# Supplementary materials

# Climatic means and weather extremes exert large impacts on wheat yields in a major global breadbasket

**Table S1** Developmental stages of winter wheat in the Northwest and Southeast of Ukraine

|  |  |  |  |
| --- | --- | --- | --- |
| **Region** | **Vegetative phase I** | **Winter dormancy** | **Vegetative phase II** |
| Northwest | 1 September - 31 October | 1 November - 10 March | 11 March - 30 April |
| Southeast | 20 August - 31 October | 1 November - 10 March | 11 March - 25 April |
|  |  |  |  |
| **Region** | **Reproductive phase** | **Grain filling** |  |
| Northwest | 1 May - 10 June | 11 June - 25 July |  |
| Southeast | 26April - 31 May | 1 June - 15 July |  |

Sources: (Frederiks et al., 2015; Morgun et al., 2018; USDA, 2021)

**Table S2** Description of climatic mean and weather extreme variables. For each province and each day, we calculated all variables for which the respective conditions were met on that day. The variable value was then either equal to a measurement (TMIN, TMAX, TAVG, P, SPEI, GDD, HP), or was calculated by approximating the within-day temperature change (EDD, HWwithP, HWnoP), or was calculated as the difference between a temperature measurement and a temperature threshold (TNW, FwithSC, FnoSC, LF)

|  |  |  |  |
| --- | --- | --- | --- |
| **Name** | **Abbr.** | **Conditions** | **Calculation** |
| *Climatic means* | | | |
| Minimum temperature | TMIN | None | TMIN |
| Maximum temperature | TMAX | None | TMAX |
| Average temperature | TAVG | None | TAVG |
| Precipitation | P | None | P |
| Standardized precipitation evapotranspiration index | SPEI | None | SPEI |
| Growing degree days | GDD | TAVG is above 0°C and TMAX is below the heat threshold. | TAVG |
| *Weather extremes* | | | |
| Extreme degree days | EDD | TMAX exceeds the heat threshold. | Within-day distribution of temperature (Agostino et al. 2016) |
| Heat wave, with precipitation | HWwithP | TMAX exceeds the heat threshold and has also exceeded it for the previous two days. | Within-day distribution of temperature (Agostino et al. 2016) |
| Heat wave, no precipitation | HWnoP | TMAX exceeds the heat threshold and has also exceeded it for the previous two days. There has been no precipitation. | Within-day distribution of temperature (Agostino et al. 2016) |
| Tropical night wave | TNW | TMIN ranks among the highest 10% of all TMIN records for the respective province and day of the year, and has also ranked among them the previous two days. | Difference between TMIN and the temperature threshold that defines the highest 10% of all TMIN records |
| Heavy precipitation | HP | P ranks among the highest 10% of all P records for the respective province and day of the year. | P |
| Frost, with snow cover | FwithSC | TMIN ranks among the lowest 10% of all TMIN records for the respective province and day of the year. Snow cover is at least 10 mm. | Difference between TAVG and the temperature threshold that defines the lowest 10% of all TMIN records |
| Frost, no snow cover | FnoSC | TMIN ranks among the lowest 10% of all TMIN records for the respective province and day of the year. Snow cover is less than 10 mm. | Difference between TAVG and the temperature threshold that defines the lowest 10% of all TMIN records |
| Late frost | LF | TMAX is below 2°C and TAVG has exceeded 3°C during the four previous days. | Difference between TAVG and 2°C |

C:\Users\Schierhorn\OneDrive - IAMO\________Yield__Variability__Ukraine________\Climatic Change 2021\Revision_Climatic Change 2021\Figures_Revised\TIF\FigS1.tif

**Fig. S1** Wheat yield variability between 2010 and 2018 expressed as the coefficient of variation (CV) in percent. The CV at the national level was estimated using detrended yield data from FAO (FAOSTAT, 2019). For Ukraine, the CV was estimated using detrended provincial (oblast)-level yield data (UKRSTAT, 2019). Countries are sorted in descending order by average wheat production between 2010 and 2018 (FAOSTAT, 2019)

C:\Users\Schierhorn\OneDrive - IAMO\________Yield__Variability__Ukraine________\Climatic Change 2021\Revision_Climatic Change 2021\Figures_Revised\TIF\FigS2.tif

**Fig. S2** Mean yearly standardized precipitation evapotranspiration index (SPEI) in May and June in the Northwest and Southeast of Ukraine. SPEI<~-1 indicate drought conditions. The dashed lines refer to the intercepts and slopes of a linear regression model for each of the two regions. Source: SPEIbase v.2.6, Vicente-Serrano et al. (2010)

C:\Users\Schierhorn\OneDrive - IAMO\________Yield__Variability__Ukraine________\Climatic Change 2021\Revision_Climatic Change 2021\Figures_Revised\Fig S3.tif

**Fig. S3** Work flow

C:\Users\Schierhorn\OneDrive - IAMO\________Yield__Variability__Ukraine________\Climatic Change 2021\Revision_Climatic Change 2021\Figures_Revised\TIF\FigS4.tif

**Fig. S4** Climatic mean and weather extreme variables of the final model. Some variables were not defined from the beginning, such as heat during winter or frost during summer. For the final model, we excluded 11 variables due to a high Variance Inflation Factor (VIF). For an explanation of the different climatic mean and weather extreme variables, see Table S2

C:\Users\Schierhorn\OneDrive - IAMO\________Yield__Variability__Ukraine________\Climatic Change 2021\Revision_Climatic Change 2021\Figures_Revised\TIF\FigS5.tif

**Fig. S5** Explained variability (R²) from random forest out-of-sample predictions with different sets of climatic mean and weather extreme predictor variables, for season-long and intraseasonal variables, and for three different regions (country-wide, Northwest, Southeast), based on the models that include the province dummies. The symbols for the group comparison indicate the statistical significance of the Wilcoxon signed-rank test (not significant (ns): p > 0.05; \*: p <= 0.05; \*\*: p <= 0.01; \*\*\*: p <= 0.001; and \*\*\*\*: p <= 0.0001)

C:\Users\Schierhorn\OneDrive - IAMO\________Yield__Variability__Ukraine________\Climatic Change 2021\Revision_Climatic Change 2021\Figures_Revised\TIF\FigS6.tif

**Fig. S6** Variable importance in specific developmental stages of winter wheat expressed as percent increase in mean squared error (%IncMSE) of the climatic means and weather extremes based on the fixed threshold approach and with province dummies. Higher %IncMSE signals higher variable importance. For an explanation of the different climatic mean and weather extreme variables, see Table S2. Empty cells indicate variables that were removed due to multicollinearity or that were not defined (Figure S4)

C:\Users\Schierhorn\OneDrive - IAMO\________Yield__Variability__Ukraine________\Climatic Change 2021\Revision_Climatic Change 2021\Figures_Revised\TIF\FigS7.tif

**Fig. S7** Partial dependence of predicted yield on climatic means for the three regions and five developmental stages based on the fixed threshold approach. The x-axis shows the mean (TMIN, TMAX, SPEI) or accumulated (P, GDD) variable-specific values for the respective plant developmental stage; the y-axis shows the yields associated with these values. The shaded area around the partial dependence represents the standard deviations of the results from the 100 model runs. For an explanation of the different climatic mean and weather extreme variables, see Table S2. Empty panels indicate variables that were removed due to multicollinearity or that were not defined (Figure S4)

C:\Users\Schierhorn\OneDrive - IAMO\________Yield__Variability__Ukraine________\Climatic Change 2021\Revision_Climatic Change 2021\Figures_Revised\TIF\FigS8.tif

**Fig. S8** Partial dependence of predicted yield on weather extremes for the three regions and five plant developmental stages based on the fixed threshold approach. The x-axis shows the accumulated variable-specific values for the respective developmental stage, and the y-axis shows the yield associated with these values. The shaded area around the partial dependence represents the standard deviations of the results from the 100 model runs. For an explanation of the different climatic mean and weather extreme variables, see Table S2. Empty panels indicate variables that were removed due to multicollinearity or that were not defined (Figure S4).

C:\Users\Schierhorn\OneDrive - IAMO\________Yield__Variability__Ukraine________\Climatic Change 2021\Revision_Climatic Change 2021\Figures_Revised\TIF\FigS9.tif

**Fig. S9** Observed yield per province and yield predicted by the respective regional model for the Northwest and Southeast of Ukraine. Models are based on the percentile threshold approach and on the final set of predictor variables, including the province dummy. The range of the yield predictions represents the innermost 95% of 100 model predictions

C:\Users\Schierhorn\OneDrive - IAMO\________Yield__Variability__Ukraine________\Climatic Change 2021\Revision_Climatic Change 2021\Figures_Revised\TIF\FigS10.tif

**Fig. S10** Performance indicators of the final random forest (RF) and linear mixed-effect (LME) models using the same final selection of intraseasonal climatic mean and weather extreme variables, based on the percentile threshold approach. RMSE: Root mean squared error; R2 coefficient of determination; NSE: Nash Sutcliffe efficiency; and Willmots’ index of agreement (Willmott’s d). The final RF models include a province dummy; in the LME regression model, we added the province dummy as a random effect. The symbols for the group comparison indicate the statistical significance of the Wilcoxon signed-rank test (not significant (ns): p > 0.05; \*: p <= 0.05; \*\*: p <= 0.01; \*\*\*: p <= 0.001; and \*\*\*\*: p <= 0.0001)

C:\Users\Schierhorn\OneDrive - IAMO\________Yield__Variability__Ukraine________\Climatic Change 2021\Revision_Climatic Change 2021\Figures_Revised\TIF\FigS11.tif

**Fig. S11** Correlation among predictor variables related to temperature (A) and precipitation (B). VP1: vegetative phase I; WD: winter dormancy; VP2: vegetative phase II; RP: reproductive phase; and GF: grain filling. For an explanation of the different climatic mean and weather extreme variables, see Table S2

C:\Users\Schierhorn\OneDrive - IAMO\________Yield__Variability__Ukraine________\Climatic Change 2021\Revision_Climatic Change 2021\Figures_Revised\TIF\FigS12.tif

**Fig. S12** Ranking from the most (top) to the least (bottom) important predictor variable based on the mean %IncMSE (percent increase in mean squared error) across 100 model runs (final country-wide model, based on the percentile threshold approach), as a response to the hyperparameter mtry, i.e., the number of candidate variables from which to choose from at each node of a regression tree in the random forest. VP1: vegetative phase I; WD: winter dormancy; VP2: vegetative phase II; RP: reproductive phase; and GF: grain filling. For an explanation of the different climatic mean and weather extreme variables, see Table S2

C:\Users\Schierhorn\OneDrive - IAMO\________Yield__Variability__Ukraine________\Climatic Change 2021\Revision_Climatic Change 2021\Figures_Revised\TIF\FigS13.tif

**Fig. S13** Mean number of days with tropical night wave (TNW) events during the grain filling phase per province, across all provinces of the Northwest and Southeast of Ukraine, respectively

**References SI:**

FAOSTAT (2019) Food and Agriculture Organization of the United Nations–Statistics Division, Rome, Italy. <http://www.fao.org/faostat/en/#home>.

Frederiks TM, Christopher JT, Sutherland MW, Borrell AK (2015) Post-head-emergence frost in wheat and barley: defining the problem, assessing the damage, and identifying resistance. Journal of Experimental Botany 66:3487-3498.

Funk C, Peterson P, Peterson S, Shukla S, Davenport F, Michaelsen J, Knapp KR, Landsfeld M, Husak G, Harrison L (2019) A High-Resolution 1983–2016 T max Climate Data Record Based on Infrared Temperatures and Stations by the Climate Hazard Center. Journal of climate. <https://www.chc.ucsb.edu/data/chirtsdaily> 32:5639-5658.

Morgun V, Priadkina GA, Zborovska O (2018) Dependence of main shoot ear grain yield from stem deposited ability of winter wheat varieties. Ukrainian Journal of Ecology 8:113-118.

UKRSTAT (2019) Agriculture of Ukraine: Statistical yearbook, State Statistics Service of Ukraine, Kiev. <http://www.ukrstat.gov.ua>.

USDA (2021) Crop Calendars for Ukraine, Moldova and Belarus. <https://ipad.fas.usda.gov/rssiws/al/crop_calendar/umb.aspx>. USDA Foreign Agricultural Service. U.S. Departmenet of Agriculture.

Vicente-Serrano SM, Beguería S, López-Moreno JI (2010) A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. Journal of climate 23:1696-1718.