Gettysburg College Headquarters

Volume 2 Article 4

2023

Climate Change: The Ultimate Cereal Killer: The Impact of Temperature and Precipitation on Agricultural Yields

Hayley Huber
Washington and Lee University, huberh23@mail.wlu.edu

Robert Salita
Washington and Lee University, salitar22@mail.wlu.edu

Ruth Abraham
Washington and Lee University, abrahamr22@mail.wlu.edu

Climate Change: The Ultimate Cereal Killer: The Impact of Temperature and Precipitation on Agricultural Yields

Abstract

The global food supply depends on agricultural production, but as the negative effects of climate change are exacerbated by human activity, how will agriculture need to change to accommodate both climate change and the increasing population? In order to understand what adaptations will be necessary, we perform analysis on the relationship between climate change (temperature and precipitation) and crop yields (barley, rice, and soybean). We take a multinational approach, using ten countries for each model, to see the global impact of climate change on production. Testing many models, we settle on country-specific time trends, eliminating many confounding variables by focusing on climate's effect on variations from the trend. For all three crops, the analysis shows that temperature has a significant effect on output while precipitation has a negligible effect. The models account for upwards of 96% of the variation from the trend for each crop on a year-by-year basis. In a similar way to how irrigation has altered agriculture's reliance on natural water supplies, we now need to focus on developing technology to counteract the effects of increasing temperatures on crop growth.

Keywords

climate change, agricultural yield

Cover Page Footnote

Advised by Professor Alice Zhang, Ph.D. Washington and Lee University Economics Department Winter 2022

Climate Change: The Ultimate Cereal Killer: The Impact of Temperature and Precipitation on Agricultural Yields – *Hayley Huber, Robert Salita, and Ruth Abraham, Washington and Lee University*

I. Introduction

To meet the increasing needs of a rapidly growing international population, global agricultural yields have been on steady increase since the 1970s. However, Earth is slowly approaching its estimated carrying capacity of 9-10 billion people (Wolchover 2011). As global population growth inevitably slows down, we must be cognizant of how agricultural output will respond and how that response will affect the populations of both developed and developing countries. Because the global population's existence depends on available food supply, understanding the future of agriculture is imperative to our existence. Thus, to comprehend the urgency of the issues we will inevitably face over the next century, we must understand the complex relationship between agriculture and climate that was created in the Anthropocene.

As global demands for agricultural products increase with an increasing population, more energy is expended to provide enough yields to support the population. Meanwhile, as temperature and precipitation are affected by climate change, growing crops on a per unit basis becomes evermore challenging as well. Our research aims to explore how climate change is affecting agricultural yields so that we may learn what kinds of adaptation strategies are needed and gain insight into the possibilities of the future.

Although many studies have been conducted to see the effects of climate change on agricultural production within specific nations, none so far have taken a more comparative and global approach. Our study allows us to compare specific crop productions across countries and allows us to compare differences in crop sensitivity against other crops.

This research paper explores the impacts of climate change on multinational agricultural production of certain crops. Specifically, we look at the effects of temperature and precipitation on multinational production of barley, rice, and soybeans using a country-specific time trend model. We hypothesize that as mean temperature increases up to a certain point (degrees Celsius), rice yields will increase before hitting a maximum and then decrease. Likewise, as precipitation increases to a certain point (millimeters per year), rice yields (tons) will increase until a certain point before decreasing. In a similar fashion, soybean yields (tons) will decrease both with increasing temperature and increasing precipitation. Finally, we predict that barley yields (tons) will decrease more dramatically than the other crops due to increasing temperature and will decrease with increasing precipitation.

II. Literature Review

To better understand the current and historical approaches to economic research related to climate and agriculture, we explored several prominent economic and scientific papers. In our research, we seek to explore the impacts of climate change on multinational agricultural production of certain crops. We found that there exist more than 220 economic papers related to climate and agriculture, yet we only find that 4% of these papers prior to 2011 examine geographic distribution of crops (White, et al. 2011). This literature review will cover models, methods, data, and general findings established by previous research.

A. Models / Methods / Data

One method that researchers utilized to measure the impact of climate change on agriculture is via change in farmland value. Mendelsohn, Nordhaus, and Shaw used the Ricardian approach to estimate the economic impacts of climate change based on a cross-sectional analysis of farmland values (prices of farmland). Specifically, they regressed farmland values on a set of climate and control variables and found that “higher temperatures in all seasons, [except for fall,] ... reduce average farm values while more precipitation outside of autumn increases farm values.” (Mendelson et al. 1994). Additionally, their research estimated a lower impact on US agriculture than the traditional production function approach. The strength of their approach is its ability to measure the long run impact from climate change given likely climate adaptations by farmers. However, John Antle notes that the Ricardian approach fails to measure true agricultural production and cannot be used to analyze structural or policy innovations that would change the effects of climate change. This shortcoming limits the practical uses and implications of their research. Further, Antle argues that many economic studies on the effects of climate change depend on agriculture production function and, as such, tend to underestimate technological and economic innovation and adaptation, which Mendelsohn, Nordhaus, and Shaw seem to have successfully avoided (Antle 1995).

Another method, as described by Antle, uses General Circulation Models (GCMs) to estimate the effects of CO_2 accumulation on climate. The GCMs are based on grid blocks of 2,500 square kilometers, which is too large to accurately capture spatial vulnerability, and is therefore considered unreliable for variables other than temperature. This, Antle argues, warrants low confidence in estimates derived from these.

Furthermore, White et al. uses “ecophysiological models to forecast potential impacts of climate change on future agricultural productivity and to examine options for adaptation by local stakeholders and policy makers” (White et al. 2011). They also found that assuming “a low baseline CO_2 level may exaggerate projected impacts of increased CO_2” which can dramatically impact policy implications and adaptation strategies and the urgency to execute them. Interestingly, about 40% of the papers studied by White et al. used the CERES (Crop Environment Resource Synthesis) and/or EPIC (Erosion Productivity Impact Calculator) models. However, many of these papers do not adequately justify their use of particular models nor their selection of particular geographic regions (White et al. 2011). On the other hand, Phillips, Lee, and Dodson (1996) endorse the EPIC model as a sound estimating tool for yield citing “the simulated mean yields were always within 7% of the mean measured yields and were not significantly different ($P > 0.05$) from any of them.” The models used in all of the papers that we read have significant contributions to the field and provide a good framework, but they also have drawbacks that we need to account for when developing our model.

B. *Research Findings*

In 10% of papers, the findings are related solely to theory put forward by the paper (White, et al. 2011). The theory-only papers focus on fleshing out models, some of which we discussed above, and discussing potential independent variables and functional forms. For example, Antle writes that “understanding the impacts of climate exchange on agriculture … will require a better understanding of the long-term path of innovation, land use, and the dynamic behavior of managed ecosystems.” (Antle 1995). Antle and others seek to spell out the methods and models used by others so that future research has a strong theoretical foundation to build upon.

The impacts of climate change on agricultural yields of soybeans, barley, and rice have also been extensively detailed with 84% of papers discussing impact to some degree (White, et al. 2011). Global warming threatens agricultural yields in their existing locations through desertification and land degradation. Global temperature increases, too, have noticeably changed societies' food systems (Yamanoshita 2019). Phillips, Lee, and Dodson (1996) predict, "3% decreases in both corn and soybean yields in response to a 2°C temperature increase at baseline precipitation levels." These staple crops suffer from the compounding effects of rising temperature and less precipitation to further drive down expected overall yields. For luxury crops, such as wine and coffee, it is predicted that, "by 2050, the area of California suitable for wine growing could be down to nearly half of what it is today (2013)," and "by 2080, [a] study's model predicts a best-case scenario of a 65-percent reduction in the number of suitable locations for the plant, with the worst case projection a nearly 100-percent reduction," which somewhat contradicts Lobell and Gourdji's finding that net crop yields will not decrease as discussed later (Mayer 2013). In the short term, existing locations that are renowned for producing specific crop types will suffer. Even well-known adaptation strategies like irrigation techniques can strain limited water resources in areas suffering from the effects of climate change.

On the other hand, adaptation has been covered by very few papers as only 20% of papers discuss adaptation at all and less than 5% focus solely on adaptation. (White et al. 2011) Kurukulasuria and Mendelsohn 2008 emphasize that, "crop choices are more sensitive to temperature than precipitation." In response to rising temperatures, maize-millet, maize-groundnut, and fruits- vegetables, and cowpea suffer where sorghum and all other crops increase the probability. Knowing this, African farmers deal with the continued consequences of climate change through crop switching buffering the magnitude of losses incurred in response to continually changing temperature and precipitation patterns. Adaptation strategies are typically established in reaction to climate change instead of as preventative measures.

Lobell and Gourdji found that "even in the most pessimistic scenario, it is highly unlikely that climate change would result in a net decline in global agricultural yields," contradictory to what seems apparent in the IPCC 2021 reports and Mayer 2013 (Lobell and Gourdji 2012). We want to highlight that this analysis is from a decade ago, which makes us question the validity and relevance of their results because we now have much more complete data and possibly more accurate climate change projections. However, Lobell and Gourdji do add much useful information to our analysis of climate change and agriculture. First, they spell out the five primary pathways in which temperature affects crop yields. They also point out that with higher precipitation comes greater flooding frequency and intensity which will inevitably lead to crop damage. Further, changes in the wet season will disrupt traditional farming practices which may have social and economic consequences (Lobell and Gourdji 2012). Aside from crop damage resulting from heat and rain, "... rising [temperature], along with higher atmospheric CO_2, may favor the growth and survival of many pests and diseases specific to agriculture" exacerbating the negative effects of climate change on crop yields.

C. Final thoughts on prior research

Through this literature review, we found impactful data and research done that will help us frame our paper. The models and data used were very informative in describing how we can go about building our own model. However, we also found limitations and gaps in the research that we aim to improve upon with our research paper. Prior to our evaluation of past papers, we struggled to find crops and countries that would be most prudent to study. However, White et al. revealed which crops and countries were understudied. Rice, soybean, and barley are three of the five crops that take up the largest harvesting area, but are much less studied than maize and wheat. For instance, rice takes up more land than maize but is studied in 50% fewer research papers than maize. This is due to the fact that its top producers, China and India, release little research on this in the English-language, limiting the scope of its use.

How will soybean, rice, and barley outputs change as a result of changes in temperature and precipitation? These crops are three of the five crops that take up the largest harvesting area, making our findings important to the climate change adaptation conversation. Some previous research indicates that there will be zero net change to agricultural production due to climate change while others suggest that climate change will have negative effects on agriculture, forcing adaptation (Lobell and Gourdji 2012, Mayer 2013).

Rice, soybean, and barley grow in radically different temperatures and humidities which allows us to see how climate change impacts yields in different climate zones. We can apply insights from the models and findings of previous papers to these understudied crops. Rice tends to grow best in hot, humid regions that see an average temperature range between 21-37 degrees Celsius. The highest temperature that rice can tolerate is about 40 degrees Celsius (Farmer Portal). As the mean temperature increases to above 40 degrees, producing rice becomes much more difficult, despite sufficient precipitation. Soybeans optimally grow where mean temperatures range from 16-21 degrees Celsius and where the soil is well drained, suggesting that increasing precipitation will negatively affect yields (Albert 2020). Barley tends to grow best in cooler, drier climates. Barley is quite resistant to frost and so is preferentially grown in cooler regions. We would predict that as cooler climatic regions become warmer, countries in such regions will shift from barley production to a warmer-climate crop, thus reducing barley yields.

Additionally, we now see that the global comparison will be a helpful addition to the climate-agriculture conversation. Adaptation, whether it is crop switching within a given region, shifting agricultural production into higher latitudes, or even, adjusting the growing time to match with changing seasons, is an extremely important driver of current research yet very few papers discuss it. As such, our paper will focus on adaptation in our Discussion section. In our paper, we aim to add to the conversation by focusing on multinational agricultural impact and adaptation as a result of climate change.

III. <u>Data Description</u>

For our topic, we have two sources of data: World Bank Climate Change Knowledge Portal and Our World in Data Agricultural Production data. The Climate Change Knowledge Portal (CCKP) provides us with country-level temperature and precipitation time-series data. Meanwhile, Our World in Data provides us with country-level agricultural production time-series data by crop. The CCKP presents the World Bank Group's operational team's raw climate and model-based projection data combined with 15 global circulation models and comprehensive physically-based models of climate change made available by the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Reports. While the time-series spans as far back as 1901 and makes projections up until 2099, the projections may fail to include unprecedented advances in technology or development causing predictions to be under- or overstated. This comprehensive data set is presented to policymakers and other global professionals and is produced by reputable experts in the field. However, for our analysis, we will not be using projected data; we are only using recorded climate data up to 2018. The country category provided allows users to compare climate datasets at the national level. The spatial and temporal resolutions that we intend to employ are annual national average temperatures in degrees Celsius and annual national precipitation levels in millimeters. The CCKP will provide us with sound climate data in order to track climate change over time.

Our World in Data receives its data from the United Nations Food and Agricultural Organization (FAO). “The main data source is official statistics from FAO member countries, collected either through annual production questionnaires (APQ) distributed to countries, from national publications or from official country websites.” (FAO). The main drawback to this type of data is that the variable sources can impact the reliability of data and how we compare data for different countries. If some data is obtained from official sources while other data is obtained in a dramatically different way, comparing the two sets of data could lead to biased results. The variable time spans nearly six decades covering the years 1961 to 2018 and the dataset has information on most countries as well as select aggregated regions. There are a total of 6,775 data points (distinct year, country/region pairs) in the barley data set, 8,549 data points in the rice data set, and 6,041 data points in the soybean data set. The units of production for all three data sets are measured in tons. From this data set, we will be analyzing yearly production of our three crops.

We will join these data sets in order to have data points for every year-country pair that contain information on both climate data and production data. We will be using 10 countries that produce all three crops in addition to another 10 unique countries that produce at least one of the three crops. Additionally, since we only have production data starting at 1961, we will not be using climate data from before this year either. This results in 58 years and 38 countries worth of data (two countries overlap in two of the individual crop data sets). Our final data set contains 2,320 data points with mean temperature, average precipitation, and total production as the variables in each of these data points. This is split up into the four distinct data sets: one per crop, and one with all three crops which will then be used to run our models.

IV. Methodology

Our research will examine the relationship between climate change and multinational agricultural production of certain crops. In particular, we will analyze the effects of rising temperatures and precipitation on soybean, rice, and barley yields across the global landscape. Both agricultural yield and agricultural production, here, will be defined as total output in tons.

To test our hypothesis, we will regress climate data from the Climate Change Knowledge Portal onto agricultural data collected from the World Bank. Our independent variables in our regression analysis are temperature and precipitation measured in degrees Celsius and millimeters per year, respectively. Our dependent variables are rice, soybean, and barley outputs. We predict nonlinear relationships between our independent and dependent variables and so employ a nonlinear regression model. We will employ four different regressions to model the effects of climate change on specific crop outputs, one for each crop and the fourth for our composite analysis. The general model appears as follows:

$$\ln(Y_{it}) = \beta_0 + \beta_1 T_{it}^2 + \beta_2 T_{it} + \beta_3 P_{it}^2 + \beta_4 P_{it} + FE + x_{it} + \varepsilon_{it}$$

where $\ln(Y_{it})$ is the percent change in crop (rice, soybean, or barely) output in a given year in a given country, T is temperature in degrees Celsius, P is precipitation in millimeters, FE is fixed effects, and epsilon is the error term. In our analysis, we employ different combinations of fixed effects and country-specific time trends in an effort to determine the model that best fits our data. Note that technological changes that affect all countries would ordinarily be accounted for by time fixed effects, but we can’t be certain that technological innovations will or already do so.

Our strategy helps to eliminate threats to causal inference due to technological changes. Other threats to causal inference in our analysis will be addressed in the Discussion section.

Using this panel data model, we assume (1) no perfect multicollinearity, (2) variables are independently and (3) identically distributed (IID), and large outliers are unlikely. Temperature and precipitation are likely correlated but are not perfectly so, thus satisfying the first assumption. We believe that the error terms between countries are not correlated, satisfying the second assumption, but recognize that this may not be the case. If the latter is true, then we can correct for it using clustered standard errors in our analysis. Finally, our time series data should allow us to correct for possible outliers, thus satisfying our final assumption. Outliers are discussed further in the Discussion section.

V. <u>Results</u>

We ran a series of regressions including different combinations of fixed effects (FE) and country-specific time trends (CSTT) for each crop. Specifically, we used regressions with no FE, with time FE only, with country FE only, with both time and country FE, with CSTT, and with both CSTT and country FE. Tables 1 - 4 show all of the models that we used.

Most of our coefficients in each of the models are not statistically significant. We found that temperature coefficients have a higher magnitude than precipitation across the board. In fact, many of the precipitation coefficients were at or just above 0 in absolute value. Additionally, coefficient signs tended to change based on which model we were using.

The no-FE model had the lowest R-squared value for each of the three crops and the composite (model that includes all three crops). The time-only and the country-only FE models had comparable R-squared values, generally in the lower range (0.1-0.25). However, the time-only and country-only FE models for rice had R-squared values above 0.8, far higher than the results for soybean and barley. For each crop and the composite, the R-squared value for the combined time and country FE model was greater than either of the FE models alone. The combined CSTT and county FE model for each of the crops and the composite had R-squared values higher than the combined time and country FE, but the difference between these values tended to be less than .03 except for soybean which had a ~.07 difference. This large difference is the likely driver behind the .05 R-squared difference between models for the composite. The CSTT model (excluding other FE) had the highest R-squared values across the board, each of the values at or above .96. The country-specific time trend model for rice yielded an astonishing R-squared value of 1.000. The results of each model can be found in the Appendix, Tables 1-4.

Excluding constants, rice had the highest amount of statistically significant results, most of which were at the 5% level or lower. Comparing results across models, we found that the CSTT-only regressions for each crop consistently had the highest R-squared values, leading us to believe it is the best fit model for our data. Table 5 shows the country-specific time trend model for each of the crops and the composite. As shown, very few results are statistically significant, except for temperature on rice, which is significant at the 1% level. The signs on the temperature coefficients are negative for all crops except for barely. The signs on precipitation coefficients, despite the values equaling near 0, are all negative except for rice. Finally, the square terms for each of the crops are all positive, except for barley which has negative signs on both square terms.

VI. Discussion

By using CSTT, we measure the yearly deviation in output from the general time trend in each country. Negative coefficients can be interpreted as causing negative variation in output from the trend and positive coefficients as causing positive output variations from the trend. Temperature coefficients have a higher magnitude than precipitation across the board; many of the precipitation and precipitation-squared coefficients are near or at zero, contrary to our prediction. This indicates that agricultural yields are more sensitive to changes in temperature than precipitation. In other words, changes in temperature cause larger deviations from the trend than does precipitation. Technological advances, like irrigation --which allows farmers to control water exposure to crops--, might explain why we achieve this result.

Thailand, a top rice exporter, was able to confirm supplying irrigation water was a rather effective adaptation strategy to help its rice production when compared to changing planting date and reduction in fertility stress through proper nutrient management. (Boonwichai 2021) Another explanation for precipitation having a negligible effect also stems from the fact that although annual precipitation increases in magnitude, its effects may not have manifested themselves during the cropping period for soybean, rice, or barley leaving no observable differences in yield. (Dahal 2018) Bannayan et. al. (2010) strongly notes that timing of precipitation dictates a crop's success crop's yield in a particular yield. Thus, changes in precipitation would have little to no effect on agricultural yields, as our model shows, if the seasonality of precipitation was affected in a certain way.

The signs on the resulting coefficients generally follow our predictions. As shown in Table 5, increasing temperature leads to negative variation from the trend for all crops. Total rice, soybean, and barley yield variations are negatively affected by increasing temperature. The temperature-squared term is zero, making the temperature and yield variation relationship linear. The coefficient is statistically significant at the 1% level, and combined with the high R-squared, this is an extremely strong relationship. A potential limitation to our results is the small samplesize. With ten countries in each category, we can only make conclusions for multinational trends; a correction strategy that a future paper could take would be to include more countries' agricultural yields into our final CSTT model.

Similarly, the temperature-squared coefficient for soybean is zero, so the relationship between temperature and soybean yield is also a simple negative linear relationship. As temperatures increase, variation in soybean yield from the trend will continue decreasing, eventually causing net soybean yield to decrease as well.

Barley, however, has a positive coefficient for temperature and a negative coefficient for temperature-squared, different from the other crops, suggesting that the variation caused by temperature will eventually stop increasing and start decreasing, as visualized by an inverted parabola. Our exact position on this curve is unclear; for each country, we do not know if variation in yields are increasing at a decreasing rate or decreasing altogether. However, we can still say that the overall effect of temperature on barley is negative in the long run.

Opposite to barley, the temperature coefficient for rice is positive and the temperature-squared coefficient is negative. Variations in rice yield caused by temperature would be modeled as an upward-facing parabola. This means that variations in rice yield may be decreasing currently, but will start increasing in the long-run. As with barley, we do not know our precise location on the curve. One explanation for this trend might be that colder-climate countries will eventually begin to produce rice as they warm due to climate change. This explanation would result in greater production of rice despite rising temperatures. However, our data does not account for other possible future climate scenarios. For instance, we do not have the temperature range to account for even higher increases in temperature that may cause potential new producers of rice to lose this newfound ability to do so. Although our model makes it seem that climate change has a positive impact on rice production, more analysis is needed to see long-term effects of a global increase in temperature on rice yields.

It’s important to note that the rice coefficients are much higher and more statistically significant than the others. For example, a one degree increase in temperature leads to a more than 200% negative deviation from the trend; i.e. rice yields decrease by a large relative amount (Figure 5). We suspect this could be due to the fact that most rice is produced in east Asian countries, which may be subject to poor record keeping over our time interval.

Unlike temperature, the coefficients for precipitation and precipitation-squared are all virtually zero. Thus, the signs on these coefficients have no practical interpretation. This leaves us with, most simply, a model for variations in crop yield as a function of temperature. Note that the coefficients for precipitation and precipitation squared for each of the crops in each of our other models are all practically 0 (Tables 1-4). This supports our inference that technological advances like irrigation have mitigated the effects of precipitation on agricultural production.

An important question regarding our analysis is whether or not there is a relationship between temperature and precipitation. If these variables are collinear, then our results might not hold as the model would be severely affected by collinearity. Intuitively, we know that rising temperature isn’t *always* associated with rising precipitation. For example, as temperature increases in Sub-Saharan Africa, we wouldn’t expect precipitation to increase because it’s a desert! Similarly, we wouldn’t expect a decrease in precipitation in the Amazon with increasing temperature. Figure 3 shows the relationship between temperature and precipitation for our chosen countries. As shown, there are horizontal clusters of points that indicate temperature can increase without increasing precipitation. Likewise, there are vertical clusters that suggest that precipitation can increase with increasing temperature. The distributions of temperature and precipitation by country support this analysis (Figures 1-2). The analytical consequence is that we can be confident that the precipitation coefficients are zero for a reason other than collinearity.

Another potential threat to our analysis is the existence of production outliers; there are some countries that produce much higher yields than countries we compare them to, particularly for soybean and rice (Figure 4). These outliers aren't necessarily anomalous; we chose the top producers for each crop and so expect a fair range between the highest top producers and the lowest top producers. However, these outliers may still have affected our results.

VII. <u>Conclusion</u>

We are able to confirm that agriculture is an especially climate-sensitive human activity. Revisiting our earlier claims from the literature review section, we can confirm the work of Kurukulasuria and Mendelsohn (2008) that crops are more sensitive to temperature than the precipitation climate variable. Oresults suggest that agricultural yields are negatively affected by climate change and left unmitigated, net global agricultural yields will likely fall, contrasting Lobell and Gourdji. Specifically, agricultural yields of top crops like soybeans, rice, and barley are threatened by rising temperatures. This fact necessitates adaptation and other mitigation strategies because under almost all emissions scenarios identified by the IPCC (Intergovernmental Panel on Climate Change), temperature rates will continue to rise.

Historically, farmers typically respond to climate change by adjusting farming practices or adopting a new crop altogether. (Korres 2016) With temperatures increasing at a rate of .18°C per decade, global agricultural outputs are exceedingly threatened (Lindsey and Dahlman 2021) The top five soybean-producing countries have witnessed reduced soybean yields after 0.5 °C rise in temperature. While adaptation strategies such as planting earlier in the season and changing variety delay temperature's effect and ultimately, help to maintain the upkeep of soybean yields in response to small rises, their effectiveness will be thwarted beyond a rise of 2 °C. (Rose et. al. 2016) A Korres (2016) study established that with inevitable temperature rise, the best way to sustain rice-yields in the short term is cultivar selection–breeding rice strains to be more heat-resistance or heat-tolerant–and reorganizing planting dates to harvest before extreme heat hits. This suggests that R&D in crop genetic engineering might be a useful strategy in dampening the negative effects of temperature on yields.

Similarly, increasing crop diversity and physically protecting seeds during the most pivotal part of their growing will enhance resiliency in the face of climate change. In order to sustain barley yields, seed-sowing windows must be adjusted accordingly. (Kalra et. al 2008) All the climate change impact studies warn of the doom brought upon by the work of rising temperatures and encourage subsequent research and development in adaptation strategies.

As mentioned earlier, precipitation's seemingly negligible effect on agricultural yields, likely due to technological advances in irrigation. Overall, adapting to climate change in an effort to safeguard the global food supply is in the world's best interest. Further country-specific research should be conducted to explain and shed light on specific impacts by climate-region. This would determine the effect of climate change on individual crops and identify where crop-switching would need to be enacted. However, with rising food needs, food security can be stabilized only when the effects of climate change on agriculture are mitigated. Unadulterated anthropogenic climate change will increase temperatures, decrease yields, and intensify humanitarian crises such as world hunger. This requires the development and implementation of adaptation strategies that are best fit for each region and the intended crop. If this is able to be implemented, then, the effects of temperature can be lessened and agriculture can become a less climate-sensitive activity.

Appendix

Table 1.

Climate Change on Soybean Output

VARIABLES	No FE ln(Soybean)	Time FE ln(Soybean)	Country FE ln(Soybean)	Time & Country FE ln(Soybean)	Country Specific Time Trend ln(Soybean)	Country Specific Time Trend & Country FE ln(Soybean)
Precipitation	0.001	0.001	-0.001	-0.002	-0.001	0.000
	(0.001)	(0.001)	(0.002)	(0.002)	(0.002)	(0.001)
Temperature	-0.013	-0.012	-0.072	-0.099	-0.101	-0.027
	(0.013)	(0.010)	(0.080)	(0.093)	(0.079)	(0.107)
Precip. Sq.	-0.000	-0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Temp. Sq.	0.001**	0.001***	0.001	0.002	0.000	0.002
	(0.001)	(0.000)	(0.003)	(0.004)	(0.004)	(0.004)
Constant	5.161***	5.160***	5.887***	6.599***		4.623***
	(0.408)	(0.475)	(1.169)	(1.620)		(1.390)
Observations	580	580	580	580	580	580
R-squared	0.032	0.111	0.188	0.260	0.960	0.334

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 2.

Climate Change on Barley Output

VARIABLES	No FE ln(Barley)	Time FE ln(Barley)	Country FE ln(Barley)	Country & Time FE ln(Barley)	Country Specific Time Trend ln(Barley)	Country Specific Time Trend & Country FE ln(Barley)
Precipitation	-0.001	-0.001*	-0.000	-0.001	0.001	0.002
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Temperature	-0.208***	-0.199***	0.080	0.028	0.161	-0.143
	(0.051)	(0.049)	(0.106)	(0.123)	(0.111)	(0.145)
Precip. Sq.	0.000	0.000	-0.000	0.000	-0.000	-0.000*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Temp. Sq.	0.007***	0.007***	-0.008*	-0.001	-0.013**	0.014*
	(0.002)	(0.002)	(0.005)	(0.006)	(0.005)	(0.008)
Constant	6.908***	6.896***	6.080***	5.753***		4.641***
	(0.358)	(0.316)	(0.792)	(0.929)		(0.841)
Observations	580	580	580	580	580	580
R-squared	0.035	0.144	0.221	0.321	0.975	0.345

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 3.

Climate Change on Rice Output

VARIABLES	No FE ln(Rice)	Time FE ln(Rice)	Country FE ln(Rice)	Time & Country FE ln(Rice)	Country Specific Time Trend ln(Rice)	Country Specific Time Trend & Country FE ln(Rice)
Precipitation	0.001***	0.000	0.000	-0.000	-0.000	-0.000
	(0.000)	(0.001)	(0.001)	(0.000)	(0.000)	(0.000)
Temperature	0.470***	-1.171***	-1.171***	-1.563***	-2.278***	0.101
	(0.081)	(0.111)	(0.111)	(0.169)	(0.169)	(0.086)
Precip. Sq.	-0.000	0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Temp. Sq.	-0.014***	0.044***	0.044***	0.036***	0.053***	-0.003
	(0.002)	(0.003)	(0.003)	(0.004)	(0.003)	(0.002)
Constant	11.281***	18.116***	18.116***	32.455***		15.612***
	(0.804)	(0.972)	(0.972)	(2.166)		(0.718)
Observations	580	580	580	580	580	580
R-squared	0.339	0.826	0.826	0.924	1.000	0.967

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 4.

Climate Change on Total Rice, Soybean, Barley Output

VARIABLES	No FE ln(Total RSB)	Time FE ln(Total RSB)	Country FE ln(Total RSB)	Time & Country FE ln(Total RSB)	Country Specific Time Trend ln(Total RSB)	Country Specific Time Trend & Country FE ln(Total RSB)
Precipitation	-0.002***	-0.002***	-0.001	0.001	0.000	0.001
	(0.000)	(0.000)	(0.001)	(0.002)	(0.001)	(0.001)
Temperature	-0.018	-0.018*	-0.264***	-0.089	-0.267***	0.118
	(0.012)	(0.009)	(0.058)	(0.083)	(0.058)	(0.100)
Precip. Sq.	0.000***	0.000***	0.000	0.000	0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Temp. Sq.	0.000	0.000	0.002	0.008***	0.000	-0.002
	(0.001)	(0.000)	(0.003)	(0.003)	(0.003)	(0.004)
Constant	6.198***	6.176***	8.803***	3.615**		3.852***
	(0.181)	(0.144)	(1.343)	(1.713)		(1.428)
Observations	580	580	580	580	580	580
R-squared	0.048	0.158	0.120	0.222	0.972	0.297

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 5.

Climate Change on Agriculture Using Country-Specific Time Trends

VARIABLES	Country Specific Time Trend ln(Rice)	Country Specific Time Trend ln(Soybean)	Country Specific Time Trend ln(Barley)	Country Specific Time Trend ln(Total RSB)
Precipitation	-0.000	-0.001	0.001	0.000
	(0.000)	(0.002)	(0.001)	(0.001)
Temperature	-2.278***	-0.101	0.161	-0.267***
	(0.169)	(0.079)	(0.111)	(0.058)
Precip. Sq.	0.000	0.000	-0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Temp. Sq.	0.053***	0.000	-0.013**	0.000
	(0.003)	(0.004)	(0.005)	(0.003)
Observations	580	580	580	580
R-squared	1.000	0.960	0.975	0.972

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Figure 1.

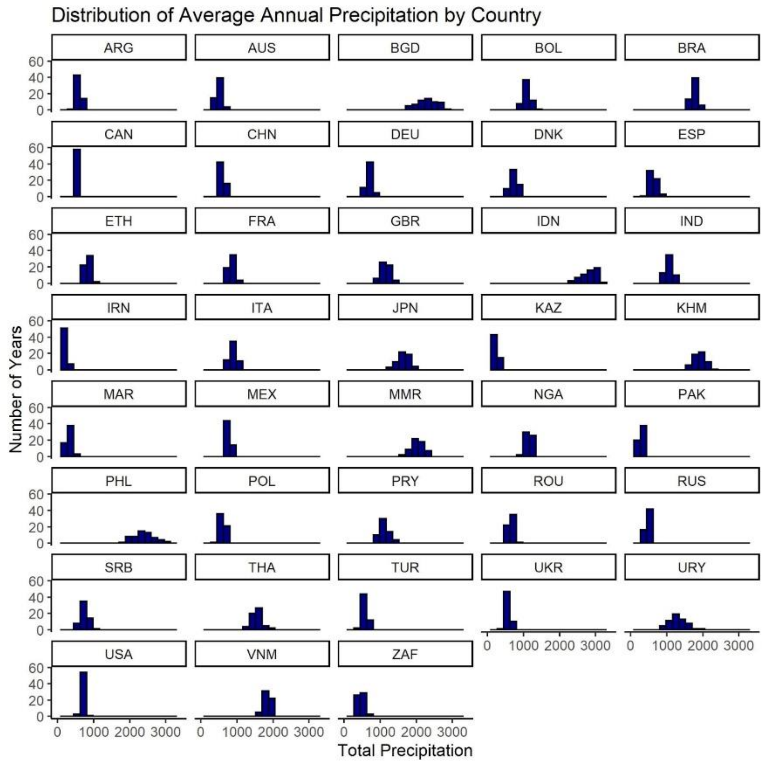


Figure 2.

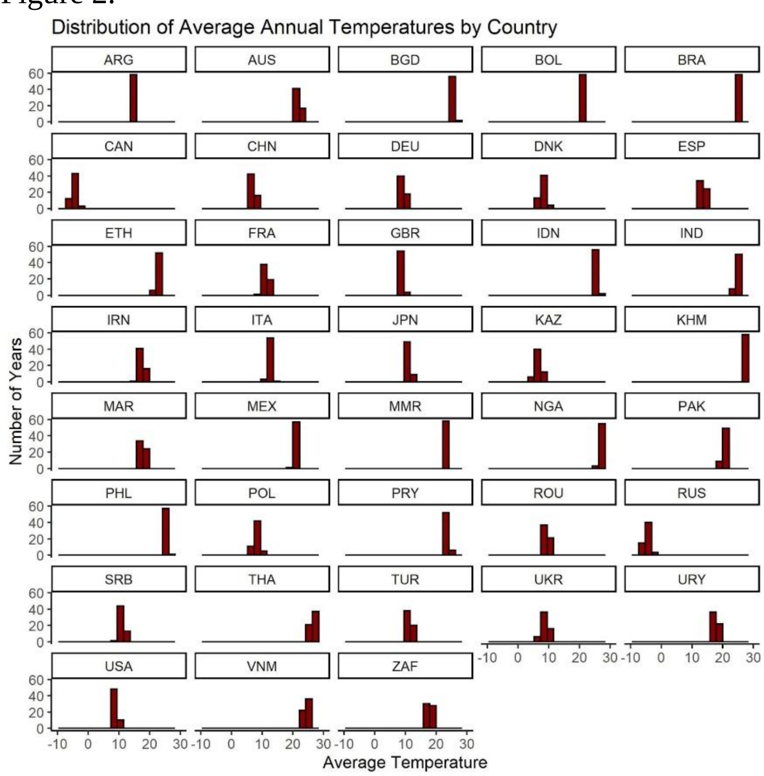


Figure 3.

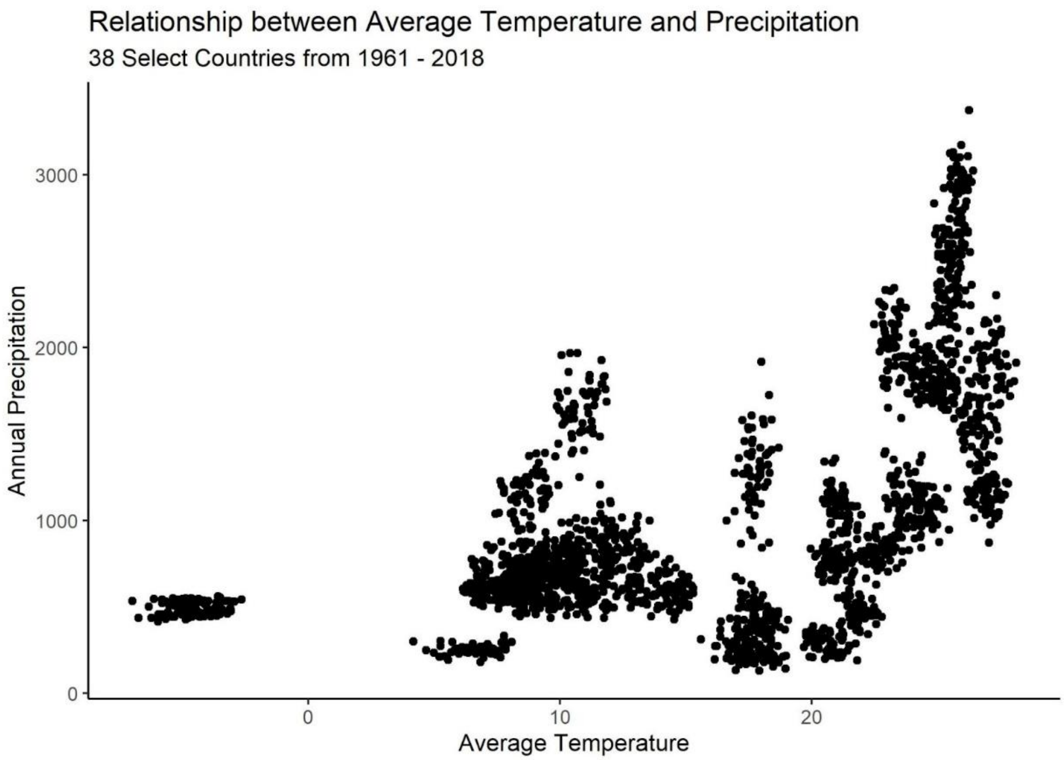
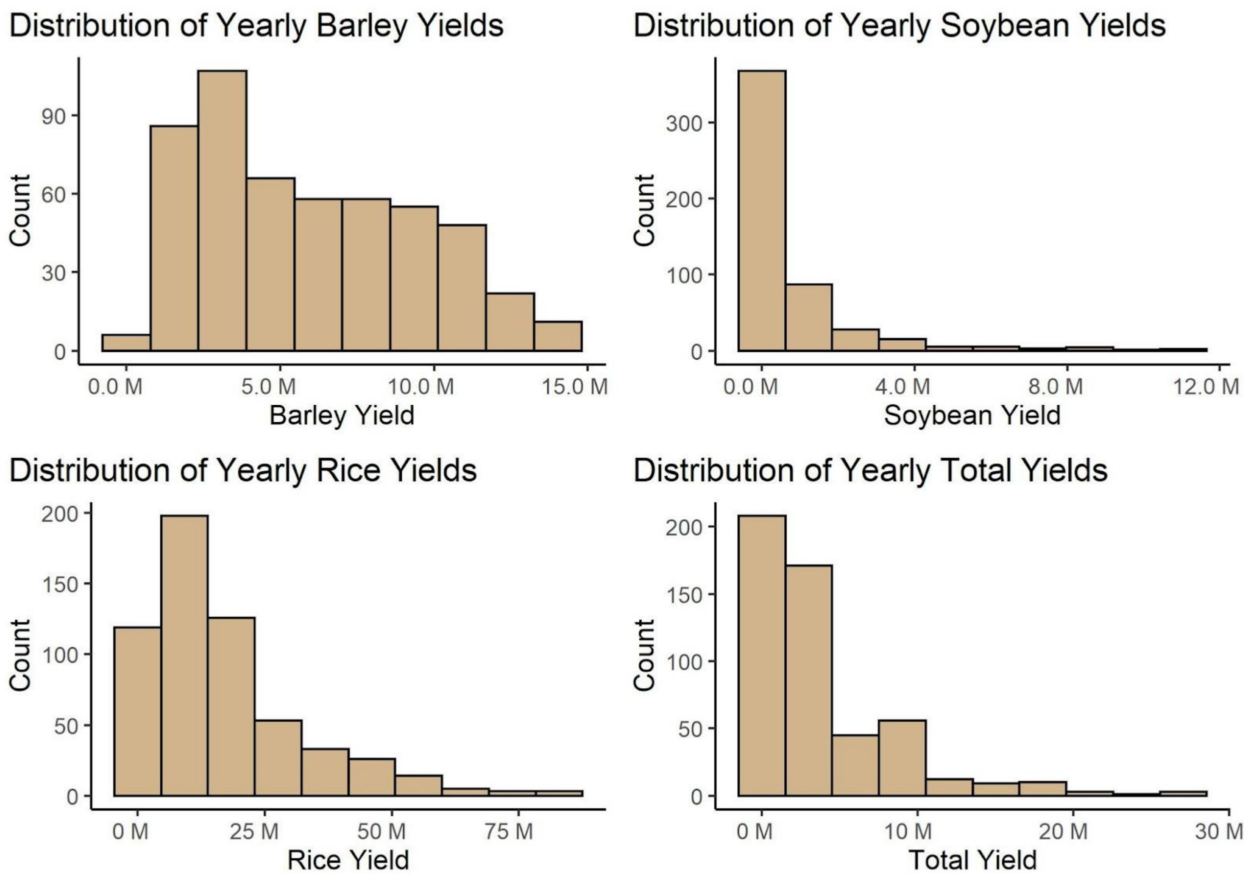

Relationship between Average Temperature and Precipitation
38 Select Countries from 1961 - 2018
Annual Precipitation
3000
2000
1000
0
0
10
20
Average Temperature

Figure 4.


Distribution of Yearly Barley Yields
Count
90
60
30
0
0.0 M
5.0 M
10.0 M
15.0 M
Barley Yield
Distribution of Yearly Soybean Yields
Count
300
200
100
0
0.0 M
4.0 M
8.0 M
12.0 M
Soybean Yield
Distribution of Yearly Rice Yields
Count
200
150
100
50
0
0 M
25 M
50 M
75 M
Rice Yield
Distribution of Yearly Total Yields
Count
200
150
100
50
0
0 M
10 M
20 M
30 M
Total Yield

Works Cited

"Agriculture & Horticulture Corner." *Farmer Portal : Home Page*, https://farmer.gov.in/cropstaticsrice.aspx.

Albert, Steve. "How to Grow Soybeans." *Harvest to Table*, 5 Nov. 2020, https://harvesttotable.com/how_to_grow_soybean.

Antle, John M. "Climate Change and Agriculture in Developing Countries." *American Journal of Agricultural Economics*, vol. 77, no. 3, 1995, pp. 741–46. *JSTOR*, https://doi.org/10.2307/1243244.

Bannayan, Mohammad, et al. "Effects of precipitation and temperature on crop production variability in northeast Iran." International journal of Biometeorology 55.3 (2011): 387-401.

Boonwichai, Siriwat, et al. "Adaptation strategies for rainfed rice water management under climate change in Songkhram River Basin, Thailand." Journal of Water and Climate Change 12.6 (2021): 2181-2198.

C, Nelson, Gerald, et al. *Climate Change: Impact on Agriculture and Costs of Adaptation*. Intl Food Policy Res Inst, 2009.

Climate Change and Its Impact on Agriculture | IJSRP February 2013 Publication. http://www.ijsrp.org/research-paper-0414.php?rp=P282518. Accessed 26 Feb. 2022.

Dahal, Vaskar, Sudip Gautam, and Rabin Bhattarai. "Analysis of the long-term precipitation trend in Illinois and its implications for agricultural production." Water 10.4 (2018): 433.

Fortin, Mathieu. "Nonlinear Regression." European non-wood forest products Network. https://www.nwfps.eu/wp-content/uploads/2012/07/Fortin-NonlinearModels.pdf. Accessed 29 Sept. 2014.

Korres, N. E., et al. "Temperature and drought impacts on rice production: An agronomic perspective regarding short-and long-term adaptation measures." Water resources and rural development 9 (2017): 12-27.

Kurukulasuriya, Pradeep, and Robert Mendelsohn, editors. "Crop Switching as a Strategy for Adapting to Climate Change." *African Journal of Agricultural and Resource Economics*, 2008. *AgEcon Search*, https://doi.org/10.22004/ag.econ.56970.

Lindsey, Rebecca, and LuAnn Dahlman. "Climate change: Global temperature." Climate. gov 16 (2020).

Lobell, David B., and Sharon M. Gourdji. “The Influence of Climate Change on Global Crop Productivity.” *Plant Physiology*, vol. 160, no. 4, 2012, pp. 1686–97. *JSTOR*, https://www.jstor.org/stable/41812017.

Mayer, Amy. “Climate Change Already Challenging Agriculture: Wine and Coffee Producers Respond to Hotter, Drier Conditions.” *BioScience*, vol. 63, no. 10, 2013, pp. 781–87. *JSTOR*, https://doi.org/10.1525/bio.2013.63.10.2.

Mendelsohn, Robert, et al. “The Impact of Global Warming on Agriculture: A Ricardian Analysis.” *The American Economic Review*, vol. 84, no. 4, 1994, pp. 753–71. *JSTOR*, https://www.jstor.org/stable/2118029.

Phillips, Donald L., et al. “Sensitivity of the US Corn Belt to Climate Change and Elevated CO2: I. Corn and Soybean Yields.” *Agricultural Systems*, vol. 52, no. 4, Dec. 1996, pp. 481–502. *ScienceDirect*, https://doi.org/10.1016/S0308-521X(96)00014-5.

Rising, James, and Naresh Devineni. “Crop Switching Reduces Agricultural Losses from Climate Change in the United States by Half under RCP 8.5.” *Nature Communications*, vol. 11, no. 1, Oct. 2020, p. 4991. *PubMed*, https://doi.org/10.1038/s41467-020-18725-w.

Ritchie, Hannah, and Max Roser. “Agricultural Production.” *Our World in Data*, Mar. 2020. *ourworldindata.org*, https://ourworldindata.org/agricultural-production.

Rose, Gillian, et al. "Impact of progressive global warming on the global-scale yield of maize and soybean." Climatic Change 134.3 (2016): 417-428.

Schlenker, Wolfram, and Michael J. Roberts. “Nonlinear Temperature Effects Indicate Severe Damages to U.S. Crop Yields under Climate Change.” *Proceedings of the National Academy of Sciences*, vol. 106, no. 37, Sept. 2009, pp. 15594–98. *DOI.org (Crossref)*, https://doi.org/10.1073/pnas.0906865106.

White, Jeffrey W., et al. “Methodologies for Simulating Impacts of Climate Change on Crop Production.” *Field Crops Research*, vol. 124, no. 3, Dec. 2011, pp. 357–68. *ScienceDirect*, https://doi.org/10.1016/j.fcr.2011.07.001.

Wolchover, Natalie. “How Many People Can Earth Support?” NBC News, 11 Oct. 2011, www.nbcnews.com/id/wbna44860924.

World Bank Climate Change Knowledge Portal. https://climateknowledgeportal.worldbank.org/. Accessed 11 Mar. 2022.

Yamanoshita, Makino. *IPCC Special Report on Climate Change and Land*. Institute for Global Environmental Strategies, 2019. *JSTOR*, https://www.jstor.org/stable/resrep22279.