Title: Temperature changes are associated with nonlinear effects on wheat yield in Pakistan

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Abstract

Pakistan is among the top five countries most affected by the changing climate. Despite the heavy reliance on the agricultural sector, the evidence of the impact of climate change on its staple crops is limited, both in scope and approach. A deeper understanding of the mechanisms and behavior of the weather variables and their impact on crop yields holds the key to Pakistan's progress towards sustainable growth and food security. This study estimates the effects of temperature changes on the production of the wheat crop in Pakistan. The focus is on the nonlinear yield response to the changing temperature. A unique dataset of daily weather observations and temperature exposure bins was used, which combines with the yearly district-level wheat yields from 1981 through 2017. The results show that wheat yield in Pakistan has a nonlinear response to the changes in the temperature which vary considerably within the growing season. The results indicate that low temperatures of below 4℃ are particularly detrimental to the wheat yields, as are the high temperatures in all three periods of the growing season. Moreover, a uniform increase of 2°C is predicted to decrease the wheat yield by about 10%. The out-of-sample predictions indicate that the study model with heat exposure bins performs better than the model with average temperature specifications.

Introduction

As a result of warming temperatures, a lot of attention has been directed towards studying the impacts of climate change and possible adaptation pathways. The agricultural sector is directly affected by the changing climate, as the climate variables serve as key inputs to the agricultural production process. For Pakistan, the relationship between climate and agriculture is of key relevance due to its extreme vulnerability to climate change (Eckstein et. al., 2018) and heavy reliance on the agriculture sector. The agricultural sector contributes to a quarter of its GDP and employs over 40% of the labor force (Pakistan, 2009).

This paper aims to provide a deeper understanding of the effects of temperature changes on the production of wheat crop in Pakistan. The focus is on the nonlinear yield response to the changing temperature. Wheat is the staple crop of Pakistan and accounts for 14 percent of value-added in agriculture and 3 percent of Pakistan's GDP. It is grown by about 80 percent of farmers on 40 percent of the country's total cultivated land (FAO, 2013). Therefore, sustainable growth in wheat production is of key importance to the economy of Pakistan.

By utilizing the global gridded daily weather dataset, this study provides evidence to a clear gap in the literature of climate impacts on crop yields in Pakistan. Based on the literature review, we did not find any study that employs daily weather data to estimate the nonlinear effects of weather variables on crop yields in Pakistan. Previous studies have used monthly or even yearly averages of the weather variables, which run the risk of losing substantial variations in the data and lead to biased estimates of the nonlinear effects (Schlenker & Roberts, 2009). Following the approach proposed by Schlenker & Roberts (2009), this study estimates the nonlinear effects of temperature on the wheat yield by preserving the daily variations in the data. The temperature distribution within a day was approximated using a synodal function (Snyder, 1985) to provide hourly exposure for each degree Celsius. These exposure variables provide the time the wheat crop was exposed to each 1°C temperature intervals. These variables were then summed across all days of the growing season. The study further divides the growing season into 3 three-month periods to disaggregate the effects on different stages of the crop cycle. In addition to the estimation of the nonlinear effects based on the historical data, future warming impacts for a uniform increase in the daily temperature of 1°C and 2°C were also calculated.

The results show that the wheat yield in Pakistan has a nonlinear response to the changes in the temperature. The nonlinearity varies significantly in the three periods within the growing season. Depending on the period, both the low and the high extremes of the temperature show detrimental effects.

Methods

Data: The agricultural data includes yearly wheat production and crop area observations for 59 districts of Pakistan ranging from the year 1981 through 2017. These districts cover the entire provinces of Punjab and Sindh which account for over 80% production of wheat in Pakistan. The data were obtained from the Pakistan Bureau of Statistics (PBS) through its yearly Agricultural Statistics of Pakistan publications. This is the most disaggregated level data available on crop yields in Pakistan. The yield variable equals total district-level production divided by hectares harvested.

The weather data were obtained from the Climate Prediction Centre (CPC) dataset which is developed by the American National Oceanic and Atmospheric Administration (NOAA) using the optimal interpolation of quality-controlled gauge records of the Global Telecommunication

System (GTS) network (Fan & Van den Dool, 2008). It provides daily observations of minimum and maximum temperature and precipitation variables on a spatial resolution of global 0.50 x 0.50-degree latitude/longitude grids. The subset for Pakistan was extracted through latitude and longitude information of each district obtained from the weather station data by the Pakistan Meteorological Department.

Since the weather data was at the daily level, following Schlenker & Roberts (2009), the within-day distribution of temperature was approximated using a sinusoidal curve between the predicted minimum and maximum temperature. This hourly exposure for each degree Celsius was then aggregated for each day in each district to achieve annual district-level observations for the wheat-growing season of September through May.

Model: Equation 1 shows the study regression model where y_{it} is the log wheat yield in kgs per hectare for district *i* and year *t*, $trend_t$ and $trend_t^2$ are the linear and quadratic trend variables, $precip_{it}$ is the precipitation in millimeters along with its quadratic approximation, and d_i are district fixed effects. The $\sum_{k=1}^{9} \delta_k \, bin_{ikt}$ are the nine exposure bin variables; the first sums up the exposure below 4°C and the rest of the seven bins are constructed with the increments of 5°C except for 30°C – 35°C which is further divided into two bins of 3°C increments to disaggregate the impact of higher temperatures. Following is the list of all the temperature exposure bin created:

- Exposure Bin 1: All temperatures below 4°C
- Exposure Bin 2: Temperatures from 5°C to 9°C
- Exposure Bin 3: Temperatures from 10°C to 14°C
- Exposure Bin 4: Temperatures from 15°C to 19°C
- Exposure Bin 5: Temperatures from 20°C to 24°C
- Exposure Bin 6: Temperatures from 25°C to 29°C
- Exposure Bin 7: Temperatures from 30°C to 32°C
- Exposure Bin 8: Temperatures from 33°C to 35°C
- Exposure Bin 9: Temperatures from 35°C and above

Upon estimation, exposure bin 9 was omitted from the model to avoid the dummy variable trap.

Equation 1: Regression Model

$$y_{it} = \sum_{k=1}^{7} \delta_k \, bin_{ikt} + \beta_1 \, precip_{it} + \beta_2 \, precip_{it}^2 + trend_t + \, trend_t^2 + \, d_i + \, \varepsilon_{it}$$

The quadratic time trend was included to control for technological change and the district-specific fixed effects ensure controls for time-invariant heterogeneity such as soil type and quality.

Equation 2: Warming Impacts

$$impact = \, 100 \left\{ e\left[\hat{\beta}(bin^1 - bin^0) - 1 \right] \right\}$$

Warming impacts: Following Shew et. al. (2020), the warming impacts were calculated for a uniform increase in the daily temperature of 1°C and 2°C. For this, exposure bins were recalculated with an increase of 1°C and yield change was simulated based on the initial regression parameters and yield estimates. Similarly, the same steps were repeated for the 2°C warming scenarios. Equation 2 shows the formula for the calculation of the warming impacts where *bin* is the vector of temperature exposure bins for increased (1) and initial (0) models.

Results

Wheat yields have a nonlinear response to changes in temperature. The study attempts to provide evidence on the nonlinear response of wheat yields to changes in temperature. The top-left panel in Fig. 1A shows the marginal effect of each exposure bin on the wheat yield across the entire growing season from September through May. The solid line represents the change in the mean log yield if the wheat crop is exposed for 24 hours to each exposure bin. The red dotted lines represent the 95% confidence interval using standard errors clustered by year.

Fig. 1A shows nonlinear response of wheat yield to changes in temperature when considering the entire growing season. Exposure to low temperatures (below 4°C) and highs (above 33°C) has the most adverse impact on the yield. The temperatures between 5°C to 9°C and 25°C to 33°C shows a positive yield response which is above the mean level.

The results show significant variations within the growing season. To further understand the nonlinear behavior of the yield response to temperature, the growing season was divided into three three-month periods: Fall (September-November), Winter (December-February), and Spring (March-May). The hourly exposures were recalculated and then aggregated for each degree Celsius using the sinusoidal curve. The marginal effect for the eight exposure bins was then calculated for each season. Fig. 1B shows these marginal effects for each period.

Figure 1A: Marginal Effects of Temperature on Wheat Yield in Growing Season

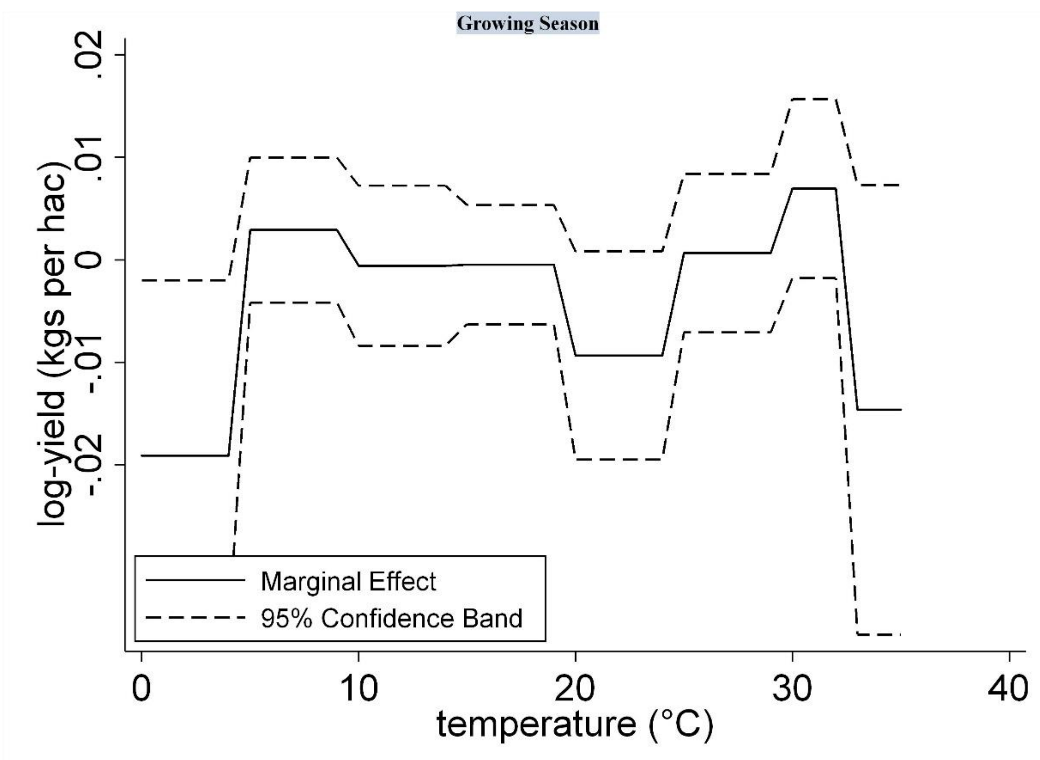
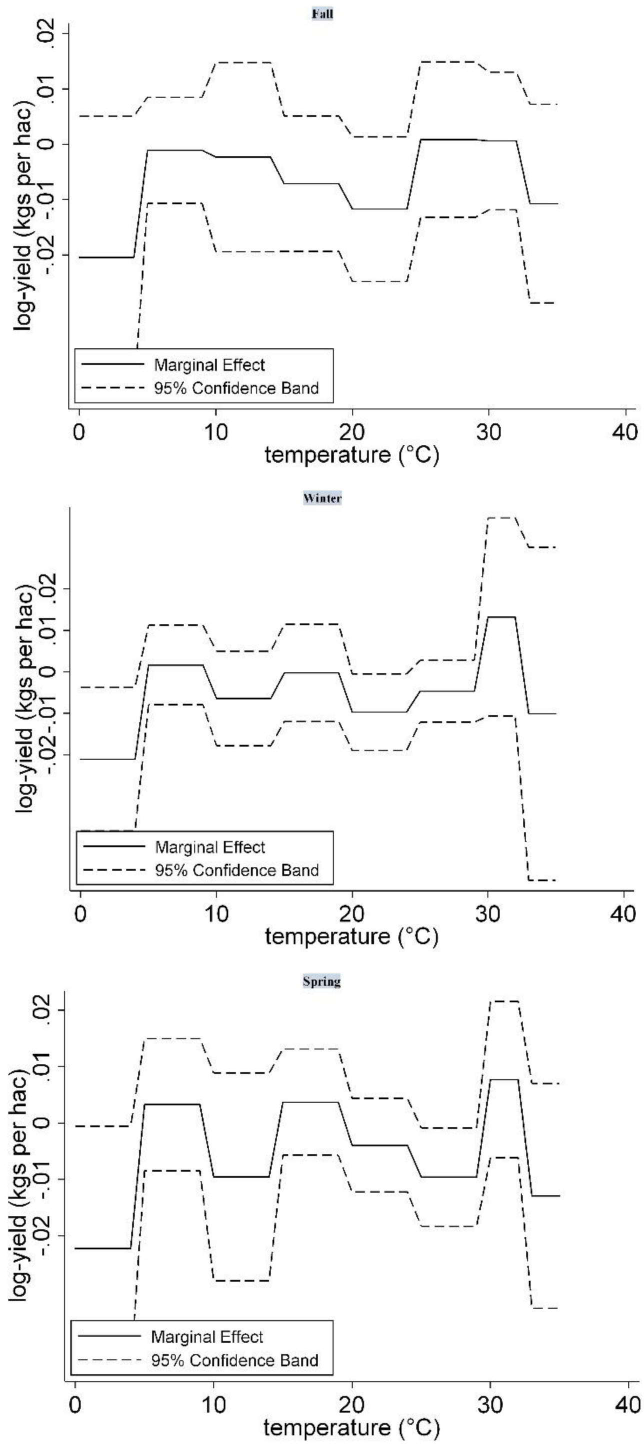


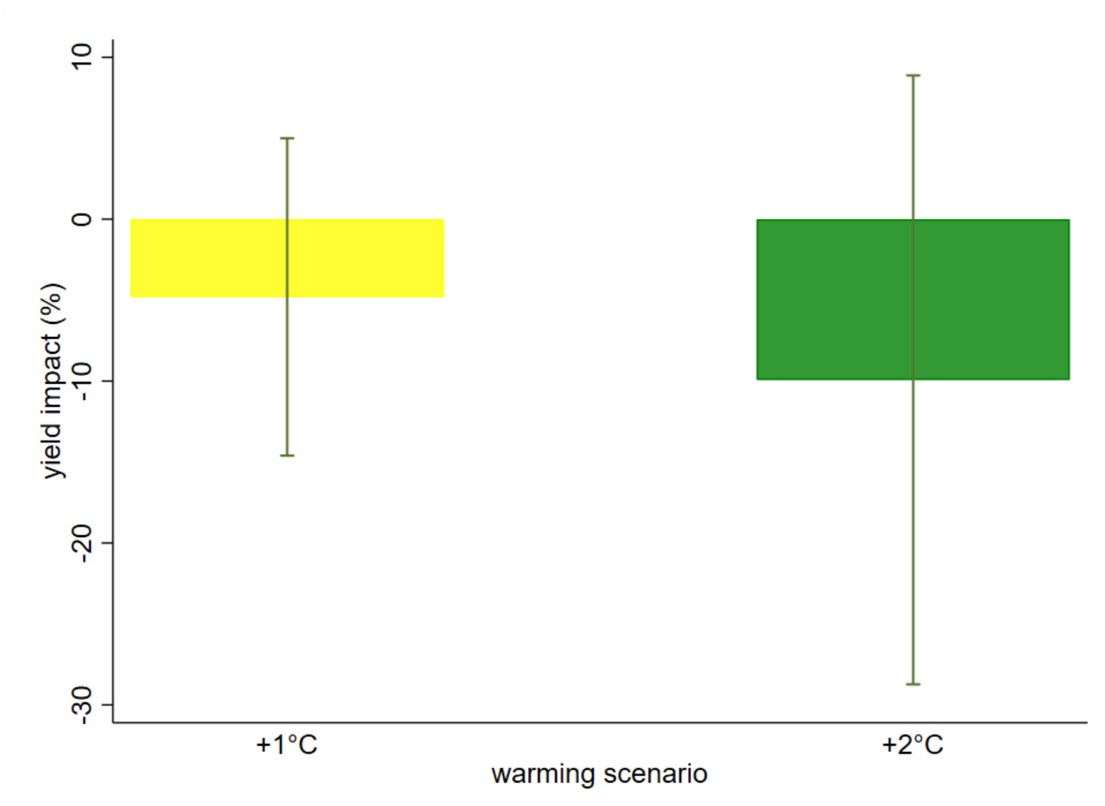
Figure 2B: Marginal Effects of Temperature on Wheat Yield in Three Periods



The results provide a better understanding of how the lower and higher temperatures affect the wheat yield. Following the response in the growing season panel, the most damaging effect is caused by the exposure to extremely low (below 4°C) and extremely high (over 33°C) temperatures in all seasons. The Spring season shows greater yield sensitivity whereas the other two show relatively less variation after the 4°C. The optimal exposure temperatures are 25°C - 33°C for Fall and 30°C – 33°C for Spring, and Winter seasons.

The predicted warming impacts suggest a negative yield response to increasing temperature. The warming impacts are based on a uniform increase in the historical daily minimum and maximum temperature and estimated using the Delta Method of asymptotic approximation for large samples (Shew et. al, 2020). To implement this, the *nlcom* command in STATA 15 was used. Fig. 2 shows these impacts as the percentage change in mean yield under both +1°C and +2°C scenarios relative to the historical climate for each season. Panel 1 (top left) shows the warming impacts for the entire season; it shows a yield reduction of 4.8% and 9.9% for both scenarios, respectively.

Figure 3: Warming Impacts



The out of sample predictions show the highest reduction in RMSE for the exposure bins model. Following Schlenker & Roberts (2009), the study model with exposure bins as the explanatory set of variables was compared with two other specifications: (i) base model with no weather variables, (ii) a model with the annual average temperature for the nine-month growing season. The comparison was made using the root-mean-squared error (RMSE) of out-of-sample predictions. The three models were estimated for 1000 times for 80% of the observations. The estimates are then used to predict the remaining 20% observations for each sample.

Table 1: RMSE of Out of Sample Predictions

	Base Model	*Average Temperature Model*	*Exposure Bins Model*
Root Mean Squared Error (RMSE)	.3238077	.2985914	.2775373

The results show that the model with exposure bins have the highest improvement in making out of sample predictions followed by the model with average temperature. This shows that the study model performs 15.5% better than the base model.

Discussion

Previous studies on the linkage of weather and crop yields can be divided into statistical and agronomic studies. Earlier regression-based approaches mainly used monthly or yearly averages of weather variables which dilutes significant variations leading to biased estimates of nonlinear effects. Agronomic studies fix this by incorporating the complete distribution of daily or sub-daily variables into rich theoretical models to simulate the yield response. These studies focus on the dynamic plant growth process and are difficult to estimate in a regression framework (Schlenker & Roberts, 2009). The limitation of agronomic studies is that the predictions are limited to the simulated crops only. A hybrid approach used by the seminal study on nonlinear impacts of temperature on crop yields by Schlenker and Roberts (2009) combined the benefits of both approaches by calculating the time a crop is exposed to each 1-degree temperature intervals. By doing this, they incorporated the complete weather distribution along with making predictions on historically observed yields. Other studies that follow this approach include Tack et. al., (2015); Shew et. al., (2020); Ortiz-Bobea et. al., (2019). This paper follows this approach which allows the flexibility to draw nonlinear effects of weather on crop yields in a regression framework.

Despite the considerable uptake of this approach in the last decade, the evidence from Pakistan is still limited to the use of monthly averages of weather variables (Siddiqui et. al., 2012; Ali et. al., 2017), the annual averages (Shakoor, et al., 2011), or the growing season averages (Janjua et. al., 2010; Hanif et. al., 2010). As argued by Schlenker and Roberts (2009), the average weather variables can cause biased nonlinear estimates. Moreover, our literature review suggests that the use of global gridded datasets is also not utilized to extract daily data for Pakistan. Parkes et. al., (2019) provides a review of the availability and sensitivity of the gridded datasets available for South Asia.

This study provides its contribution by preserving the variations in the daily data to inform the nonlinear estimation of temperature effects. The results provide cut points in the temperature ranges for positive and negative yield responses. The evidence can help inform future research in climate adaptation of wheat yields in Pakistan.

However, the research can be further improved by redefining the within-season periods per the crop growth stages depending upon the availability of district level data on sowing and harvesting dates. Moreover, robustness checks by using other gridded datasets and variables of degree days can provide useful insights. Finally, the role of water stress, for instance through soil moisture, as defined by Ortiz-Bobea et. al., (2019), can be a useful approach to provide a more holistic understanding of climatic drivers of agricultural yields.

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