesen JE, Patil RH, Ruget F, Rumbaur C, Takac J, Trnka M, Bindi M, caldag B, Ewert F, Ferrise R, Mirschel W, Saylan L, Siska B, Roeter R (2011) Simulation of winter wheat yield and its variability in different climates of Europe: A comparison of eight crop growth models. Eur J Agron 35:103-114

Reidsma P, Ewert FA (2008) Regional farm diversity can reduce vulnerability of food production to climate change. Ecol Soc 13:1-16

Rowhani P, Lobell DB, Linderman M, Ramankutty N (2011) Climate variability and crop production in Tanzania. Agr Forest Meteorol 151:449-460

Sacks WJ, Kucharik CJ (2011) Crop management and phenology trends in the U.S. Corn Belt: Impacts on yields, evapotranspiration and energy balance. Agr Forest Meteorol 151:882-894

Supit I, van Diepen CA, Boogaard HL, Ludwig F, Baruth B (2010a) Trend analysis of the water requirements, consumption and deficit of field crops in Europe. Agr Forest Meteorol 150:77-88

Supit I, van Diepen CA, de Wit AJW, Kabat P, Baruth B, Ludwig F (2010b) Recent changes in the climatic yield potential of various crops in Europe. Agr Syst103:683-694

Wriedt G, van der Velde M, Aloe A, Bouraoui F (2009) A European irrigation map for spatially distributed agricultural modelling. Agr Water Manage 96:771-789

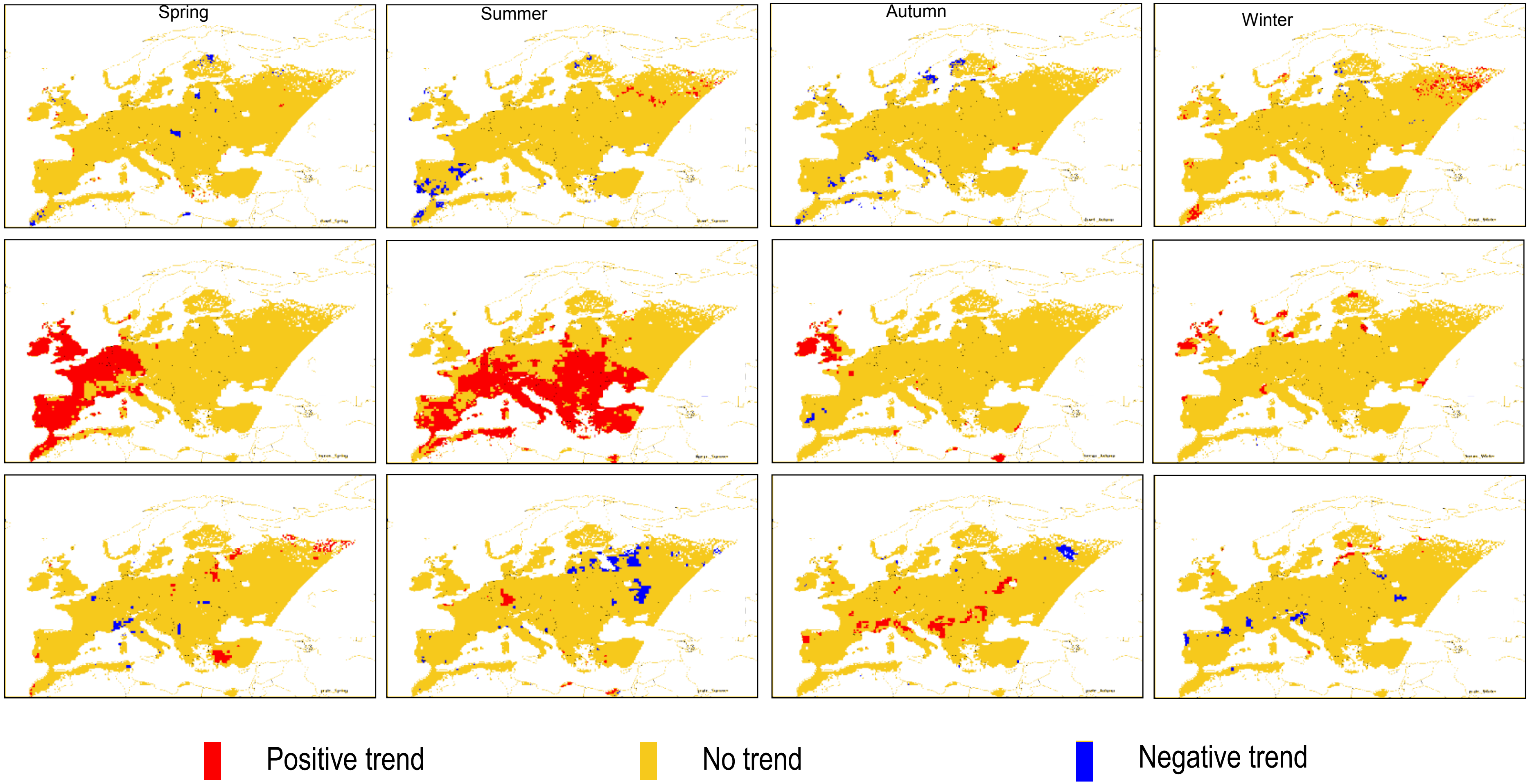


Fig. S1. Maps of the seasonal average radiation (first row), mean temperature (second row) and precipitation (third row) trends from 1976 to 2005. The trend was tested using the Cox–Stuart sign test at significance level p<0.05.

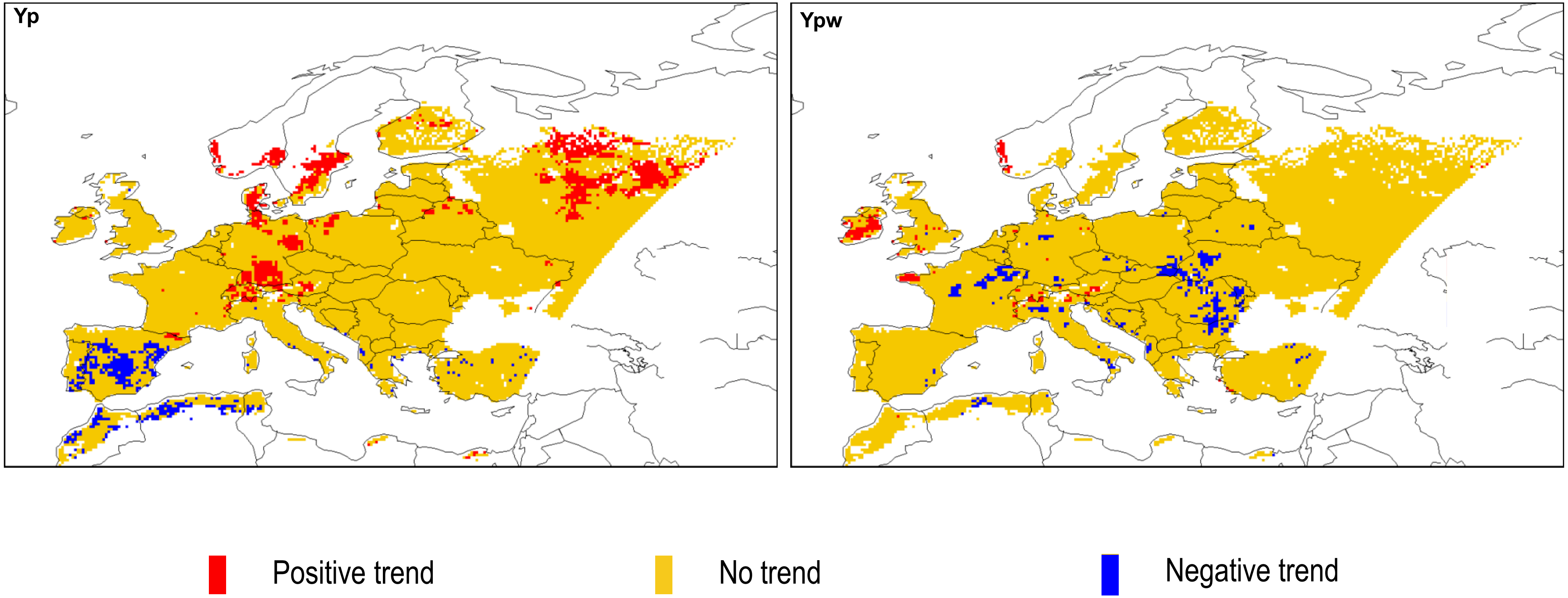


Fig. S2. The potential yield and the water-limited yield trends from 1976 to 2005. The trend was tested using the Cox–Stuart sign test at a significance level $p<0.05$. *Yp* represents the estimated potential yield without water limitation whereas *Ypw* represents the estimated potential yield taking into account water limitation.

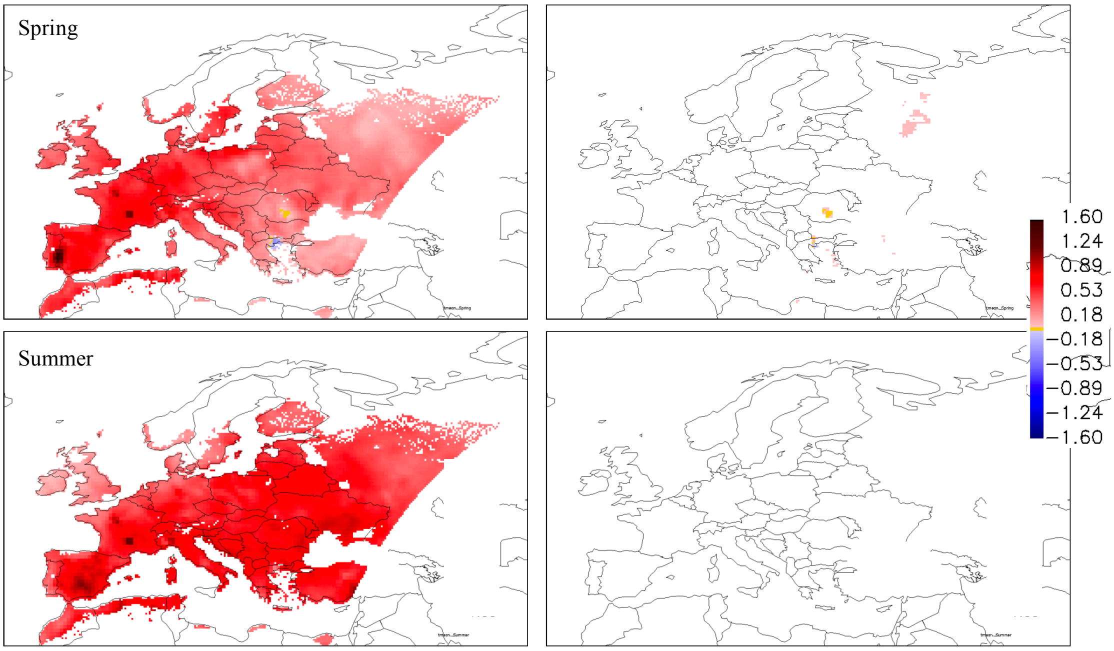
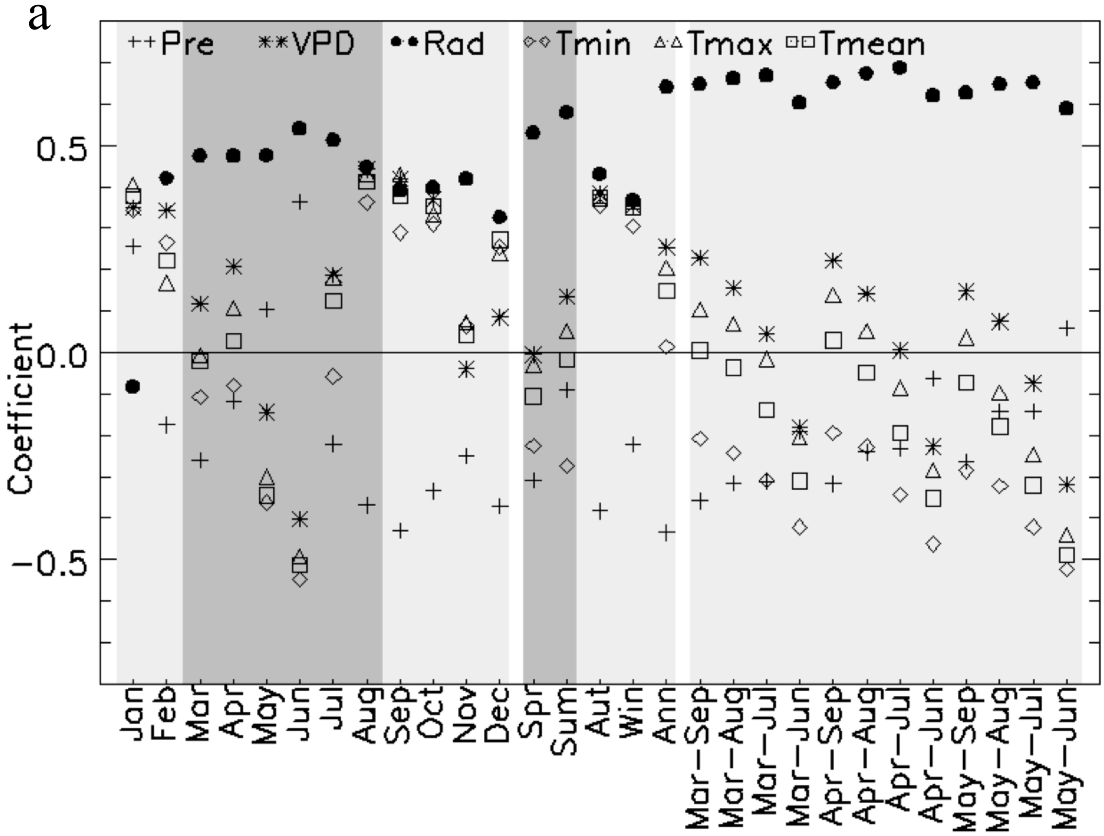


Fig. S3. The linear trends of the daily mean temperature for spring and summer from 1976 to 2005 (°C per decade). The linear regression model was used to estimate the trend. The panels on left side show the linear trend without significance check. The panels on the right side display the linear trend of temperature change only for significance level $p<0.05$.

a



b

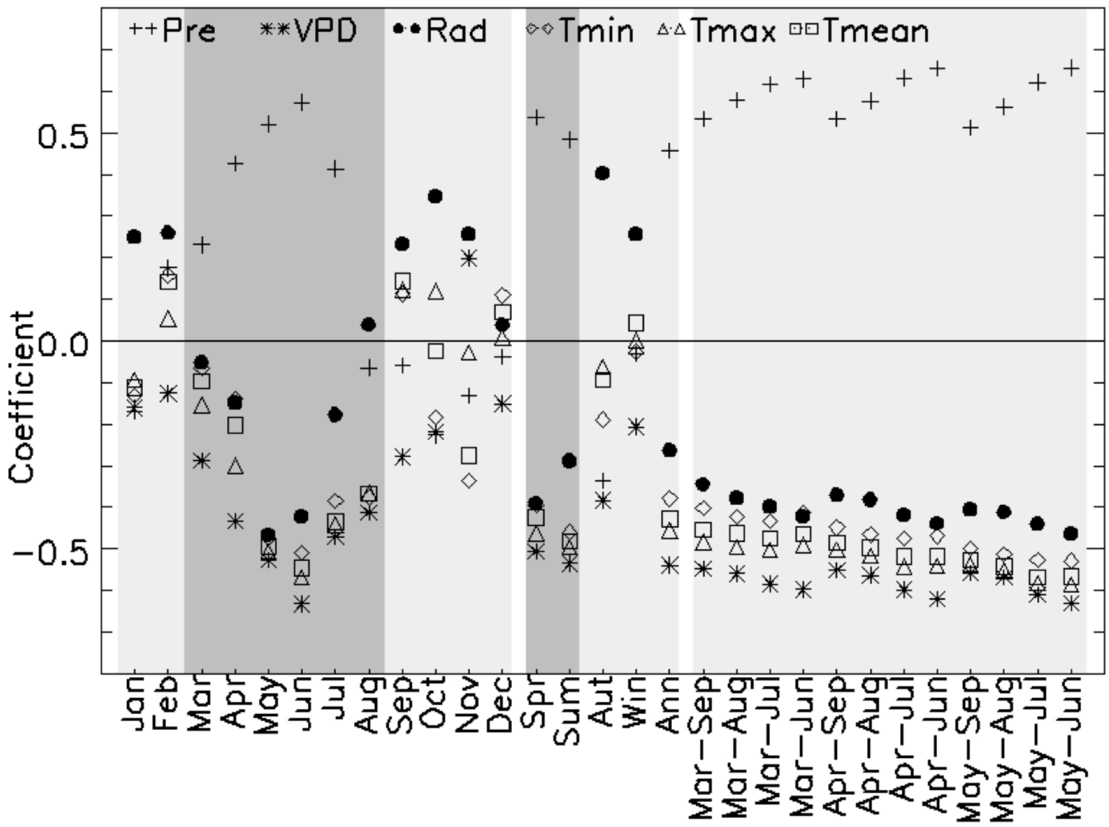


Fig. S4. Weighted average coefficients for the correlation between climate variables and potential yield (a) and water-limited yield (b) across Europe from 1976 to 2005. The panels shows weighted average Spearman's correlation coefficient at a significance level p<0.05. Pre is precipitation. VPD is vapour pressure deficit. Rad is global solar radiation. Tmin, Tmax and Tmean are minimum, maximum and mean daily temperature, respectively. The investigated time periods are divided into three groups (monthly, seasonal and hotspots). The spring and summer periods for the monthly and seasonal groups are highlighted with a dark grey shading, because the growth of winter wheat is most sensitive to weather condition at this time. X-axis labels (time name) is the abbreviation of the month names.

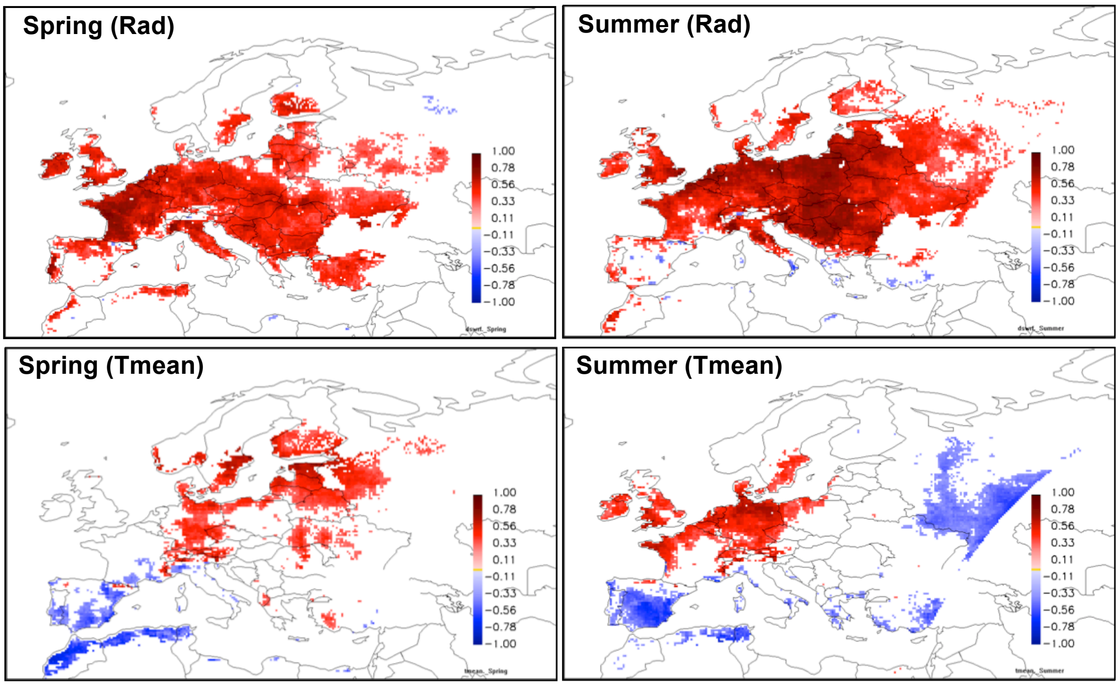


Fig. S5. The spatial patterns of the correlation coefficients between potential yield and radiation (upper two panels) and daily temperature (lower two panels) for spring and summer across Europe for the period 1976-2005. Spearman's correlation coefficient was defined to be statistical significant at significance level $p<0.05$. Rad is global solar radiation and Tmean is daily mean temperature.

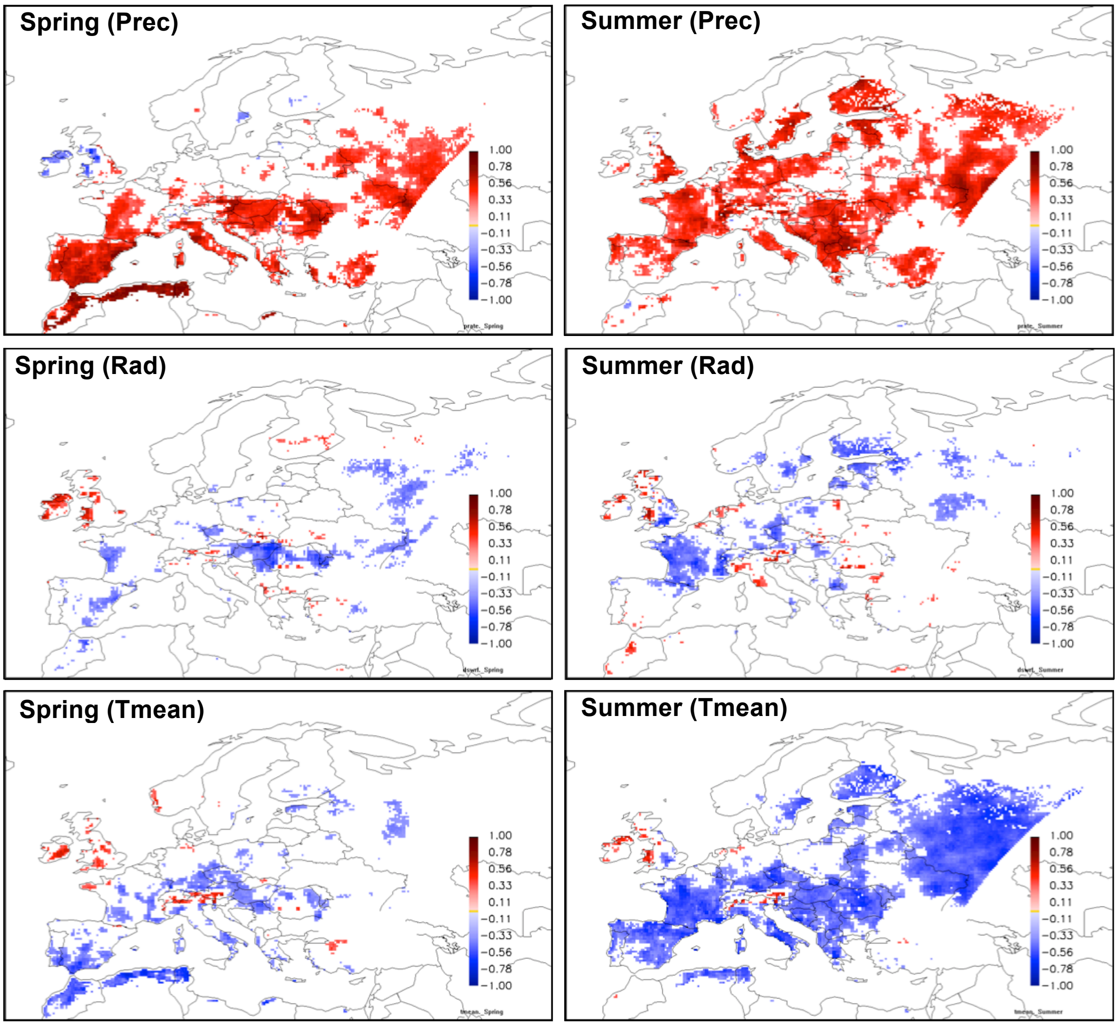


Fig. S6. Spatial distribution patterns of the correlation coefficient between the rain-fed potential yield and precipitation (upper two panels), radiation (middle two panels) and daily mean temperature (lower two panels) for spring and summer across Europe during the period 1976-2005

Spearman's correlation coefficient was defined to be statistical significant at significance level $p<0.05$. Prec is precipitation, Rad is global solar radiation and Tmean is daily mean temperature.