How do weather extremes and climate trends influence wheat yields in Ukraine?

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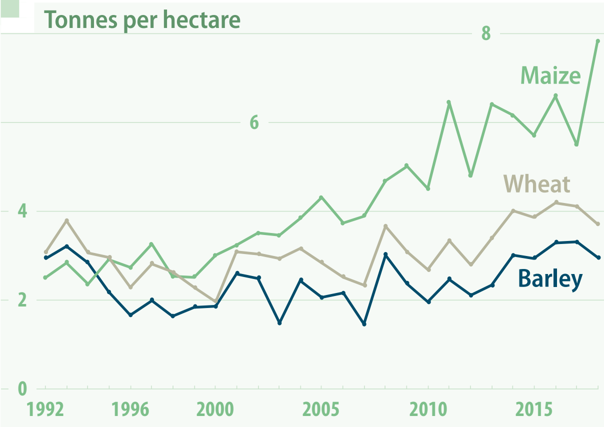
Introduction

Ukrainian agriculture is already feeling the effects of climate change. In the future the challenges may be even greater. The problem cannot, however, be easily seen in the agricultural statistics, for the figures often show positive trends. For example, whereas around the turn of the millennium almost 30 million tonnes of cereals were harvested annually in Ukraine, the output is almost twice that today. This is primarily a consequence of the rise in per-hectare yields. Since the year 2000, yields of almost all important crops have increased substantially. Wheat yields have risen from 2.5 tonnes per hectare (t/ha) to more than 4 t/ha (**Figure 1**). Over recent years maize yields have increased from 3 t/ha to sometimes considerably more than 5 t/ha, albeit with significant annual fluctuations. As a result of the rise in yields, Ukraine has become one of the leading global cereal exporters. From 2014–15 Ukraine was the third largest and in 2018 the fourth largest exporter of maize, and in 2016 the fifth largest exporter of wheat (FAOSTAT 2020). The growth in yields can be attributed to improvements in technology as well as greater use of inputs such as chemical fertilisers. This development is not the consequence of better weather conditions resulting from climate change.

Figure 1: Yields in Ukraine, 1992–2018



It must be noted, however, that because of the country's continental position, climate change has proceeded at a faster rate in Ukraine over the past decades than in many maritime regions. Using freely available, high-resolution raster data (HARRIS et al. 2020) we calculated that the average annual temperature in Ukraine rose by 2.1°C between 1985 and 2018, while the global increase over this period was only 1.1°C. Average annual temperature, however, does not tell the whole story as far as agriculture is concerned. More relevant are the temperatures in spring and early summer—a key period for the growth of cereals and thus for yields. The average June temperature in Ukraine rose even further, by about 2.2°C between 1985 and 2018. In addition, historic climate data show that large parts of Ukraine, especially the important areas of cultivation to the south of Kiev, have experienced declining patterns of rainfall since 1980 (MÜLLER et al. 2016). Given these factors, an empirical study demonstrating that, without climate change, Ukraine would have achieved somewhat higher yields in recent years (RAY et al. 2019), comes as no surprise.

Table 1: The variation coefficient for yield, cropland, production, and export of the most important global producers of cereals from 2000 to 2018. The variation coefficient is a standardized measure of dispersion and high values (orange and red) show great variability.

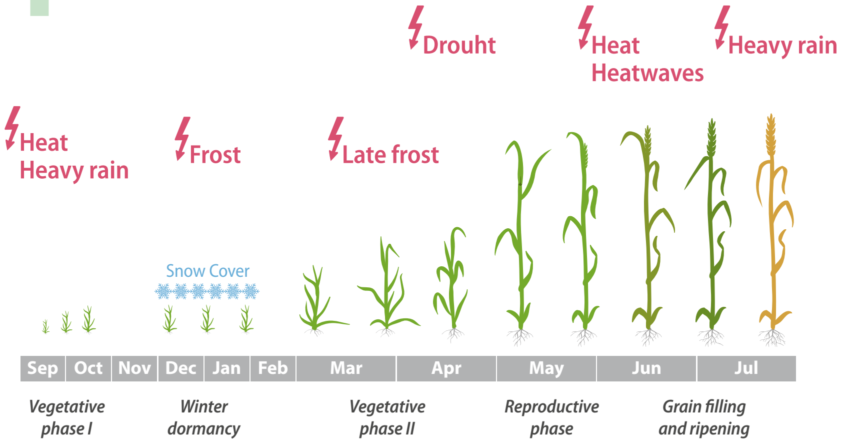
	Yield			Cropland			Production			Export		
	Barley	Maize	Wheat	Barley	Maize	Wheat	Barley	Maize	Wheat	Barley	Maize	Wheat
Argentina	17.2	14.0	14.0	56.1	35.2	19.2	62.9	44.5	20.7	79.4	46.5	35.2
Australia	22.2	17.0	23.7	10.6	19.8	8.9	24.2	19.6	26.5	35.1	74.4	29.7
Canada	13.7	12.7	17.8	24.8	10.5	7.2	19.0	20.1	19.0	36.6	79.9	20.8
China	7.7	9.4	13.1	40.3	22.8	4.3	42.3	30.8	14.3	223.1	158.2	55.2
EU	8.1	11.0	7.4	6.7	5.9	3.0	6.3	10.3	9.0	46.0	70.2	37.0
India	14.0	18.4	9.6	7.7	11.8	6.7	13.4	28.5	15.1	168.7	100.9	115.9
Kazakhstan	19.3	14.4	18.6	21.5	22.0	8.1	32.8	35.2	23.1	72.7	114.2	32.4
Pakistan	3.6	30.1	7.5	21.7	13.6	4.5	21.7	41.5	11.2	N. A.	157.9	68.4
Russia	13.5	26.9	18.0	12.7	52.2	9.6	17.6	69.2	26.9	55.0	109.0	67.4
Turkey	14.1	31.4	11.0	4.4	9.3	6.3	15.7	36.0	8.2	140.8	113.7	58.8
Ukraine	22.7	27.6	22.8	21.6	46.5	16.5	19.7	65.2	31.5	43.0	91.8	70.0
United States	10.5	10.3	9.4	29.1	7.8	11.3	21.5	15.1	10.6	81.5	20.1	13.1

Ukraine is one of the countries with the highest yield variability

One of the biggest problems for Ukrainian agriculture is the high volatility of yields. Using the variation coefficient, **Table 1** shows the extent to which yields of the most important global producers of cereals varied between 2000 and 2018. We chose this period because, prior to 2000, yield variability in Ukraine was also linked to the turbulent processes of transition after the collapse of the Soviet Union. Yield variability in Ukraine between 2000 and 2018 for wheat, barley and maize were comparatively very high (**Table 1**). Wheat yields in Ukraine after 2000 varied even more than in Kazakhstan and only slightly less than in Australia, both countries which are well known for substantial yield variability tied to climate volatility. In the EU and the USA, yield variability was far smaller than in Ukraine. Besides yields, the total area under cultivation in Ukraine was also subject to considerable annual variation and thus contributed to the marked rise and fall of annual production volumes, which was also reflected in volatile export volumes of cereals.

> In short, Ukraine may be an important actor on global cereals markets, but also a relatively unreliable one as far as production and export volumes are concerned.

Figure 2: The development of winter wheat and potential extreme weather events that can negatively impact yield



This is especially relevant for countries like Egypt, which meet their demand for cereals predominantly through imports from eastern Europe.

Long-term climactic conditions and extreme weather events

The climatic and weather conditions during the entire growth phase influence crop development and thus yields. The literature distinguishes between long-term climatic conditions and extreme weather events. Long-term climatic conditions include average temperature, total precipitation and growing degree days. Growing degree days refer to the total of daily temperatures when the minimum tolerable temperature for a particular plant is exceeded and the maximum tolerable temperature is not surpassed. For its total growth phase, but also during individual phases of growth (e.g. flowering), an arable crop needs certain amounts of energy and water. High yields, therefore, can only be achieved when certain values of growing degree days are met and sufficient volumes of water are available to the plant. By contrast, extreme weather events such as frost, extreme heat and drought have a short-term effect on plant growth, are unpredictable and rare, and can also significantly reduce the yield even if the average climatic conditions are optimal.

Various extreme weather events influence plant growth in certain phases (**Figure 2**). Heat stress limits the plant's photosynthetic activity, can reduce the ear fertility and upset the process of corn formation, which has a negative impact on yields (FAROOQ et al. 2011). It has been shown, for example, that temperatures above 34˚C during the grain-filling phase of fructification can have substantial negative effects on the yield, especially if the heat persists for several successive days—a so-called heatwave—and no rainfall occurs. Heat and heatwaves at night can put a brake on plant growth too (SADOK and JAGADISH 2020). During winter dormancy, severe frost can damage winter crops, especially if there is no snow cover to insulate the young plants from the cold. Late frost in spring, after winter dormancy and when the plants have adapted to spring warmth, often have a negative impact on yields too. Downturns in yields can also result from heavy rain, especially when these wash chemical fertilisers and plant protection products from the field, damage part of the harvest and prevent the use of harvesting machinery. The interplay of several factors impacting the yield can mean that their effect is intensified or weakened. The methodological challenge in a statistical analysis of yield-affecting climatic and weather conditions is to determine precisely the individual effects and functional relations of climate factors as well as understanding these functional relations.

Which extreme weather events influence yield variability in Ukraine?

We asked ourselves which climatic factors can explain the high yield variability in Ukraine. To answer this we focused on the effect of extreme weather events on yields, which is especially important for Ukraine because there is considerable evidence that extreme weather events such as heatwaves, heavy rain and frost have a substantial impact on the yields of cereals. The influence of such events on yields in Ukraine has not been systematically investigated before. We used daily climate data from 190 weather stations scattered across the entire country (**Figure 3**). From this data we calculated long-term climate variables (e.g. precipitation and growing degree days) as well as extreme weather variables—see **Table 2**—for each of the 25 Ukrainian provinces. We used annual yield data for winter wheat at the province level from 1985 to 2018 and removed from this the linear trend component of the yields to exclude other factors impacting yields such as developments in agricultural technology. In addition, all the variables were specifically calculated for the five most important growth phases of winter wheat—see **Figure 2**—to understand in which phase the various extreme weather events restrict plant growth. To quantify the influence of climate and weather variables on the yield, we used Random Forests, a machine learning algorithm which uses many uncorrelated decision trees for regression. Random forests can estimate climate-related yield variability much more accurately than traditional regression methods (JEONG et al. 2016, LENG and HALL 2020). Because of regional differences in biophysical conditions, we estimated the model separately for the steppe region in the south-east and for the north-west of the country (**Figure 3**).

Our model findings show that wheat yield variability in Ukraine has been strongly affected by climatic factors in general and extreme weather events in particular. Put together, all extreme weather events account for about half of the yield variability between 1985 and 2018. The increase in explained variability is relatively small if long-term climate variables are considered in addition to ex-

Figure 3: Locations of the 190 weather stations (black dots) in the north-west and in the steppe region

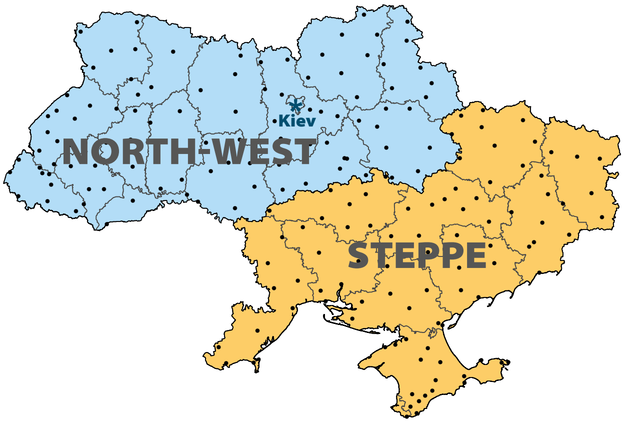


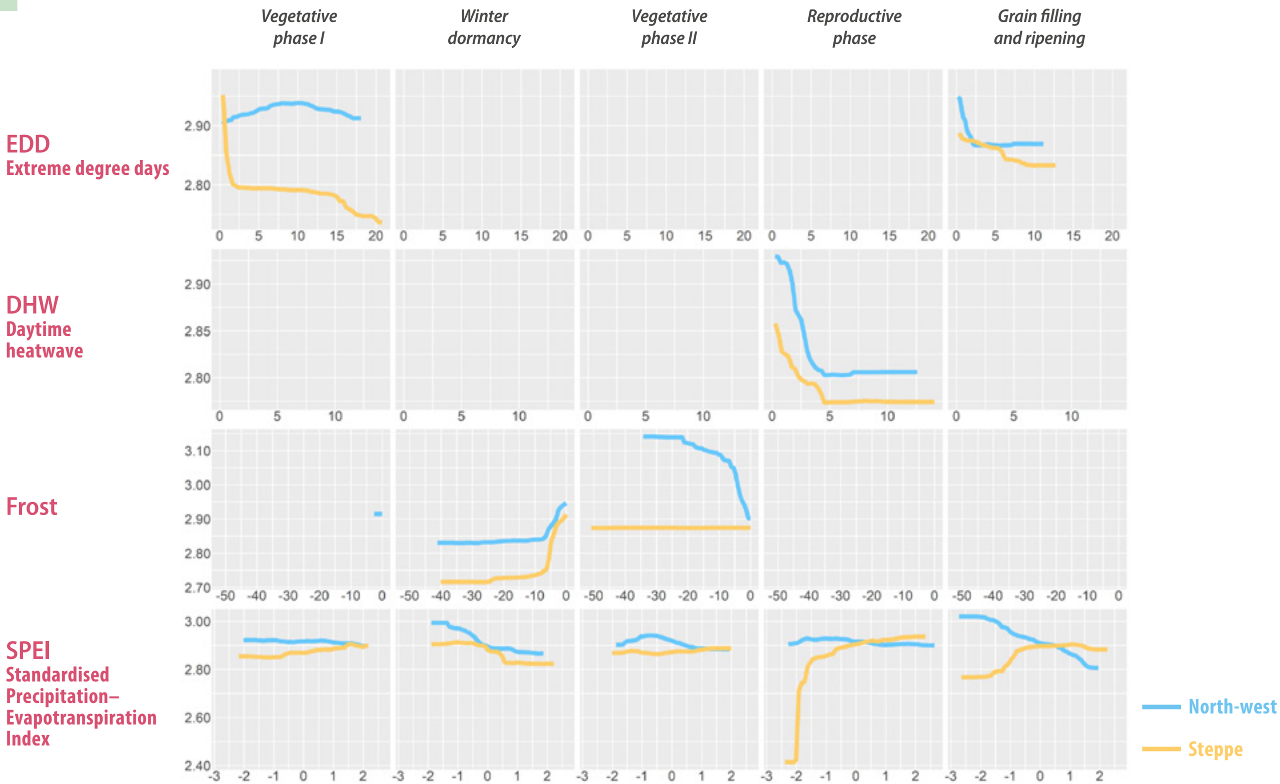
Table 2: Extreme weather variables calculated for each development phase for winter wheat using daily weather station data

Name	Calculation
Extreme degree days (EDD)	Totalling the daytime temperatures above a specific value (e.g. 34°C in July)
Daytime heatwave (DHW)	Like EDD but only when the specific value is surpassed on at least three days in succession
Heatwave without precipitation	Like DHW but only when no rain falls during the heatwave
Night-time heatwave	Like DHW but with specific values for night (e.g. 20°C in July)
Frost	Totalling the daytime temperatures below 0°C
Late frost	Totalling the daytime temperatures below 0°C when preceded by a warmer phase of four days or more with at least 3°C
Heavy rain	Totalling the precipitation when the daily rainfall is greater than the long-term 90th percentile within a month

treme weather events in the model. With the Random Forests method, functional relations between the independent variables and the dependent variable can be depicted. **Figure 4** shows the estimated functional relationship between extreme degree days and yield in the last few weeks before harvest, i.e. during grain filling and ripening. Here, the negative relationship is clearly evident. Heatwaves, both during the daytime and at night, also reduce the yield, especially when they occur during the reproductive phase. Our findings furthermore show that the wheat yield fell as a result of extreme frost events as well, even though this effect was limited to the steppe region in the south-east (**Figure 4**). Although severe frosts occurred in the north-west of Ukraine too, the young plants there were regularly protected by a sufficiently thick layer of snow. Late frost, on the other hand, does not yet seem to have been a major problem for wheat.

As far as the effect of precipitation is concerned, our findings show a regionally differentiated picture. In the steppe region, water stress during the reproductive phase and during grain filling and ripening was a major factor that reduced yields (**Figure 4, SPEI**). In the north-

Figure 4: Relationship between yield (y-axis) and various extreme weather variables (x-axis) for the five development phases of winter wheat for the north-west (blue) and the steppe (yellow)



west, however, water stress barely had a negative impact on yields, whereas heavy rain in the weeks before harvest led to decreases in yields (see also: FAO and ITPS 2015). This was probably due to the resultant waterlogging, which reduced the number of grains per plant and thus the yield as a whole.

In conclusion, our findings clearly show that various extreme weather events have had a substantial impact on wheat yield variability in Ukraine. In some cases this impact varies considerably between the north-west and the steppe, requiring measures tailored to the regions, such as the choice of crop varieties, to counter the big climatic challenges. Our findings therefore provide a scientific basis to develop adaptation measures that reduce yield variability in the face of ongoing climate change.

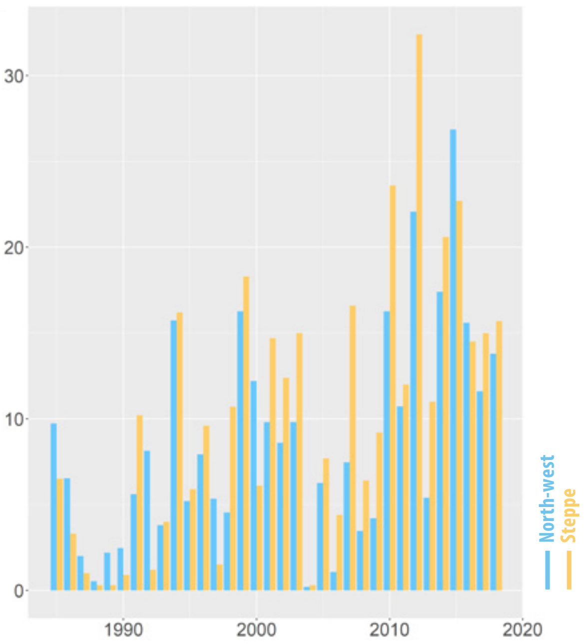
Measures to reduce yield variability

Water and frost stress in the south-eastern steppe as well as heat and heatwaves throughout Ukraine are the major causes of the severe yield variability. Heatwaves have increased considerably in Ukraine since 1985 (**Figure 5**), which suggests that their frequency and intensity will continue to grow. Measures that could counter climate-induced yield variability should therefore be investigated and developed further for Ukraine.

> An important starting-point here is soil protection, for 40% of agriculturally used soils in Ukraine are already degraded and have lost a large proportion of their original organic matter (SCHIERHORN and MÜLLER 2020).

Implementing measures of conservation agriculture, such as no-till farming and extended crop rotation, can help to improve the soil structure and lead to an increase in humus content. In this way the soil temperature can be reduced and water can be stored more effectively in the ground, making it available to plants during periods of drought. According to the FAO, only a little more than 4% of cropland for cereals in Ukraine is farmed using conservation practices (EISENRING et al. 2019). Similar methods to those used in conservation agriculture are found in organic farming. Until now, only around 300 farms in the

Figure 5: Mean number of heatwave days per province in the steppe (yellow) and north-west (blue)



Ukraine, which cultivate less than 1% of farmland, follow the principles of organic agriculture (SCHIERHORN and MÜLLER 2020). Experts are anticipating a large increase in organic farming, however (EISENRING et al. 2019). Such increase may lead to the production of cereals that are more resilient to climate and weather fluctuations, even though the area of cropland needed for the same production volumes is higher in organic farming than in conventional farming, and the yields are correspondingly lower.

Much research is needed to identify how crop varieties can best help to improve both conventional and organic farming. Plant breeding plays an important role in adapting agriculture to ever-more frequent extreme weather conditions and climate change. Research into frost, heat and drought-resistant cereal varieties, for example, promises good results for effective adaptation to climate change. Our research shows that the effect of hot, tropical nights on cereal yields needs to be studied further. At present, winter wheat is the dominant crop in Ukraine, but it is possible that climate change, especially warmer winters, will see summer crops being favoured. Overall, agricultural research with a focus on climate change is of great importance to Ukraine, for agriculture is one of the sectors that drives the country's economy. How Ukrainian agriculture adapts to climate change, however, is also of great international importance.

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Sources and credits

Title Radar image of central Ukraine, taken by Space Shuttle Endeavour in April 1994 © Courtesy NASA/JPL-Caltech

The detail shows the data evaluation of a 35 x 35 km area in the intensively farmed region of central Ukraine. At the time the image was taken, most fields were uncultivated—these are dark brown and purple. Bright lines show field boundaries of hedges and trees. The larger yellow areas are riparian forest of the Dnieper (top left) and a small tributary (below).

Fig. 1 Yields of maize, wheat, and barley in Ukraine, 1992–2018 © Own presentation. Data: UKRSTAT, 2019. Agriculture of Ukraine: Statistical yearbook, State Statistics Service of Ukraine, Kiev http://www.ukrstat.gov.ua [05.07.2021]

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