Climate, Land Productivity, and Agricultural Adaptation in Ukraine

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Abstract

Using the combination of farm-level data from 46,799 farms spanning 2004 to 2020, and the daily temperature and precipitation data from the Coordinated Regional Downscaling Experiment program (CORDEX), we examine the impacts of climate change on crop yield and farmers' adaption behaviors in Ukraine. Our empirical results first suggest that the overall rising temperature is associated with short-run rises in the yields of all five main crops. While for cold season crops (winter wheat and spring barley), crop yield responds negatively to exposure to or heat accumulation in temperature intervals above a crop-specific stressful temperature bound (30/31°C). The other nonnegligible climate factor we found that contributes to the short-run variation in crop yield is the daily diurnal temperature range in the growing season (especially for spring season crops). In terms of adaptation, we find evidence that unveils the adaptations of winter wheat to long-run temperature change and adaptations of sunflower, soybean, and corn to long-run precipitation change. Furthermore, we find that the rise in long-run temperature is positively associated with the cropping shares of winter wheat and sunflower, while negatively associated with the share of spring barley, corn, and soybean. Also, the crop structure is found more diversified as the long-run temperature and volatility of daily temperature in the growing season rise.

Keywords: Climate change, Land productivity, Agricultural adaptation;

JEL Codes: Q54, Q10;

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1. Introduction

The impacts of climate, which refers to the relatively long-term pattern of weather, on land productivity have been felt throughout the world in recent decades. While the two components of weather or climate—temperature and precipitation can affect land productivity through numerous mechanisms such as aerial and soil humidity, nutrient, growth of other life forms such as weeds, insects or bacteria, etc., the exact climate impacts on agriculture also depend largely on the adaptation capacities the agricultural sector has to mitigate changes in climate conditions. Such adaptations include not only the adjustments at the farm level in breeding strategy (Mortimore et al., 2000, Fosu-Mensah et al., 2012), irrigation management (de Loë et al., 1999), weeding practice (Scott et al., 2014), pest management (Chen and McCarl, 2001), disease control, etc., but also the adaptations at the government or society level such as weather prediction, infrastructure investment, R&D investment on new technologies, etc.

As one of the largest crop exporters in the world, Ukraine plays an important role in the world food supply chain. With 41.5 million hectares of agricultural land covering 70% of the country and about 25% of black soil reserves on the planet, Ukraine's agriculture sector generated approximately 9.3% of the nation's GDP and 14.11% of employment in 2020. Given the importance of the agriculture sector in Ukraine and its vulnerability to climate change, understanding the exact impacts of climate change on agriculture production in Ukraine is important. However, little has been known about the effect of changing climate on crop yields and agricultural production in Ukraine.

Our study aims at investigating the impacts of climate change on Ukraine's agriculture production. More specifically, we first study the yield responses of the five main crops—winter wheat, spring barley, sunflower, soybean, and corn to changes in climate conditions. We then investigate whether the implicit adaptation in crop production is suggested based on the crops' yield responses to long- and short-run changes in climate conditions. Furthermore, we study Ukraine farmers' explicit adaptation to climate change in crop structure and diversification. A farm-level dataset with a relatively large sample size (46,799 farms), collected by Ukraine's State Statistics Department every year from 2004 to 2020 (except for 2015), and the daily temperature and precipitation data from the Coordinated Regional Downscaling Experiment program (CORDEX) are combined for our empirical analysis.

Our study contributes to the literature in several aspects. First, our estimated impacts of climate change on agriculture production and adaptation using farm-level data with such a large sample size can be an important supplement to existing studies conducted in Ukraine, as most related studies apply either regional data or household-level survey data with a relatively small sample size. Second, we empirically justify the non-neglectable impacts of the diurnal temperature range (the difference between daily maximum and minimum temperature) on crop yields. Moreover, our study summarizes the applicability of several widely adopted empirical methods in studying the impacts of climate change on agriculture production and technical details in applying these methods in contexts such as Ukraine where the temperature is more temperate.

The rest of the paper is structured as follows. The following chapter introduces the data and empirical methods we apply for our analysis. Chapter 3 presents our empirical results and chapter 4 concludes the paper.

2. Data and Empirical Methods

A. Data

We combine the farm-level survey data collected by Ukraine's State Statistics Department and rayon-level climate data from the Coordinated Regional Downscaling Experiment program (CORDEX) for our analysis.

The farm-level data collects information on cropped areas of crops and outputs from farms in Ukraine, which results in an average sample size of 46,799 farms each year from 2004 to 2020 (except 2015). As a comparison to the macro-level data, the aggregated cereal and wheat production in our dataset accounts for 84% of the national cereal production (59.79 out of 70.77 million tons, FAO[3]) and 76% of the national wheat production (21.58 out of 28.38 million tons, USDA[4]) accordingly in 2020. We restrict our analysis to five major crops in Ukraine—winter wheat, spring barley, sunflower, soybean, and corn.

Data on temperature and precipitation comes from the Coordinated Regional Downscaling Experiment (CORDEX) program, which is sponsored by the World Climate Research Program (WCRP). The CORDEX provides information on daily precipitation and daily maximum, daily average, and daily minimum temperature for each rayon (sub-district) in Ukraine. The temperature and precipitation data are processed and merged with the survey data based on rayon information.

B. Empirical Methods for Measuring Yield Responses to Climate

Given the sufficiency of rainfall in Ukraine indicated in the data, we mainly focus on investigating the impacts of temperature on crop yields and adaptations. Nonetheless, rainfall is still an important determinant of crop yields in the context of Ukraine and as a result, the precipitation-related variables are included as the main controls in all of our estimations.

We start with applying the Fixed Effects (FE) estimation to investigate the short-run yield response of the five main crops to the changing climate conditions based on the following model:

$$y_{vt} = \beta Temp_{vt} + \gamma Prec_{vt} + c_v + \lambda_t + \delta_t + \epsilon_{vt} \quad (1)$$

where y_{vt} is the log of crop yield in village v and year t. $Temp_{vt}$ is a vector of temperature-related variables, $Prec_{vt}$ is a vector of precipitation-related variables, c_v is the village fixed effects that absorbed time-invariant

[3] Data source: https://www.fao.org/faostat/en/#country/230

[4] Data source: https://www.fas.usda.gov/data/ukraine-grain-and-feed-annual-5

factors that affect agricultural outcomes at the village level, λ_t indicates the year fixed effects and ϵ_{it} is the error term. All climate variables in our analysis are calculated based on crop-specific growing seasons.

To address the nonlinearity in crops' yield response to temperature, we first follow the method that has been widely used in literature by assuming the crop yield is proportional to the total exposure of heat, and temperature effects on yields are cumulative over time (Schlenker and Roberts, 2009; Gong and Chen, 2020). We assume

$$y_{it} = \int_{\underline{h}}^{\overline{h}} g(h)\phi_{it}(h)\ dh + \delta z_{it} + c_i + \lambda_t + \epsilon_{it} \quad (2)$$

where y_{it} is the log of crop yield at location i in year t, $g(h)$ is the growth function and $\phi_{it}(h)$ is the time distribution of heat over the growing season at location i in year t. $\underline{h}$ and $\overline{h}$ indicate the lower and upper bounds of temperature over the period. z_{it} denotes other control factors, which include the quadratic form of average daily precipitation in the growing season. c_i captures the time-invariant location-fixed effect to control for time-invariant heterogeneity and λ_t is the year fixed effects, ϵ_{it} is the error term.

We estimate the growth function $g(h)$ in equation (2) under two specifications. First, we consider a step function with a different growth rate in each 3°C temperature interval and estimate the following equation:

$$y_{it} = \sum_{j=\underline{h},\ \underline{h}+3,\ \underline{h}+6,\dots}^{\overline{h}} \rho_j \left[\Phi_{it}(j+3) - \Phi_{it}(j)\right] + \delta z_{it} + c_i + \lambda_t + \epsilon_{it} \quad (3)$$

where $\Phi_{it}(j+3) - \Phi_{it}(j)$ is measured by the exposure time in the growing season when the temperature is between j and $j+3$. We apply the sine curve approach (Allen, 1976) to simulate daily temperature distribution, in which the within-day distribution of temperature is fitted by a sine curve based on daily maximum and minimum temperature, and the daily exposure to each temperature interval will be calculated and aggregated as the exposure of the whole growing season.

The second specification we apply for estimating growth function in (2) is defined as the quasi-GDD approach, in which only two temperature intervals are included in the equation. Under this specification, the exposure to temperature intervals within the “ideal” temperature threshold $[l_0, l_1]$ shares the same growth function (expected to be positive) while the exposure to temperature intervals above the upper-temperature threshold l_1 shares the same growth function. The resulted model we estimate under this specification becomes

$$y_{it} = \beta_1 \left[\Phi_{it}(l_1) - \Phi_{it}(l_0)\right] + \beta_2 \left[\Phi_{it}(\overline{h}) - \Phi_{it}(l_1)\right] + \delta z_{it} + c_i + \lambda_t + \epsilon_{it} \quad (4)$$

For each crop, we fix the lower temperature threshold l_0 and loop for all possible upper-temperature thresholds l_1 to find the appropriate temperature thresholds based on the panel estimation results and conclusions from previous specifications.

Moreover, we also apply the approach of growing degree days (GDDs) to capture the nonlinear effect of temperature on crop yield by estimating the equation

$$y_{it} = \beta_1 GDDs_{it}^{l_0,l_1} + \beta_2 SDDs_{it}^{l_1} + \delta z_{it} + c_i + \lambda_t + \epsilon_{it} \quad (5)$$

where $GDDs_{it}^{l_0,l_1}$ is the growing degree days (GDDs hereafter) when the lower and upper temperature thresholds are set as l_0 and l_1 accordingly, $SDDs_{it}^{l_1}$ denotes stressful degree days (SDDs hereafter) measured by the heat accumulation when the temperature is above the upper-temperature threshold l_1.

For any given temperature threshold, GDDs and SDDs are calculated based on the same sine curve approach. More specifically, the GDDs and SDDs of each day are calculated based on the simulated daily temperature distribution using the sine curve approach, which is the integral area between the given temperature threshold (l_0, l_1) on the simulated daily temperature distribution curve, after which the daily data are aggregated to calculate the GDDs and SDDs in the growing season.

C. Empirical Methods for Measuring Adaptations to Climate

In most literature, the agricultural adaptations to climate change are normally measured by farmers' responses in specific adaptation behavior such as the adoption of new varieties or technologies, the investment in the irrigation system, etc. However, our survey data doesn't contain information on farmers' behavioral changes except for the crop structure. Consequently, we first investigate the agricultural adaptation implicitly through the yield response of crops to the changing climate conditions and then study the explicit adaptation in crop structure and diversification to climate change.

To measure the adaptation implicitly, we apply the approach inspired by the model specified by Mérel and Gammans (2021), which provides a new insight into the estimation of short- and long-run yield responses to unveil the long-run adaptation to climate change. The long-run climatic adaptation model can be specified as

$$y_{it} = \beta_1 x_{it} + \beta_2 x_{it}^2 + \beta_3 (x_{it} - \overline{x}_i)^2 + c_i + \lambda_t + \mu_{it} \quad (6)$$

where y_{it} is the log of crop yield at location i in year t, x_{it} is the weather realization (temperature or precipitation) in year t, the climate variable $\overline{x}_i = \frac{1}{T}\sum_t x_{it}$ is the sample average of x_{it}.

The term $(x_{it} - \overline{x}_i)^2$ in equation (6) reflects the (squared) distance between contemporaneous weather and a location's normal climate, of which the coefficient β_3 is expected to be negative if long-run adaptations to climate change exist as it reflects that, conditional on the contemporaneous weather realization, crop yields in locations with an underlying climate closer to that realization are higher (due to the implicit adaptation to climate) than in locations for which that realization happens to be unusual.

To measure the explicit adaptation to climate change, we apply the two-limit random effect model for estimating farmers' response in land shares and crop diversification, measured by the Herfindal index (Bradshaw et al., 2014), to lagged climate-related variables such as the long-run means of daily temperature/precipitation and the lagged standard deviation of daily temperature/precipitation in the growing season.

3. Empirical Results

This section presents our empirical results of the estimated responses in crop yields and adaptations to climate.

We start with estimating the short-run response of crop yields to some simple measures of climate, such as average daily temperature, diurnal temperature range, and exposure to extreme temperatures in the growing season to gain some basic knowledge of the crops. On basis of this, we estimate the more precise nonlinear yield responses of the crops to exposure to different temperature intervals and heat accumulation (GDDs and SDDs). Furthermore, we investigate the implicit agricultural adaptations from crops' yield response to the changing climate conditions and the farmers' explicit adaptation in crop structure and diversification.

Our analysis mainly focuses on 5 main crops in Ukraine—winter wheat, spring barley, sunflower, soybean, and corn. Since the growing seasons of these crops are not the same, variables related to the growing season such as temperature bins and GDDs are crop specific.

A. Yield responses to short-run temperature variation

Table 1 reports the estimated results on yield responses of winter wheat to changes in different measures of temperature from FE regression, which shows the short-run effects of weather change on yields. The results indicate that the yield of winter wheat responds positively to the overall rising temperature (column 1) or daytime temperature (column 2), while falls when the overnight temperature rises (column 3) in the growing season. Moreover, such results are consistent with the results on diurnal temperature change (column 5), indicating that the winter wheat yields respond positively to the diurnal temperature range when the average daily temperature is controlled. Results from the last three columns of Table 1 indicate that the winter wheat yields respond positively to the exposure to extremely low overnight temperature (number of days when daily minimum temperature is below 0 °C) while are negatively associated with the exposure to extremely high daytime temperature (number of days when daily maximum temperature is above 24 °C).

(Insert Table 1)

Results on spring barley, as shown in Table 2, are similar to winter wheat, while the change in overall daily temperature doesn’t seem to have a significant impact on the yield of spring barley. It is indicated that the growth of spring barley responds positively to warmer daytime temperatures (column 2) while negatively to warmer overnight temperatures (column 3). Unlike winter wheat which favors exposure to extremely low temperatures, the exposure to extremely low temperatures has no significant yield impacts on spring barley. However, spring barley yields also respond negatively to exposure to extremely high temperatures (columns 6).

(Insert Table 2)

Table 3 presents results on sunflower, indicating that sunflower also favors a higher daytime temperature and a lower overnight temperature, as well as a larger diurnal temperature range. As a hot season crop, the sunflower also benefits from exposure to extremely high temperatures (measured by the number of days when the daily maximum temperature exceeds 28 °C). This can be possible if the temperature threshold we set doesn’t reach the temperature level that would hurt the growth of sunflowers yet. Moreover, exposure to extremely cold overnight temperatures has no significant impact on sunflower yields.

(Insert Table 3)

Table 4 reports the estimated results on soybean, which indicates that the overall rising temperature can benefit soybean yield. While, unlike the previous three crops, the overnight temperature (column 4) and the diurnal temperature range (column 5) have no significant impacts on soybean yield. Correspondingly, exposure to extremely cold temperatures is not significantly associated with the soybean yield either (column 6).

(Insert Table 4)

As shown in Table 5, the overall rising daily temperature (column 1) or daytime temperature (column 2) are positively associated with corn yield. However, the impacts of overnight temperature (column 4) and diurnal temperature range (column 5) on corn yield are not significant. The result from column 6 indicates that the corn yield, like the other two hot season crops—sunflower and soybean, responds positively to exposure to extremely high temperatures while is not significantly associated with exposure to extremely low temperatures. Moreover, the insignificant coefficient of daily temperature seems to indicate that the positive impacts of the overall rising temperature on corn yield are mainly due to the increased exposure to relatively high temperatures (28 °C for instance) rather than the overall rising temperature. This is consistent with the ambiguous yield impacts of corn's exposure to different temperature intervals.

(Insert Table 5)

The estimated non-linear yield responses of the five main crops to exposures to 3-degree temperature intervals in the growing season by estimating equation (3) are shown in Figure 1, in which the coefficients of the 3 °C-temperature intervals and their 95% confidence intervals are shown on the graph. The results indicate that, relative to exposure to a temperature below 0°C, extra exposure to most temperature intervals above 9 °C and below 30 °C significantly improves the yield of winter wheat, while extra exposure to temperatures above 30 °C would more likely harm the crop. Similar results are shown on spring barley, the other winter season crop, of which the yield responds positively to exposure to most temperature intervals above 6 °C and below 30 °C while extra exposure to temperatures above 30 °C would more likely harm the yield.

(Insert Table 6)

For winter wheat and spring barley, we define the lower temperature threshold as 6 °C and loop for all possible upper-temperature thresholds from 25 °C to 34°C and estimate equation (4)—the quasi-GDD specification and the results are reported in Table 6 and Table 7. The results show similar non-linear yield responses of these two crops as in the 3-degree specification—the exposure to temperature intervals below the stressful threshold—30/31°C can benefit crop yields while the exposure to temperatures above the threshold would harm their yields.

(Insert Table 7)

While for the other three hot season crops—sunflower, soybean, and corn, we could not find specific upper-temperature thresholds above which crop yields respond negatively to the rise in exposure or heat accumulation. The yield impacts of exposure to temperature intervals on these three crops are more ambiguous than on winter wheat and spring barley. Consequently, we didn't apply the quasi-GDD specification and estimate equation (4) for these three crops.

Table 8 reports the results from estimating equation (5) under the GDDs specification, in which the term stressful degree days (SDDs) are removed from the equation for the three summer season crops—sunflower, corn, and soybean. The results are consistent with what we find under the temperature bins approach. For the two cold season crops—winter wheat and spring barley, crop yields respond positively to GDDs while negatively to SDDs. For the other three hot season crops—sunflower, corn, and soybean, the heat accumulation (GDDs) is positively associated with crop yields.

B. Implicit Adaptations to Climate

The approach we apply to unveil the long-run adaptations to climate change is borrowed from Mérel and Gammans (2021) who justified that one can investigate the implicit agricultural adaptations by estimating the yield response to weather and climate conditions in one equation. We would test, conditional on the contemporaneous weather realization, whether the crop yields in locations where the underlying climate conditions are closer to that realization are relatively higher than in locations where the realization happens to be unusual. More specifically, we estimate equation (6) for each crop and check the negativity of the estimated coefficient (β_3) of the "climate penalty" term $(x_{it} - \overline{x}_i)^2$. The estimated results are shown in Table 9.

The results provide evidence of long-run adaptation in winter wheat production to temperature changes with significant negative coefficients of the "climate penalty" term (columns 1 and 2), indicating that the yield of winter wheat, conditional on the temperature realization, is relatively higher in locations where farmers are more familiar with the temperature (temperature realization is closer to long-run temperature). Furthermore, the significant negative coefficient of the (squared) precipitation deviation from the long-term mean also provides evidence of adaptations in winter wheat production to precipitation change in the long run (i.e., crop yields in locations where the long-term average precipitation level is closer to the contemporaneous realization of precipitation, conditional on the realization, are relatively greater). However, the result fails to provide evidence of long-run adaptations in spring barley production to temperature or precipitation change (i.e., negative β_3). For the rest of the three hot season crops—sunflower, soybean, and corn, we find evidence of long-run adaptations to precipitation change but not to temperature change.

The surprising positive coefficients of the "temperature penalty" term on the three hot season crops implicitly indicate their yields, conditional on the contemporaneous realization of temperature, are even smaller in locations where farmers are already familiar with the temperature. Such results bring up our concern on the applicability of the approach we apply in unveiling the long-run adaptation to climate in contexts where the dome-shaped relationship does not apply so well in relating the crop yields to contemporaneous temperature, as the model is derived based on the commonly used quadratic-in-weather specification.

C. Explicit Adaptations in Crop Structure and Diversification

We apply a simple two-limit random-effects Tobit model to investigate the impacts of (lagged) climate variables (5-year mean of daily temperature and precipitation in the growing season) on crop shares and diversification (measured by Herfindal Index) with the control on (lagged) weather volatilities (standard deviation of daily temperature and precipitation in the growing season) and the total cropping area of each farm. The results are shown in Table 10.

The results in Table 10 first indicate that the total cropping area is positively associated with the land shares of winter wheat, sunflower, corn, and soybean while negatively associated with the share of spring barley, which is consistent with the declining sown area of spring barley and rising sown area of the rest four crops over time as shown in our descriptive results.

For the two cold season crops, the long-run temperature is positively associated with the land share of winter wheat (column 1) and negatively associated with the share of spring barley (while not significant, column 2), this is consistent with the relatively more significant impacts of the overall rising temperature on winter wheat (Table 1) than on spring barley (Table 2). For the other three hot season crops, the rising long-term temperature is positively associated with the land share of sunflower while negatively associated with the land share of soybean and corn, while our previous results indicate that the overall rising temperature has positive yield impacts on all these three crops (mainly due to the increased exposure to temperatures above 27/28 °C). One possible explanation is that the marginal improvement in profitability of planting more sunflowers is greater than planting more corn or soybean (due to the difference in marginal revenue or marginal cost), even though warming temperature has similar yield impacts on these crops. Moreover, the long-term precipitation is positively associated with the land share of winter wheat and soybean while negatively associated with the share of spring barley and corn.

The results on the Herfindal index (column 6) indicate that the crop structure is more diversified when the long-term temperature rises or becomes more volatile. This could be explained by the increasing need in sharing climate risk by planting more types of crops or the increasing number of cultivable crops as the temperature rises in the context of Ukraine.

4. Conclusion

Given the complexity of crop growth and its interaction with climate conditions, as well as the potential adaptations that can be applied in agricultural practices by farmers, assessing the exact impacts of climate change on agriculture production is never an easy task. In most cases, the results vary across crops and depend largely on the environment of the studied area (climate conditions, soil type, etc.), as well as the empirical approaches researchers apply.

Our empirical results on yield responses of crops to short-run changes in climate conditions (mainly temperature) indicate that the overall rising temperature is positively associated with the yields of all the five main crops in Ukraine. While for the two cold season crops—winter wheat and spring barley, the crop yield can be related to short-run temperature with a dome-shaped curve—the exposure to or heat accumulation in temperate temperature intervals ([6°C, 29/30 °C] for winter wheat and [6°C, 30/31°C] for spring barley) can benefit their yields while exposure to or heat accumulation in temperature intervals above a "stressful" temperature bound (29/30 °C for winter wheat, 30/31°C for spring barley) can harm the crop growth. For the other three hot season crops—sunflower, corn, and soybean, the positive yield impacts of the rising temperature are mainly due to the increased exposure to or heat accumulation in temperature intervals above 27/28°C rather than the overall increasing daily temperature. The impacts of exposure to or heat accumulation in temperature intervals above 8/°C on yields of these crops are ambiguous. The relatively temperate climate conditions in Ukraine could explain the ineffectiveness of the dome-shaped curve in relating the yield of these crops to temperature, contradicting to results on these crops found in other studies (i.e., the temperature in Ukraine rarely reaches a stressful temperature that is too high for hot season crops).

The other important conclusion we draw from our analysis is the importance of the diurnal temperature range in affecting crop yields (especially for cold season crops). We find that neglecting the synchronous change of daytime and overnight temperature and their distinct impacts on crop yields can significantly underestimate or mistakenly estimate the yield impact of the overall temperature changes. Such property of crops provides extra challenges for researchers in analyzing explicit impacts of climate conditions on agricultural production.

Moreover, our results unveil significant adaptation in winter wheat production to long-run temperature change but no clear evidence of adaptation to temperature is shown on spring barley. We also find evidence of adaptation to long-term precipitation change for sunflower, soybean, and corn. However, as we explained in previous sections, the applicability of the approach we apply in unveiling the long-run adaptation to climate change might be undermined if the dome-shaped relationship between crop yields and temperature is not suggested.

Furthermore, our empirical results on explicit agricultural adaptations to climate change indicate that the rise in long-run temperature is positively associated with the cropping share of winter wheat and sunflower, while negatively associated with the share of spring barley, corn, and soybean. While the yield-climate relationships we discover can partially explain such results, other factors we neglect in our analysis due to the data constraints such as relative output and input prices could be other contributors. Moreover, we also find that the crop structure is more diversified as the long-run temperature and volatility of daily temperature in the growing season rise.

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Figures and Tables

Figure 1. Yield response of winter wheat to 3-degree temperature intervals

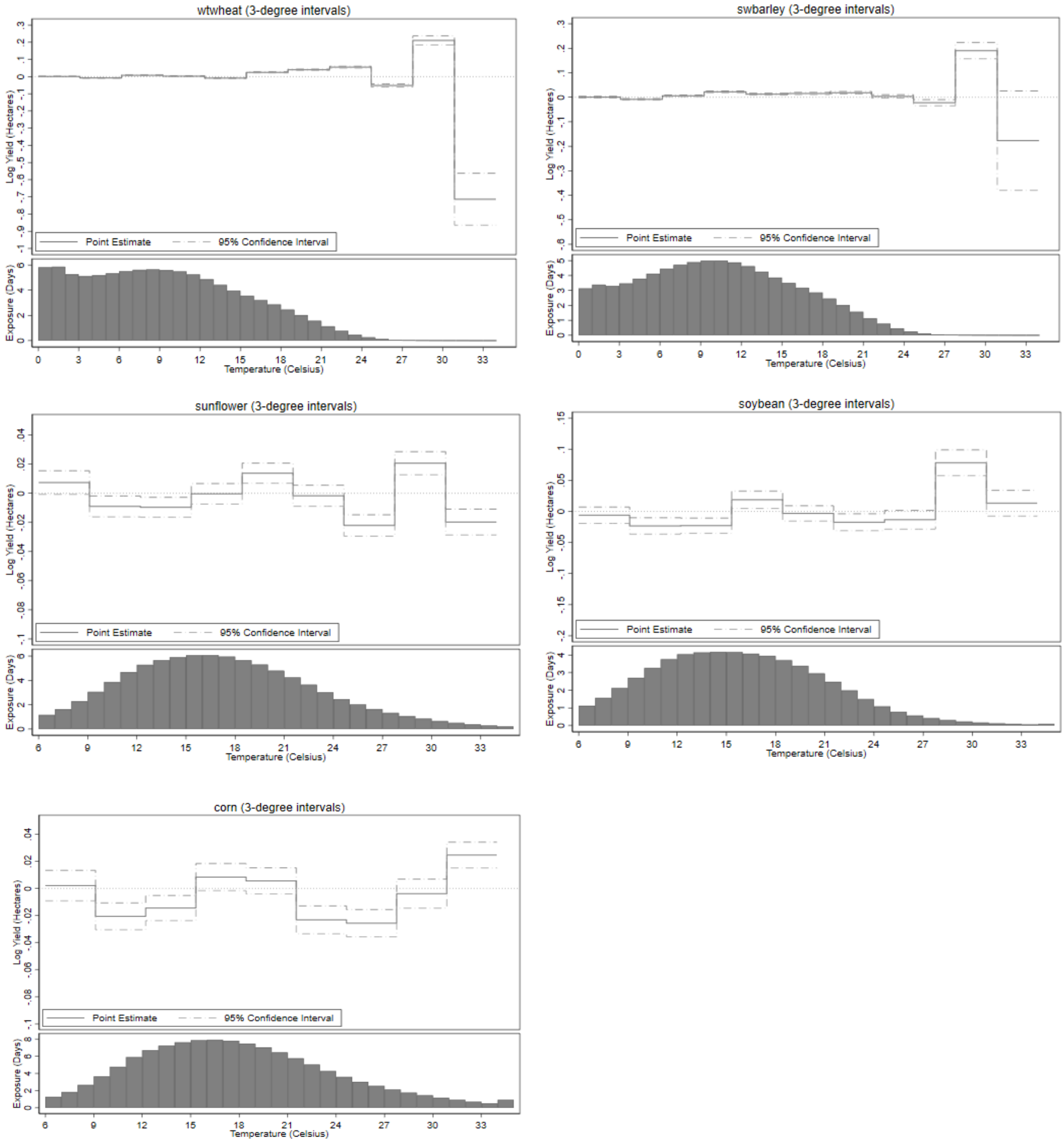

Table 1. Estimated effects of weather variation on winter wheat yield from FE estimation

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable	log(yield)	log(yield)	log(yield)	log(yield)	log(yield)	log(yield)
Daily temperature	0.052***				0.039***	0.083***
	(0.012)				(0.011)	(0.013)
Daytime temperature		0.068***		0.116***		
		(0.010)		(0.012)		
Overnight temperature			-0.013	-0.087***		
			(0.008)	(0.009)		
Diurnal temperature range					0.099***	0.111***
					(0.009)	(0.009)
# of days (Tmin < 0 °C)						0.005***
						(0.001)
# of days (Tmax > 24 °C)						-0.040***
						(0.004)
SD. of daily temperature	0.026**	0.035***	-0.035***	-0.016	-0.007	0.013
	(0.011)	(0.009)	(0.010)	(0.010)	(0.010)	(0.011)
Prec (mm)	-0.102***	-0.063*	-0.110***	-0.020	-0.023	-0.029
	(0.034)	(0.036)	(0.033)	(0.035)	(0.035)	(0.039)
$Prec^2$ (mm*mm)	-0.003	-0.006	-0.002	-0.011	-0.010	-0.004
	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.007)
SD. of daily precipitation	0.025***	0.022***	0.024***	0.019***	0.019***	0.015***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
Constant	0.713***	0.174	1.529***	0.089	-0.019	-0.785***
	(0.171)	(0.195)	(0.098)	(0.190)	(0.192)	(0.227)
Observations	155,215	155,215	155,215	155,215	155,215	155,215
R-squared	0.579	0.580	0.579	0.582	0.582	0.586
Level	Village	Village	Village	Village	Village	Village
Fixed Effects	Vill, Yr	Vill, Yr	Vill, Yr	Vill, Yr	Vill, Yr	Vill, Yr

Note: All climate-related variables are calculated based on crop-specific growing season; standard errors are clustered at the rayon level; *** p<0.01, ** p<0.05, * p<0.1

Table 2. Estimated effects of weather variation on spring barley yield in FE estimation

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable	log(yield)	log(yield)	log(yield)	log(yield)	log(yield)	log(yield)
Daily temperature	0.018				0.006	0.018
	(0.013)				(0.012)	(0.015)
Daytime temperature		0.044***		0.056***		
		(0.010)		(0.011)		
Overnight temperature			-0.014	-0.037***		
			(0.010)	(0.011)		
Diurnal temperature range					0.048***	0.050***
					(0.009)	(0.009)
# of days (Tmin < 0 °C)						0.001
						(0.001)
# of days (Tmax > 24 °C)						-0.020***
						(0.004)
SD. of daily temperature	-0.036***	-0.019***	-0.060***	-0.041***	-0.050***	-0.042***
	(0.008)	(0.006)	(0.008)	(0.008)	(0.008)	(0.009)
Prec (mm)	-0.162***	-0.146***	-0.161***	-0.139***	-0.140***	-0.141***
	(0.028)	(0.029)	(0.028)	(0.029)	(0.029)	(0.032)
$Prec^2$ (mm*mm)	0.018***	0.017***	0.017***	0.017***	0.017***	0.018***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
SD. of daily precipitation	0.017***	0.015***	0.017***	0.014***	0.014***	0.013***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)
Constant	1.017***	0.451**	1.379***	0.543***	0.697***	0.496**
	(0.173)	(0.183)	(0.090)	(0.185)	(0.189)	(0.224)
Observations	123,716	123,716	123,716	123,716	123,716	123,716
R-squared	0.569	0.570	0.569	0.570	0.570	0.570
Level	Village	Village	Village	Village	Village	Village
Fixed Effects	Vill, Yr	Vill, Yr	Vill, Yr	Vill, Yr	Vill, Yr	Vill, Yr

Note: All climate-related variables are calculated based on crop-specific growing season; standard errors are clustered at the rayon level; *** p<0.01, ** p<0.05, * p<0.1

Table 3. Estimated effects of weather variation on sunflower yield from FE estimation

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable	log(yield)	log(yield)	log(yield)	log(yield)	log(yield)	log(yield)
Daily temperature	0.048***				0.036***	-0.003
	(0.008)				(0.008)	(0.010)
Daytime temperature		0.041***		0.055***		
		(0.007)		(0.009)		
Overnight temperature			0.007	-0.030***		
			(0.008)	(0.011)		
Diurnal temperature range					0.039***	0.025***
					(0.009)	(0.009)
# of days (Tmin < 0 °C)						0.013
						(0.009)
# of days (Tmax > 28 °C)						0.008***
						(0.001)
SD. of daily temperature	-0.049***	-0.051***	-0.025*	-0.049***	-0.055***	-0.037**
	(0.014)	(0.014)	(0.013)	(0.014)	(0.014)	(0.014)
Prec (mm)	-0.153***	-0.150***	-0.199***	-0.149***	-0.136***	-0.126***
	(0.025)	(0.025)	(0.024)	(0.026)	(0.025)	(0.025)
$Prec^2$ (mm*mm)	0.016***	0.017***	0.022***	0.019***	0.017***	0.014***
	(0.004)	(0.003)	(0.004)	(0.004)	(0.004)	(0.004)
SD. of daily precipitation	0.013***	0.013***	0.014***	0.011***	0.011***	0.011***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Constant	0.022	-0.080	0.788***	-0.069	-0.240	0.510***
	(0.148)	(0.159)	(0.107)	(0.159)	(0.167)	(0.195)
Observations	112,644	112,644	112,644	112,644	112,644	112,644
R-squared	0.612	0.612	0.612	0.612	0.612	0.613
Level	Village	Village	Village	Village	Village	Village
Fixed Effects	Vill, Yr	Vill, Yr	Vill, Yr	Vill, Yr	Vill, Yr	Vill, Yr

Note: All climate-related variables are calculated based on crop-specific growing season; standard errors are clustered at the rayon level; *** p<0.01, ** p<0.05, * p<0.1

Table 4. Estimated effects of weather variation on soybean yield from FE estimation

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable	log(yield)	log(yield)	log(yield)	log(yield)	log(yield)	log(yield)
Daily temperature	0.041***				0.039***	0.029***
	(0.009)				(0.010)	(0.010)
Daytime temperature		0.037***		0.031***		
		(0.007)		(0.009)		
Overnight temperature			0.032***	0.012		
			(0.010)	(0.013)		
Diurnal temperature range					0.008	0.003
					(0.010)	(0.011)
# of days (Tmin < 0 °C)						-0.003
						(0.012)
# of days (Tmax > 28 °C)						0.039***
						(0.011)
SD. of daily temperature	0.145***	0.139***	0.152***	0.137***	0.145***	0.149***
	(0.018)	(0.018)	(0.018)	(0.018)	(0.018)	(0.018)
Prec (mm)	0.046*	0.055**	0.024	0.048*	0.052*	0.051*
	(0.028)	(0.028)	(0.028)	(0.029)	(0.029)	(0.029)
$Prec^2$ (mm*mm)	-0.008**	-0.009***	-0.007**	-0.008***	-0.008***	-0.009***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
SD. of daily precipitation	-0.007	-0.007	-0.005	-0.007	-0.007	-0.007
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
Constant	-0.664***	-0.776***	-0.307***	-0.756***	-0.721***	-0.523***
	(0.139)	(0.146)	(0.096)	(0.150)	(0.155)	(0.173)
Observations	57,578	57,578	57,578	57,578	57,578	57,578
R-squared	0.539	0.539	0.539	0.539	0.539	0.540
Level	Village	Village	Village	Village	Village	Village
Fixed Effects	Vill, Yr	Vill, Yr	Vill, Yr	Vill, Yr	Vill, Yr	Vill, Yr

Note: All climate-related variables are calculated based on crop-specific growing season; standard errors are clustered at the rayon level; *** p<0.01, ** p<0.05, * p<0.1

Table 5. Estimated effects of weather variation on corn yield from FE estimation

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable	log(yield)	log(yield)	log(yield)	log(yield)	log(yield)	log(yield)
Daily temperature	0.047***				0.041***	0.002
	(0.012)				(0.014)	(0.016)
Daytime temperature		0.040***		0.038***		
		(0.010)		(0.014)		
Overnight temperature			0.033**	0.004		
			(0.014)	(0.019)		
Diurnal temperature range					0.016	-0.002
					(0.016)	(0.016)
# of days (Tmin < 0 °C)						-0.021
						(0.014)
# of days (Tmax > 28 °C)						0.006***
						(0.001)
SD. of daily temperature	-0.040**	-0.043**	-0.026	-0.043**	-0.043**	-0.049***
	(0.019)	(0.019)	(0.018)	(0.020)	(0.020)	(0.019)
Prec (mm)	0.033	0.032	-0.001	0.032	0.038	0.073*
	(0.040)	(0.040)	(0.036)	(0.040)	(0.041)	(0.043)
$Prec^2$ (mm*mm)	-0.009	-0.007	-0.006	-0.008	-0.008	-0.014**
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.006)
SD. of daily precipitation	-0.002	-0.003	-0.001	-0.003	-0.004	-0.003
	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)
Constant	0.674***	0.580**	1.147***	0.579**	0.583**	1.402***
	(0.247)	(0.251)	(0.192)	(0.251)	(0.255)	(0.301)
Observations	91,383	91,383	91,383	91,383	91,383	91,383
R-squared	0.610	0.610	0.610	0.610	0.610	0.610
Level	Village	Village	Village	Village	Village	Village
Fixed Effects	Vill, Yr	Vill, Yr	Vill, Yr	Vill, Yr	Vill, Yr	Vill, Yr

Note: All climate-related variables are calculated based on crop-specific growing season; standard errors are clustered at the rayon level; *** p<0.01, ** p<0.05, * p<0.1

Table 6. Nonlinear yield response of winter wheat to temperature (quasi-GDDs specification)

Dependent variable:	Log (yield)									
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Threshold (°C)	25	26	27	28	29	30	31	32	33	34
Exposure: 6°C - Threshold (*100)	0.500***	0.522***	0.528***	0.520***	0.517***	0.513***	0.509***	0.513***	0.516***	0.516***
	(0.045)	(0.045)	(0.045)	(0.045)	(0.045)	(0.045)	(0.045)	(0.045)	(0.045)	(0.045)
Exposures: > Threshold (*100)	-0.997**	1.636***	4.851***	5.193***	2.055	-12.747**	-82.090***	-220.577***	-1,848.294**	-
	(0.409)	(0.578)	(0.864)	(1.464)	(2.662)	(6.158)	(15.813)	(52.181)	(865.094)	
Observations	111,774	111,774	111,774	111,774	111,774	111,774	111,774	111,774	111,774	111,774
R-squared	0.534	0.533	0.534	0.534	0.533	0.533	0.534	0.534	0.533	0.533

Note: Daily precipitation and its square term are controlled; Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Table 7. Nonlinear yield response of spring barley to temperature (quasi-GDDs specification)

Dependent variable:	Log (yield)									
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Threshold (°C)	25	26	27	28	29	30	31	32	33	34
Exposure: 6°C - Threshold (*100)	1.449***	1.464***	1.466***	1.451***	1.436***	1.430***	1.422***	1.420***	1.419***	1.421***
	(0.082)	(0.081)	(0.081)	(0.081)	(0.081)	(0.081)	(0.081)	(0.081)	(0.081)	(0.081)
Exposures: > Threshold (*100)	3.365***	6.196***	10.766***	15.291***	19.484***	34.522***	10.386	-227.123***	-3,401.757***	-
	(0.539)	(0.751)	(1.114)	(1.923)	(3.584)	(8.279)	(20.827)	(63.068)	(712.562)	
Observations	81,539	81,539	81,539	81,539	81,539	81,539	81,539	81,539	81,539	81,539
R-squared	0.545	0.546	0.546	0.546	0.546	0.545	0.545	0.545	0.546	0.545

Note: Daily precipitation and its square term are controlled; Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Table 8. Effects of GDDs and SDDs on crop yields

Dependent variable:	Log (yield)				
	(1)	(2)	(3)	(4)	(5)
	Wheat	Barley	Sunflower	Soybean	Corn
$GDDs^{6,30}$ (Mar-Jun, *100)	0.152***				
	(0.007)				
$SDDs^{30}$ (Mar-Jun, *100)	-50.623***				
	(7.339)				
$GDDs^{6,31}$ (Apr-Jun, *100)		0.152***			
		(0.011)			
$SDDs^{31}$ (Apr-Jun, *100)		-88.917***			
		(29.709)			
$GDDs^{8}$ (Jun-Aug, *100)			0.019***		
			(0.007)		
$GDDs^{10}$ (Jun-Jul, *100)				0.135***	
				(0.014)	
$GDDs^{10}$ (Jun-Sep, *100)					0.048***
					(0.007)
Constant	0.482***	0.228***	0.356***	0.002	0.888***
	(0.041)	(0.053)	(0.076)	(0.066)	(0.093)
Observations	111,774	81,539	80,645	35,191	55,239
R-squared	0.535	0.545	0.550	0.514	0.600

Note: Daily precipitation and its square term are controlled; Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Table 9. Estimated weather and climate impacts on crop yields

Dependent variable:	Log (yield)									
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Wheat		Barley		Sunflower		Soybean		Corn	
Temp in GS	-0.037***	-0.015*	-0.144***	0.016	0.154**	0.177***	0.650***	0.229***	-0.644***	-0.185**
	(0.003)	(0.008)	(0.039)	(0.020)	(0.070)	(0.053)	(0.102)	(0.063)	(0.096)	(0.091)
(Temp in GS)^2	0.009***	0.004***	0.011***	0.002	-0.004**	-0.004***	-0.017***	-0.005***	0.015***	0.005**
	(0.000)	(0.001)	(0.002)	(0.001)	(0.002)	(0.001)	(0.003)	(0.002)	(0.002)	(0.002)
(Temp - 5-year mean Temp)^2	-0.020***	-0.005***	0.002	0.010***	0.008	0.026***	0.080***	0.073***	0.036***	0.084***
	(0.001)	(0.001)	(0.004)	(0.002)	(0.006)	(0.005)	(0.011)	(0.008)	(0.011)	(0.010)
Prec in GS	-0.025*	-0.092***	-0.042	-0.161***	-0.288***	-0.232***	-0.063	-0.066**	-0.095	-0.106***
	(0.013)	(0.035)	(0.055)	(0.035)	(0.048)	(0.025)	(0.038)	(0.027)	(0.066)	(0.040)
(Perc in GS)^2	-0.003	0.007	0.006	0.026***	0.060***	0.043***	0.010*	0.009**	0.023**	0.025***
	(0.003)	(0.007)	(0.011)	(0.007)	(0.009)	(0.005)	(0.005)	(0.004)	(0.011)	(0.007)
(Prec - 5-year mean Prec)^2	-0.115***	-0.034**	0.004	-0.016	-0.106***	-0.070***	0.001	-0.031***	-0.125***	-0.129***
	(0.005)	(0.014)	(0.016)	(0.011)	(0.010)	(0.007)	(0.008)	(0.005)	(0.016)	(0.012)
Constant	0.807***	1.176***	1.023***	0.683***	-1.030	-0.978**	-5.875***	-1.761***	7.852***	3.096***
	(0.021)	(0.065)	(0.196)	(0.115)	(0.663)	(0.494)	(0.846)	(0.537)	(1.085)	(0.905)
Observations	244,581	155,215	216,171	123,716	205,102	112,644	51,579	57,578	102,208	91,383
R-squared	0.641	0.579	0.634	0.569	0.668	0.614	0.631	0.542	0.698	0.615
Level	Farm	Village	Farm	Village	Farm	Village	Farm	Village	Farm	Village
Period	2000-2014	2000-2020	2000-2014	2000-2020	2000-2014	2000-2020	2000-2014	2000-2020	2000-2014	2000-2020
FE	Farm, year	Vill, year	Farm, year	Vill, year	Farm, year	Vill, year	Farm, year	Vill, year	Farm, year	Vill, year

Note: Standard errors are clustered at the rayon level; *** p<0.01, ** p<0.05, * p<0.1

Table 10. Estimated climate effects on crop shares and diversification

Dependent variable:	Share of cropping area/Herfindal index					
	(1)	(2)	(3)	(4)	(5)	(6)
	Wheat	Barley	Sunflower	Soybean	Corn	Herfindal
Total cropping area	0.000***	-0.000***	0.000***	0.000***	0.000***	-0.000***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Lagged 5-year mean temperature	0.039***	-0.001	0.216***	-0.211***	-0.033***	0.111***
	(0.002)	(0.002)	(0.003)	(0.007)	(0.004)	(0.001)
Lagged SD. of temperature	-0.027***	0.013***	0.016***	0.138***	-0.019***	0.011***
	(0.001)	(0.002)	(0.003)	(0.009)	(0.005)	(0.001)
Lagged 5-year mean precipitation	0.112***	-0.129***	-0.005	0.124***	-0.022**	-0.019***
	(0.005)	(0.005)	(0.005)	(0.010)	(0.009)	(0.004)
Lagged SD. of precipitation	-0.002	0.002**	-0.009***	-0.021***	0.005***	0.000
	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)
Constant	-0.136***	0.235***	-3.710***	0.606***	0.111	-0.535***
	(0.024)	(0.031)	(0.059)	(0.137)	(0.089)	(0.026)
Observations	577,545	577,545	577,545	577,545	577,545	577,545

Note: Standard errors are clustered at the rayon level; *** p<0.01, ** p<0.05, * p<0.1