Climate Change Impacts on US Wheat Production through Crop Abandonment

Oladipo, Obembe
Department of Agricultural Economics
Kansas State University
obembeoladipo@ksu.edu

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Background

Change in climatic conditions is becoming one the major challenges facing agricultural production globally as demand for staple food will surge as the world population hits 9 billion by 2050. Despite the fact that advancement in agriculture production has improved agricultural productivity, risk due to climate change has increased. Wheat is one of the important staple food consumed globally with USA producing 8% of the world production (Bond and Liefert, 2015). It may be difficult to guarantee stable production of staple food in the future as extreme heat events in the spring and freezing temperatures in the fall are considered to be the largest drivers of wheat yield loss (Tack et al., 2015). For example, Kansas, the leading state in winter wheat production abandoned 1.05 million acres (11.1 percent of the planted acres) in 2013 due to below freezing temperature in the second week of April and mostly above normal temperatures throughout June. According to Ray et al. (2015), climate variability accounts for 32 to 39% variability in crop yield. Variability in weather creates risk in agriculture, influencing management practice, intensity of crop choice, and making it difficult for farmers to change decisions when the decision had been made.

Over the years, different studies have analyzed the impact of climate variability on yield of different crops (Kang et al., 2009; Lobell and Burke, 2010; Xu et al., 2016). Yield used in most of these estimations were calculated from production divided by acres harvested. Other types of yield used were hybrid yield (Iizumi and Ramankutty, 2016) and field trial yield (Tack et al., 2015). Although previous studies have shown similar effects from warming on different types of yield (Schlenker and Roberts, 2009; Tack et al., 2015), the use of yield calculated from harvested acres may underestimate the effect of extreme freezing or heat events on yield (Schlenker and Roberts, 2009). Yield used may not capture the weather effects on the portion of the field that is not harvested. Maunder (2012) explained that yield information that does not consider abandonment can lead to inflated estimates.

Different approaches have been used to measure the effect of climate change on crops. Schlenker and Roberts (2009) used piecewise linear, step function and polynomial specifications to explain the nonlinear effects of temperature on corn, soybean and cotton. Tack et al. (2015) extended the piecewise linear approach of Schlenker and Roberts (2009) by adding freeze variables to explain the effect of exposure to below zero degree temperature on winter wheat yield, and implementing time separability to explain how weather variables affects the physiological processes of winter wheat at different growth stage and temperature. Winter wheat is planted in the fall, goes through vernalization during the winter (Herbek and Lee, 2009), resisting freeze and reaches maturity in the spring when the condition is ideal. Proper understanding of the relationship between weather variables and wheat development is needed for correct econometric specification in explaining temperature effects on winter wheat. Different temperature ranges are needed for optimal winter wheat production (Acevedo et al., 2002; Porter and Gawith, 1999). Bunting et al. (1982) explained that winter wheat is mostly planted when the daily temperature is mostly between 8-16^{o}C while an optimal temperature ranging between 12-15^{o}C is needed for germination (Acevedo et al., 2002). Porter and Gawith

(1999) review of temperature on growth and development summarized lethal limits that can affect wheat cultivars from different studies. The minimum and maximum lethal temperatures calculated from different studies are -17.2^{o}C and 47^{o}C respectively.

Summaries from different literatures show that temperature range between 8-25^{o}C is needed in the fall for germination (Acevedo et al., 2002), temperature between 3-10^{o}C is needed during winter for vernalization (Herbek and Lee, 2009; Robertson et al., 2004) and temperature below zero is damaging for yield in the spring (Shroyer et al., 1995). Tack et al. (2015) show that yield will increase when temperature is between 10-17^{o}C during fall, 5-10^{o}C during winter and 18-34^{o}C during spring. Lobell et al. (2012) using satellite measurements of wheat grown in northern India show that wheat senescence accelerates at temperature above 34^{o}C. Tack et al. (2015) approach allows in practice to model on how weather event affects each stage of growth, and the cumulative effects of weather variables on yield.

Mendelsohn (2007) defines crop failure and uses empirical analysis to explore the extent at which climate and soils variables can be used to explain the root of crop failure. Mendelsohn (2007) work shows how temperature variables alone can explain 34% of the variation in average crop failure rates across counties. To maximize wheat production, optimal climate environment is needed for crop's development. Tack et al. (2015) used an empirical approach to show how an additional freezing day in the fall will result in a 9% reduction in wheat yield. Although crop failure and abandonment are defined differently based on what is lost or harvested, both are affected by extreme climatic conditions. Crop failure is the same as crop abandonment when there is a complete loss of crop.Maunder (2012) explained that poor condition can lead to significant crop abandonment with the abandoned portion more sensitive to the climate impacts. My primary objective is to examine the impact of the changing climate variables on winter wheat production through crop abandonment.

In this paper, I estimate the total impact of weather variables on production that can be explained through its impact on harvested yield (production divided by harvested acres) and crop abandonment (portion of the planted acres not harvested). Leaving out crop abandonment when estimating warming effects on yield may underestimate the overall impact of heat on yield. Crop abandonment can be a pre-planting or post planting decision. Pre-planting abandonment decision is made before the farmer is committed to the cultivation of any type of crop due to different factors ranging from projected extreme weather or change of enterprise. Post planting crop abandonment decision is mainly related to the performance of crop on the field and moral hazard (Chen et al., 2007). Farmers decisions and choices are affected by changing weather conditions that determine the performance of the crop. Depending on the stage of production or crop growth stage, a farmer may decide to abandon a portion of the planted acreage if the degree of possible damage by extreme heat or freeze is severe. The initial cost of production at this stage may be considered as sunk cost for this portion of the field. If the whole field is not damage from the extreme weather event, efforts and resources can be diverted to the rest of the field if there is a prospect of better yield. Crop abandonment depends on the proportion of the planted acres that is not harvested. When there is complete loss of crops on a farm, this is called crop failure (Mendelsohn, 2007).

I examine the nonlinear effects of weather variables on production through crop abandonment. My primary contribution is quantifying separately the impacts of increasing temperature on different components of production. My paper builds on the Tack et al. (2015) where weather effects on the whole acres is accounted for in the estimation. Crop abandonment accounts for the difference in effect of weather on planted and harvested yields. Only 55% of the total impact of extreme heat in the spring is explained by harvested yield leaving out the impact of weather on the area of field not harvested.

Data

I used a panel data set of USDA data on production, planted and harvested acres for dryland winter wheat producing counties in Kansas from 1981 to 2014 and climate data while controlling for heterogeneity over location and time (Torres-Reyna, 2007). The objective of this study is to examine the impact of the changing climate variables on winter wheat production through crop abandonment. Crop abandonment (ca_{ist}) variable was calculated as a difference between 1 and the ratio of harvested acres to planted acres. Crop abandonment is between $0 < ca_{ist} \leq 1$ (Figure 1). Since planted yield per net planted was not reported for all Counties and years where harvested yield was reported, yield per net planted acre was calculated from the production data reported. I used the daily weather data from PRISM[1] to construct the weather variables from September to May by following Schlenker and Roberts (2009) and Tack et al. (2015). Following Tack et al. (2015), weather effects were defined within each season of the growing period; fall (September-November), winter (December-February) and spring (March-May). Total precipitation was constructed for each season.

Each degree days was calculated using a sinusoidal interpolation of minimum and maximum temperature exposure within each day (Schlenker and Roberts, 2006). Following Tack et al. (2015) and Schlenker and Roberts (2009), a piecewise linear regression was estimated over different possible thresholds within each season. There is no literature guide on what thresholds bounds should be within each growing season. The same principle used by Tack et al. (2015) was adopted by restricting the lower threshold at least five degrees above zero and ten degrees below the maximum observed temperature, while the upper threshold is restricted to be five degrees above the lower threshold and five degrees below the maximum for fall and spring. The performance of the piecewise linear regressions depends on the restriction placed on the bounds and how the bounds are determined and the method used in selecting the optimal thresholds.

The optimal thresholds for the harvested and planted models were selected from the models with the best fit based on r-squared. The optimal thresholds for crop abandonment model was selected based on a model that minimized Bayesian information

[1]PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu

criterion (BIC) as r-squared may not be the best criteria for model selection in this case. These thresholds were used to construct temperature exposure for each season during the growing period. Low degree days for each season during the growing period measures degree days between zero and lower threshold. The medium degree days measures degree days between lower and upper threshold while the high degree days measures degree days above upper threshold. Freeze variables measures exposure in days to below zero degree Celsius. These thresholds vary across seasons within the growing period (Table 2). To capture the impact of warming, observed daily minimum and maximum temperature were increased by 1^oC up to 5^oC. New weather variables were constructed for each increase in daily weather variable to simulate the effect of increasing warning effects.

Empirical Method

Iizumi and Ramankutty (2016) defines annual production as a product of harvested yield, harvested area and cropping intensity. For this study, the cropping intensity for dryland winter wheat is one. Let superscript H and P denote harvested and planted. Let y^H_{ist} be denoted as harvested yield and y^P_{ist} be denoted as the planted yield. All the dependent variables for yield models are transformed to their log form. Let y^H_{ist} be explained as a function of weather variables W_{ist}(temperature, precipitation) given that other variables are controlled for in the empirical analysis using fixed effects;

$$y_{ist} = f(W_{ist}) \tag{1}$$

Let harvested acres and planted acres be denoted as $Acres^H(W_{ist})$ and $Acres^{P}$[2] respectively and the ratio of harvested acres to planted acres be represented as $A^R(W_{ist})$. Crop abandonment ($ca_{ist}(W_{ist})$) can be defined as;

$$ca_{ist}(W_{ist}) = 1 - A^R(W_{ist}) \tag{2}$$

The effect of weather on crop abandonment can be represented as ;

$$\frac{\partial ca_{ist}(W_{ist})}{\partial W_{ist}} = -\frac{\partial A^R(W_{ist})}{\partial W_{ist}} \tag{3}$$

If $ca_{ist}(W_{ist}) = 0$, $Acres^H(W_{ist})= Acres^P$ then ;

$$y^P_{ist}(W_{ist}) = y^H_{ist}(W_{ist}) \tag{4}$$

$$Production^P = Production^H \tag{5}$$

Production can be redefined as;

$$y^P_{ist}(W_{ist}) \times Acres^P = y^H_{ist}(W_{ist}) \times Acres^H(W_{ist}) \tag{6}$$

If $ca_{ist}(W_{ist}) \neq 0$ and assuming crop abandonment is accounted/adjusted for in total

[2] Assuming $\frac{\partial Acres^P}{\partial W_{ist}} = 0$

production, then planted yield can be expressed as;

$$y^P_{ist}(W_{ist}) = y^H_{ist}(W_{ist}) \times A^R(W_{ist}) \tag{7}$$

To explain the impact of warming on production through its impact on harvested yield and crop abandonment, then,

$$\frac{\partial y^P_{ist}(W_{ist})}{\partial W_{ist}} = \frac{\partial y^H_{ist}(W_{ist})}{\partial W_{ist}} \times A^R(W_{ist}) + \frac{\partial A^R(W_{ist})}{\partial W_{ist}} \times y^H_{ist}(W_{ist}) \tag{8}$$

Replacing $\frac{\partial A^R(W_{ist})}{\partial W_{ist}}$ in equation 8 with -$\frac{\partial ca_{ist}(W_{ist})}{\partial W_{ist}}$ from equation 3, then

$$\frac{\partial y^P_{ist}(W_{ist})}{\partial W_{ist}} = \frac{\partial y^H_{ist}(W_{ist})}{\partial W_{ist}} \times A^R(W_{ist}) - \frac{\partial ca_{ist}(W_{ist})}{\partial W_{ist}} \times y^H_{ist}(W_{ist}) \tag{9}$$

$$y^{P'}_{ist} = y^{H'}_{ist}.A^R_{ist} - ca^{'}_{ist}.y^H_{ist} \tag{10}$$

The primes denote first derivatives. $ca^{'}_{ist}.y^H_{ist}$ explains the proportion of warming impact on production through crop abandonment.

My research used the same preferred econometric specification as Tack et al. (2015) but I separately estimate the nonlinear effect of weather variables on (1) planted and harvested yields and (2) crop abandonment. Crop abandonment will be estimated as a non-linear model using logit quasi-maximum likelihood estimator because it is easy to estimate and the method produces a consistent estimator of coefficient which is normally distributed.

$$y_{its} = \alpha_i + \theta_{ti}T + \theta_{t2}T^2 + f(\beta_i; w_{ist}) + \varepsilon_{ist} \tag{11}$$

$$E(ca_{it}) = G(\alpha_i + \theta_{ti}T + \theta_{t2}T^2 + f(\beta_i; w_{ist}) + \varepsilon_{ist}) \tag{12}$$

where G(·) is a probit function. Let seasons within the growing periods be 1, 2 and 3 for fall, winter and spring respectively,

$$\begin{aligned} f(\beta_i; w_{jst}) = & \sum_{s=1}^{3} \beta_{1s} Freeze_{ist} + \sum_{s=1}^{3} \beta_{2s} DDLow_{ist} + \sum_{s=1}^{3} \beta_{3s} DDMedium_{ist} \\ & + \sum_{s=1}^{3} \beta_{4s} DDHigh_{ist} + \sum_{s=1}^{3} \beta_{5s} prec_{ist} + \sum_{s=1}^{3} \beta_{6s} prec^2_{ist} \end{aligned} \tag{13}$$

County fixed effects (α_i) was used to absorb all unobserved county-specific time invariant determinants and quadratic trend time to capture changes in management practices like planting date and technological change. Standard errors will be clustered by state to adjust for temporal correlation. The yield models will be tested to know if the coefficients are the same. The predicted impact of change in weather variables will be estimated as a change in yield relative to change in the baseline scenario using equation 14 for yields' models and equation 15 for crop abandonment.

$$Impact = e^{(w_i - w_o)\hat{\beta}_i} - 1 \tag{14}$$

$$Impact = \Phi\left((w_i - w_o)\hat{\beta}\right) \quad (15)$$

Result and Discussion

Table 3-5 shows the results of the estimations of equations 11 and 12. Table 2 shows that time separability is necessary for crop like wheat where crops goes through different temperature requirement during development. Table 2 shows the optimal thresholds for different sub-periods within each growing period. The lower and upper thresholds 10^oC and 15^oC respectively during fall is consistent with the range of temperature required for germination and growth during fall (Acevedo et al., 2002), likewise the low temperature requirement during the winter for vernalization, 5^oC and 10^oC and moderate temperature to reach maturity in the spring. The thresholds for the winter and spring are different for the harvested and planted yield models. Depending on the area that is harvested, planted yield is smaller when compared to harvested yield. The yields are the same when crop abandonment is 1. Planted yield model has a bigger thresholds in the winter when compared to the harvested yield model. The lower threshold bound for the harvested yield model in the spring is lower by 4^oC when compared to the planted yield lower threshold bound.

The clustered standard errors are 4 times bigger than the robust standard errors. The first and the second column of table 3 has the results from the harvested and planted yield estimation while the last column is for the crop abandonment. The major driver of yield loss from the yields' models is freeze and extreme heat in the spring. Spring is when plants grow to maturity after hardiness in the winter. An additional day of freeze in the spring reduces planted yield by 4% while harvested yield is reduced by 2.5%. The impact of spring freeze is more severe for planted yield as yield is reduced by 4% while it increases crop abandonment by 5.5% for an additional day of exposure to temperature below zero in the spring. Extreme warm in the spring lowers harvested yield by 4.5% while the effect on planted yield is almost twice. Freezing temperatures during the spring brings about freeze injuries ranging from leaf chlorosis to floret sterility that have moderate to severe effects on yield (Shroyer et al., 1995).

Warm temperatures during the winter stops hardening very early, setting the crop for further damage when cold temperature sets in during spring (Li et al., 2015). High degree days during winter lowers yields by 1-1.2%. Precipitations are significant for all the sub-periods with an exceptions to the winter and spring of the crop abandonment's model. Interaction between precipitation in the spring and high degree days lower the warning effect of extreme heat on harvested yield. An equality test was done to compare the coefficients of the two yields' models in order to know if the weather effects are the same (Table 4). The coefficients are not the same for spring's medium and high degree days. The answer still remain the same when the thresholds were switched between models. The coefficients of planted yield model is at least 1.1 times bigger than the coefficient of harvested yield model for all sub-periods with exception to fall.

Although extreme temperature during fall is not significant for both yields' models, it is significant for crop abandonment. Extreme heat during fall causes damage during grain filling, poor tillering and hardening (Shroyer et al., 1995) which lower yields and increases crop abandonment. Freeze during the fall and spring are the major cause of crop abandonment as both conditions increase crop abandonment by 6% respectively. Extreme temperature condition during spring lowers the area of planted acres that is not harvested by 12%. Agronomic conditions that do not support wheat development increases crop abandonment.

Using equation 10, the total impact of weather variables on yield was estimated using marginal estimates of weather variables from harvested yield and crop abandonment models. Table 5 summarizes the impact of weather variables on the components of production. The first and second columns have the proportion of weather impact on yield and crop abandonment. The total effect is the difference in weather impact on yield and the crop abandonment. Crop abandonment accounts for the reduction in production as extreme heat during fall lowers yield and harvested area. There is an attenuation bias as the total effects of weather is underestimated by harvested yield alone. Crop abandonment accounts for the difference in the effects of weather on planted and harvested yields. During extreme heat of spring, harvested yield only account for 55% of the total effect of weather on yield leaving out the warming impact on the portion of the field not harvested. Good weather conditions lower crop abandonment. 24%(proportion of impact=$\frac{ca'_{ist} \cdot y^H_{ist}}{Totaleffect}$) of the total effect of weather on winter wheat yield can be explained by crop abandonment for an additional day of exposure to temperature below zero in the spring.

The Overall effects of increasing temperature was predicted using the preferred specification. The result shows that an increasing temperature lowers yield and increase crop abandonment (Figure 2). As the temperature increases, there is approximately 10% net reduction in yield for every 1^oC increase in daily minimum and maximum temperature. Warming effects increase the area of land not harvested by approximately 5% as the temperature increases. Reduction in harvested acres raises crop abandonment as daily temperature increases. The warming effects have a huge proportion effect on crop abandonment than yields. When degree days were switched between the yields' models, the impact on yields are less than $\pm 1\%$ (Figure 3 & 4). For the piecewise thresholds of harvested and yield models, the warming impact is higher for harvested yield than planted yield under the $+1^oC$ and 2^oC scenarios. When planted yield model degree days were used to estimate the effect of warming on harvested yields, warming effects under $+1^oC$ scenario remain the same. As temperature increases, yield drops and crop abandonment increases.

Conclusion

In this paper, I examine the nonlinear effects of weather variables on production through crop abandonment. My result shows that time separability is necessary for crops like winter wheat that needs different temperature bounds for optimal productivity when developing econometric model. Exposure to temperature below zero and extreme heat in the spring are some of the major causes of yield loss and Crop abandonment. Crop abandonment increases will adverse weather condition. 24% of the total effect of weather on winter wheat yield can be explained by crop abandonment for an additional day of exposure to temperature below zero in the spring. Idea weather conditions drives down crop abandonment. My primary contribution is separating the impacts of increasing temperature on different components of production. Leaving out crop abandonment when estimating warming effects on yield may underestimate the impact of heat on yield. My estimation accounts for the total effects of weather variables on winter wheat.

References

Acevedo, E., P. Silva, and H. Silva (2002). Wheat growth and physiology. *Bread Wheat. Improvement and Production. Food and Agriculture Organization of the United Nation. Rome*, 39–70.

Bond, J. and O. Liefert (2015). USDA Economic Research Service-USDA Wheat Baseline, 2015-24.

Bunting, A., M. Dennett, J. Elston, and C. Speed (1982). Climate and crop distribution. *Food, nutrition and climate/edited by Sir Kenneth Blaxter and Leslie Fowden*.

Chen, S.-L., M. J. Miranda, et al. (2007). Effects of insurance on farmer crop abandonment.

Herbek, J. and C. Lee (2009). A comprehensive guide to wheat management in kentucky. *US Department of Agriculture, M. Scott Smith, Director, Cooperative Extension Service, University of Kentucky College of Agriculture, Lexington, and Kentucky State University, Frankfort*.

Iizumi, T. and N. Ramankutty (2016, March). Changes in yield variability of major crops for 19812010 explained by climate change. *Environmental Research Letters 11*(3), 034003.

Kang, Y., S. Khan, and X. Ma (2009, December). Climate change impacts on crop yield, crop water productivity and food security A review. *Progress in Natural Science 19*(12), 1665–1674.

Li, X., J. Cai, F. Liu, Q. Zhou, T. Dai, W. Cao, and D. Jiang (2015). Wheat plants exposed to winter warming are more susceptible to low temperature stress in the spring. *Plant Growth Regulation 77*(1), 11–19.

Lobell, D. B. and M. B. Burke (2010). On the use of statistical models to predict crop yield responses to climate change. *Agricultural and Forest Meteorology 150*(11), 1443–1452.

Lobell, D. B., A. Sibley, and J. I. Ortiz-Monasterio (2012). Extreme heat effects on wheat senescence in india. *Nature Climate Change 2*(3), 186–189.

Maunder, W. J. (2012). *Dictionary of global climate change.* Springer Science & Business Media.

Mendelsohn, R. (2007). What causes crop failure? *Climatic change 81*(1), 61–70.

Porter, J. R. and M. Gawith (1999). Temperatures and the growth and development of wheat: a review. *European Journal of Agronomy 10*(1), 23–36.

Ray, D. K., J. S. Gerber, G. K. MacDonald, and P. C. West (2015). Climate variation explains a third of global crop yield variability. *Nature communications 6*.

Robertson, L. D., S. O. Guy, and B. D. Brown (2004). Southern idaho dryland winter wheat production guide. *University of Idaho, College of Agriculture and Life Sciences. BUL 827*, 12.

Schlenker, W. and M. J. Roberts (2006). Nonlinear effects of weather on corn yields. *Applied Economic Perspectives and Policy 28*(3), 391–398.

Schlenker, W. and M. J. Roberts (2009). Nonlinear temperature effects indicate severe damages to US crop yields under climate change. *Proceedings of the National Academy of sciences 106*(37), 15594–15598.

Shroyer, J. P., M. E. Mikesell, and G. M. Paulsen (1995). *Spring freeze injury to Kansas wheat.* Cooperative Extension Service, Kansas State University.

Tack, J., A. Barkley, and L. L. Nalley (2015, June). Effect of warming temperatures on US wheat yields. *Proceedings of the National Academy of Sciences 112*(22), 6931–6936.

Torres-Reyna, O. (2007). Panel data analysis fixed and random effects using stata (v. 4.2).

Xu, H., T. E. Twine, and E. Girvetz (2016, May). Climate Change and Maize Yield in Iowa. *PLOS ONE 11*(5), e0156083.

Appendix

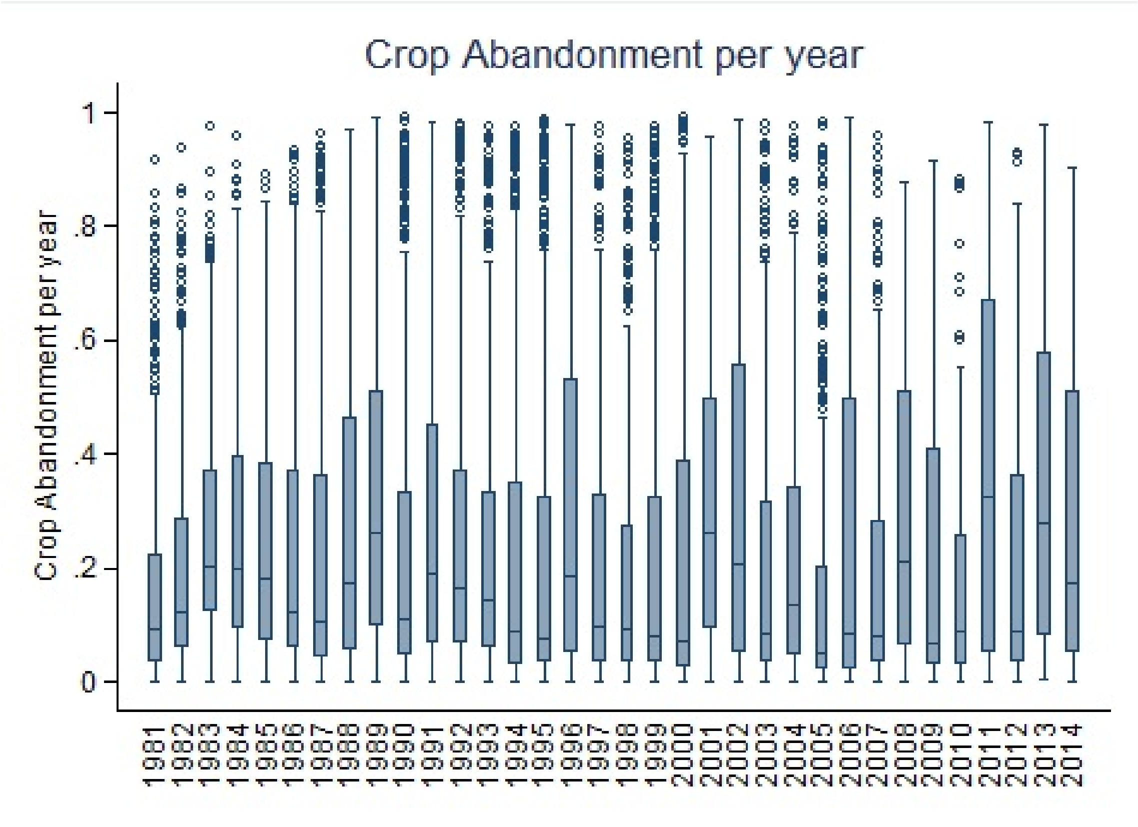

Figure 1: **Annual box-plots showing distribution and variability of crop abandonment over time**.Crop abandonment is the difference between 1 and the ratio of harvested acres to planted acres. The county measures were used to construct box-plots for each year. Each box is defined by the upper and lower quartile, with the median depicted as a horizontal line within the box. The endpoints for the whiskers are the upper and lower adjacent values, which are defined as the relevant quartile +/- three-halves of the interquartile range, and circles represent data points outside of the adjacent values.

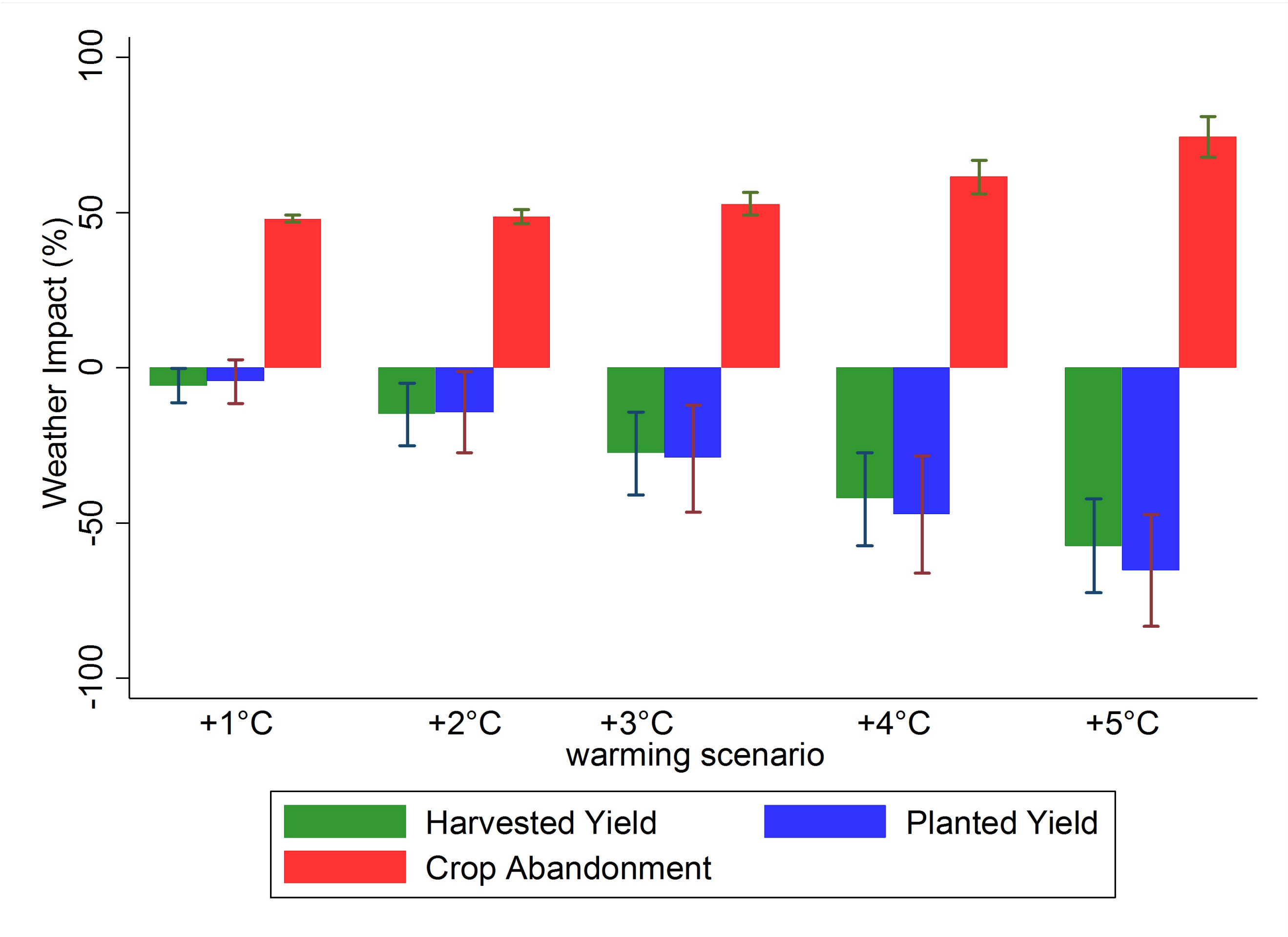

Figure 2: Predicted impact of warming on winter wheat yields and crop abandonment under different scenarios across the sub-periods as the daily minimum and maximum temperatures are increased by 1^oC upto 5^oC. Thresholds from piecewise models were used to model the effect of warming on crop abandonment, harvested and planted yield for each of the scenarios using preferred specification. The bars show the warming impact on crop abandonment and yields for each of the scenarios. Bars show 95% confidence intervals using standard error clustered by year.

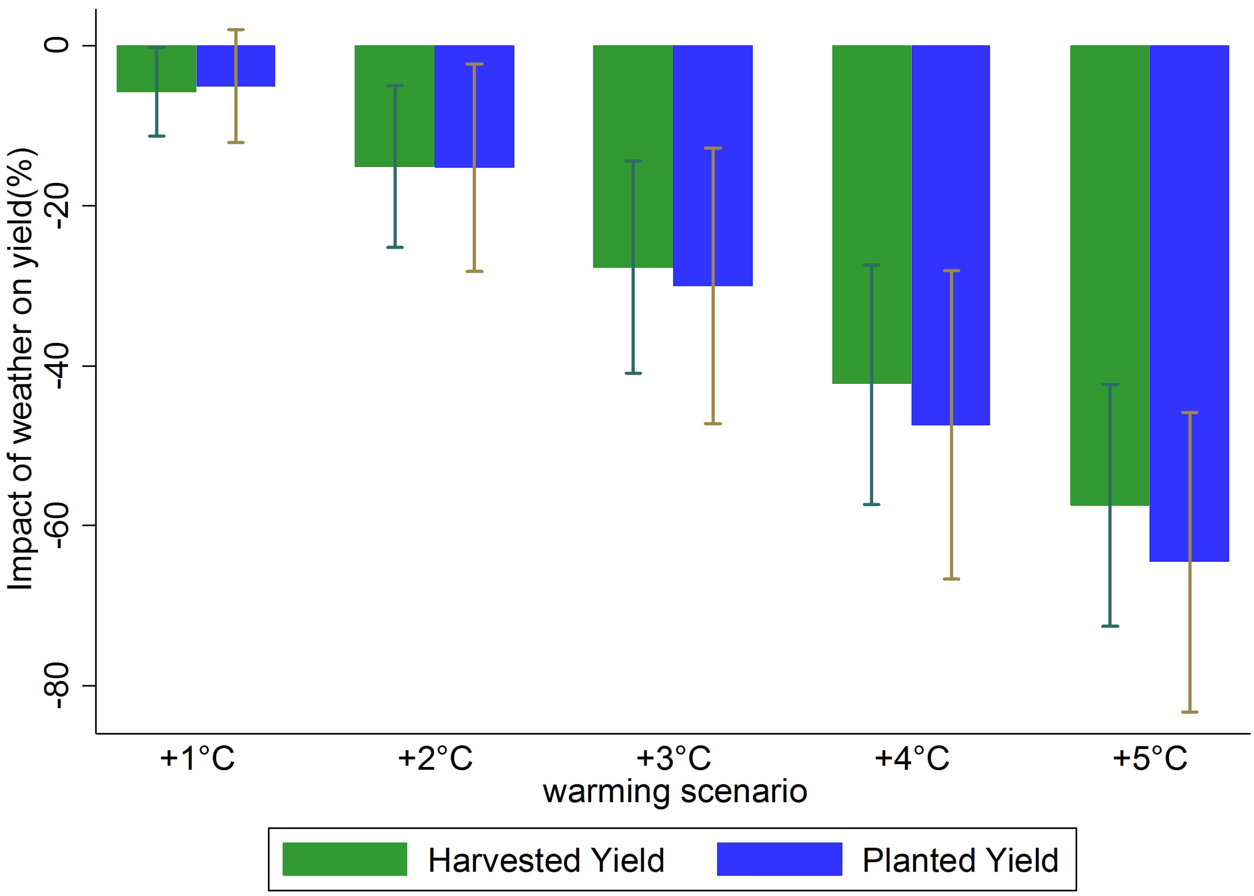

Figure 3: Predicted impact of warming on winter wheat yield under different scenarios across the sub-periods as the daily minimum and maximum temperatures are increased by 1^oC up to 5^oC. Thresholds from piecewise harvested yield model was used to model the effect of warming on both harvested and planted yields for each of the scenarios using preferred specification. The bars show the warming impact on yields and harvested acres for each of the scenarios. Bars show 95% confidence intervals using standard error clustered by year.

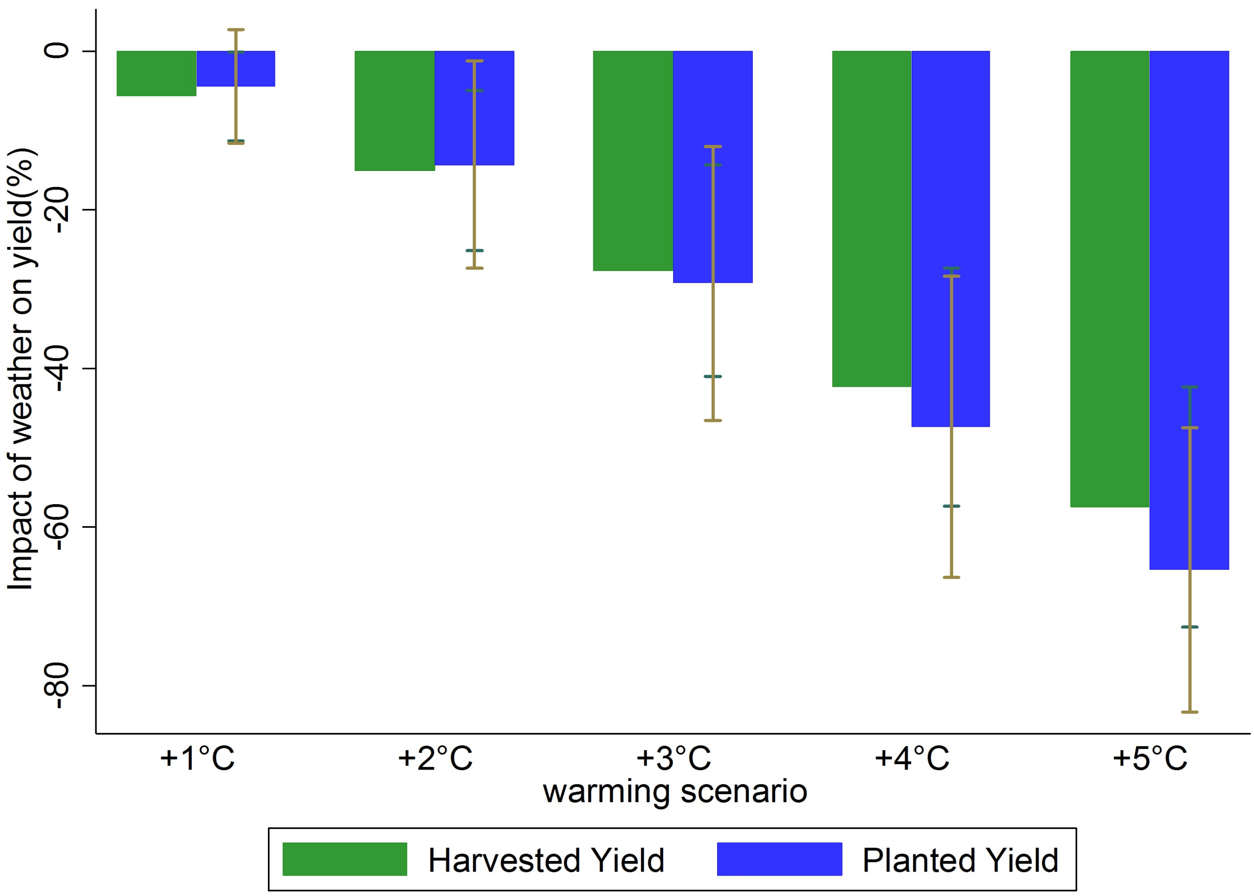

Figure 4: Predicted impact of warming on winter wheat yield under different scenarios across the sub-periods as the daily minimum and maximum temperatures are increased by 1^oC up to 5^oC. Thresholds from piecewise planted yield model was used to model the effect of warming on both harvested and planted yields for each of the scenarios using preferred specification. The bars show the warming impact on yields and harvested acres for each of the scenarios.Bars show 95% confidence intervals using standard error clustered by year.

Table 1: Descriptive statistics of yields and weather variables

		Yield (bu/acre)		Tmin (^oC)			Tmax (^oC)			Aggregate Precipitation (mm)		
State	Abandonment*	Yield^{H+}	Yield^{P+}	Fall	Winter	Spring	Fall	Winter	Spring	Fall	Winter	Spring
Kansas	0.11	34.97	31.89	6.09	-6.24	4.94	20.52	6.88	19.22	168.09	80.96	226.80
	(0.13)	(10.21)	(11.10)	(1.86)	(2.04)	(1.95)	(1.58)	(2.32)	(1.79)	(97.57)	(50.00)	(95.88)
Counties	105											
Years	1981 - 2014											

Note:Crop abandonment has no unit. Yield^P and Yield^H represent yield calculated from production divided by planted and harvested acres respectively over years. Weather variables are calculated over growing season.

Table 2: Optimal thresholds from piecewise linear models

	Harvested Yield Model		Planted Yield Model		Crop Abandonment model	
Variable	Threshold	mean ± SD.	Threshold	mean ± SD	Threshold	mean $\pm SD$
Degree Days low:Fall	0-10 ^oC	716.86 ± 49.74	0-10 ^oC	716.87± 49.74	0-22 ^oC	1156.99 ± 100.80
Degree Days Medium:Fall	10-15 ^oC	243.47 ± 26.99	10-15^oC	243.47± 26.99	22-27 ^oC	58.46 ± 14.45
Degree Days High:Fall	15+ ^oC	277.57 ± 53.34	15+^oC	277.57± 53.34	27+ ^oC	22.46 ± 12.97
Degree Days low:Winter	0-5 ^oC	172.66 ± 38.54	0-7^oC	215.55± 50.75	0-7^oC	215.55 ± 50.75
Degree Days Medium:Winter	5-11 ^oC	95.82 ± 31.95	7-12^oC	60.81± 23.09	7-12 ^oC	60.81 ± 23.10
Degree Days High:Winter	11+ ^oC	30.86 ±18.64	12+^oC	22.98± 15.15	12+ ^oC	22.99 ± 15.15
Degree Days low:Spring	0-20 ^oC	1077.61 ± 113.24	0-24^oC	1129.94± 125.64	0-24 ^oC	1129.94 ± 125.64
Degree Days Medium:Spring	20-30 ^oC	75.77 ± 27.09	24-30^oC	23.45 ± 12.37	24-31 ^oC	24.29 ± 13.23
Degree Days High:Spring	30+ ^oC	2.02 ± 2.95	30+^oC	2.02 ± 2.95	31+ ^oC	1.17 ± 2.00

Note: The thresholds were estimated through piecewise regression over all possible thresholds. The optimal thresholds for yields' models were selected from the models with highest r-squared. The thresholds for crop abandonment was selected from a model that best minimize Bayesian information criterion.

Table 3: Specification measures of weather effect on yields and harvested acres

Estimates (1)	YieldHarvest (2)	YieldPlanted (3)	Crop Abandonment (4)
Freeze Days :Fall (Ten Days)	-0.3482	-0.4406	0.5717**
	(0.2081)	(0.2994)	(0.2483)
Freeze Days:Winter (Ten Days)	-0.0808*	-0.0898	0.0664
	(0.0451)	(0.0591)	(0.0718)
Freeze Days:Spring (Ten Days)	-0.2542*	-0.4023**	0.5553**
	(0.1353)	(0.1830)	(0.2223)
Degree Days low:Fall (Ten Days)	-0.0402	-0.0380	0.0173
	(0.0258)	(0.0373)	(0.0129)
Degree Days Medium:Fall (Ten Days)	0.0311	0.0187	-0.1050*
	(0.0321)	(0.0489)	(0.0569)
Degree Days High:Fall (Ten Days)	-0.0033	-0.0023	0.1184**
	(0.0079)	(0.0110)	(0.0518)
Degree Days low:Winter (Ten Days)	-0.0469**	-0.0292	0.0223
	(0.0208)	(0.0200)	(0.0314)
Degree Days Medium:Winter(Ten Days)	0.0855 **	0.1083*	-0.0545
	(0.0338)	(0.0609)	(0.0931)
Degree Days High:Winter(Ten Days)	-0.1009**	-0.1208*	-0.0036
	(0.0389)	(0.0636)	(0.0781)
Degree Days low:Spring(Ten Days)	-0.0134**	-0.0162*	0.0148
	(0.0066)	(0.0082)	(0.0107)
Degree Days Medium:Spring(Ten Days)	0.0360**	0.1504**	-0.1517**
	(0.0166)	(0.0620)	(0.0749)
Degree Days High:Spring(Ten Days)	-0.4599***	-0.8176***	1.2333***
	(0.0964)	(0.2000)	(0.3239)
Precipitation(mm):Fall	0.0024***	0.0038***	-0.0052**
	(0.0006)	(0.0011)	(0.0016)
Precipitation(mm) Squared:Fall	0.0000***	0.0000***	0.0000***
	(0.0000)	(0.0000)	(0.0000)
Precipitation(mm):Winter	0.0022**	0.0027*	-0.0016
	(0.0011)	(0.0015)	(0.0023)
Precipitation(mm) Squared:Winter	0.0000***	0.0000**	0.0000
	(0.0000)	(0.0000)	(0.0000)
Precipitation(mm):Spring	0.0036***	0.0041***	-0.0021
	(0.0010)	(0.0014)	(0.0017)
Precipitation(mm) Squared:Spring	0.0000***	0.0000***	0.0000
	(0.0000)	(0.0000)	(0.0000)
Observations	2964	2964	2964
R-squared	0.5238	0.467	-
County Fixed effect	Yes	Yes	Yes
Trend	Yes	Yes	Yes
Quadratic Trend	Yes	Yes	Yes

Note: Degree days and freeze variable coefficients are multiplied by 10 for ease of presentation.*,** and *** indicate significance at 0.1 and 0.05 and 0.01 level. Figures in the parenthesis are standard errors clustered by year.

Table 4: Equality test for harvested and planted yield coefficients

Null Hypothesis	Degree days	P values
Fall		
	Low	0.8837
	medium	0.5610
	High	0.8218
Winter		
	Low	0.0164
	medium	0.4881
	High	0.4880
Spring		
	Low	0.2888
	medium	0.0146
	High	0.0039
Freeze Days :Fall		0.4199
Freeze Days :Winter		0.6130
Freeze Days :Spring		0.0179

Note: The models are clustered by year.

Table 5: Impact of weather variables on production through yield and crop abandonment

Variables (1)	$y_{ist}^{H'}.A_{ist}^{R}$ (2)	$ca_{ist}^{'}.y_{ist}^{H}$ (3)	Total effect (4)	$y_{ist}^{P}(W_{ist})$ (5)
Freeze Days :Fall	-1.0838	0.3460	-1.4299	-1.4051
Freeze Days:Winter	-0.2516	0.0402	-0.2918	-0.2863
Freeze Days:Spring	-0.7911	0.3361	-1.1272	-1.2828
Degree Days low:Fall	-0.1250	0.0105	-0.1355	-0.1212
Degree Days Medium:Fall	0.0966	-0.0635	0.1602	0.0595
Degree Days High:Fall	-0.0102	0.0717	-0.0819	-0.0073
Degree Days low:Winter	-0.1460	0.0135	-0.1595	-0.0931
Degree Days Medium:Winter	0.2660	-0.0330	0.2990	0.3454
Degree Days High:Winter	-0.3141	-0.0022	-0.3119	-0.3852
Degree Days low:Spring	-0.0418	0.0090	-0.0508	-0.0516
Degree Days Medium:Spring	0.1122	-0.0918	0.2040	0.4797
Degree Days High:Spring	-1.4314	0.7464	-2.1778	-2.6074

Note: $\frac{\partial y_{ist}^{H}(W_{ist})}{\partial W_{ist}} = \beta_i y_{ist}^{H}$ and $\frac{\partial y_{ist}^{P}(W_{ist})}{\partial W_{ist}} = \beta_i y_{ist}^{P}$. Average proportion of harvested to planted is 0.89 while the average harvested and planted yields are 34.97 and 31.89 respectively. Total effect is calculated from equation 10. Total effect= $y_{ist}^{H'}.A_{ist}^{R} - ca_{ist}^{'}.y_{ist}^{H}$