ESSAYS ON IMPACTS OF CLIMATE CHANGE ON AGRICULTURAL SECTOR IN THE U.S.

A Dissertation

by

JIYUN PARK

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2012

Major Subject: Agricultural Economics

Essays on Impacts of Climate Change on Agricultural Sector in the U.S.

ESSAYS ON IMPACTS OF CLIMATE CHANGE ON AGRICULTRAL SECTOR IN THE U.S.

A Dissertation

by

JIYUN PARK

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Approved by:

Co-chairs of Committee,	Bruce A. McCarl
	Ximing Wu
Committee Members,	Fred Boadu
	Jianbang Gan
Head of Department,	John Nichols

August 2012

Major Subject: Agricultural Economics

ABSTRACT

Essays on Impacts of Climate Change on Agricultural Sector in the U.S. (August 2012)

Jiyun Park, B.A., Konkuk University; M.A.B., Texas A&M University

Co-chairs of Advisory Committee: Dr. Bruce A. McCarl
Dr. Ximing Wu

This dissertation investigates: (1) the climate change effects on the mean and higher order moments of crop yield distributions; (2) the effects of irrigation with and without its interactive terms with climate variables; (3) the climate effects on crop mix and climate change adaptation.

The first essay explores how the climate change impacts the crop yield distribution. Using the flexible moment based approach, this study infers that external climate factors influence not only mean crop yield and variability, but also its higher order moments, skewness and kurtosis. The climate effects on each moment vary by crops.

The second essay examines the irrigation effects on the mean crop yield. While the irrigation effects estimated from the model with irrigation dummy are constant regardless of climate conditions, the irrigation effects estimated from the model with irrigation dummy and interactive variables between irrigation and climate are affected by external climate factors. This study shows that as temperature increases, the irrigation

effects are decreased and irrigation reduces damages from extreme temperature conditions. Precipitation and PDSI effects are also diminished under irrigation.

The third essay explores the effects of climate on crop producers' choice. Our findings point out that the climate factors have significant impacts on crop choice and future climate change will alter the crop mix. Under the projected climate change of increasing temperature and precipitation, wheat and soybeans cropland will be switched to upland cotton. The major producing locations of upland cotton, rice, and soybeans will be shifted to the north. However, most of corn will be still cultivated in the Corn Belt and changes in acreage planted will not be significant.

DEDICATION

To my beloved mother.

ACKNOWLEDGEMENTS

I would like to thank my committee co-chairs, Dr. McCarl and Dr. Wu, for their guidance and generous support throughout the course of this research. I am also grateful for my committee members, Dr. Boadu and Dr. Gan, for their precious time and patience in the guidance in my research. Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience. Finally, I would like to thank my mother for her love and support.

NOMENCLATURE

CD	Climate Division
CNRM: CM3	The Centre National de Recherches Meteorologiques Coupled Model Version 3
DT32	The Number of Days Where the Minimum Temperature Was Less Than 32 °F
DT90	The Number of Days Where the Maximum Temperature Was Greater Than 90 °F
FGLS	Feasible Generalized Least Squares
GCMs	Global Circulation Models
GFDL: CM2.1	The Geophysical Fluid Dynamics Laboratory Coupled Model Version 2.1
INT	Precipitation Intensity
IPCC	The Intergovernmental Panel on Climate Change
IRR	Irrigation Rate
LMM	Linear Moment Model
MRI: CGCM2.3	The Meteorological Research Institute Coupled General Circulation Model Version 2.3
NOAA-CPC	The National Oceanic and Atmospheric Administration - Climate Prediction Center

NOAA- NCDC	The National Oceanic and Atmospheric Administration - National Climate Data Center
PCP	Precipitation
PCSEs	Panel-corrected Standard Errors
PDSI	Palmer Drought Severity Index
SRES	The Special Report to Emission Scenarios
TMP	Temperature
USDA-NASS	The United States Department of Agriculture – National Agricultural Statistics Service

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

Page

CHAPTER I

GENERAL INTRODUCTION

A large body of evidences indicates that climate change is proceeding. The Intergovernmental Panel on Climate Change (IPCC WGI, 2007; IPCC WGII, 2007) asserts with 90% certainty that human-caused emissions of greenhouse gases (GHG) have accelerated climate change (IPCC WGI, 2007; IPCC WGII, 2007). Direct observations of recent climate change include increasing temperature, rising global average sea levels, changes in precipitation patterns, widespread changes in extreme temperatures, and increase in intense tropical cyclone activity (IPCC WGI, 2007; IPCC WGII, 2007).

Agriculture has a close relation with climate. Productivity of agricultural crops and livestock is directly affected by temperature, precipitation, CO_2 concentration, and extreme weather events. Moreover, because the agricultural sector is affected by other industries like energy, labor, or manufacture, there are also indirect impacts of climate change. While climate change affects agriculture directly and indirectly, agriculture also affects climate change. About 30% of global GHG emissions come from the agricultural sector including forestry (IPCC WGI, 2007; IPCC WGII, 2007) and since the costs of mitigation from agricultural sector are relatively low, agriculture is expected to play an important role in mitigating climate change (McCarl and Schneider, 2001).

Because of the close relation between climate and agriculture, climate change is

---

This dissertation follows the style of *American Journal of Agricultural Economics*.

an important research topic. There are numerous studies that investigate the link between climate change and agriculture and estimate the effects of climate change on agriculture (IPCC, 2007; Reilly et al, 2002). However, there are still many unresolved issues as most of the studies are based on strong assumptions or have limitations. Climate change has been argued to affect crop yield mean and variance which influences future crop planning and agricultural policy analysis. Higher order moments may also be changing. Previous studies that examine the effects of climate change on crop yield distributions focus on mean and variability ignoring the effects of climate change on the higher moments including skewness and kurtosis. Also irrigation has been an important topic in the previous crop productivity studies, but the relationship in irrigation and climate change is not examined. Although climate stimulated adaptations in crop mix are an important topic, it has been studied using largely simulation models without any large scale study of what observed data reveal about such adaptation. Hence, in the dissertation, I will suggest an improved model to estimate climate change effects, investigate the link between climate change and crop yields, and analyze crop adaptation as influenced by climate.

Objectives

This dissertation will pursue three objectives related to the overall problem of understanding the implications of projected climate change on agriculture:

- To develop information on how past climate has influenced past crop yield distribution including mean, variance, skewness, and kurtosis plus how future climate change will affect the mean and higher moments of crop yield distributions.
- To examine how the effect of climate differ between irrigated and dryland crop yields plus project the future consequences of projected climate change on irrigated and dryland crop yields.
- To examine the way that crop agriculture has adapted to varying climate conditions and project what further developments may happen under climate change.

Plan of Dissertation

In pursing the above objectives this dissertation contains three main essays (Chapters II-IV):

The first essay, Chapter II, reports on an investigation of the effects of climate variation on the mean and higher moments of crop yield distributions for corn, upland cotton, sorghum, soybeans, and winter wheat. In addition, the investigation will address the impacts of projected climate change on mean yield, plus yield variance, skewness and kurtosis.

The second essay, Chapters III, report on the investigation of irrigated versus dryland production on effects of changes in climate again for corn, upland cotton, sorghum, soybeans, and winter wheat. In addition, the investigation will address the impacts of projected climate change on yields, market outcomes and welfare.

The third essay, Chapter IV, reports on the investigation of the effects of climate on crop choice among major crops including barley, corn, upland cotton, rice, sorghum, soybeans, spring wheat, durum wheat, and winter wheat. In addition, the investigation will address the impacts of projected climate change on adaptation in term of crop mix.

The first and last chapters provide introduction and overall concluding comments respectively.

CHAPTER II

THE EFFECTS OF CLIMATE CHANGE ON THE MEAN AND HIGHER ORDER MOMENTS OF CROP YIELD DISTRIBUTIONS

With mounting evidence that climate change including global warming has accelerated, studies increasingly have examined the effects of climate change on agricultural crop yields (IPCC WGI, 2007; IPCC WGII, 2007). It is widely known that productivity of crops depends on climatic conditions such as temperature, precipitation, and extreme weather events. Many researchers have studied the link between climate and yields, and previous studies show that climate change has significant impacts on crop yield as reviewed below.

Climate has repeatedly been found to have a strong influence on agriculture and also that changes in climate alter average crop yields (for example see Adams et al., 1990; Reilly et al., 2002; Deschenes and Greenstone, 2007; IPCC WGI, 2007; IPCC WGII, 2007; Schlenker and Roberts, 2009). Collectively these studies indicate that the effects of climate change vary across regions and crops. Chen et al. (2004) estimated the effects of climate on crop yield levels and variances. They show that climate impacts not only average crop yields, but also yield variability. McCarl et al. (2008) investigate the influence of climate change on the stationarity of the crop yield distributions. They indicate that the stationarity does not hold and climate change will increase the variability of crop yield distributions. Schlenker and Roberts (2006) find that temperature and crop yields have a highly non-linear relationship. They argue that yields increase with temperature until about 84ºF for corn and soybeans and 91ºF for cotton, and that temperatures above these thresholds are harmful. They estimate that the slope of the decline above the optimum is significantly steeper than the incline below it.

In crop yield studies, attention has been focused on mean and variance, but higher moments of crop yield distribution, particularly the skewness, have also been studied. Gallagher (1986, 1987) presents evidence of skewed distributions for soybean and corn yields. He indicates that both corn and soybean yields are negatively skewed, and suggests that this is caused by a relatively high chance of occasional low yields and an upper limit defined by technology and plant biology. Atwood et al. (2002) examine whether residual crop yields of the state and regional level are normally distributed, and find that normality of yield residuals is consistently rejected for state and regional level samples.

Climate change likely effects the higher order moments of crop yield distributions. For example, the increasing frequency of extreme events can have adverse impacts on crop yields, rendering the yield distribution more negatively skewed. On the other hand, in some areas, higher temperature (in cold regions) might improve productivity and cause distributions to be positively skewed. There are few studies that investigate the link between climate change and skewness or other higher order moments provide a reference if there are some. In this study, we will quantitatively investigate this issue examining the effects of climate on the first four moments of the US crop yield distributions. Subsequently we will examine how climate change projections would affect the future moments of selected crop yield distributions across multiple crops and locations.

Panel Data Set for Estimation

To investigate climate effects on the moments of yield distributions a statistical panel data approach will be employed. Here data from 1981 to 2008 are used at the climate division (CD) level amounting to 344 regions in the continental US. Climate divisions are those defined by the National Oceanic and Atmospheric Administration - Climate Prediction Center (NOAA-CPC). Two types of data are needed, those on climate and those on yields.

For climate, all data except that for precipitation intensity were collected at the U.S. climate division level for the growing season. Producers in the southern states plow and harvest crops earlier than producers in the northern states and these times vary by crop. Thus data will be collected for different growing seasons using the season definitions given in table 1. The climate data collected were temperature, precipitation, the number of days where the minimum temperature was less than 32 °F (DT32), the number of days where the maximum temperature was greater than 90 °F (DT90), and the Palmer Drought Severity Index (PDSI). The data were all drawn from the NOAA - National Climate Data Center (NCDC). To develop a measure on the intensity of precipitation, we follow IPCC, 2007 and compute the ratio of total precipitation from the top 5% of the days with the highest amount of precipitation to the annual total

Table 1 Growing Season by States

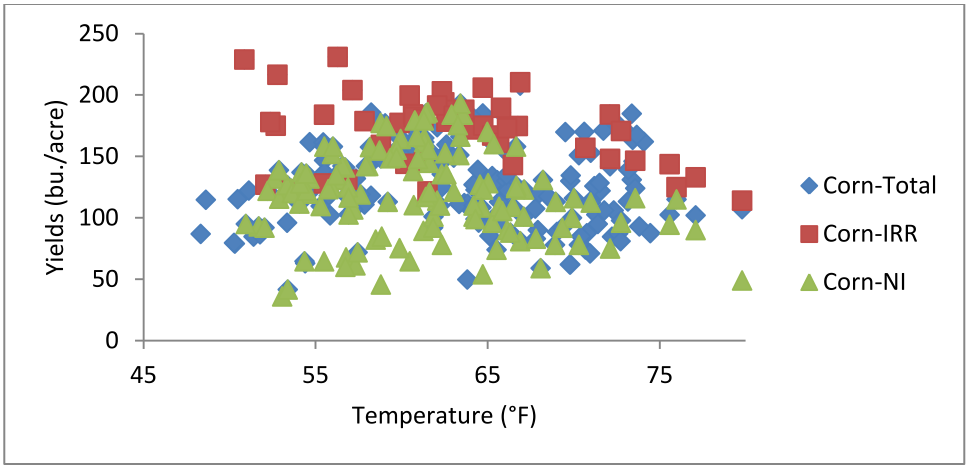
Growing season	States
Corn	
Mar-Oct	AL, AZ, AR, FL, GA, LA, MS, NM, NC, SC, TN, TX
Apr-Nov	CA, CO, CT, DE, IL, IN, IA, KS, KY, MN, MO, NE, NV, NJ, OK, RI, UT, VA, WV, WY
Apr-Dec	OH, PA
May-Dec	ID, MA, MD, MS, MI, MT, NH, NY, ND, OR, SD, VT, WA, WI
Upland Cotton	
Apr-Nov	LA, MS, MO
Apr-Dec	AL, AZ, AR, CA, FL, GA, NM, NC, OH, PA, SC, TN, TX, VA
May-Dec	CO, IL, IN, IA, KS, KY, NE, NV, OK
Sorghum	
Mar-Nov	TX
Apr-Oct	AL, AR, GA, LA, MS, SC
May-Nov	CA, CO, DE, IL, IN, IA, KS, KY, MD, MN, MO, MT, NE, NC, ND, PA, SD, TN, VA, WY
May-Dec	AZ, NM, OK
Soybeans	
Apr-Nov	AL, AR, FL, LA, MS, OK, TX
May-Nov	DE, IL, IN, IA, KS, KY, MD, MI, MN, MO, NE, NJ, NY, ND, OH, PA, SD, VA, WA, WI
May-Dec	GA, NC, SC, TN
Winter Wheat	
Sep-Jun	FL, GA
Sep-Jul	AL, AZ, CO, DE, IL, IN, IA, KS, KY, LA, MD, MS, MO, NE, NV, NJ, NM, NC, OH, OK, PA, SC, TN, TX, UT, VA, WY
Sep-Aug	ID, MI, MN, NY, ND, OR, SD, VT, WA, WI
Oct-Jul	AR, CA

Table 2 Statistical Characteristics of Variables

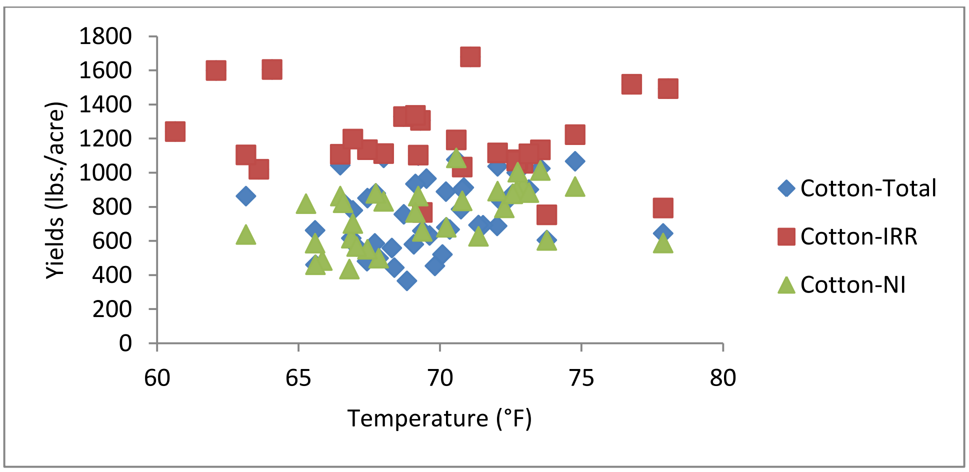
Variable	Mean	Std. Dev.	Min	Max
Corn (Obs.=5992)				
Crop yields	109.550	33.900	19.100	235.500
Temperature	61.532	7.201	43.275	81.388
DT32[a]	36.230	26.024	0.000	110.297
DT90[b]	37.977	29.655	0.000	170.941
Precipitation	26.980	9.791	2.940	68.190
PDSI	0.459	2.145	-8.061	9.304
Prec. Intensity	0.172	0.083	0.000	0.705
Irrigation rate	0.250	0.322	0.001	1.000
Upland Cotton (Obs.=1568)				
Crop yields	1.442	0.532	0.338	3.550
Temperature	68.777	3.759	58.278	79.000
DT32	19.038	13.548	0.000	69.263
DT90	78.905	30.544	11.750	182.231
Precipitation	30.617	12.842	0.990	69.160
PDSI	0.170	1.899	-4.953	7.374
Prec. Intensity	0.164	0.077	0.000	0.669
Irrigation rate	0.331	0.311	0.011	1.000
Sorghum (Obs.=1512)				
Crop yields	60.902	19.633	8.000	121.098
Temperature	66.974	5.156	52.229	80.167
DT32	20.775	16.004	0.000	67.815
DT90	61.844	29.231	5.158	172.156
Precipitation	24.288	8.191	6.920	52.550
PDSI	0.645	2.089	-5.599	9.277
Prec. Intensity	0.161	0.075	0.000	0.669
Irrigation rate	0.105	0.076	0.000	0.428
Soybeans (Obs.=4340)				
Crop yields	32.427	9.139	9.400	57.900
Temperature	64.159	4.952	50.314	77.825
DT32	22.529	12.707	0.000	68.083
DT90	37.764	27.133	0.000	125.618
Precipitation	27.610	7.943	7.500	62.200
PDSI	0.584	2.055	-5.916	9.513
Prec. Intensity	0.174	0.081	0.000	0.705
Irrigation rate	0.070	0.115	0.000	0.654

Table 2 Continued

Variable	Mean	Std. Dev.	Min	Max
Winter Wheat (Obs.=5572)				
Crop yields	45.030	15.086	8.000	120.400
Temperature	51.811	6.619	35.125	72.818
DT32[a]	115.488	47.188	3.410	219.830
DT90[b]	27.040	20.435	0.000	154.030
Precipitation	33.450	13.074	2.670	85.160
PDSI	0.430	2.045	-6.392	9.532
Prec. Intensity	0.169	0.083	0.000	0.705
Irrigation rate	0.059	0.124	0.000	1.000



(a) Corn



(b) Upland Cotton

Figure 1 Crop yields in total vs. irrigated vs. non-irrigated precipitation again at the CD level.

Crop yield data for the yields of corn, cotton, sorghum, soybeans, and winter wheat were obtained from the United States Department of Agriculture – National Agricultural Statistics Service (USDA-NASS) for counties and agricultural districts which are defined by NASS. In the data set, some counties are in multiple climate divisions and those counties are categorized in the climate division that contains largest amount of area in the county. In terms of crop yields, we use total average crop yield data. However some acreage may be irrigated and, as figure 1 displays, there are positive irrigation effects. Hence, to reflect the irrigation effect we include a measure of the proportion of irrigated lands n the model. The irrigated proportion is calculated by dividing acreage irrigated by total harvested acreage. For years when acreage irrigated data are not available, we assume that the irrigation rate is changed proportionally. The acreage data were obtained from USDA-NASS. Statistical characteristics of variables are presented in table 2.

Model Specification

Flexible Moment-based Approach

Most studies that estimate climate effects on mean and variability of crop yields employ the Just-Pope production function model (Just and Pope, 1978; Chen et al., 2004; McCarl et al., 2008). However, the Just-Pope model only estimates the mean and variance and does not consider skewness or higher moments. Hence, to examine the effects of climate change on the higher order moments of crop yield distributions, we use a linear moment model (LMM) introduced by Antle (1983) to estimate not only mean of output, but the higher moments as functions of inputs. LMM is sufficiently flexible to relax the restrictions implied by conventional production function specifications (Antle 1983). So LMM is also called a flexible moment-based approach.

The basic concept of the flexible moment-based approach is that the production function is specified as a term that gives the relationship between exogenous variables and the mean output level, the first moment, and while there is a second function used that gives the relationship between exogenous variables and the higher moments of output such as variability, skewness, and kurtosis.

The LMM is defined as follows. The mean function is

(1) $$y_j = X_j\gamma_1 + u_j, j = 1, \dots, N.$$

where y_j is crop yield in the jth location, X_j is a vector of independent explanatory variables that potentially influence crop yields, and u_j is a heteroskedastic disturbance term with a mean of zero. Then the ith moment function is

(2) $$u_j^i = X_j\gamma_i + v_{ij}, E(v_{ij}) = 0, i \geq 2, j = 1, \dots, N$$

so that the LMM contains a different parameter vector γ_i for each moment function.

To estimate the function Antle uses a three-step feasible Generalized Squares method (1981). In the three-step FGLS method, using $\hat{u}^i$ and $\hat{u}^{2i}$, which are estimated from the i^{th} and $2i^{th}$ moment functions, he construct estimates of covariance matrix, Ω_i, $\hat{\Omega}_i$, and compute the feasible GLS estimators,

(3) $\tilde{\gamma}_1 = \left(X'\widehat{\Omega}_1^{-1}X\right)^{-1} X'\widehat{\Omega}_1^{-1}y$

(4) $\tilde{\gamma}_i = (X'\widehat{\Omega}_i^{-1}X)^{-1}X'\widehat{\Omega}_i^{-1}\hat{u}_i\,, i \geq 2\,,$

where $\widehat{\Omega}_1$ is defined as the diagonal matrix of the $\hat{u}^2$ and $\widehat{\Omega}_i, i \geq 2,$ as the diagonal matrix of the $[\hat{u}^{2i} - \left(\hat{u}^i\right)^2]$.

This procedure, feasible GLS, provides consistent estimates of γ. However, Beck and Katz (1995) show the feasible GLS method produces standard errors that lead to extreme overconfidence in panel models with heteroskedastic and contemporaneously correlated errors, and suggest an alternative estimator of the standard errors, panel-corrected standard errors (PCSEs). In the model **Ω** is an NT × NT block diagonal matrix with an N × N matrix of contemporaneous covariances, Σ, along the diagonal. An element of Σ can be estimated from

(5) $\hat{\Sigma}_{i,j} = \frac{\sum_{t=1}^{T} e_{i,t}e_{j,t}}{T},$

where $e_{i,t}$ is the OLS residual for panel *i* at time *t*.

The estimation procedure we use is

1. Using OLS, estimate the mean function, $y = X\beta + u$, and compute the residuals û.
2. Using the PCSE method, regress ln$\hat{u}^2, \hat{u}^3$ and $\hat{u}^4$ against the vector X of independent variables to develop estimates for the second, third, and fourth moments.
3. Compute the predicted value of ln$\hat{u}^2$, $\widehat{ln\hat{u}^2}$, and take the antilogarithm.
4. Estimate the mean function by weighted PCSE using the square root of the predicted variances as weights.

In the estimation, the dependent variable y is crop yields (for corn, upland cotton, sorghum, soybeans, and winter wheat) and we use the independent variables:

- growing season mean temperature, TMP in degrees Fahrenheit,
- growing season total precipitation, PCP in inches,
- squares of TMP and PCP
- time trend, t,
- counts of days exhibiting extreme temperature - days above 90 °F and days below 32 °F during the growing season, DT32 and DT90,
- the Palmer drought index, PDSI which has negative values when droughts occur and positive values when conditions are wet,
- precipitation intensity, INT which is percent of rain from 5% wettest days,
- irrigation rate, IRR which is proportion of irrigated crop land for each crop in the climate division,
- regional dummies for the regions defined in table 3, Ds, and
- interaction terms between temperature and the regional dummies.

The full equation for estimation is,

$$y_{it} = \beta_0 + \beta_1 Trend_t + \beta_2 TMP_{it} + \beta_3 TMP^2_{it} + \beta_4 DT32_{it} + \beta_5 DT90_{it} + \beta_6 PCP_{it} + \beta_7 PCP^2_{it} + \beta_8 PDSI_{it} + \beta_9 INT_{it} + \beta_{10} IRR_{it} + \beta_{11} D2_i + \beta_{12} D3_i + \beta_{13} D4_i + \beta_{14} D5_i + \beta_{15} D6_i + \beta_{16} D7_i + \beta_{17} D2_i \times TMP_{it} + \beta_{17} D2_i \times TMP_{it} + \beta_{18} D3_i \times TMP_{it} + \beta_{19} D4_i \times TMP_{it} + \beta_{20} D5_i \times TMP_{it} + \beta_{21} D6_i \times TMP_{it} + \beta_{22} D7_i \times TMP_{it} \quad (6)$$

where y is crop yield, $ln\hat{u}^2$, $\hat{u}^3$, and $\hat{u}^4$ for each moment functions.

Table 3 Definition of Regions

Region	States
D1-Central	IN, IL, IA, MI, MO, MN, OH, WI
D2-Northeast	CT, DE, ME, MD, MA, NH, NJ, NY, PA, RI, VT
D3-Southeast	AL, FL, GA, KY, NC, TN, VA, WV
D4-North Plains	KS, NE, ND, SD
D5-South Plains	AR, LA, MS, OK, TX
D6-Mountains	AZ, CO, ID, MT, NV, NM, UT, WY
D7-Pacific	CA, OR, WA

Panel Model Specification Tests

For accurate estimation, we need to know if there exists a cointegration in the data. When a linear combination of nonstationary random variables is stationary, the variables combined are said to be cointegrated. The notion of cointegration arose out of the concern about spurious or nonsense regressions in time series. In a model which includes two variables which are dominated by smooth, long term trends, it is possible to choose coefficients which make the data appear to be stationary. In fact, if the two series are both nonstationary, then we will often reject the hypothesis of no relationship between them even when none exists.

To test stationarity, we use the unit-root tests for panel data developed by Im et al. (2003) and Levin et al. (2002). The test results are given in table 4. According to the test results, the null hypothesis that all the panels contain a unit root is rejected. That is, the data are stationary and differencing is not required. We also test for serial correlation using the Wooldridge test for serial correlation in panel-data models (2002). Wooldridge's method uses the residuals, $\Delta\varepsilon_{it}$, from a regression in first-differences. The procedure regresses the residuals on their lags and tests that the coefficient on the lagged residuals is equal to -0.5 (Drukker, 2003). As presented in table 5, the mean yield models are serially correlated except sorghum. For the second and third moments, test results are not consistent. When serial correlation exists in data set, we apply AR(1) method in estimating the model.

Another standard assumption in panel data model estimation that the error terms are independent across cross sections. With a large number of time periods T and a small

Table 4 Unit-root Test Results

	Corn	Upland Cotton	Sorghum	Soybeans	Winter Wheat
Levin-Lin-Chu [a]					
Crop yield	-10.691	-2.500	-8.989	-14.548	-12.003
	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)
Temperature	-29.189	-15.701	-12.675	-26.776	-30.993
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
DT32	-27.063	-14.198	-12.870	-22.080	-25.340
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
DT90	-37.027	-13.777	-15.127	-33.327	-31.036
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Precipitation	-27.622	-16.419	-16.060	-28.329	-24.647
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
PDSI	-24.219	-15.118	-13.232	-23.297	-24.460
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Prec.Intensity	-27.045	-15.642	-11.481	-19.012	-26.829
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Im-Pesaran-Shin [b]					
Crop yield	-25.446	-14.411	-17.516	-25.219	-26.176
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Temperature	-36.821	-19.381	-18.573	-32.323	-35.822
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
DT32	-39.367	-24.090	-22.300	-36.303	-35.849
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
DT90	-40.996	-20.974	-19.565	-34.930	-39.226
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Precipitation	-38.047	-20.946	-19.560	-34.132	-40.817
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
PDSI	-31.658	-17.398	-16.256	-27.836	-28.083
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Prec.Intensity	-36.176	-19.438	-18.498	-30.628	-34.530
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)

Note: [a]Adjusted t*statistics from Levin-Lin-Chu panel unit root test with the null hypothesis of nonstationarity and p-value in the parenthesis

[b]Z-t-tilde bar statistics from Im-Pesaran-Shin panel unit root test with the null hypothesis of nonstationarity and p-value in the parenthesis

Table 5 Serial-correlation Test Results[a]

	Corn	Cotton	Sorghum	Soybeans	Wheat
Mean Yields					
F(df1, df2)	36.76 (1, 213)	4.158 (1, 55)	3.350 (1, 53)	6.017 (1, 154)	0.674 (1, 198)
Prob > F	0.0000	0.0463	0.0728	0.0153	0.4125
ln$\hat{u}^2$					
F(df1, df2)	5.413 (1, 213)	0.026 (1, 55)	0.099 (1, 53)	1.085 (1, 154)	0.894 (1, 198)
Prob > F	0.0209	0.8715	0.7548	0.2992	0.3454
$\hat{u}^3$					
F(df1, df2)	0.116 (1, 213)	12.11 (1, 55)	4.813 (1, 53)	4.452 (1, 154)	53.33 (1, 198)
Prob > F	0.7337	0.0010	0.0326	0.0365	0.0000
$\hat{u}^4$					
F(df1, df2)	2.708 (1, 213)	27.49 (1, 55)	5.817 (1, 53)	3.594 (1, 154)	242.4 (1, 198)
Prob > F	0.1013	0.0000	0.0194	0.0599	0.0000

Note: [a]Wooldridge test for autocorrelation in panel data with the null hypothesis of no first-order autocorrelation.

Table 6 Cross-sectional Correlation Test Results[a]

	Corn	Cotton	Sorghum	Soybeans	Wheat
Frees'					
Mean yield	6.061[b]	3.646[b]	2.193[b]	6.74[b]	9.483[b]
ln $\hat{u}^2$	1.681[b]	0.836[b]	0.531[b]	1.981[b]	2.264[b]
$\hat{u}^3$	11.953[b]	4.306[b]	3.52[b]	6.032[b]	8.668[b]
$\hat{u}^4$	1.681[b]	0.836[b]	0.531[b]	1.981[b]	2.264[b]
Pesaran's					
Mean yield	78.459[b]	42.72[b]	26.052[b]	73.359[b]	88.477[b]
ln $\hat{u}^2$	6.733[b]	2.241[c]	-0.307	6.108[b]	4.465[b]
$\hat{u}^3$	76.203[b]	38.511[b]	21.064[b]	56.129[b]	64.083[b]
$\hat{u}^4$	6.733[b]	2.241[c]	-0.307	6.108[b]	4.465[b]
Friedman's					
Mean yield	522.197[b]	316.666[b]	202.923[b]	528.282[b]	621.031[b]
ln $\hat{u}^2$	87.614	61.363	31.523	86.976	85.167
$\hat{u}^3$	978.842[b]	352.678[b]	282.784[b]	522.161[b]	574.099[b]
$\hat{u}^4$	87.614	61.363	31.523	86.976	85.167

Note: [a]Testing the null hypothesis of cross-sectional independence in panel-data models
[b] The null is rejected in 99% confidence level.
[c] The null is rejected in 95% confidence level.

sample size N, the Lagrange multiplier test statistic proposed by Breusch and Pagan (1980) can be used to test for cross-sectional independence. However, in our case, the numbers of observations in the sample, N, are 214 for corn, 56 for upland cotton, 54 for sorghum, 155 for soybeans, and 199 for winter wheat, and the number of estimated parameters T is 28 for all crops. Even in the sorghum case with the smallest group size, N is much larger than T. In the case with small T and large N, the Breusch-Pagan test is not appropriate. For such a case, Friedman (1937), Frees (1995, 2004), and Pesaran (2004) propose the testing methods to test the hypothesis of cross-sectional independence in panel-data models with small T and large N. We apply those three methods to test cross sectional independence and the test results are presented in table 6. In most cases, the null hypothesis of cross sectional independence is rejected and the test results indicate that models are correlated across cross sections. To take account of the cross-sectional correlation, we use PCSEs in estimation.

Estimation Results

Now we turn to estimation results for the crop yield distribution moments.

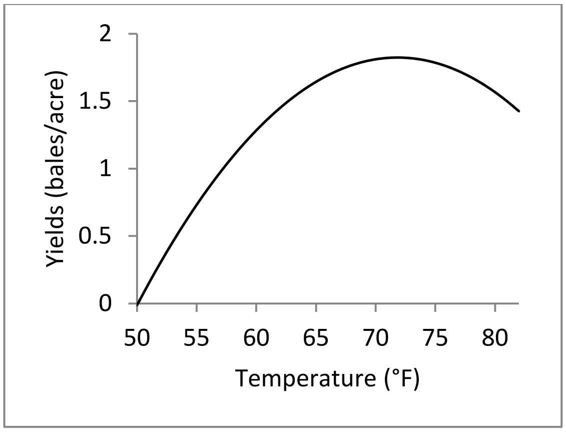
Mean Yields

The estimated coefficients of the mean yield regression from the second-stage PCSE with predicted standard deviations as weights are provided in table 7.

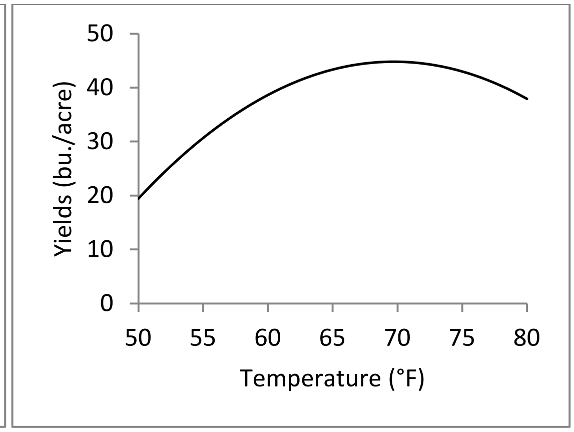
The yields of all crops but sorghum, (corn, upland cotton, soybeans, and winter

Table 7 Yield Mean Regression (Second-staged PCSE with Predicted Standard Deviations as Weights)

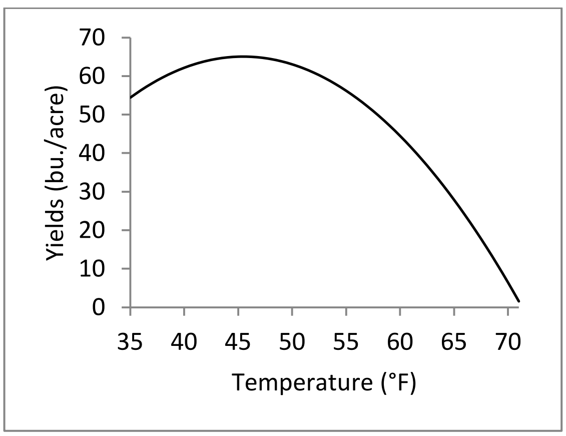
	Corn		Cotton		Sorghum		Soybeans		Wheat	
	Coef.	z	Coef.	z	Coef.	z	Coef.	z	Coef.	z
Trend	1.3339	8.89	0.0132	3.96	0.3276	3.73	0.3194	7.00	0.5732	9.87
TMP	7.3932	2.65	0.5535	4.05	1.6239	0.41	9.0820	5.17	8.8456	9.38
TMP^2	-0.0377	-1.54	-0.0039	-4.33	0.0048	0.17	-0.0651	-4.54	-0.0973	-9.29
DT32	-0.0795	-0.80	0.0001	0.02	0.0839	0.71	0.0374	0.84	-0.1104	-3.55
DT90	-0.9021	-14.08	-0.0086	-6.53	-0.4812	-10.75	-0.2308	-11.66	0.0424	1.14
PCP	0.1020	0.34	0.0012	0.18	1.0222	2.98	0.4045	3.06	0.7028	4.75
PCP^2	-0.0073	-1.68	-0.0001	-0.69	-0.0209	-3.66	-0.0072	-3.83	-0.0093	-5.02
PDSI	0.9101	2.86	0.0045	0.55	0.9863	3.09	0.2143	1.57	-0.3347	-1.89
INT	1.6456	0.31	-0.2782	-1.65	0.2643	0.04	0.2818	0.13	-0.3406	-0.09
IRR	27.5598	5.02	0.5703	4.15	21.3315	2.41	6.9101	4.07	6.1211	2.99
D2	52.7168	2.15					25.8731	1.33	-39.5715	-4.08
D3	-38.2502	-0.98	-0.5326	-0.23	168.040	3.45	-10.0121	-0.67	-33.7622	-2.99
D4	-100.911	-4.09			-46.7383	-1.07	-19.5210	-1.79	12.0020	1.83
D5	-124.722	-1.89	-2.4592	-1.03	-83.4699	-1.82	-101.154	-3.96	-119.456	-6.42
D6	-113.496	-4.70	-7.6894	-3.07	-99.6920	-1.97			-49.2523	-5.59
D7	95.3798	2.14	-3.2581	-1.14					22.7165	1.78
Temp×D2	-1.1941	-2.79					-0.5212	-1.71	0.7720	3.82
Temp×D3	0.0751	0.12	0.0086	0.25	-2.7672	-3.84	0.0177	0.08	0.5731	2.64
Temp×D4	1.6295	3.64			0.6092	0.92	0.2997	1.69	-0.4549	-3.26
Temp×D5	1.4768	1.50	0.0369	1.03	0.9628	1.41	1.3722	3.60	1.9321	5.77
Temp×D6	2.2794	5.72	0.1234	3.32	1.1659	1.47			0.9851	5.30
Temp×D7	-0.8974	-1.26	0.0665	1.55					-0.1652	-0.62
Constant	-178.373	-2.15	-18.1597	-3.35	-46.1590	-0.32	-280.244	-5.13	-154.859	-6.67
Wald χ^2 *(df)*	1813.96 (22)		770.03 (18)		911.56 (18)		685.99 (18)		2940.11 (22)	
Prob > χ^2	0.0000		0.0000		0.0000		0.0000		0.0000	



(a) Upland cotton

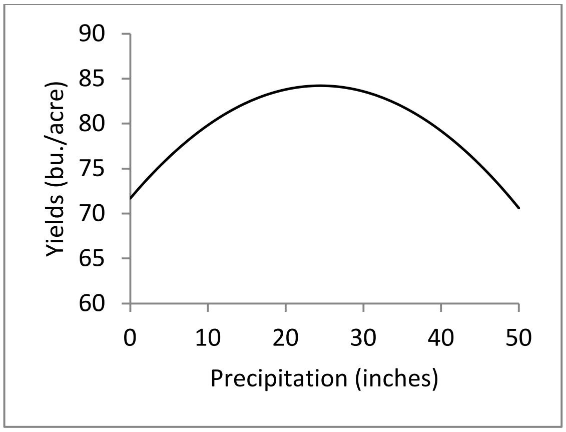


(b) Soybeans

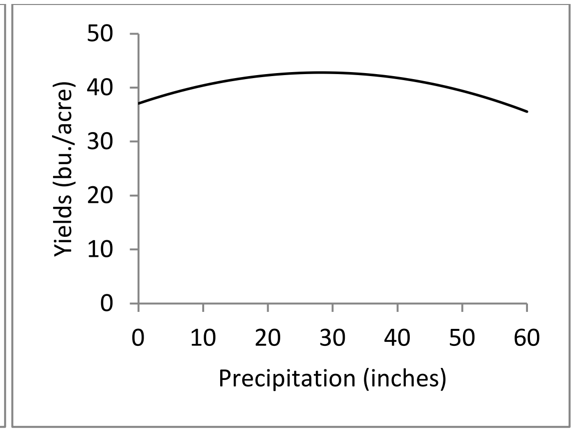


(c) Winter wheat

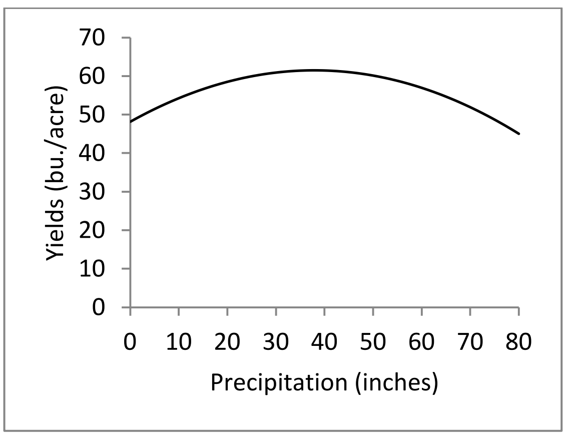
Figure 2 Temperature effects on crop yields



(a) Sorghum



(b) Soybeans



(c) Winter wheat

Figure 3 Precipitation effects on crop yields wheat) are found to be affected to mean temperature in the growing period. The results show that corn yield is linearly correlated to temperature, while higher temperatures are found to cause yields of upland cotton and soybeans to increase at a decreasing rate. We find as did Schlenker and Roberts that when temperature is high, the yields decline with a peak occurring at 71°F for upland cotton and 69°F for soybeans. In case of winter wheat, we found, yield is negatively correlated with temperature in these temperature ranges likely because of the low temperature peak (figure 2). We find that the incidence of days with extreme temperatures have negative impacts on crop yields. The signs on the coefficients for the number of days with maximum temperature greater than or equal to 90°F are negative for all crops except for winter wheat. For winter wheat, the sign on the number of days with minimum temperature less than or equal to 32 °F is negative. This implies that most crops are damaged by extremely high or low temperatures.

As figure 3 shows, sorghum, soybeans, and winter wheat yields are sensitive to the total precipitation. The effect of precipitation on mean corn and upland cotton yields is not significant. For sorghum and soybeans, higher precipitation decreases crop yields. Yield of upland cotton increases with higher precipitation. The effect of an increase in the Palmer drought index (reflecting a lesser incidence of drought) is positive and significant for corn and sorghum. Hence, we find that yields of corn and sorghum increase in wet conditions or conversely decrease under drought. The coefficients on the irrigation ratio are positive for all crops. It suggests that increased incidence of irrigation is beneficial for all crop yields.

For winter wheat, comparing Central and Pacific regions, in North Plains, crop yield is less responsive to temperature, while in other regions, crop yield is lower and responds more to temperature. In North and South Plains, soybean yield are lower but are more sensitive to change in temperature. Sorghum in South Plains and upland cotton in Mountains also have lower yields but are more sensitive to temperature. For corn, in North Plain and Mountains regions, crop yield is lower and responds more to temperature, and vice versa in Pacific.

As expected, the coefficients on the deterministic time trend as a proxy of technical improvement are positive and significant for all crops. That indicates that technical improvement increases crop yields.

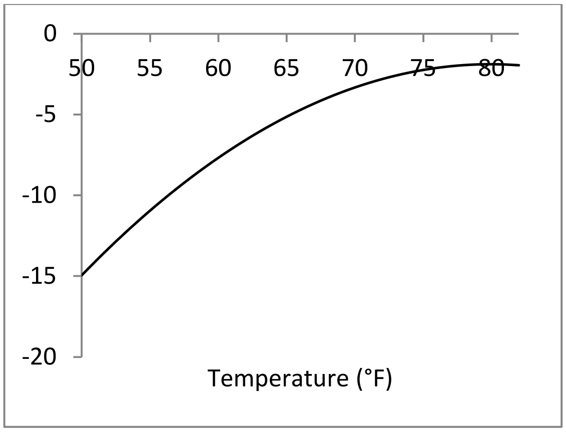
Variability

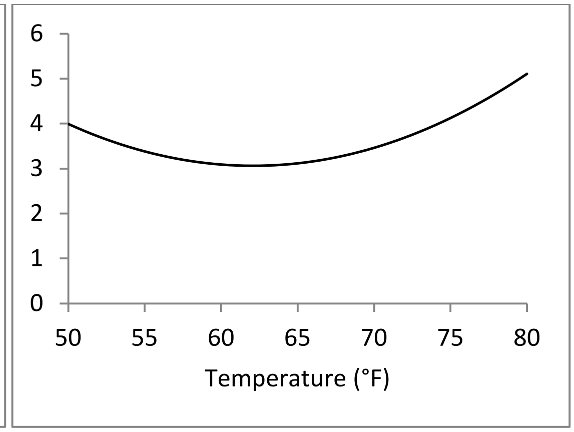
The regression results for the yield variance are presented in table 8. The interpretation of a positive coefficient in this table implies that an increase in the value of that variable leads to a higher yield variance. Notice that for all crops, the joint significance test rejects the null hypothesis that the variability of crop yields is not determined by the explanatory variables in the model, implying that variance of all crop yields is non stationary and that climate causes changes in yield variance.

The effects of temperature on yield variability differ by crop (figure 4). First of all, temperature has no significant effects on corn and sorghum yield variability. For soybeans, higher temperature decreases yield variability in the temperature range below 63°F but increases it for the temperature range above 63°F. In contrast, a higher

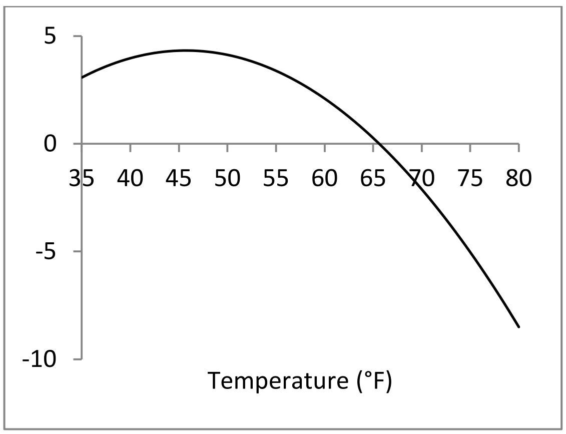
Table 8 Log Yield Variance ($ln\hat{u}^2$) Regression

	Corn		Cotton		Sorghum		Soybeans		Wheat	
	Coef.	z	Coef.	z	Coef.	z	Coef.	z	Coef.	z
Trend	0.0261	4.02	0.0107	1.06	0.0358	5.44	0.0303	4.81	0.0294	6.41
TMP	-0.2698	-1.35	2.3307	3.03	0.5005	0.67	-0.7895	-2.06	0.9987	5.78
TMP^2	0.0023	1.27	-0.0146	-3.20	-0.0041	-0.72	0.0064	1.98	-0.0109	-5.55
DT32	-0.0049	-0.70	0.0092	0.54	-0.0051	-0.37	0.0066	0.71	-0.0062	-1.37
DT90	0.0078	2.20	0.0137	2.16	0.0084	1.59	0.0152	3.19	0.0037	0.85
PCP	0.0320	1.42	-0.0079	-0.21	0.0455	1.02	-0.0628	-1.78	-0.0596	-3.04
PCP^2	-0.0005	-1.48	0.0000	0.09	-0.0003	-0.38	0.0009	1.69	0.0009	3.61
PDSI	-0.0254	-1.10	0.0166	0.41	-0.0306	-0.86	0.0058	0.21	-0.0625	-2.89
INT	-0.1670	-0.39	-1.6090	-1.79	0.3053	0.41	0.1237	0.20	0.7977	1.66
IRR	0.2610	0.65	-0.9259	-1.48	-1.3802	-1.04	0.3780	0.77	2.5157	6.56
D2	-4.3040	-2.17					-10.1886	-1.35	-2.3132	-1.20
D3	4.4974	1.48	18.2995	0.70	15.4379	1.66	3.4238	1.18	-10.7284	-3.51
D4	0.0998	0.07			1.5882	0.21	-5.6638	-3.19	1.6902	1.50
D5	5.9287	1.34	26.8900	1.03	-4.7782	-0.56	16.1519	2.76	-14.6157	-3.82
D6	5.1732	3.33	27.8851	1.07	0.5962	0.06			0.0948	0.06
D7	8.4566	4.04	23.3324	0.88					4.4632	2.30
Temp×D2	0.0735	2.16					0.1498	1.29	0.0274	0.67
Temp×D3	-0.0757	-1.61	-0.2667	-0.69	-0.2030	-1.47	-0.0628	-1.38	0.1951	3.33
Temp×D4	0.0004	0.02			-0.0152	-0.13	0.0898	3.14	-0.0504	-2.10
Temp×D5	-0.0918	-1.37	-0.3833	-0.99	0.0710	0.56	-0.2513	-2.90	0.2691	3.80
Temp×D6	-0.0919	-3.64	-0.3954	-1.02	-0.0039	-0.03			0.0233	0.68
Temp×D7	-0.1315	-3.63	-0.3284	-0.83					-0.0820	-2.02
Constant	11.6395	2.03	-95.6154	-2.69	-13.3176	-0.53	26.8942	2.33	-18.0505	-4.49
Wald χ^2 *(df*	200.10 (22)		118.57 (18)		231.52 (18)		201.19 (18)		2888.54 (22)	
Prob > χ^2	0.0000		0.0000		0.0000		0.0000		0.0000	



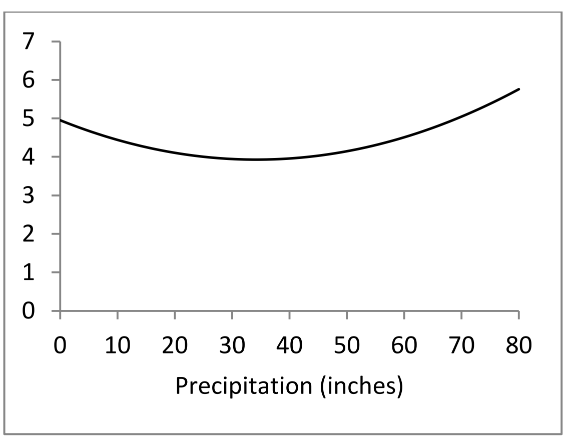


(a) Upland cotton (b) Soybeans



(c) Winter wheat

Figure 4 Temperature effects on $ln\hat{u}^2$



(a) Winter wheat

Figure 5 Precipitation effects on $ln\hat{u}^2$

temperature decreases the variance of winter wheat yield and increases that for upland cotton. Increases in the number of days with maximum temperature greater than or equal to 90°F increases the yield variance of corn, upland cotton and soybeans.

For winter wheat, increases in rainfall decrease yield variability in the range below 34 inches of total precipitation, but increases it above that (figure 5). That is, excessive high precipitation increases yield variability. The effects of precipitation on variability of corn, upland cotton, sorghum, and soybeans yields are statistically insignificant. Variability of winter wheat is reduced with a higher PDSI (lower incidence of drought), but increases with higher rainfall intensity and greater proportions of irrigated land.

For corn, Mountain, and Pacific regions have relatively high but less sensitive variability and Northeast has relatively low but more sensitive variability. In South Plain, soybeans variability is higher and less responsive to temperature, and vice versa in North Plain. For winter wheat, comparing with Central region, yields are less variable, but the variability is more closely correlated with temperature change in Southeast and South Plain, and vice versa in Pacific.

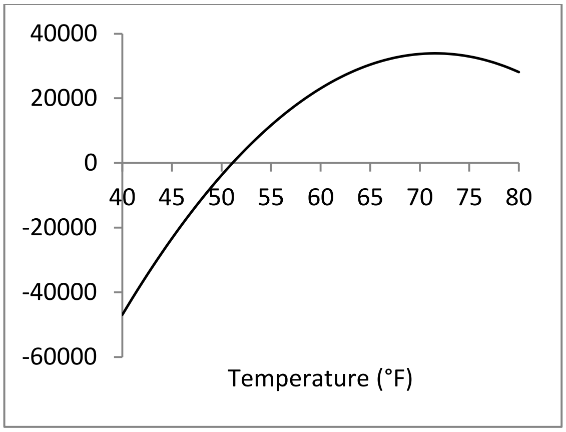
The variance of corn, sorghum, soybeans, and winter wheat are positively correlated with the time trend.

Skewness

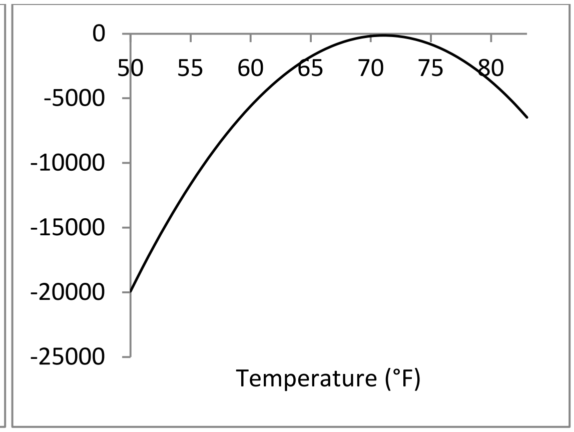
For the 3rd moment regression, we use cubes of the residuals from the OLS estimation at the first-stage as dependent variables. The regression results are presented in table 9. The

Table 9 $\hat{u}^3$ Regressions

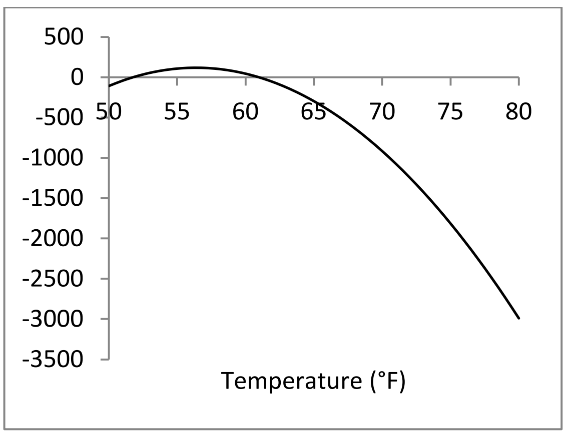
	Corn		Cotton		Sorghum		Soybeans		Wheat	
	Coef.	z	Coef.	z	Coef.	z	Coef.	z	Coef.	z
Trend	339.696	1.35	0.0016	1.28	34.2099	0.63	-2.0801	-0.36	-0.0554	0.00
TMP	11622.4	2.39	0.0854	1.20	6335.39	2.58	627.100	1.99	983.857	1.09
TMP^2	-81.2146	-1.84	-0.0008	-1.51	-44.5693	-2.47	-5.5621	-2.12	-13.5096	-1.36
DT32	461.932	2.21	-0.0012	-0.82	86.5510	1.41	-2.8685	-0.46	-36.2387	-1.73
DT90	713.926	4.71	0.0016	2.80	3.4061	0.13	4.9873	1.64	-40.4646	-1.61
PCP	-6717.65	-6.56	-0.0127	-2.21	85.474	0.42	-86.1423	-3.03	-116.304	-1.25
PCP^2	67.8144	5.25	0.0002	2.33	0.0748	0.02	1.1291	2.98	1.1848	1.08
PDSI	6368.17	6.28	0.0075	1.35	-188.573	-1.30	49.3646	1.96	79.0388	0.50
INT	-7730.66	-0.55	-0.0501	-0.52	1245.75	0.41	-18.1715	-0.06	-960.506	-0.38
IRR	-31043.9	-4.66	-0.0280	-0.57	-15728.4	-2.11	452.384	1.30	13362.3	2.11
D2	-11885.1	-0.31					-4617.53	-2.11	-7123.96	-1.55
D3	65347.3	1.03	-0.4548	-0.83	91052.0	2.17	-6649.83	-2.67	-25402.1	-2.62
D4	12319.9	0.27			61598.6	2.84	-680.340	-0.38	-7708.96	-1.88
D5	1122729	6.16	-0.7878	-1.31	-30369.4	-1.26	-9120.84	-1.95	-39677.7	-2.60
D6	126489	3.45	0.0319	0.04	44060.0	1.73			-70611.1	-1.40
D7	281743	5.40	0.2609	0.36					-6307.54	-0.29
Temp×D2	449.952	0.68					76.0784	2.21	135.951	1.42
Temp×D3	-934.812	-0.93	0.0067	0.83	-1182.90	-2.02	107.814	2.76	484.739	2.60
Temp×D4	-996.804	-1.27			-921.132	-2.73	3.8419	0.13	161.293	1.79
Temp×D5	-15789.3	-6.00	0.0116	1.31	479.039	1.31	142.616	2.04	725.140	2.61
Temp×D6	-3328.62	-5.08	-0.0017	-0.16	-620.843	-1.53			1644.50	1.39
Temp×D7	-5854.55	-6.28	-0.0069	-0.62					88.2403	0.20
Constant	-307224	-2.10	-2.0841	-0.84	-228812	-2.69	-16183.9	-1.71	-7479.29	-0.36
Wald χ^2 *(df*	246.09 (22)		19.94 (18)		38.34 (18)		31.22 (18)		63.45 (22)	
Prob > χ^2	0.0000		0.3361		0.0035		0.0271		0.0000	



(a) Corn

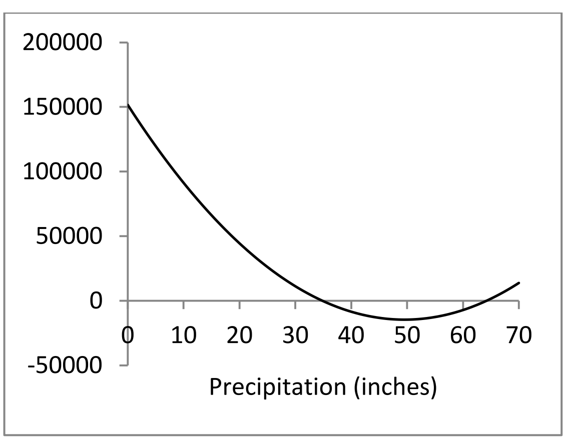


(b) Sorghum

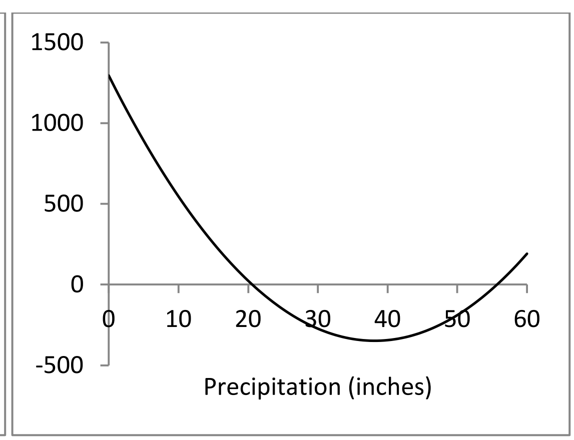


(c) Soybeans

Figure 6 Temperature effects on $\hat{u}^3$



(a) Corn



(b) Soybeans

Figure 7 Precipitation effects on $\hat{u}^3$

interpretation of a positive coefficient in this table implies that an increase in the associated variable leads the yield distribution to be more positively skewed, so negative results show a negative skew. Qualitatively, a negative skew indicates the left tail is longer, the mass of the distribution is concentrated on the right of the figure and it has relatively few low values. And a positive skew indicates that the right tail is longer, the mass of the distribution is concentrated on the left of the figure, and it has relatively few high values. As table 9 indicates, for upland cotton, the joint significant test fails to reject the null hypothesis that the skewness of crop yields is not determined by explanatory variables in the model. That is, the yield distribution of upland cotton is symmetric and unaffected by external factors.

For temperature, the coefficients for corn, sorghum, and soybeans have the same coefficient sign (figure 6). Skewness increases with higher temperature at a decreasing rate until it peaks at, 71°F for corn and sorghum and 57°F for soybeans, and decreases at temperatures above the peak. For corn, positive signs are found on the number of days with minimum temperature less than or equal to 32°F and the number of days with maximum temperature greater than or equal to 90°F meaning these factors contribute to a positive skew which has a long right tail and high possibility of values less than mean so relatively few high values.

For corn and soybeans, precipitation affects skewness (figure 7). Higher precipitation decreases the amount of skewness when precipitation is less than 50 and 38 inches for corn and soybeans, respectively, but increases when precipitation is above those levels. That is, extremely low or high rainfall makes the distribution more positively skewed. Wet conditions under the PDSI increase the positive skewness of the corn and soybean yield distributions. Irrigation ratio is negatively correlated with skewness of corn and sorghum, while it is positively related to skewness of winter wheat.

Comparing other regions, corn skewness is relatively high but less sensitive to change in temperature in South Plains, Mountain, and Pacific regions. Sorghum in the Southeast and North Plains has skewness which is higher but negatively correlated to temperature. For soybeans, in Eastern and South Plain regions, skewness is relatively low and more affected by temperature. For winter wheat, in Southern region, its skewness is lower but more sensitive to change in temperature.

Finally, the time trend and the rainfall intensity have no significant impact on the skewness of crop yield distributions.

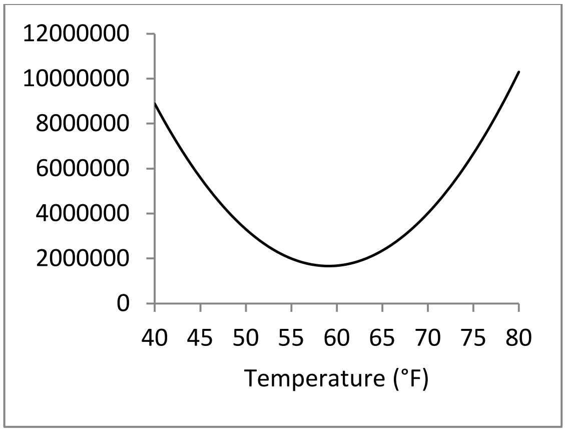
Kurtosis

The regression results for the kurtosis are presented in table 10. Here $\hat{u}^4$ were the dependent variable. The interpretation of a positive coefficient in this table implies that an increase in the associated variable leads to an increase in the amount of kurtosis of the yield distribution. A low kurtosis means and a low and even distribution with fat tails, whereas a high kurtosis means a distribution concentrated toward the mean with skinny tails.

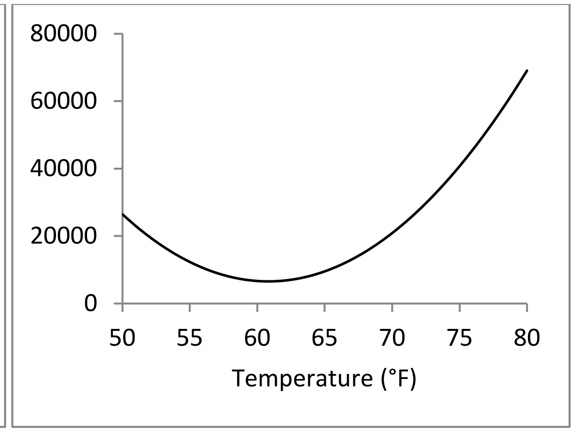
Temperature has no significant effects on upland cotton, sorghum, and winter wheat yield kurtosis. As figure 8 depicts, for corn and soybeans, a higher temperature

Table 10 $\hat{u}^4$ Regressions

	Corn		Cotton		Sorghum		Soybeans		Wheat	
	Coef.	z	Coef.	z	Coef.	z	Coef.	z	Coef.	z
Trend	44035.0	4.83	0.0033	2.20	3084.46	2.87	235.562	3.49	1582.68	1.44
TMP	-2339804	-5.99	0.2097	1.79	-132458	-1.73	-20690.6	-4.85	6053.49	0.09
TMP^2	19791.5	5.38	-0.0016	-1.84	847.147	1.47	170.101	4.71	-129.011	-0.17
DT32	-8762.12	-0.75	-0.0002	-0.14	-1536.55	-1.10	-40.3808	-0.46	-1406.68	-1.16
DT90	30231.6	3.51	0.0008	1.33	1223.59	1.99	116.855	2.42	-1678.45	-1.15
PCP	-428480	-4.67	-0.0158	-2.11	4927.31	0.78	-1343.05	-2.12	-5735.36	-1.10
PCP^2	4689.56	4.38	0.0002	2.05	-39.0313	-0.32	16.8972	2.02	57.3203	0.96
PDSI	297579	3.83	0.0065	0.98	-11132.8	-3.35	473.995	1.06	3528.92	0.38
INT	-950575	-1.03	-0.0492	-0.42	35035.5	0.42	-1972.07	-0.44	-1018.57	-0.01
IRR	-755898	-1.38	-0.0592	-1.23	-131432	-0.60	-576.615	-0.11	1302479	2.15
D2	-201375	-0.11					113730	3.87	112191	0.65
D3	2.75e+07	6.17	-0.0991	-0.27	3914563	3.58	147449	4.37	-123842	-0.19
D4	-2.32e+07	-8.31			-1298779	-2.47	-153934	-5.97	-40946.9	-0.19
D5	1.15e+08	7.08	-0.4611	-0.75	-1001337	-1.78	396251	4.85	43365.5	0.04
D6	8101607	5.26	0.8238	1.25	-1316091	-2.01			-7315334	-1.97
D7	1.35e+07	4.66	0.3161	0.56					2979064	1.91
Temp×D2	14612.62	0.46					-1809.82	-3.91	-3200.66	-0.90
Temp×D3	-430224	-6.12	0.0016	0.29	-51878.3	-3.43	-2336.10	-4.41	2175.01	0.17
Temp×D4	380504	7.67			20744.9	2.55	2551.02	5.99	288.575	0.06
Temp×D5	-1634880	-7.05	0.0073	0.81	14987.6	1.75	-5855.61	-4.87	-843.144	-0.05
Temp×D6	-218583	-6.50	-0.0120	-1.26	20698.3	1.97			177893	2.03
Temp×D7	-306164	-5.70	-0.0071	-0.78					-59609.2	-1.87
Constant	7.67e+07	6.81	-6.6388	-1.69	4928147	1.93	649441	5.08	345050	0.21
Wald χ^2 *(df*	349.74 (22)		62.74 (18)		84.20 (18)		158.57 (18)		58.66 (22)	
Prob > χ^2	0.0000		0.0000		0.0000		0.0000		0.0000	

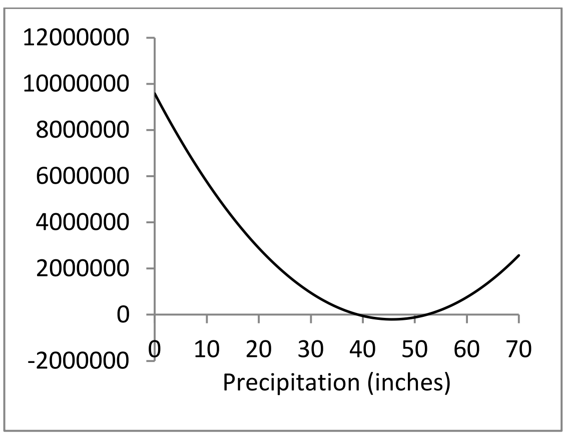


(a) Corn

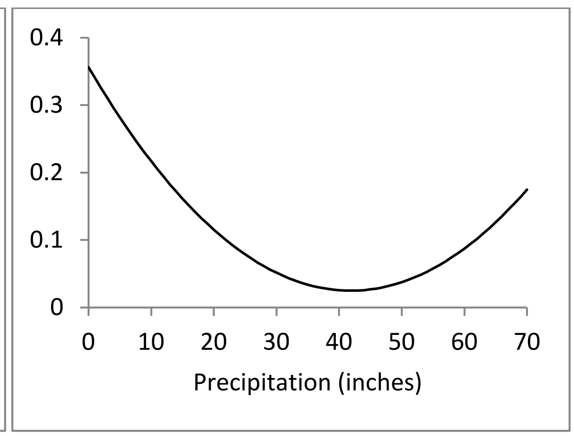


(b) Soybeans

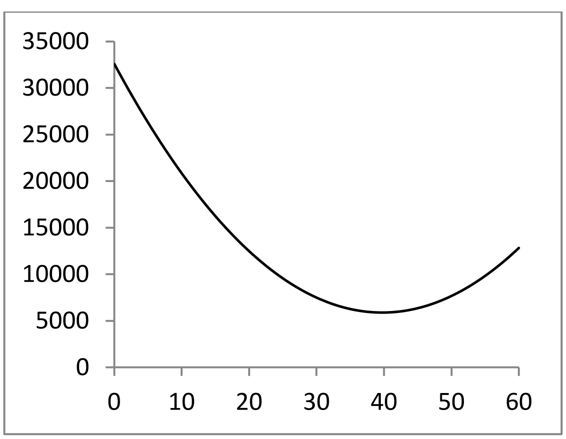
Figure 8 Temperature effects on $\hat{u}^4$



(a) Corn



(b) Upland cotton



(c) Soybeans

Figure 9 Precipitation effects on $\hat{u}^4$

decreases kurtosis in the temperature range below about 60°F but increases it under for the temperature range above the peak. Increases in the number of days with maximum temperature greater than or equal to 90°F increases the yield kurtosis of corn, sorghum and soybeans.

For corn, upland cotton, and soybeans, increases in rainfall decreases kurtosis in the range below 45.7, 39.5, and 39.5 inches of total precipitation respectively, but increases above that (figure 9). The effects of precipitation on kurtosis of sorghum and winter wheat yields are statistically insignificant. With a higher PDSI (lower incidence of drought), kurtosis of corn is increased and that of sorghum is decreased.

For corn, South Plain region exhibits the most sensitive kurtosis to temperature and North Plains has the least sensitive. In North Plain and Mountains, sorghum kurtosis is more responsive to temperature, and vice versa in Southeast. For soybeans, comparing with Central region, the kurtosis is more closely correlated with temperature change in North Plains, and vice versa in Eastern and South Plains. The kurtosis of corn, upland cotton, sorghum, and soybeans is positively correlated with the time trend.

Simulation

In this section, we evaluate the potential effects of future climate change projections on the yield distributions. To gauge the effects, we evaluate our estimated models under the climate change projections constructed for IPCC-2007 using the Centre National de Recherches Meteorologiques (CNRM), NOAA - Geophysical Fluid Dynamics

Laboratory (GFDL) and Meteorological Research Institute (MRI) models. Data for these projections were drawn from the IPCC Data Distribution Centre under SRES A1B scenario (2000). Each projection hereafter called GCM includes specific changes in regional precipitation and temperature (tables 11 and 12). To investigate the likely impacts of change in temperature and precipitation on future crop yield mean, variance, skewness, and kurtosis, these climate change projections are plugged into the estimated functions from the previous section.

The simulation results for mean crop yields are given in table 13. The projected changes differ by crop and region. The simulation results show that climate change will increase the mean yields of corn, upland cotton, sorghum, and soybeans nationally, while winter crop yields of wheat will decrease. For corn, the MRI projected climate change will decrease crop yield in Pacific region, while the GDFL and CNRM projections lead to a decrease in yields in eastern regions. In MRI and GDFL, upland cotton in Mountains and Pacific is expected to decrease and in CNRM, upland cotton in Pacific is expected to decrease. Sorghum will increase and winter wheat will decrease regardless of regions and GCMs except winter wheat in Mountains. Climate change will decrease soybeans in Pacific under MRI and in eastern regions under GDFL and CNRM. The simulation results for standard deviation of crop yields are given in table 14. Variability of soybeans will be increased and that of winter wheat will be decreased in most of regions except South Plains for soybeans and Mountains for winter wheat. The projected changes on variability for corn, upland cotton, and sorghum differ by GCMs and periods. For example, for sorghum, the MRI projected climate changes will decrease

Table 11 Percentage Changes in Temperature and Precipitation under Alternative Climate Change Projections from Global Circulation Models in 2040-2069

	Corn		Cotton		Sorghum		Soybeans		Wheat	
	TMP	PCP	TMP	PCP	TMP	PCP	TMP	PCP	TMP	PCP
CNRM: CM3										
Central	2.51	10.90	4.42	-5.43	3.13	5.11	2.97	6.95	6.59	6.34
Northeast	1.17	45.77			1.02	46.84	1.14	44.15	4.23	20.86
Southeast	1.21	37.43	2.04	31.60	0.14	41.16	1.16	26.17	3.52	1.76
N. Plains	5.87	51.18	7.32	17.91	4.72	53.82	4.72	53.82	17.80	42.93
S. Plains	4.04	10.05	2.98	1.49	3.45	8.80	2.97	1.08	6.07	-28.31
Mountains	3.98	66.15	-0.05	12.34	3.27	90.22			9.44	77.46
Pacific	4.79	-28.12	-3.29	-72.70	-0.61	-74.08	9.87	-47.45	1.52	5.49
GFDL: CM2.1										
Central	1.22	-16.02	5.94	-29.69	2.45	-28.90	2.42	-23.83	2.34	-5.76
Northeast	-4.42	20.01			-6.63	13.42	-4.26	13.46	-2.60	12.34
Southeast	-0.26	0.60	1.60	2.34	-0.49	-2.03	0.72	-4.72	-0.06	-11.55
N. Plains	7.11	-2.44	8.57	-1.73	6.86	-4.52	6.86	-4.52	16.11	10.88
S. Plains	4.75	-22.02	4.39	-27.53	5.24	-27.56	4.59	-30.35	3.59	-35.54
Mountains	0.06	59.52	-5.85	61.82	1.46	70.44			3.35	97.57
Pacific	3.08	-26.21	-7.19	-29.28	-3.59	-27.15	6.38	-42.81	-1.57	20.71
MRI: CGCM2.3										
Central	-0.20	-25.98	6.07	-34.12	0.70	-33.64	0.35	-30.13	4.81	-21.90
Northeast	0.33	-4.54			2.28	-11.26	-0.11	-9.97	4.66	-13.00
Southeast	1.57	-7.88	3.74	-4.16	0.30	-11.23	2.43	-12.87	5.21	-17.54
N. Plains	3.99	-1.64	4.31	6.31	2.98	-3.98	2.98	-3.98	15.79	5.57
S. Plains	3.83	-18.75	3.67	-19.18	3.63	-21.39	3.53	-23.53	7.71	-35.72
Mountains	1.77	11.26	-0.89	-10.29	2.80	25.27			7.29	33.58
Pacific	-4.03	-30.45	-5.48	-65.79	-2.31	-72.74	-6.45	-23.79	-0.89	-6.90

Table 12 Percentage Changes in Temperature and Precipitation under Alternative Climate Change Projections from Global Circulation Models in 2070-2099

	Corn		Cotton		Sorghum		Soybeans		Wheat	
	TMP	PCP	TMP	PCP	TMP	PCP	TMP	PCP	TMP	PCP
CNRM: CM3										
Central	7.15	5.00	9.61	-8.12	7.85	-3.18	7.32	0.07	13.25	3.88
Northeast	4.17	43.52			3.75	46.56	3.81	41.48	8.85	21.75
Southeast	4.70	34.93	5.90	32.76	3.84	38.86	4.88	26.53	8.11	2.74
N. Plains	10.77	44.98	12.80	8.97	9.39	46.57	9.39	46.57	24.07	38.76
S. Plains	8.44	1.92	7.61	-2.61	7.89	2.45	7.52	-4.30	11.51	-31.93
Mountains	8.09	66.46	3.18	15.51	7.22	88.90			14.65	76.94
Pacific	8.27	-17.53	-0.24	-76.74	2.48	-75.38	13.45	-39.98	6.02	9.73
GFDL: CM2.1										
Central	4.60	-11.37	8.53	-30.66	5.49	-26.09	5.61	-20.50	5.53	1.60
Northeast	-0.92	23.34			-3.34	17.66	-1.09	15.77	0.86	17.05
Southeast	2.63	5.49	4.44	8.54	2.19	3.40	3.41	0.79	2.82	-4.65
N. Plains	10.44	-4.03	11.58	-4.29	9.92	-7.18	9.92	-7.18	19.07	10.64
S. Plains	7.35	-22.03	6.81	-23.67	7.70	-25.24	6.94	-27.96	6.05	-33.34
Mountains	3.78	57.13	-2.16	51.16	5.00	69.77			6.92	95.13
Pacific	5.49	-26.12	-4.40	-43.73	-0.46	-48.26	8.29	-35.07	1.20	16.09
MRI: CGCM2.3										
Central	2.56	-25.94	8.60	-34.62	3.33	-34.99	3.04	-30.93	8.01	-19.09
Northeast	2.45	-2.60			4.17	-8.46	1.96	-6.86	7.01	-12.69
Southeast	3.68	-5.40	5.32	-0.51	2.08	-7.79	4.02	-9.57	7.28	-17.77
N. Plains	7.10	-6.12	6.96	1.86	5.96	-7.73	5.96	-7.73	19.28	5.28
S. Plains	6.05	-21.16	5.74	-22.08	5.67	-23.19	5.63	-27.55	10.31	-38.66
Mountains	4.45	13.82	1.30	-0.74	5.57	27.27			10.53	36.93
Pacific	-1.40	-22.84	-3.03	-57.76	0.04	-68.20	-4.03	-18.21	1.83	-0.64

Table 13 Change in Crop Yields under Alternative Climate Change Projections from Global Circulation Models

	2040 - 2069					2070 - 2099				
	Corn	Cotton	Sorghum	Soybeans	Wheat	Corn	Cotton	Sorghum	Soybeans	Wheat
MRI: CGCM2.3										
Central	0.0175	0.0392	0.0655	-0.0167	-0.0288	0.0300	0.0297	0.0846	0.0001	-0.0328
Northeast	0.0044			-0.0189	-0.0176	0.0122			-0.0132	-0.0205
Southeast	0.0005	0.0230		0.0030	-0.0393	0.0100	0.0250		0.0000	-0.0544
N. Plains	0.0285	0.0642	0.0598	0.0388	-0.1012	0.0524	0.0748	0.0921	0.0593	-0.1184
S. Plains	0.0480	0.0311	0.1236	0.0181	-0.1241	0.0507	0.0222	0.1428	0.0200	-0.1309
Mountains	0.1102	-0.1445	0.3272		0.1597	0.1167	-0.0432	0.3465		0.1300
Pacific	-0.0148	-0.1401		-0.1481	-0.0048	-0.0049	-0.0652		-0.0747	-0.0133
GFDL: CM2.1										
Central	0.0205	0.0380	0.0592	0.0114	-0.0098	0.0323	0.0291	0.0859	0.0237	-0.0175
Northeast	-0.0335			-0.0145	-0.0148	-0.0122			0.0017	-0.0125
Southeast	-0.0223	-0.0039		-0.0070	0.0100	-0.0047	0.0126		-0.0077	-0.0224
N. Plains	0.0719	0.1031	0.1466	0.0711	-0.1001	0.0846	0.0933	0.1750	0.0767	-0.1070
S. Plains	0.0570	0.0292	0.1550	0.0158	-0.0903	0.0594	0.0170	0.1838	0.0219	-0.0925
Mountains	0.1079	-0.2484	0.2849		0.1722	0.1286	-0.0672	0.3439		0.1446
Pacific	0.0102	-0.1892		0.0752	0.0015	0.0154	-0.0970		0.0886	-0.0117
CNRM: CM3										
Central	0.0088	0.0277	0.0303	0.0216	-0.0179	0.0375	0.0196	0.0905	0.0315	-0.0466
Northeast	-0.0254			-0.0131	-0.0260	-0.0073			-0.0099	-0.0326
Southeast	-0.0425	-0.0017		-0.0267	-0.0538	-0.0121	0.0180		-0.0294	-0.0990
N. Plains	0.0253	0.0916	0.1172	0.0549	-0.1207	0.0638	0.0922	0.1883	0.0758	-0.1781
S. Plains	0.0330	0.0235	0.1199	0.0125	-0.0831	0.0522	0.0215	0.1829	0.0277	-0.1315
Mountains	0.0809	0.0465	0.2556		0.1866	0.1163	0.1371	0.3265		0.1507
Pacific	0.0210	-0.0809		0.1147	-0.0142	0.0258	-0.0048		0.1302	-0.0375

Table 14 Change in Standard Deviation under Alternative Climate Change Projections from Global Circulation Models

	2040 - 2069					2070 - 2099				
	Corn	Cotton	Sorghum	Soybeans	Wheat	Corn	Cotton	Sorghum	Soybeans	Wheat
MRI: CGCM2.3										
Central	0.0068	1.0257	-0.2040	0.1573	-0.1766	0.0212	1.4991	-0.2231	0.1884	-0.2219
Northeast	0.0337		-0.0837	0.1166	-0.2307	0.0988		-0.0992	0.2664	-0.3021
Southeast	0.0037	-0.0187	-0.0641	0.1918	-0.1950	-0.0046	0.0143	-0.2051	0.2523	-0.2350
N. Plains	-0.0029	0.8712	-0.0260	0.1179	-0.2794	0.0099	1.6218	-0.0633	0.2729	-0.3802
S. Plains	-0.0424	-0.1605	-0.1222	-0.0217	-0.2765	-0.0472	-0.2667	-0.1527	-0.0472	-0.3406
Mountains	-0.0162	-0.0071	0.0889		0.0247	-0.0846	0.0619	0.1042		-0.0332
Pacific	0.1453	-0.2891	-0.0781	0.3025	0.4272	0.0342	-0.1436	-0.0953	0.1779	0.2816
GFDL: CM2.1										
Central	0.0030	0.9917	-0.1610	0.0981	-0.0787	0.0240	1.4763	-0.1745	0.1442	-0.1010
Northeast	-0.1110		0.1133	-0.2368	0.1574	-0.0288		0.1217	-0.0916	0.1441
Southeast	0.0235	-0.0971	0.1573	0.1535	-0.1328	0.0032	-0.0448	-0.0799	0.2510	-0.1134
N. Plains	0.0291	2.1576	-0.0759	0.4100	-0.2890	0.0551	3.2810	-0.1243	0.6920	-0.3751
S. Plains	-0.0471	-0.2023	-0.1664	-0.0157	-0.2098	-0.0465	-0.3298	-0.1931	-0.0593	-0.2621
Mountains	0.0779	-0.2348	0.1784		-0.0397	-0.0166	-0.0876	0.1891		-0.0588
Pacific	-0.2019	-0.4047	-0.0042	0.0333	0.3696	-0.2650	-0.2339	-0.0621	-0.0164	0.2909
CNRM: CM3										
Central	0.0044	0.6804	-0.0018	0.0171	-0.0957	0.0512	1.6179	-0.1043	0.1261	-0.2692
Northeast	0.0328		0.1593	0.1457	-0.1392	0.1411		0.1113	0.4192	-0.3015
Southeast	-0.0417	-0.0545	0.1732	0.1069	-0.0513	-0.0498	0.0118	-0.1770	0.2260	-0.1360
N. Plains	0.0361	1.7069	0.1385	0.1913	-0.3349	0.0866	3.7271	0.0503	0.6195	-0.5114
S. Plains	-0.0130	-0.1300	0.0030	-0.0833	-0.2297	-0.0166	-0.3738	-0.1014	-0.1428	-0.3755
Mountains	-0.0363	-0.0473	0.2310		-0.0741	-0.1237	0.0016	0.2447		-0.1647
Pacific	-0.2447	-0.1510	-0.0959	0.0257	0.3102	-0.3205	0.0341	-0.1376	-0.0099	0.1005

Table 15 Change in the 3rd Moments, Skewness, under Alternative Climate Change Projections from Global Circulation Models

	2040 - 2069					2070 - 2099				
	Corn	Cotton	Sorghum	Soybeans	Wheat	Corn	Cotton	Sorghum	Soybeans	Wheat
MRI: CGCM2.3										
Central	1.0938	-0.2123	-1.0409	-0.4935	-0.9167	0.3616	-0.2618	-0.6574	-0.2585	-1.0948
Northeast	0.0332		0.0397	-0.0655	-0.3277	0.0329		0.1115	0.7400	-0.5314
Southeast	0.0504	-0.3702	-0.1961	-0.2076	0.4355	0.0220	-0.3583	-0.2579	-0.0484	0.3659
N. Plains	0.2850	-0.0756	-0.6474	-0.0069	-0.4571	0.2159	-0.0883	-0.7588	0.0652	-0.5343
S. Plains	-0.8321	-0.0307	0.0606	0.0643	0.0158	-1.1992	-0.0604	0.0998	0.0006	-0.1002
Mountains	-0.7644	0.0162	0.2354		0.5818	-0.5786	-0.0190	0.2406		0.4410
Pacific	-1.1490	-4.1769	0.0242	0.1104	-0.3962	-1.1872	0.4958	0.0093	0.1522	-0.4688
GFDL: CM2.1										
Central	0.8951	-0.2458	-0.7295	-0.3372	-0.6385	0.2406	-0.2863	0.1567	0.0602	-0.8036
Northeast	-0.3211		-2.7810	1.4873	0.3364	-0.1602		-0.0400	1.3974	-0.2241
Southeast	-0.0285	-0.3214	-0.2179	0.5866	0.1382	-0.0438	-0.3443	-0.2995	0.2422	0.1701
N. Plains	0.4373	-0.1496	-0.9522	0.1605	-0.4984	0.1760	-0.1731	-1.0471	0.2188	-0.5342
S. Plains	-1.2081	-0.0007	0.6555	0.0885	0.0550	-1.5904	-0.0724	0.1788	-0.0840	0.0362
Mountains	-1.4168	-0.0536	0.3452		0.4516	-1.1227	-0.0498	0.2896		0.3559
Pacific	-0.6060	-3.7610	0.0286	0.3634	-0.4317	-0.4830	0.4571	0.0097	0.3515	-0.5014
CNRM: CM3										
Central	0.0382	-0.2636	0.3728	0.1293	-0.9601	0.1030	-0.6084	0.7716	0.2343	-1.6093
Northeast	-0.3830		1.3245	3.1254	-0.2314	-0.1808		0.2566	3.0564	-0.9713
Southeast	-0.2210	-0.2641	-0.0036	0.4223	0.2412	-0.1386	-0.3322	-0.2941	0.2547	0.4493
N. Plains	-3.5932	-0.1709	-0.5600	0.3601	-1.2286	-0.6674	-0.2448	-0.8880	0.3921	-1.4902
S. Plains	-1.6549	-0.0686	-0.1983	-0.1072	0.0517	-2.2048	-0.1692	0.0533	-0.8472	-0.1085
Mountains	-1.3494	-0.0373	0.4363		0.6544	-1.1767	-0.0641	0.3341		0.5146
Pacific	-0.6083	-4.1441	0.0131	0.3559	-0.4639	-0.2029	0.5223	-0.0015	0.2604	-0.8097

Table 16 Change in the 4th Moments, Kurtosis, under Alternative Climate Change Projections from Global Circulation Models

	2040 - 2069					2070 - 2099				
	Corn	Cotton	Sorghum	Soybeans	Wheat	Corn	Cotton	Sorghum	Soybeans	Wheat
MRI: CGCM2.3										
Central	0.1209	0.0222	-0.0399	0.0905	0.0019	0.0850	-0.0096	-0.0481	0.0727	-0.0085
Northeast	0.0293		-0.0357	0.0411	0.0546	0.0213		-0.0381	0.0192	-0.0479
Southeast	0.0305	0.0134	-0.0239	0.0453	0.0018	0.0201	0.0031	-0.0551	0.0412	-0.0624
N. Plains	0.0499	0.0073	-0.0156	0.0544	-0.0303	0.0727	0.0075	-0.0179	0.0815	-0.0257
S. Plains	-0.1550	-0.0027	0.0134	0.0132	-0.0463	-0.1896	-0.0180	0.0241	0.0098	-0.0370
Mountains	-0.0320	0.0147	-0.0150		0.1377	-0.0318	0.0052	-0.0167		0.1624
Pacific	0.2141	0.1810	0.0681	0.1149	0.1293	0.1305	0.0973	-0.0435	0.0567	0.0841
GFDL: CM2.1										
Central	0.0613	0.0101	-0.0611	0.0576	-0.0045	0.0377	-0.0162	-0.0654	0.0561	-0.0133
Northeast	-0.0626		0.0933	0.0148	0.0059	-0.0449		0.0363	-0.0120	-0.0125
Southeast	0.0193	-0.0034	0.0707	0.0381	-0.0214	0.0054	-0.0042	0.0033	0.0365	-0.0283
N. Plains	0.0981	0.0126	-0.0170	0.1240	-0.0382	0.1081	-0.0013	-0.0122	0.1387	-0.0287
S. Plains	-0.1331	0.0094	0.0256	0.0266	-0.0021	-0.2030	-0.0237	0.0402	0.0108	-0.0115
Mountains	-0.1271	-0.0629	0.0146		0.0881	-0.1892	-0.0312	-0.0003		0.1219
Pacific	-0.0176	0.0175	0.2703	0.0285	0.1195	-0.0604	0.0626	-0.0176	0.0060	0.0763
CNRM: CM3										
Central	-0.0359	-0.0235	-0.0385	0.0054	-0.0247	0.0164	-0.0684	-0.0699	0.0496	-0.0328
Northeast	-0.0729		0.0196	-0.0371	-0.0254	-0.0329		-0.0069	-0.0243	-0.0425
Southeast	-0.0374	0.0188	0.0061	0.0047	0.0081	-0.0182	0.0035	-0.0861	0.0285	-0.0824
N. Plains	-0.0917	-0.0112	0.0211	0.0196	-0.0788	0.0269	-0.0222	0.0123	0.0938	-0.0590
S. Plains	-0.3020	-0.0226	0.0291	-0.0352	-0.0326	-0.3556	-0.0635	0.0529	-0.0284	-0.0448
Mountains	-0.0689	-0.0202	0.0156		0.1694	-0.1115	-0.0187	0.0013		0.2042
Pacific	0.2741	0.2228	-0.2114	0.0320	0.0829	0.2459	0.1419	-0.1150	0.0180	0.0092

variability of crop yield in all regions except the Mountains, while the CNRM projected climate changes will increase variability in all regions except the Central and Pacific for 2040-2069.

The simulation results on skewness and kurtosis vary by crop, region, and scenario (tables 15 and 16). Skewness of crops except soybeans decreases in most of the scenarios. For soybeans, skewness decreases by up to 50% under the MRI, but it increases by up to 95% under the GDFL and CNRM. Kurtosis for soybeans and winter wheat is projected to be increase by climate change on national scale. However, for other crops, corn, upland cotton, and sorghum, changes in skewness vary by GCMs and periods. In the case of corn, the MRI project in all regions except South Plains and Mountain, kurtosis increase, while the GDFL project in all regions except Central, Southeast, and North Plains, kurtosis decreases.

Conclusions

This study estimates effects of climate variables on yields of corn, upland cotton, sorghum, soybeans, and winter wheat, across the U.S. This is accomplished by estimating a flexible moment approach production function using a panel data set by climate division for the years 1981 to 2008. We also investigate the impacts of projected climate change on future crop yield distributions in terms of the mean, variance, skewness, and kurtosis. Our regression results show that the climate conditions contribute in a statistically significant way to not only average crop yields but to their variability, skewness, and kurtosis. In particular, we find that that the effects of temperature on mean yields are inconsistent by crop and for some crops, insignificant. Extremely low or high temperatures cause damage to the crop yields. Most of the mean crop yields initially positively respond to increasing precipitation but at a decreasing rate. The climate effects on variability vary by crops. Except upland cotton and winter wheat, the skewness of crop yields is affected by temperature or precipitation or both. The effect of precipitation on skewness is non-linear and convex, while the effect of precipitation is non-linear and convex. For soybeans, as temperature increases, initially, mean yield increases, variability and kurtosis decrease, and the yield distribution becomes more positively skewed. However, all impacts are strictly concave or convex. Therefore, after its peak, mean yield decreases, variability and kurtosis increase, and the yield distribution becomes more negatively skewed.

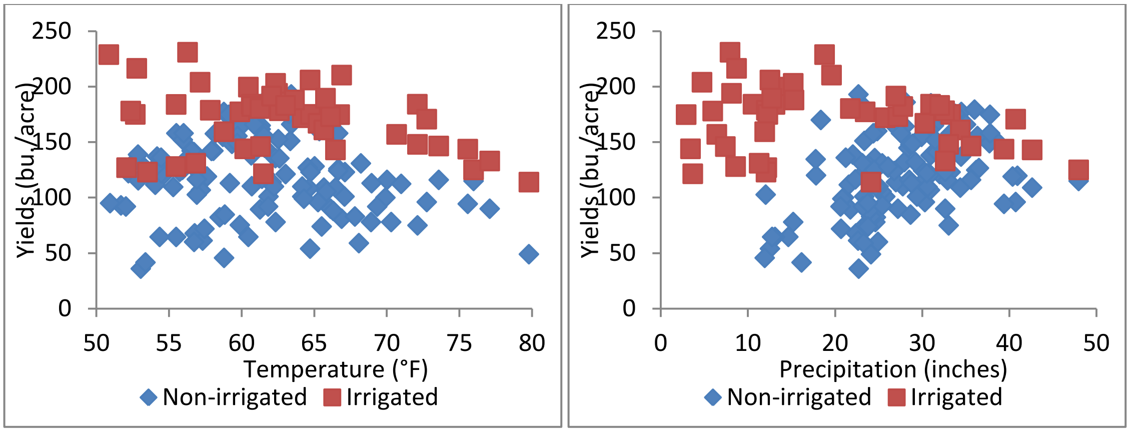
Simulation over climate change projections evaluates how future projected climate change may influence future yield distributions. Our study shows that climate change increases future mean yields for the most crops excluding winter wheat, while decreases future variability of yield for all crops excluding soybeans. Changes in skewness and kurtosis differ by crop, region, and scenario. These results imply that the standard assumptions of stationarity and normality do not hold as we find that the key climate variables evolved over time. Regarding such diverse things as return to agricultural investments, appropriate setting of crop insurance premiums and greenhouse gas mitigation action planning, our results should be considered in policy making. It appears likely that climate change will alter not only mean but also the variability, and will also lead significant change in the skewness and kurtosis of crop yield distributions.

CHAPTER III

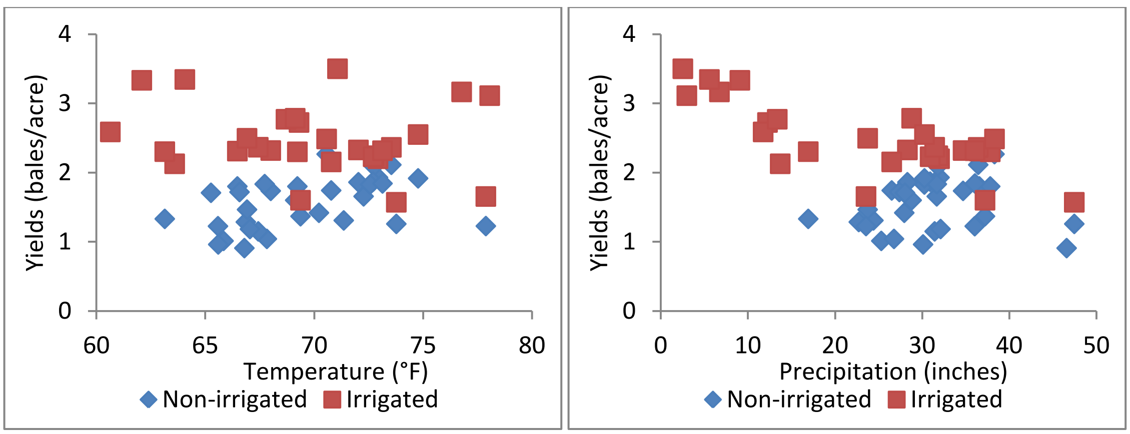
ARE THERE DIFFERENTIAL CLIMATE CHANGE EFFECTS ON IRRIGATED AND DRYLAND CROP YIELDS?

Irrigation is the managed application of water to the land or soil that assists growing of crops. According to the Agriculture Census, 16.6% of U.S. harvested cropland is irrigated and most of U.S. irrigated cropland is used to grow corn, cotton, rice, soybeans, and winter wheat. In the case of rice, 100% of U.S. acreage is grown in irrigated cropland. About half of the cropland is in Arkansas, California, Nebraska, and Texas, and most of cropland in California is irrigated. As figure 10 shows, crop yields on irrigated lands are significantly higher than those in non-irrigated lands. Although irrigation is one of the most important factors which affect crop yields, few studies consider irrigation in the function of estimating crop productivity.

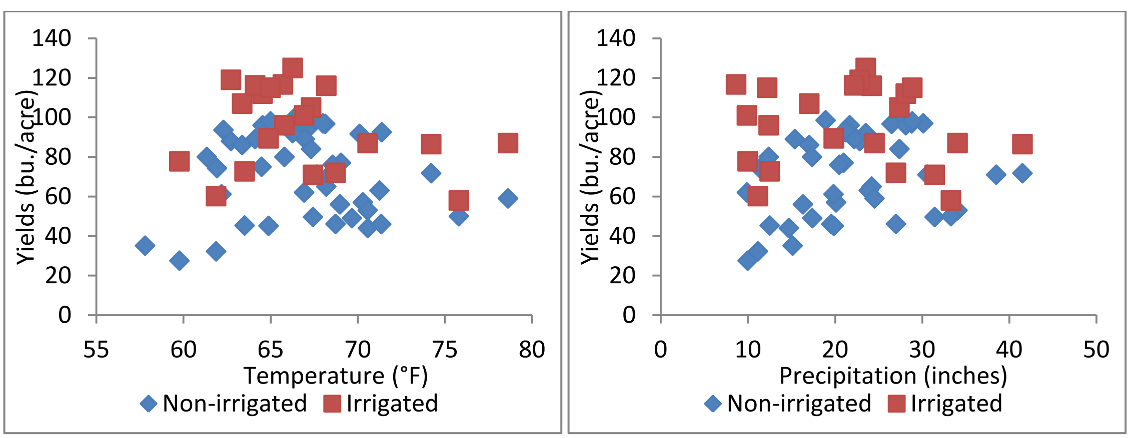
Payero et al. (2006) quantify the yield response of corn to deficit irrigation and determine which of several seasonal water variables correlated best to corn yield in a semiarid regions in Nebraska. They find that yield increased linearly with seasonal irrigation, but the relationship varied from year to year. To test the crop water stress index (CWSI) as a potential tool for irrigation scheduling and yield estimation, Irmak et al. (2000) conducted an experiment to monitor and quantify water stress, and to develop parameters for irrigation scheduling and grain yield of summer-grown corn as a function of CWSI under Mediterranean semiarid cropping conditions. Permitting the seasonal average CWSI value to exceed more than 0.22 resulted in decreased corn grain yield.



(a) Corn

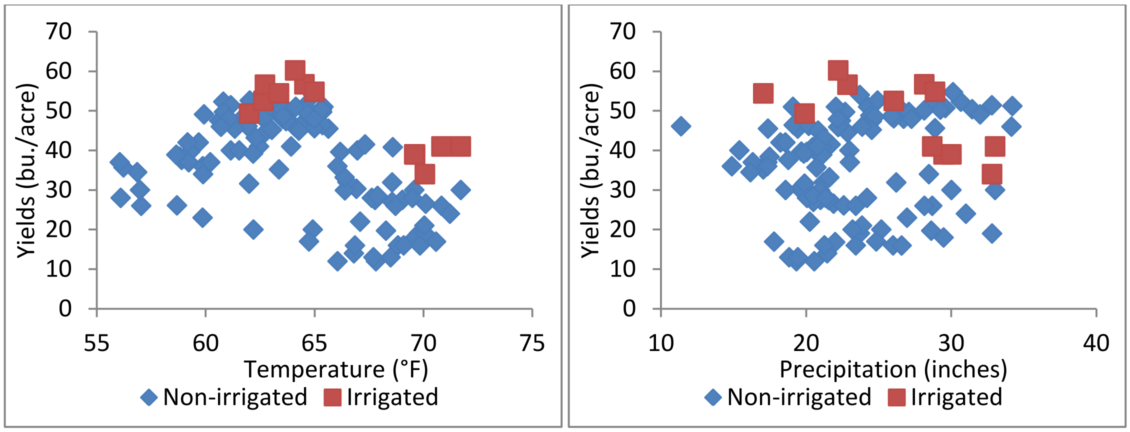


(b) Upland Cotton

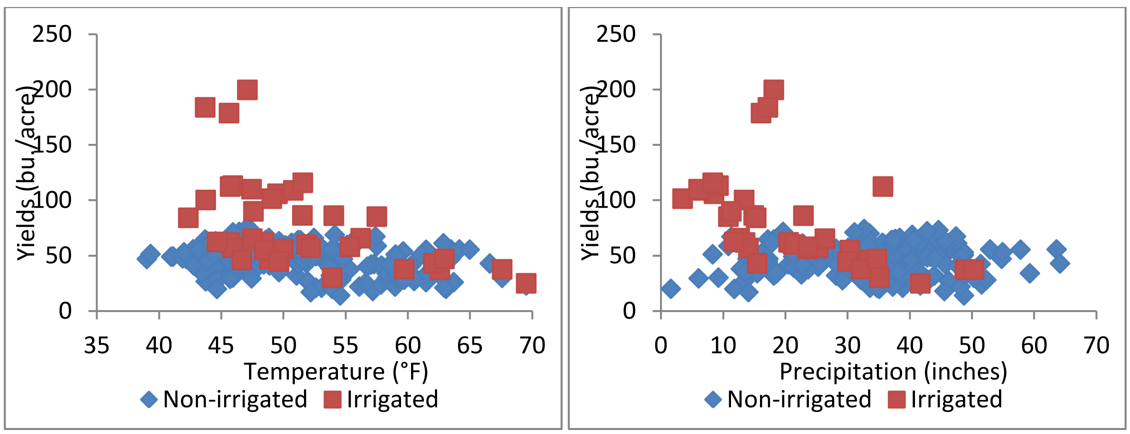


(c) Sorghum

Figure 10 Crop yields in year 2007



(d) Soybeans



(e) Winter Wheat

Figure 10 Continued

Stone et al. (1996) conducted research to establish the yield and water application relationship of corn, sorghum and sunflower in Kansas and they suggested sorghum is a better choice than corn at less than 206 mm of irrigation, whereas corn is a better choice than sorghum at more than 206 mm of irrigation. Sammis (1981) observed a linear water production function for cotton, but this function was applicable only for the two areas in southern New Mexico where the study was conducted. Zhang and Oweis (1999) conducted supplemental irrigation (SI) experiments in northern Syria to evaluate water and yield relations for bread wheat and durum wheat. In this study, quadratic crop production functions with the total applied water were developed and used to estimate the levels of irrigation water for maximizing yield, net profit and levels to which the crops could be under-irrigated without reducing income below that which would be earned for full SI under limited water resources.

However, previous studies used field experimental method to assert irrigation effects on crop yields and field experiments are conducted in limited locations. Due to the characteristics of the experimental methods used in these studies, degrees of irrigation can be controlled but other external factors can not be fully considered. Hence, it is hard to apply the estimated irrigation effects in productivity models for more broad scope and few studies that examine climate effects on crop yields pay attention to irrigation impacts on crop yields. Most of studies show climate has significant effects on crop yields but irrigation effects are ignored (Chen, McCarl, and Schimmelpfennig 2004; McCarl, Villavicencio, and Wu 2008; Schlenker and Roberts 2009).

In this essay, to improve crop productivity models, we investigate climate and irrigation effects on crop yields. Then using our statistical results, crop yields under alternative projected climate change scenarios are estimated. Finally, we explore the market outcomes and welfare implications of economic units given climate-induced shifts in yields across US regions.

Data

Irrigation

To investigate irrigation and climate effects on crop yields, we use data for corn, upland cotton, sorghum, soybeans, and winter wheat. These crops have large share of total U.S. irrigated cropland. For corn, upland cotton, sorghum, soybeans, and winter wheat, 15%, 37%, 12%, 8%, and 7% of harvested cropland are irrigated respectively. Table 17 presents the statistical characteristics of variables and the differences between irrigated and non-irrigated crop yields. Irrigated crop yields are higher by 40%, 55%, 46%, 26%, and 67% than non-irrigated crop yields for corn, upland cotton, sorghum, soybeans, and winter wheat respectively. Compared with non-irrigated data for all crops, precipitation in irrigated area is lower by up to 42% and the number of days where the maximum temperature was greater than 90 °F is greater by up to 120%. Differences in average temperature were not great. This reflects the fact that irrigation is used more often in dry conditions.

Irrigated and non-irrigated crop yield data by county are obtained from USDA-

Table 17 Statistical Characteristics of Variables

	Non-irrigated				Irrigated			
Variable	Mean	Std.Dev.	Min	Max	Mean	Std.Dev.	Min	Max
Corn	(obs=3429)				(obs=1242)			
Yield	101.5	32.82	13.1	193.0	142.3	31.34	62.6	235.5
TMP	59.9	6.21	46.5	81.4	62.2	7.68	46.6	81.4
DT32	39.8	24.19	0.0	114.0	35.9	28.74	0.0	114.0
DT90	29.2	30.28	0.0	182.0	64.1	37.84	2.0	182.0
PCP	28.1	7.78	7.6	54.2	17.6	8.85	2.2	48.0
PDSI	0.69	2.08	-5.66	9.30	0.39	2.50	-6.12	8.28
Cotton	(obs=891)				(obs=756)			
Yield	564.5	203.4	83.0	1088	877.1	260.3	176.0	1704
TMP	69.0	3.82	60.7	79.0	69.6	4.59	58.2	79.0
DT32	14.5	11.99	0.0	55.0	17.9	19.10	0.0	96.0
DT90	78.0	33.71	0.0	175.0	99.9	35.27	21.0	193.0
PCP	32.6	9.36	10.3	57.3	23.8	13.01	0.9	57.2
PDSI	0.32	1.82	-4.19	6.25	0.24	2.09	-4.95	7.37
Sorghum	(obs=1215)				(obs=594)			
Yield	59.3	21.96	8.5	128.0	86.2	16.74	25.7	125.0
TMP	65.6	4.85	50.4	80.2	65.9	5.32	55.6	80.1
DT32	21.3	14.69	0.0	61.0	25.1	15.78	0.0	61.0
DT90	56.0	34.25	0.0	183.0	78.5	34.46	4.0	183.0
PCP	22.9	7.60	6.9	46.8	19.0	6.03	4.4	41.8
PDSI	0.69	2.18	-5.60	9.51	0.79	2.22	-5.59	9.68
Soybeans	(obs=2916)				(obs=324)			
Yield	33.1	9.24	9.5	56.4	41.7	8.57	24.0	61.4
TMP	62.3	4.22	50.3	73.6	64.9	4.37	55.9	73.6
DT32	26.0	14.14	0.0	78.0	23.2	13.83	0.0	51.0
DT90	27.6	23.26	0.0	120.0	52.2	23.05	4.0	118.0
PCP	26.3	7.24	7.5	51.4	25.3	8.35	9.7	49.2
PDSI	0.62	2.10	-5.92	9.51	0.68	2.31	-4.65	7.29
Wheat	(obs=4914)				(obs=999)			
Yield	43.6	13.54	5.8	90.1	72.9	34.69	20.0	215.3
TMP	51.1	6.72	35.1	72.8	51.6	7.22	38.6	72.8
DT32	118.8	50.17	0.0	252.0	119.3	61.01	0.0	226.0
DT90	27.5	23.02	0.0	154.0	46.0	27.78	0.0	154.0
PCP	32.7	13.06	1.6	85.2	18.9	8.71	3.5	62.7
PDSI	0.50	2.05	-6.63	9.53	0.36	2.52	-6.00	8.72

NASS. Using the county level data, we calculate crop yield data at climate division level. In the data set, some counties are in multiple climate divisions and those counties are categorized in the climate division that contains the largest part of the county.

Climate Data

All climate data were collected at the U.S. climate division level for growing seasons. Data from 1981 to 2007 are used at the climate division level. The climate metrics collected were temperature, precipitation, the number of days where the minimum temperature was less than 32 °F, the number of days where the maximum temperature was greater than 90 °F, and the Palmer Drought Severity Index (PDSI). All data were drawn from the NOAA - National Climate Data Center (NCDC).

Model Specification

Crop Productivity Model

Crop yield model with irrigation dummy variable (Model 1) is given as follows,

(1) $$y_{it} = \beta_{TD}TD_t + \beta_T T_{it} + \beta_{T2}T_{it}^2 + \beta_{DT32}DT32_{it} + \beta_{DT90}DT90_{it} + \beta_P P_{it} + \beta_{P2}P_{it}^2 + \beta_{PD}PD_{it} + \gamma_d Ds_i + \gamma_t(Ds_i \times T_{it}) + \boldsymbol{\delta IRR_{it}}$$

where y is crop yield; TD is time trend; T is temperature; DT32 is the number of days where the minimum temperature was less than 32 °F; DT90 is the number of days where the maximum temperature was greater than 90 °F; P is precipitation; PD is PDSI; Ds are regional dummy variables; Ds×T are interactive variables between region and temperature; IRR is irrigation dummy.

Assume that there is correlation between irrigation and climate conditions, since irrigation is used in dry or harsh conditions or is used to assist in growing crops requiring high precipitation. Under this assumption, we include the interactive terms between irrigation and climate variables in the productivity model (Model 2).

(2) $$y_{it} = \beta_{TD}TD_t + \beta_T T_{it} + \beta_{T2}T_{it}^2 + \beta_{DT32}DT32_{it} + \beta_{DT90}DT90_{it} + \beta_P P_{it} + \beta_{P2}P_{it}^2 + \beta_{PD}PD_{it} + \gamma_d Ds_i + \gamma_t(Ds_i \times T_{it}) + \boldsymbol{\delta_d IRR_{it}} + \boldsymbol{\delta_T(IRR_{it} \times T_{it})} + \boldsymbol{\delta_{DT32}(IRR_{it} \times DT32_{it})} + \boldsymbol{\delta_{DT90}(IRR_{it} \times DT90_{it})} + \boldsymbol{\delta_P(IRR_{it} \times P_{it})} + \boldsymbol{\delta_{P2}(IRR_{it} \times P_{it}^2)} + \boldsymbol{\delta_{PD}(IRR_{it} \times PD_{it})}$$

Irrigation Effects

Given the estimated results, we can calculate the marginal irrigation effect. The marginal irrigation effect is the effect of change in irrigation incidence on crop yield. In our model, irrigation variable is discrete dummy with 0 and 1. The marginal or expected irrigation effect is calculated as follows,

(3) $$\frac{\Delta y}{\Delta IRR} = E[y|IRR = 1] - E[y|IRR = 0].$$

In Model 1 (1), since irrigation variable is a dummy, the expected irrigation effect is constant regardless of other exogenous variables.

(4) $$\text{Expected Irrigation Effect} = \hat{\delta}$$

In Model 2 (2), since irrigation interacts with climate, the expected irrigation effect changes as other climate variables changes. Therefore, the irrigation effect can be expressed as a function of climate variables,

(5) $$\text{Expected Irrigation Effect} = \hat{\delta}_d + \hat{\delta}_T T_{it} + \hat{\delta}_{DT32} DT32_{it} + \hat{\delta}_{DT90} DT90_{it} + \hat{\delta}_P P_{it} + \hat{\delta}_{P2} P_{it}^2 + \hat{\delta}_{PD} PD_{it}\ .$$

Empirical Results

Based on the serial and cross-sectional correlation test results (table 18 and 19), panel specific auto-correlation and cross-sectional correlation are taken into account in the PCSE estimation as necessary. In addition, the panel unit root test results reject the null hypothesis of non-stationarity suggesting no differencing the data before the estimation (table 20).The parameter estimates of the proposed crop productivity functions are presented in tables 21 and 22, where the models are estimated by the PCSE method explained in chapter II. The coefficients on the deterministic time trend as a proxy of technical improvement are positive and significant for all crops. This indicates that technical improvement increases crop yields.

Climate Effects for Non-irrigated Crop Yields

The yields of all crops are found to be affected by mean temperature in the growing period. The results show that higher temperatures cause crop yields to increase at a decreasing rate. When temperature crosses a threshold yields decline (figures 11 and

Table 18 Serial Correlation Tests Results[a]

	Corn	Cotton	Sorghum	Soybeans	Wheat
without Interactive terms					
F (df1, df2)	11.4 (1, 172)	22.8 (1, 60)	4.9 (1, 66)	7.1 (1, 119)	10.9 (1, 218)
Prob > F	0.0009	0.0000	0.0290	0.0084	0.0011
with Interactive terms					
F (df1, df2)	10.6 (1, 172)	22.9 (1, 60)	3.4 (1, 66)	5.0 (1, 119)	11.3 (1, 218)
Prob > F	0.0013	0.0000	0.0658	0.0269	0.0009

Note: [a]Wooldridge test for autocorrelation in panel data with the null hypothesis of no first-order autocorrelation.

Table 19 Cross-sectional Correlation Test Results[a]

	Corn	Cotton	Sorghum	Soybeans	Wheat
without Interactive terms					
Frees'	8.559[b]	4.167[b]	2.738[b]	6.038[b]	8.807[b]
Pesaran's	73.624[b]	48.183[b]	32.173[b]	66.464[b]	70.226[b]
Friedman's	499.139[b]	345.514[b]	254.270[b]	448.479[b]	503.151[b]
with Interactive terms					
Frees'	7.389[b]	4.357[b]	2.909[b]	6.189[b]	8.734[b]
Pesaran's	70.400[b]	49.369[b]	35.517[b]	67.702[b]	70.646[b]
Friedman's	474.240[b]	359.520[b]	277.518[b]	463.385[b]	507.304[b]

Note: [a]Testing the null hypothesis of cross-sectional independence in panel-data models
[b] The null is rejected in 99% confidence level.

Table 20 Unit-root Test Results

	Corn	Cotton	Sorghum	Soybeans	Wheat
Levin-Lin-Chu [a]					
Crop yield	-9.29 (0.00)	-1.11 (0.13)	-10.89 (0.00)	-9.97 (0.00)	-14.90 (0.00)
TMP	-22.91 (0.00)	-12.90 (0.00)	-12.52 (0.00)	-22.13 (0.00)	-29.63 (0.00)
DT32[b]	-22.16 (0.00)	-12.94 (0.00)	-14.50 (0.00)	-17.94 (0.00)	-23.16 (0.00)
DT90[c]	-28.21 (0.00)	-11.09 (0.00)	-14.19 (0.00)	-25.92 (0.00)	-27.20 (0.00)
PCP	-23.51 (0.00)	-15.78 (0.00)	-16.84 (0.00)	-23.46 (0.00)	-25.12 (0.00)
PDSI	-22.13 (0.00)	-15.40 (0.00)	-13.51 (0.00)	-19.84 (0.00)	-25.44 (0.00)
Im-Pesaran-Shin [b]					
Crop yield	-22.36 (0.00)	-11.80 (0.00)	-18.82 (0.00)	-20.05 (0.00)	-28.44 (0.00)
TMP	-29.99 (0.00)	-18.95 (0.00)	-18.58 (0.00)	-25.47 (0.00)	-36.85 (0.00)
DT32	-33.24 (0.00)	-23.63 (0.00)	-22.81 (0.00)	-29.11 (0.00)	-34.33 (0.00)
DT90	-32.77 (0.00)	-17.67 (0.00)	-18.94 (0.00)	-27.96 (0.00)	-36.53 (0.00)
PCP	-33.28 (0.00)	-21.06 (0.00)	-21.48 (0.00)	-28.66 (0.00)	-41.96 (0.00)
PDSI	-27.31 (0.00)	-17.19 (0.00)	-17.13 (0.00)	-22.78 (0.00)	-27.70 (0.00)

Note: [a]Adjusted t*statistics from Levin-Lin-Chu panel unit root test with the null hypothesis of nonstationarity and p-value in the parenthesis

[b]Z-t-tilde bar statistics from Im-Pesaran-Shin panel unit root test with the null hypothesis of nonstationarity and p-value in the parenthesis

Table 21 Crop Yield Regression with Irrigation Dummy Variable (Model 1)

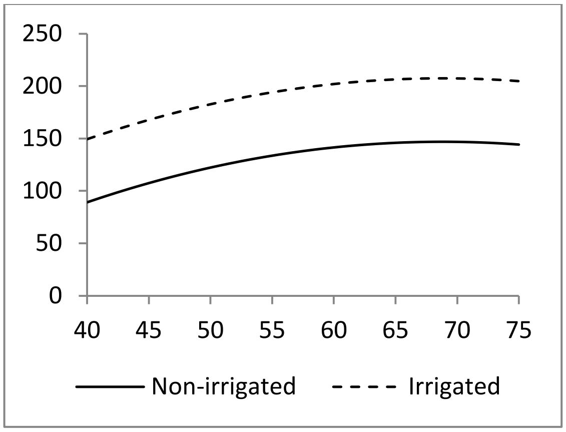
	Corn		Upland Cotton		Sorghum		Soybeans		Winter Wheat	
	Coef.	z	Coef.	z	Coef.	z	Coef.	z	Coef.	z
Trend	1.4700	7.70	9.4578	4.90	0.4903	3.57	0.3720	6.48	0.5132	6.20
TMP	9.5868	3.35	349.0766	6.88	16.1567	4.28	10.0942	4.44	5.6556	4.43
TMP^2	-0.0697	-2.80	-2.1436	-5.86	-0.1259	-4.44	-0.0753	-3.98	-0.0570	-4.34
DT32	-0.2229	-4.20	-2.1311	-2.80	-0.0908	-1.11	-0.0141	-0.51	-0.0169	-1.38
DT90	-0.4997	-9.16	-2.2064	-6.23	-0.2529	-7.78	-0.1330	-8.02	-0.0549	-2.22
PCP	0.4833	1.30	2.8568	0.77	1.2720	3.82	0.3359	1.91	0.5548	4.62
PCP^2	-0.0098	-1.55	-0.0433	-0.81	-0.0286	-4.59	-0.0058	-2.16	-0.0089	-6.75
PDSI	0.8902	2.49	2.2142	0.54	1.3624	4.08	0.4870	3.09	-0.0306	-0.17
Irrigation	60.3451	20.10	275.526	20.04	32.3543	21.14	13.4613	14.21	25.4773	22.13
D2	58.0884	2.27							-45.5499	-3.64
D3	6.8896	0.20	1707.35	1.78	-147.885	-1.97	11.9259	0.74	-12.4789	-0.72
D4	-26.0793	-0.97			-138.372	-2.85	-21.0424	-1.74	-0.9447	-0.08
D5	49.7540	0.85	423.057	0.48	-245.595	-4.15	-69.1595	-1.93	-63.9022	-2.63
D6	-159.908	-6.44	-1819.12	-2.14	-143.256	-2.15			-3.2950	-0.18
D7	71.6192	1.48							21.6464	1.15
Temp×D2	-1.3813	-2.98							0.8567	3.37
Temp×D3	-0.6616	-1.18	-56.8770	-5.48	1.7093	1.55	-0.3524	-1.38	0.1404	0.43
Temp×D4	-0.0679	-0.15			1.9282	2.61	0.2787	1.41	-0.3185	-1.21
Temp×D5	-1.0121	-1.13	-37.7811	-9.06	3.2274	3.60	0.8025	1.51	0.8262	1.87
Temp×D6	2.2630	5.12			1.8977	1.80			0.1994	0.52
Temp×D7	-0.9776	-1.19	-22.4060	-1.71					-0.2765	-0.73
Constant	-205.217	-2.44	-11077.5	-6.53	-443.463	-3.42	-303.252	-4.40	-99.0426	-3.08
R^2	0.8613		0.7105		0.8554		0.8158		0.7729	
Wald χ^2 *(df)*	1586.20 (21)		1562.71 (15)		1538.06 (17)		798.25 (15)		2527.28 (21)	
Prob > χ^2	0.0000		0.0000		0.0000		0.0000		0.0000	

Table 22 Crop Yield Regression with Irrigation Dummy and Interactive Variables (Model 2)

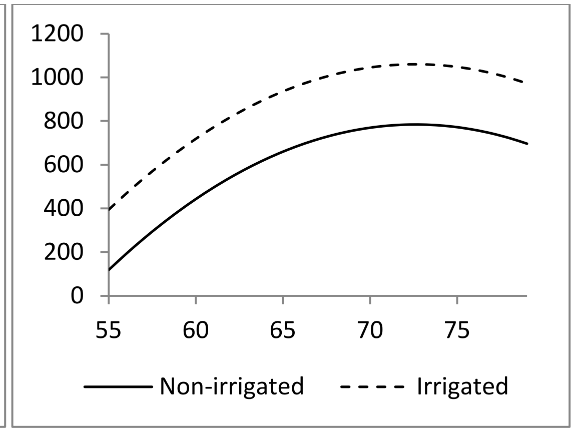
	Corn		Upland Cotton		Sorghum		Soybeans		Winter Wheat	
	Coef.	z	Coef.	z	Coef.	z	Coef.	z	Coef.	z
Trend	1.4423	8.23	9.1610	4.82	0.4161	3.66	0.3727	6.69	0.5189	6.57
TMP	9.5097	3.25			11.6743	4.01	9.6187	4.16	5.6956	4.90
TMP^2	-0.0641	-2.54	-1.8935	-5.09	-0.0918	-4.13	-0.0707	-3.67	-0.0594	-5.01
DT32	-0.2202	-3.97	-1.7224	-1.70	-0.0118	-0.16	-0.0059	-0.21	-0.0248	-1.91
DT90	-0.6846	-11.25	-2.9812	-7.22	-0.1823	-5.26	-0.1452	-8.25	-0.0469	-1.87
PCP	0.7987	1.61	12.0292	2.53	2.9062	6.34	0.4682	2.46	0.9224	6.85
PCP^2	-0.0178	-2.30	-0.1692	-2.56	-0.0519	-6.46	-0.0080	-2.72	-0.0124	-8.35
PDSI	1.8886	4.21	6.3258	1.16	1.5134	3.65	0.5293	3.12	-0.1688	-0.89
Irrigation	263.269	8.43	1827.538	4.88	60.0865	3.57	53.1482	3.40	97.3255	6.27
Irr×TMP	-3.7842	-7.74	-20.6288	-3.98	-0.1161	-0.45	-0.4255	-1.70	-0.9156	-3.76
Irr×DT32	0.1032	1.17	-0.7867	-0.82	0.2072	3.03	-0.0484	-0.94	-0.0064	-0.24
Irr×DT90	0.6071	9.29	1.6047	3.67	0.0488	1.57	0.0759	3.56	-0.0475	-1.26
Irr×PCP	0.1541	0.26	-13.9137	-2.99	-1.8542	-3.10	-0.9996	-3.64	-1.2962	-4.93
Irr×PCP^2	-0.0029	-0.27	0.1939	2.96	0.0252	2.09	0.0153	3.62	0.0115	2.88
Irr×PDSI	-2.3831	-5.05	-9.7110	-1.74	-0.8802	-2.24	-0.5276	-2.37	0.4924	1.63
D2	57.6410	2.22							-51.0178	-3.95
D3	-13.1350	-0.37	2380.60	2.31	29.4982	0.47	13.5821	0.82	-20.2443	-1.26
D4	-33.7911	-1.13			-134.280	-2.93	-16.8604	-1.31	-0.7102	-0.06
D5	29.2540	0.50	897.733	0.98	-208.488	-3.75	-40.5761	-1.18	-117.217	-4.68
D6	-278.909	-7.89	-1517.53	-1.86	-258.771	-4.59			-12.6834	-0.75
D7	4.8025	0.10							-0.3269	-0.02
Temp×D2	-1.3613	-2.89							0.9589	3.68
Temp×D3	-0.3526	-0.62	264.5623	5.25	-0.8257	-0.88	-0.3806	-1.46	0.2870	0.94
Temp×D4	0.1112	0.23			1.8571	2.67	0.2125	1.01	-0.2896	-1.18
Temp×D5	-0.6099	-0.68	286.5984	5.33	2.6603	3.18	0.3969	0.78	1.7929	3.99

Table 22 Continued

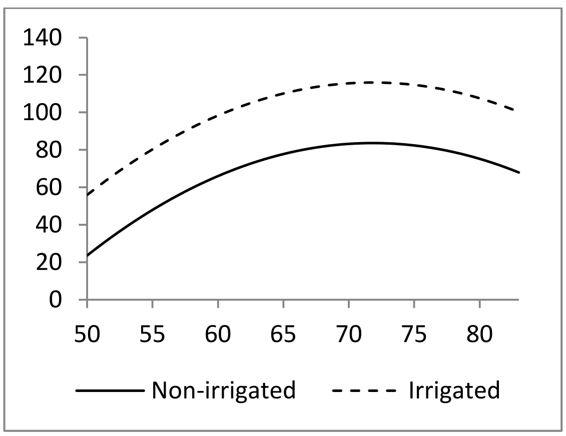
	Corn		Upland Cotton		Sorghum		Soybeans		Winter Wheat	
	Coef.	z	Coef.	z	Coef.	z	Coef.	z	Coef.	z
Temp×D6	4.0723	6.92	325.6822	6.19	3.7633	4.29			0.4398	1.22
Temp×D7	-0.1987	-0.25	307.4599	6.15					0.2278	0.59
Constant	-218.834	-2.52	-11147.5	-6.32	-325.407	-3.29	-293.490	-4.19	-102.952	-3.46
R^2	0.8659		0.7085		0.7103		0.8283		0.7772	
Wald χ^2 *(df*	1731.14 (27)		1813.39 (21)		3618.40 (23)		1112.40 (21)		3439.28 (27)	
Prob > χ^2	0.0000		0.0000		0.0000		0.0000		0.0000	



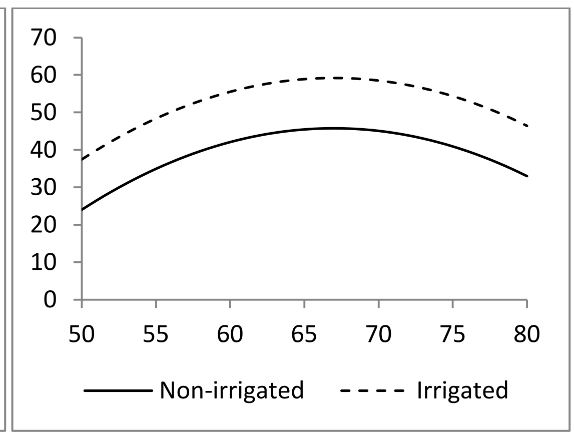
(a) Corn



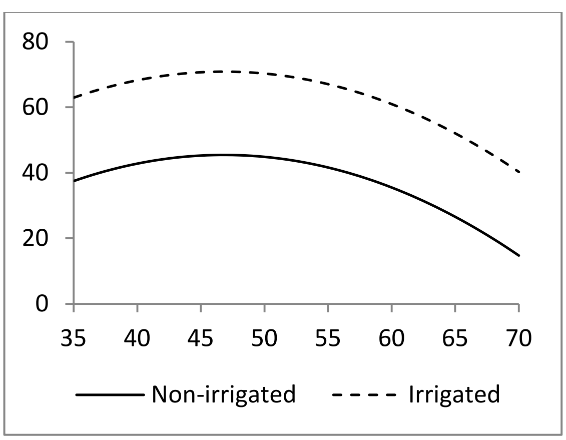
(b) Upland Cotton



(c) Sorghum



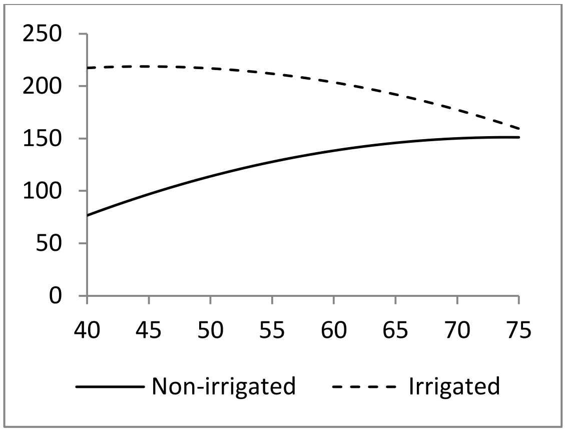
(d) Soybeans



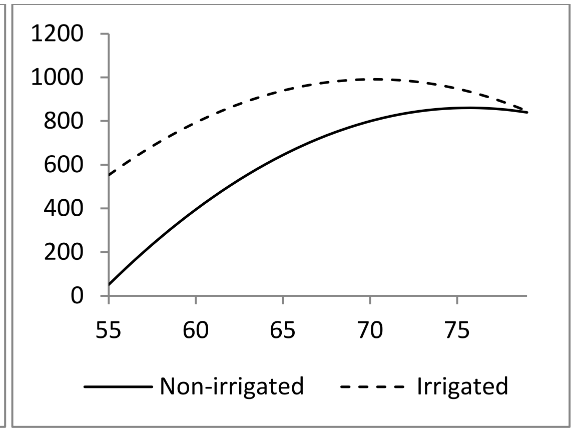
(e) Winter Wheat

Figure 11 Temperature effects in Model 1

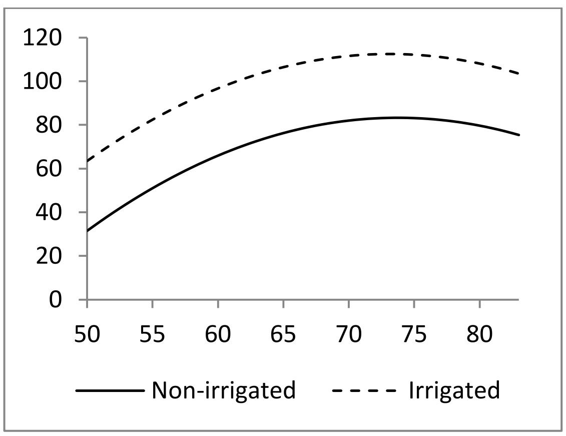
Note: Unit of all crops are bu/acre, except for cotton, which has unit in lbs/acre, and unit of temperature is °F.



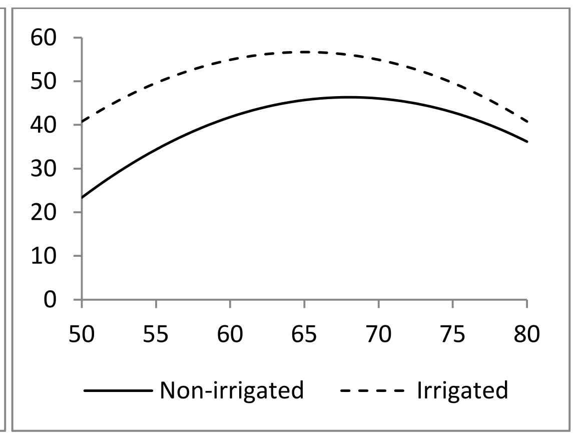
(a) Corn



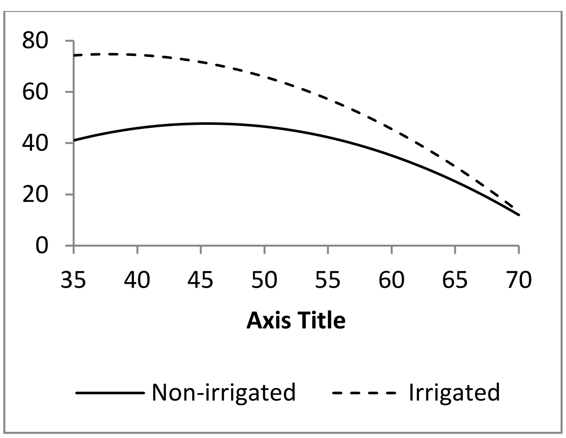
(b) Upland Cotton



(c) Sorghum



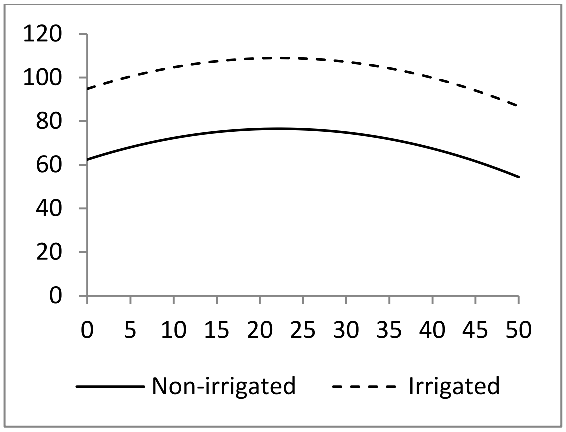
(d) Soybeans



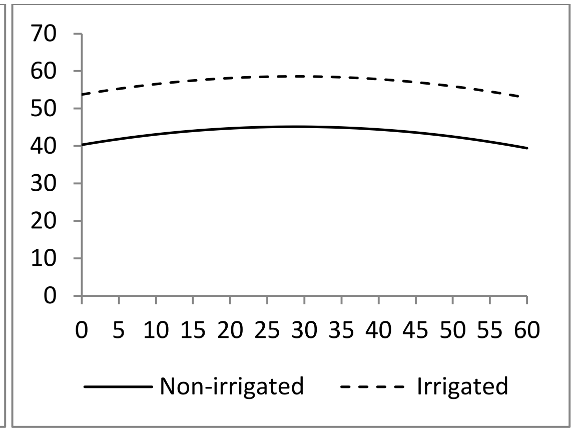
(e) Winter Wheat

Figure 12 Temperature effects in Model 2

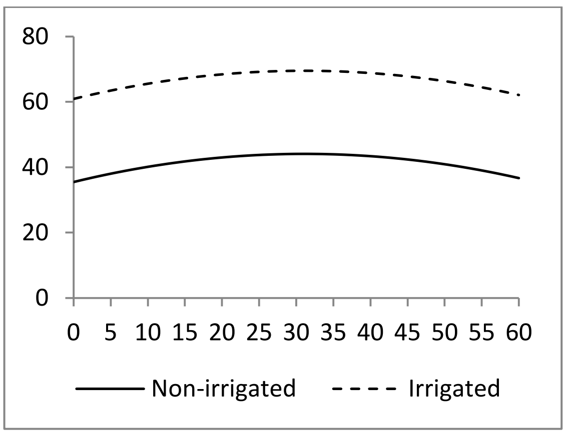
Note: Unit of all crops are bu/acre, except for cotton, which has unit in lbs/acre, and unit of temperature is °F.



(a) Sorghum



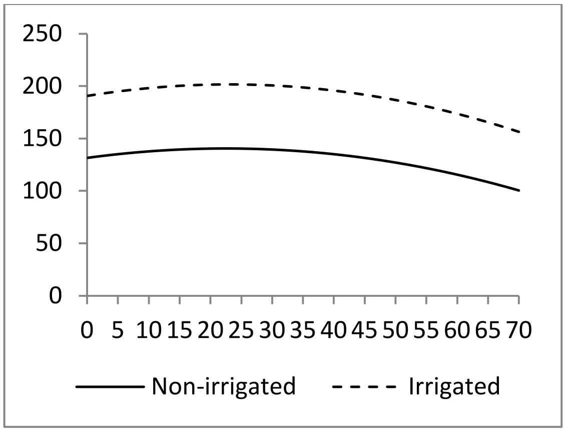
(b) Soybeans



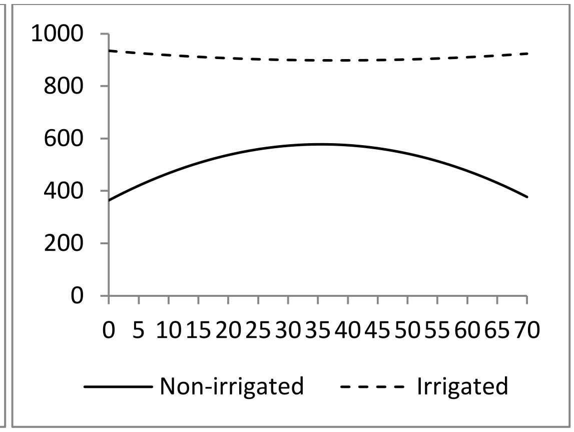
(c) Winter Wheat

Figure 13 Precipitation effects in Model 1

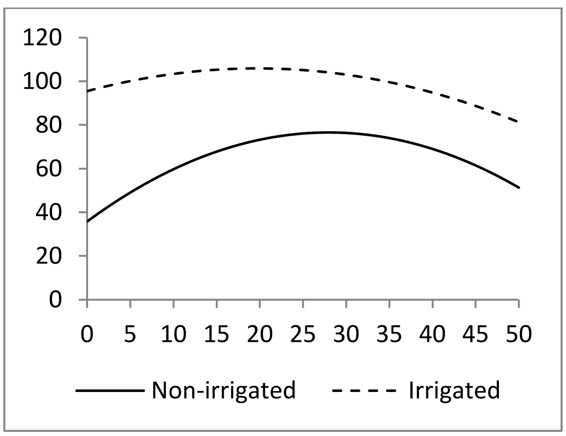
Note: Unit of all crops are bu/acre and unit of precipitation is inches.



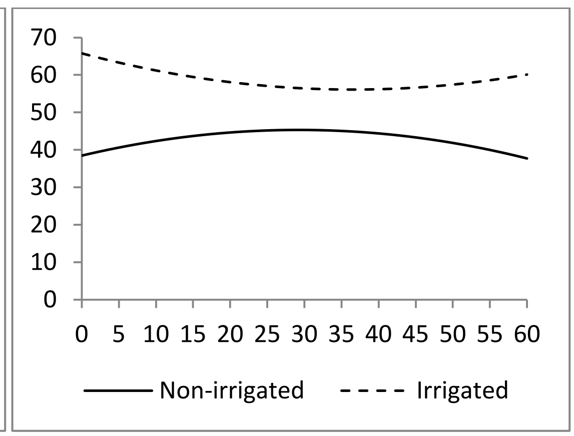
(a) Corn



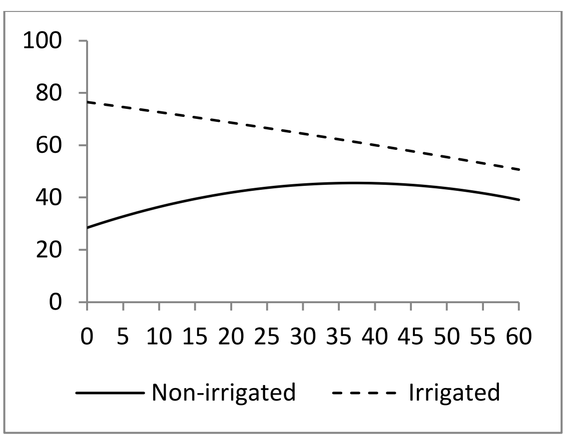
(b) Upland Cotton



(c) Sorghum



(d) Soybeans



(e) Winter Wheat

Figure 14 Precipitation effects in Model 2

Note: Unit of all crops are bu/acre, except for cotton, which has unit in lbs/acre, and unit of precipitation is inches.

12). Sorghum, soybeans, and winter wheat, which have low irrigation rates, have similar peaks in both Model 1 and Model 2, while for corn and upland cotton, which have relatively high irrigation rates, peaks in Model 1 are lower than those in Model 2 meaning irrigation alleviates some of the effects of hot temperatures. In addition, response of non-irrigated yields to temperature is similar in Model 1 and Model 2 but are slightly more responsive to change in temperature in Model 2.

We find that the incidence of days with extreme temperatures have negative impacts on crop yields in both Model 1 and 2. The signs on the number of days with maximum temperature greater than or equal to 90°F are negative for all crops in Model 1 and for all crops except for winter wheat in Model 2. The sign on the number of days with minimum temperature less than or equal to 32 °F is negative for corn in Model 1 and corn and upland cotton in Model 2. This implies that most crops are damaged by extremely high or low temperatures. Model 2 estimates that non-irrigated corn, upland cotton, and soybeans are harmed more by the incidence of days with extremely high temperatures than Model 1 does, while estimates sorghum and winter wheat are estimated to be harmed less than Model 1 does.

In Model 1, sorghum, soybeans, and winter wheat react to the total precipitation. As precipitation increases, crop yields also increase until a peak at 22, 29, and 31 inches for sorghum, soybeans, and winter wheat respectively. When precipitation is higher than its peak, crop yields decrease with higher precipitation (figure 13). In Model 2, yields of all crops are affected by precipitation and their peaks occur at 22, 36, 28, 29, and 37 inches for corn, upland cotton, sorghum, soybeans, and winter wheat respectively (figure 14). Non-irrigated yields are more responsive to change in precipitation in Model 2.

The effect of increase in the Palmer drought index (reflecting a lesser incidence of drought) is positive and significant for corn, sorghum, and soybeans in both Model 1 and Model 2. Hence, we find that yields of those crops increase in wet conditions and decrease under drought. For all crops, the estimated effects of PDSI on non-irrigated crop yields are greater in Model 2 than Model 1.

Irrigation Effects

As stated in equation 4, the marginal irrigation effect in Model 1 is constant regardless of other climate variables. Figures 11 and 13 show the constant irrigation effects on crop yields under given temperature and precipitation. Irrigation lifts all crop yields upward. When including interactions for climate variables (Model 2), we found that irrigation not only increases crop yields but also reduces climate effects.

- Irrigation reduces temperature effects on crop yields for corn, upland cotton, soybeans, and winter wheat. As figure 12 shows, as temperature increases, the irrigation effects are decreasing and at high temperature there is no significant difference between irrigated and non-irrigated crop yields. This implies that irrigation loses its effectiveness as temperature rises.
- For corn, upland cotton, and soybeans, irrigation reduces unfavorable effects from the incidence of days with maximum temperature greater than or equal to 90°F by 89%, 54%, and 52% respectively.

- For upland cotton and soybeans, irrigation overcomes the precipitation effects. In case of upland cotton, the precipitation effects on crop yields are almost removed by irrigation. Therefore, irrigated upland cotton yields are consistent across different levels of precipitation. Irrigation effects on sorghum and winter wheat yields decrease as precipitation increases. For sorghum and winter wheat, irrigation is more effective in the low precipitation conditions. (figure 14)
- For corn, sorghum, and soybeans, PDSI effects are decreased with irrigation. The beneficial effects of increase in PDSI are reduced by 58% for sorghum and 99% for soybeans. Moreover, with irrigation, corn yields decrease as PDSI increases.

Regional Effects

Because we include regional dummies and interactive terms between region and temperature and use Central region for base region, temperature variables should be understood as the effect of temperature for Central region. Coefficients for all of the interactive terms reflect the differences between the temperature effects over a given region with respect to Central region.

Compared to other regions, corn yields in Northeast respond relatively less to changes in temperature, and yields in Mountains respond relatively more to changes in temperature. Soybean yields have no regional effects. Upland cotton in Southeast region is less sensitive to temperature. In Model 1, crop yields of sorghum in South Plains and winter wheat in Northeast are most sensitive to change in temperature, while in Model 2, crop yields of upland cotton and sorghum in Mountains and winter wheat in South Plains are most sensitive to change in temperature. That implies that the worse the growing condition is, the more sensitive to temperature crop yield is.

Simulation

To do the projection, we use the parameters estimated from historical data with climate variables derived from several climate projections. We utilize two global climate models (GCMs) inform the IPCC under the A1B scenario from the Special Report to Emission Scenarios (IPCC, 2000). The GCMs include the Geophysical Fluid Dynamics Laboratory Coupled Model version 2.1 (GFDL: CM2.1) and the Meteorological Research Institute coupled general circulation model version 2.3 (MRI: CGCM2.3). Through the IPCC Data Distribution Center, we obtained the projected changes in temperature and precipitation for two periods, 2040-2069 and 2070-2099 for each climate model. We use the average of observed temperature and precipitation in 1991-2000 as the baseline data. In forming the projections, we draw monthly mean temperature and monthly total precipitation and average them to generate growing seasonal temperature and precipitation variables. We then predict crop yields using baseline climate data and alternative projected climate data.

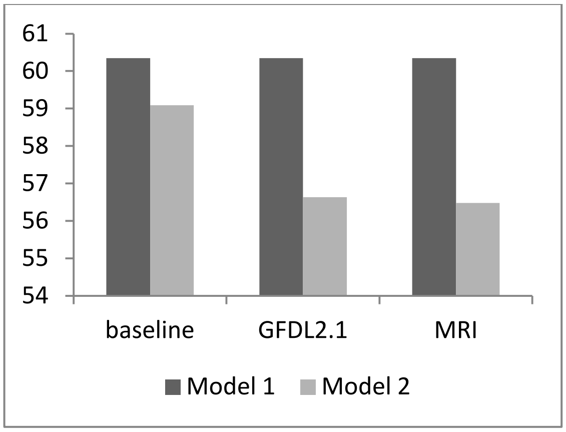
Irrigation effects estimated from Model 1 are consistent regardless of climate changes. In Model 2, irrigation effects in Mountains and Pacific regions are greater than those in other regions (table 23, figures 15 and 16). Because of relatively low temperature

Table 23 Irrigation Effects from Model 2 under Alternative Climate Change Projections from Global Circulation Models

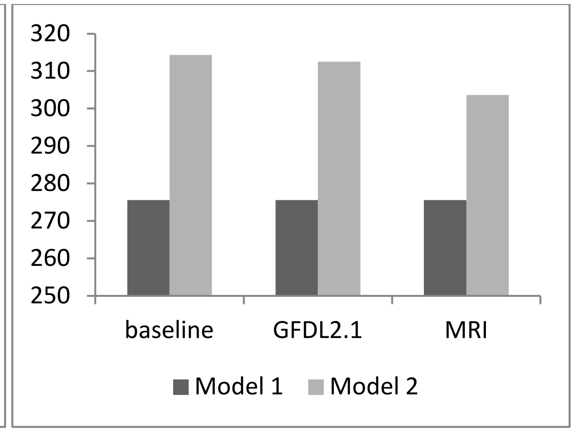
	2040-2069					2070-2099				
	Corn	Cotton	Sorghum	Soybeans	Wheat	Corn	Cotton	Sorghum	Soybeans	Wheat
Baseline										
Central	52.8		24.9	10.4	19.6	52.8		24.9	10.4	19.6
Northeast	55.9		25.7	11.6	13.9	55.9		25.7	11.6	13.9
Southeast	43.4	283.1	24.6	11.8	7.1	43.4	283.1	24.6	11.8	7.1
N. Plains	66.2		31.5	12.5	28.8	66.2		31.5	12.5	28.8
S. Plains	49.1	266.1	28.1	13.3	5.0	49.1	266.1	28.1	13.3	5.0
Mountains	81.8	491.9	48.8		37.6	81.8	491.9	48.8		37.6
Pacific	69.7	388.1	47.0	15.2	21.5	69.7	388.1	47.0	15.2	21.5
GFDL: CM2.1										
Central	50.0		29.1	11.1	19.4	42.6		28.1	10.1	16.8
Northeast	65.2		24.8	12.0	13.7	57.5		24.2	11.2	11.8
Southeast	44.1	267.4	25.3	11.9	8.6	37.5	234.0	24.7	11.2	6.3
N. Plains	51.7		31.6	11.5	20.3	44.9		31.7	11.1	19.1
S. Plains	38.7	249.1	33.5	14.9	8.8	33.1	211.0	32.8	14.1	6.8
Mountains	81.8	504.7	40.1		25.6	74.6	472.0	39.8		24.5
Pacific	62.7	515.7	50.2	18.2	18.6	57.9	506.7	52.3	16.8	18.4
MRI: CGCM2.3										
Central	53.3		30.4	12.1	21.4	47.2		30.4	11.6	19.4
Northeast	55.4		27.3	12.2	13.4	50.7		26.7	11.5	12.2
Southeast	39.9	238.2	26.1	11.7	6.4	35.2	217.6	25.5	11.2	5.3
N. Plains	57.9		32.0	12.3	21.2	51.5		32.2	11.9	19.8
S. Plains	40.7	244.9	32.2	14.5	6.9	35.9	221.6	32.5	14.4	6.2
Mountains	78.2	517.3	45.5		30.6	72.9	483.2	44.9		28.8
Pacific	77.6	561.7	55.3	18.7	23.7	72.3	516.5	54.6	17.6	21.3

Table 24 Percentage Changes in Irrigation Effects from Model 2 under Alternative Climate Change Projections from Global Circulation Models

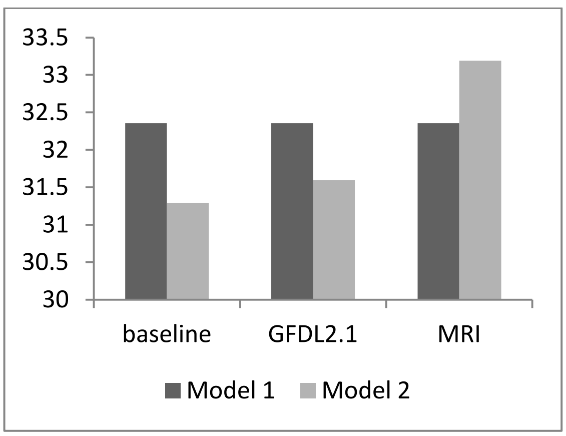
	2040-2069					2070-2099				
	Corn	Cotton	Sorghum	Soybeans	Wheat	Corn	Cotton	Sorghum	Soybeans	Wheat
GFDL: CM2.1										
Central	-5.26		16.88	6.80	-1.43	-19.37		13.19	-2.82	-14.25
Northeast	16.57		-3.60	4.09	-1.29	2.83		-6.00	-2.81	-14.74
Southeast	1.68	-5.55	2.65	0.82	21.87	-13.53	-17.33	0.18	-4.37	-11.13
N. Plains	-21.92		0.22	-8.38	-29.65	-32.20		0.54	-11.88	-33.70
S. Plains	-21.18	-6.36	19.05	12.58	77.20	-32.66	-20.70	16.47	6.12	36.54
Mountains	0.09	2.60	-17.84		-31.86	-8.73	-4.05	-18.56		-34.91
Pacific	-10.02	32.90	6.84	20.30	-13.52	-17.02	30.58	11.21	11.13	-14.45
MRI: CGCM2.3										
Central	0.94		22.22	17.05	9.16	-10.51		22.39	11.75	-1.31
Northeast	-0.97		6.06	5.25	-3.60	-9.25		3.65	-0.85	-12.07
Southeast	-7.90	-15.85	6.06	-0.84	-9.32	-18.90	-23.12	3.65	-5.02	-24.39
N. Plains	-12.63		1.45	-1.90	-26.20	-22.24		2.23	-4.82	-31.17
S. Plains	-17.12	-7.94	14.39	9.12	37.52	-26.95	-16.70	15.46	8.59	23.97
Mountains	-4.41	5.17	-6.75		-18.58	-10.86	-1.77	-8.08		-23.43
Pacific	11.27	44.76	17.66	23.51	10.35	3.70	33.10	16.03	16.28	-0.62



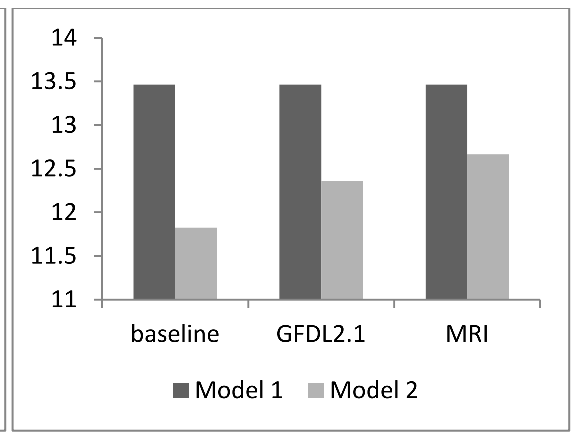
(a) Corn



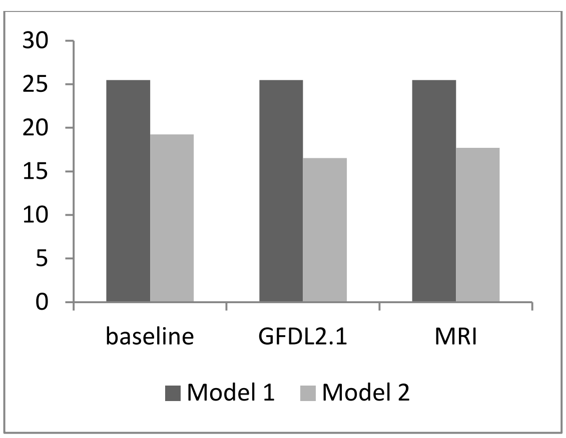
(b) Upland Cotton



(c) Sorghum



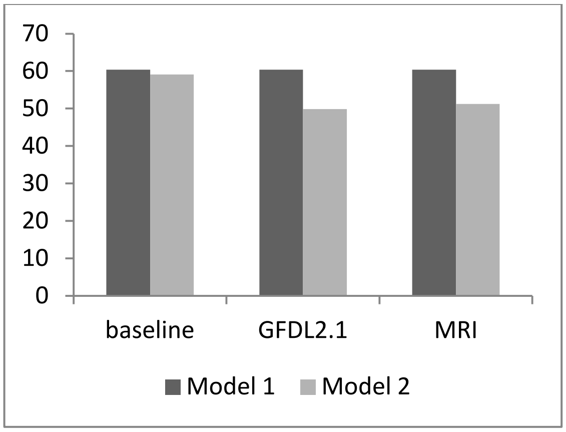
(d) Soybeans



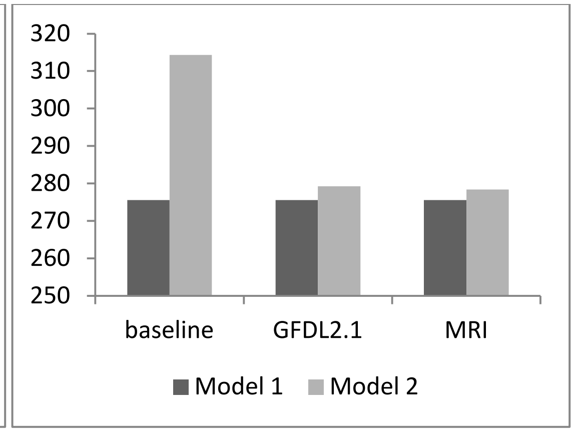
(e) Winter Wheat

Figure 15 Irrigation effects under projected Global Circulation Models for 2040-2069

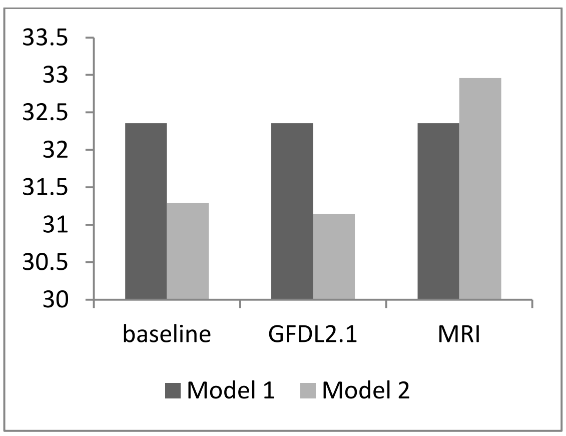
Note: Unit of all crops are bu/acre, except for cotton, which has unit in lbs/acre.



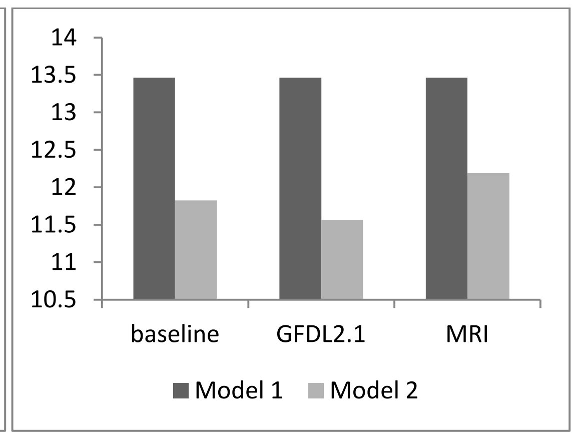
(a) Corn



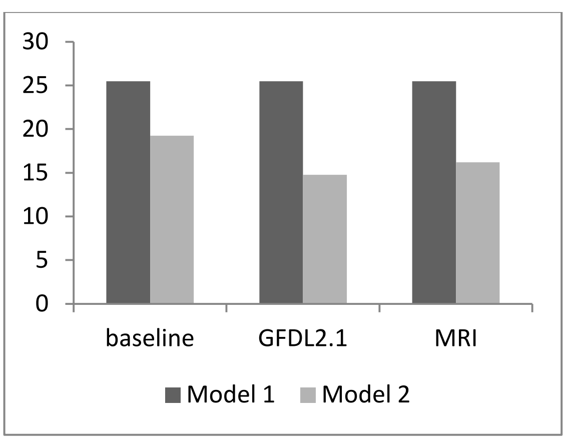
(b) Upland Cotton



(c) Sorghum



(d) Soybeans



(e) Winter Wheat

Figure 16 Irrigation effects under projected Global Circulation Models for 2070-2099

Note: Unit of all crops are bu/acre, except for cotton, which has unit in lbs/acre.

and precipitation, irrigation is more beneficial in these regions. In addition, in Mountains and Pacific regions, irrigation effects from Model 2 are greater than those from Model 1, while in other regions, irrigation effects from Model 2 are lower.

Climate change effects on irrigation effects estimated by Model 2are presented in table 24. For corn, the benefits of irrigation on yields are expected to decrease in most regions and particularly in South and North Plains regions, the irrigation effects decrease by up to 32%. In 2040-2069, irrigation effects on upland cotton will increase in Mountains and Pacific and decrease in other regions. In 2070-2099, irrigation effects on upland cotton will decrease in all regions excluding Pacific. For sorghum, in the Northeast and Mountains under scenario projected from GDFL-CM2.1 and the Mountains under scenario projected from MRI-CGCM2.3, the irrigation effects are expected to decline. Simulation results for soybeans are inconsistent excluding increase in South Plains and Pacific and decrease in North Plains. Under the climate change, irrigation is predicted to be less beneficial to winter wheat yields in most of regions except South Plains.

Nationally, under the scenario projected from GDFL-CM2.1 for 2070-2099, irrigation effects are decreased for all crops, but under alternative scenarios, climate change reduces positive effects of irrigation for corn, upland cotton, and winter wheat and increase irrigation effects for sorghum and soybeans.

Conclusion

This essay estimates irrigation effects on yields of five major crops including corn, upland cotton, sorghum, soybeans, and winter wheat. This is accomplished by estimating a crop productivity function using a panel data set by climate division for the years 1981 to 2007. To examine simultaneous effects of irrigation and climate, we construct a productivity function with and without interactive terms between irrigation and temperature. We also investigate the impacts of projected climate change on irrigation effects.

We find that estimated results for non-irrigated yields are consistent to the mean yield estimations in chapter 2. All crops are significantly affected by climate. In Model 1 which includes only dummy variable of irrigation, crop yields are increased by 60, 276, 32, 13, and 26 lbs for corn, upland cotton, sorghum, soybeans, and winter wheat respectively. These irrigation effects are required to be constant regardless of climate conditions. In the other hand, the irrigation effects estimated from Model 2 which include both irrigation dummy and interactive variables between irrigation and climate are affected by external climate factors such as temperature, extreme temperature conditions, precipitation and PDSI. We find that as temperature increases, the irrigation effects are decreased and irrigation reduces damages from extreme temperature conditions. Precipitation and PDSI effects are also diminished under irrigation.

To investigate how future projected climate change may influence future irrigation effects on crop yields, we simulate irrigated and non-irrigated crop yields over alternative climate change projections. The simulation shows that climate change increases irrigation effects for sorghum and soybeans, while decreases for other crops. Changes in irrigation incentives differ by crop, region, and scenario.

CHAPTER IV

THE EFFECTS OF CLIMATE ON CROP MIX AND CLIMATE CHANGE ADAPTATION

There is no doubt that exogenous environmental factors such as temperature and precipitation influence crop productivity on a differential basis by crop (Adams et al., 1990; Reilly et al., 2002; Deschenes and Greenstone, 2007). Therefore, when producers decide their crop choice, climate plays a critical role. That is, spatial crop yield distributions depend on the exogenous environmental factors. For example, because cotton requires a long frost-free period and a plenty of sunshine, cotton is produced only in southern states. Similarly on account of the temperature and precipitation requirements, rice also can be planted in selected states. Due to climate change, it is expected that producers will experience altered climate such as increasing temperature, change in precipitation patterns, and more frequent extreme weather events. Hence, crop choice adaptation is expected to be an important adaptation to climate change. As a consequence crop mixes are expected to change (adapt) to better accommodate the altered climate.

There are several studies that consider agri-sector adaptation to climate in other setting. Seo and Mendelsohn (2008a, 2008b) explain how African and South American farmers adapt to climate by changing the choices of livestock and crop. They found that both African and South American farmers' choices are affected by climate. With high temperature and precipitation, African farmers prefer goats and sheep to cattle. In South

America, more fruits and vegetables are planted in warmer places, while more wheat and potatoes are planted in cooler places. Also they predict that global warming will cause farmers to alter their crop and livestock mix. Seo et al. (2010) examine climate effects on South American farmers' choices of livestock species. They found that increase in temperature causes more livestock adaption and excessive humidity leads to a decrease in livestock adaption. Mu et al. (2012) examine climate effects on pasture and crop land use and livestock stocking rates in the U.S. They also project land use adaptation to climate change and estimate an associated economic impact due to the adaptation. They found that as temperature and precipitation increase, producers tend to switch crop land to pasture land.

However, there are few studies that investigate climate effects on crop mix adaptation in the U.S. This essay will examine how producers adjust current choices to a varying climate by comparing the choices of producers who face current different environmental conditions across space and time. Using a fractional multinomial logit model (following Papke and Wooldridge, 1996), we estimate the climate effects on crop mix and project crop mix adaptation to climate change scenarios from the IPCC (2000).

Data

To investigate climate effects on the crop mix, a statistical panel data approach is used. Data from 1976 to 2010 are used at the state level in the U.S. All climate data are average crop incidence in the previous 5 years. Hence, the data set used in estimation is

Table 25 Statistical Characteristics of Variables

Variable	Mean	Std.Dev.	Min	Max
Share in Cropland				
Barley	0.0575	0.1010	0.0000	0.6087
Corn	0.2720	0.2207	0.0000	0.9012
Cotton	0.0875	0.1632	0.0000	0.7916
Rice	0.0165	0.0548	0.0000	0.4146
Sorghum	0.0272	0.0602	0.0000	0.4747
Soybeans	0.2438	0.2048	0.0000	0.6996
Wheat, Spring	0.0525	0.1212	0.0000	0.6311
Wheat, Durum	0.0114	0.0431	0.0000	0.4027
Wheat, Winter	0.2316	0.2199	0.0000	0.8571
Temperature	53.2873	7.5246	39.0200	71.4433
Temperature^2	2896.1100	819.7557	1522.5600	5104.1500
DT32	114.3942	47.6923	4.6833	209.2691
DT90	39.2453	27.2947	3.3831	120.8867
Precipitation	35.4896	14.6390	7.2920	65.7340
Precipitation^2	1473.6420	1020.3350	53.1733	4320.9590
PDSI	0.3859	1.3014	-4.4672	6.1893
Prec. Intensity	0.1732	0.0544	0.0104	0.3829
Irrigation rate	0.2041	0.2731	0.0000	1.0000
# of Observations	1260			

Table 26 Definition of Regions and Its Cropland Share in 2010

Region	States	% share
D1-Central	IN, IL, IA, MI, MO, MN, OH, WI	44.1
D2-Northeast	CT, DE, ME, MD, MA, NH, NJ, NY, PA, RI, VT	1.9
D3-Southeast	AL, FL, GA, KY, NC, TN, VA, WV	5.5
D4-North Plains	KS, NE, ND, SD	27.1
D5-South Plains	AR, LA, MS, OK, TX	13.5
D6-Mountains	AZ, CO, ID, MT, NV, NM, UT, WY	5.7
D7-Pacific	CA, OR, WA	2.2

Table 27 Cropland Share by Region in 2010

	Barley	Corn	Upland Cotton	Rice	Sorghum	Soybeans	Spring Wheat	Durum Wheat	Winter Wheat
D1-Central	0.0011	0.5027	0.0031	0.0025	0.0007	0.4505	0.0156	0.0000	0.0238
D2-Northeast	0.0252	0.5130	0.0000	0.0000	0.0000	0.3549	0.0000	0.0000	0.1069
D3-Southeast	0.0051	0.2971	0.1333	0.0000	0.0000	0.4653	0.0000	0.0000	0.0992
D4-North Plains	0.0113	0.3217	0.0008	0.0000	0.0396	0.2882	0.1266	0.0295	0.1824
D5-South Plains	0.0000	0.1302	0.2236	0.0922	0.0680	0.2233	0.0000	0.0000	0.2627
D6-Mountains	0.0999	0.1177	0.0186	0.0000	0.0182	0.0000	0.2632	0.0489	0.4335
D7-Pacific	0.0400	0.0700	0.0251	0.1128	0.0000	0.0000	0.1452	0.0194	0.5875
U.S. Total	0.0109	0.3608	0.0408	0.0161	0.0212	0.3392	0.0594	0.0112	0.1405

Table 28 Cropland Share by Crop in 2010

	Barley	Corn	Upland Cotton	Rice	Sorghum	Soybeans	Spring Wheat	Durum Wheat	Winter Wheat
D1-Central	0.0449	0.6150	0.0335	0.0694	0.0138	0.5861	0.1160	0.0000	0.0748
D2-Northeast	0.0437	0.0268	0.0000	0.0000	0.0000	0.0197	0.0000	0.0000	0.0143
D3-Southeast	0.0257	0.0451	0.1788	0.0000	0.0000	0.0751	0.0000	0.0000	0.0386
D4-North Plains	0.2808	0.2414	0.0054	0.0000	0.5039	0.2300	0.5771	0.7126	0.3514
D5-South Plains	0.0000	0.0489	0.7426	0.7776	0.4334	0.0892	0.0000	0.0000	0.2533
D6-Mountains	0.5249	0.0187	0.0261	0.0000	0.0489	0.0000	0.2535	0.2497	0.1764
D7-Pacific	0.0800	0.0042	0.0134	0.1530	0.0000	0.0000	0.0533	0.0377	0.0911
U.S. Total	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

from 1981 to 2010 and includes 5348 observations. Table 25 presents statistical characteristics of variables used.

For climate, all data were collected at the annual state level. These data were temperature, precipitation, the number of days where the minimum temperature was less than 32 °F, the number of days where the maximum temperature was greater than 90 °F, and the Palmer Drought Severity Index (PDSI). The data were all drawn from the NOAA - National Climate Data Center (NCDC). To develop a measure on the intensity of precipitation, we follow IPCC, 2007 and compute the ratio of total precipitation from the top 5% days with the highest amount of precipitation to the annual total.

Crop mix data are based on acreage harvested. We focus on the nine major field crops which cover 92% of total field crop acreage harvested in 2007 (the Agriculture Census, 2007): barley (1.4%), corn for grain (35.3%), upland cotton (4.2%), rice (1.1%), sorghum (2.8%), soybeans (26.2%), spring wheat excluding durum (5.3%), durum wheat (0.9%) and winter wheat (14.7%). (Hay, forage, field and grass seeds are not included in field crops.) The data on acreage harvested were obtained from the United States Department of Agriculture – National Agricultural Statistics Service (USDA-NASS). Cropland share of crop *j* in state *i* is calculated as follows,

$$land\ share_{ij} = \frac{acre\ harvested_{ij}}{\sum_{k=1}^{J} acre\ harvested_{ik}}.$$

The U.S. cropland distribution is summarized in tables 26, 27 and 28.

As many previous studies show, there are considerable irrigation effects on crop choice. Because irrigation is used in some states, irrigation effects can offset or distort regional effects. To avoid this confounder, we include the irrigation ratio. Using the Agriculture Census (USDA-NASS, 2007) and Survey data, the irrigation rate which is calculated by dividing acreage irrigated into total harvested acreage. For years when acreage irrigated data are not available, we assume that the irrigation rate is changed proportionally.

Hypothetically cropland share should be correlated to crop price, but historical observations show that it is not in the long-term. As figure 17 and table 29 indicate, all crop prices are highly correlated each other and crop prices have moved together. After the introduction of biofuel, demand and price of energy crops such as corn is increased, but in the long term, the effect of the biofuel is not significant. Compared with 3 year average of real price from 1981 to 1983, 3 year average of real price from 2009 to 2011 is decreased by 14% - 51% for all crops (table 30). By contrast, compared with 3 year average of crop yield from 1981 to 1983, 3 year average of crop yield from 2009 to 2011 is increased by 14% - 53% (figure 18). For example, real prices of corn, rice and soybeans are decreased by 26 %, 25 %, and 23 % respectively, while yield per acre are increased 53 %, 47 %, and 48 % respectively. As a result, total production and acreage harvested are increased. Despite the price decline, producers choose corn, rice, and soybeans because of their increasing productivity. On the other hand, for barley, sorghum, durum wheat, and winter wheat, the real prices are decreased by 14 %, 27 %, 18 %, and 32 % respectively, and yield per acre are increased by 33 %, 14 %, 30 %, and 21 % respectively. However, relatively small improve in productivity, producers are like to less grow barley, sorghum, durum wheat, and winter wheat and the production also

Table 29 Correlation – Real Prices, 5 Year Average, State

	Barley	Corn	Cotton, Upland	Rice	Sorghum	Soybeans	Wheat, Spring	Wheat, Durum	Wheat, Winter
Barley	1								
Corn	0.8964	1							
Cotton, Upland	0.8657	0.9351	1						
Rice	0.8856	0.9384	0.9209	1					
Sorghum	0.9117	0.9740	0.9366	0.9534	1				
Soybeans	0.9028	0.9595	0.9650	0.9720	0.9668	1			
Wheat, Spring Other	0.8912	0.9603	0.9179	0.9677	0.9646	0.9714	1		
Wheat, Durum	0.8891	0.9417	0.9100	0.9706	0.9544	0.9598	0.9777	1	
Wheat, Winter	0.9139	0.9724	0.9405	0.9600	0.9713	0.9755	0.9824	0.9679	1

Table 30 Percentage Changes in Total Cropland Acreage, Crop Prices, Yield, and Total Production in 1981-2010

	Barley	Corn	Cotton, Upland	Rice	Sorghum	Soybeans	Wheat, Spring	Wheat, Durum	Wheat, Winter	Total
Acreage	-71.85	23.25	-10.68	1.23	-62.28	14.38	-12.65	-49.21	-39.79	-6.75
Crop price	-13.72	-25.62	-51.43	-25.30	-27.03	-23.43	-25.38	-18.07	-31.58	
Yield per acre	33.23	53.27	42.03	47.78	13.97	46.92	34.13	29.92	20.67	
Production in $	-63.51	27.60	-40.86	16.04	-63.31	17.52	-5.15	-41.35	-44.50	1.62
Production in quantity	-62.38	84.61	25.95	48.58	-57.10	67.57	17.47	-33.91	-26.88	

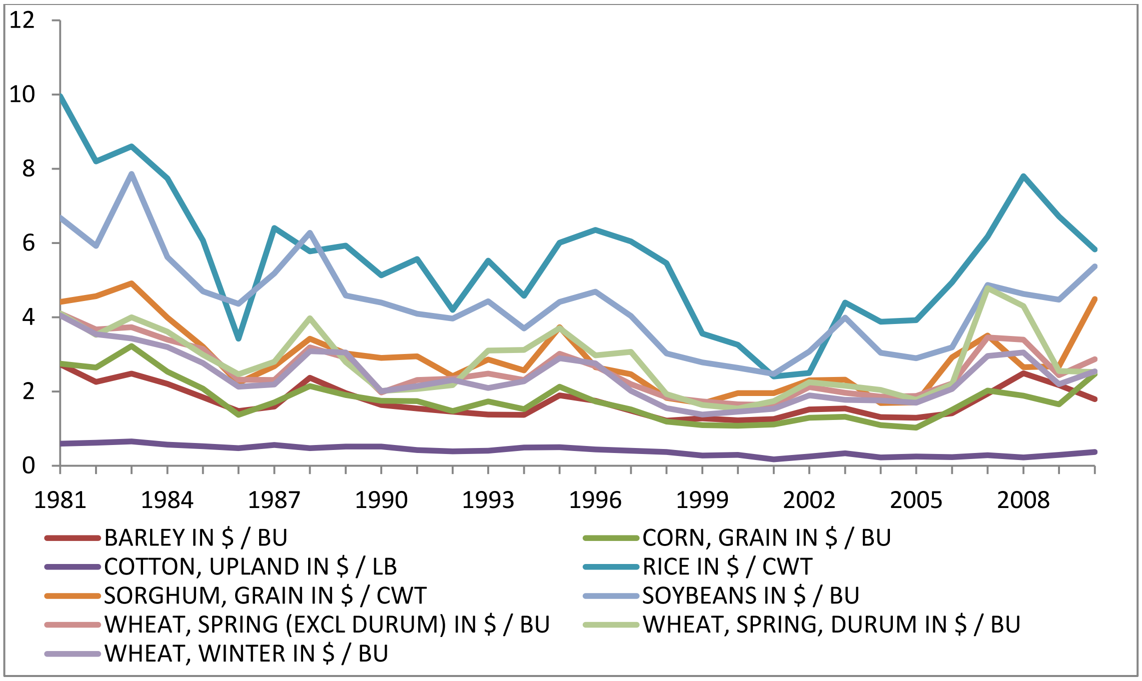


Figure 17 Real crop prices in 1981- 2011

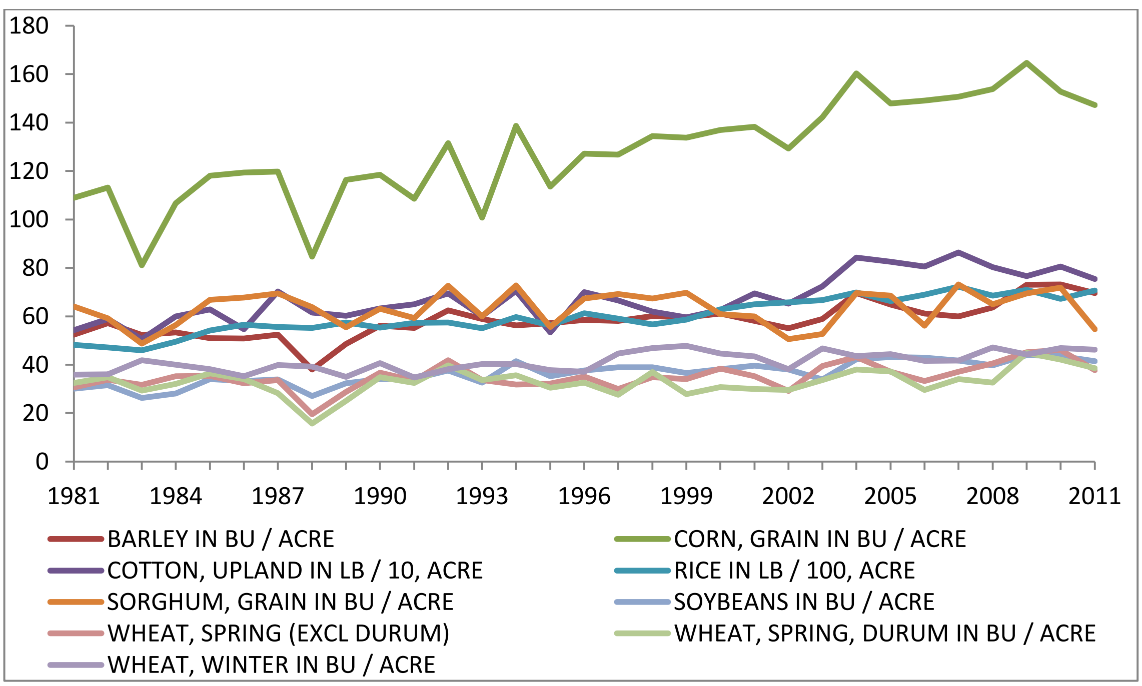


Figure 18 Crop yield per acre in 1981- 2011

decreased. In addition, for upland cotton and spring wheat, yields per acre are increased and real prices and acreage harvested are decreased. In spite of decreased acreage, the total quantity of produced is increased. Hence, when producers choose crop to cultivate, the effect of crop prices is not significant as table 30 shows. It is relative changes between price and productivity that impact on producers' welfare and choice. Therefore, we do not include crop price data in this study.

Model Specification

Fractional Multinomial Logit Model

In this essay, producers are assumed to maximize their profits. Producers choose the desired crops to yield the highest profit. However, to distribute risk and accommodate limited resource availability at key operation times, most crop producers in U.S. plant several crops rather than one crop (Baker and McCarl, 1982). Under an assumption that crop choice is mutually exclusive and exhaustive, Seo employed a multinomial logit to estimate their model. Since we use aggregated state level data unlike Seo used farm level data set, the assumption that only one crop is chosen to be cultivated in a state is not valid in this essay. Mu et al. relax this using a multinomial logit model when looking at land choices. Thus we follow Mu et al. and employ a fractional multinomial logit model to estimate climate effects on crop mix. Papke and Wooldridge introduced the fractional multinomial logit model as a method to estimate fractional response models in their study of voluntary individual contributions to retirement accounts in which the main dependent variable was the fraction of allowable contributions made by each individual (1996).

When y_{ij} is a cropland share of crop j in state i, y_{ij} is limited to be $y_{ij} \ni [0, 1]$ and $\sum_j y_{ij} = 1$. Given these limitations, the crop share is assumed to be

(1) $\mathrm{E}\left[y_{ij}|\mathbf{x}_i\right] = G\left(\mathbf{x}_i\beta_j\right), j = 1, 2, \dots, J$

, where $\mathbf{x}$ is a vector of exogenous variables and β are parameters to be estimated. One functional form that embeds y_{ij} within the unit interval is the multinomial logit functional form

(2) $$\mathrm{E}\left[y_{ij}|\mathbf{x}_i\right] = \frac{exp\ (\mathbf{x}_i\beta_j)}{\sum_{k=1}^{J} exp\ (\mathbf{x}_i\beta_k)}.$$

For the identification of the fractional multinomial model, one set of parameters is required to be normalized. Using the normalization, $\beta_1 = 0$, the estimation function is given by,

(3) $$\mathrm{E}\left[y_{ij}|\mathbf{x}_i\right] = \frac{exp\ (\mathbf{x}_i\beta_j)}{1 + \sum_{k=2}^{J} exp\ (\mathbf{x}_i\beta_k)} \text{ for } j = 2, 3, \dots, J$$

and

(4) $$\mathrm{E}\left[y_{ij}|\mathbf{x}_i\right] = \frac{1}{1 + \sum_{k=2}^{J} exp\ (\mathbf{x}_i\beta_k)} \text{ for } j = 1.$$

In the estimation, the dependent variable y is cropland share of barley, corn, upland cotton, rice, sorghum, soybeans, spring wheat, durum wheat, and winter wheat. Additionally we use the independent variables:

- time trend,
- annual mean temperature,

- annual total precipitation,
- squares of above two,
- counts of days exhibiting extreme temperature - days above 90 °F and days below 32 °F,
- the Palmer drought index, PDSI which has negative values when droughts occur and positive values when conditions are wet,
- precipitation intensity which is percent of rain from 5% wettest days,
- irrigation rate which is proportion of irrigated crop land for each crop in the climate division,
- regional dummies for the regions defined in table 26 and
- interaction terms between temperature and the regional dummies.

Results

Table 31 shows the results of the fractional multinomial logit regression of the probability of choosing each crop. Barley, the base case, has been left out of the regression. The interpretation of a positive coefficient in this table implies that an increase in the associated variable leads to a higher probability of choosing each crop and vice versa.

Figure 19 describes the estimated relationship between the probability of choosing a crop and annual mean temperature under the ceteris paribus assumption. Other variables are constant at the national average level. The figure shows that the choice of crops in the U.S. is generally temperature sensitive. For example, the probability of choosing spring wheat is higher in the low temperature area, while the probability of choosing rice is high in the high temperature area. That is, producers in cooler northern states prefer spring wheat to plant to other crops, and producers in southern states prefer rice. Actually, about 90% of spring wheat is planted in Montana, North and South Dakota, and Minnesota, and about 80% of rice is planted in Arkansas, Louisiana, Mississippi, and Texas in 2010. The rest of crops have specific ranges within the temperature range. Barley is chosen most often when temperature is close to 46 °F. Corn, soybeans and winter wheat have similar temperature ranges. They are planted in moderate temperature condition, but soybeans is preferred in relatively cooler areas. The temperature range for cultivated upland cotton and sorghum is higher than that of corn, soybeans, and winter wheat. Upland cotton and sorghum are chosen most often when temperature is about 61 °F. Upland cotton has a high cropland share in Arizona, Florida, and Texas, and sorghum has in Kansas, New Mexico, and Texas. Durum wheat is relatively cultivated often in low temperature, but even at the most favored temperature, compared to other crops, the possibility of choosing durum wheat is very low.

We find that the incidence of days with extreme temperatures have impacts on crop choice. The coefficients on DT32, the number of days with minimum temperature less than or equal to 32°F, are positive for corn, upland cotton, sorghum, soybeans, and winter wheat and negative for spring and durum wheat. The coefficients on DT90, the number of days with maximum temperature greater than or equal to 90°F, are positive for durum wheat and negative for corn, upland cotton, sorghum, soybeans, and winter

Table 31 The Fractional Multinomial Logit Regression

	Corn		Cotton		Rice		Sorghum	
	Coef.	P>|z|	Coef.	P>|z|	Coef.	P>|z|	Coef.	P>|z|
Trend	0.044	0.00	0.060	0.00	0.045	0.00	0.013	0.01
TMP	0.050	0.68	4.432	0.00	-5.091	0.00	2.733	0.00
TMP^2	0.009	0.00	-0.022	0.00	0.061	0.00	-0.008	0.00
DT32	0.106	0.00	0.073	0.00	0.021	0.09	0.134	0.00
DT90	-0.049	0.00	-0.059	0.00	-0.001	0.91	-0.025	0.01
PCP	0.236	0.00	-0.105	0.02	0.161	0.00	0.291	0.00
PCP^2	-0.002	0.00	0.002	0.00	0.000	0.52	-0.003	0.00
PDSI	-0.045	0.06	0.123	0.02	-0.308	0.00	0.094	0.02
Prec.Intensity	-0.977	0.09	2.768	0.01	-0.988	0.32	-0.636	0.58
Irrigation rate	2.277	0.00	2.309	0.00	4.984	0.00	0.286	0.36
D2	20.918	0.00	72.938	0.00	40.362	0.00	43.456	0.00
D3	6.686	0.00	28.139	0.00	94.633	0.00	24.864	0.00
D4	-6.736	0.00	-51.901	0.00	-2.659	0.57	25.289	0.00
D5	-33.847	0.00	9.522	0.15	109.826	0.00	-9.878	0.07
D6	-4.793	0.00	24.101	0.00	35.838	0.00	26.605	0.00
D7	8.657	0.00	48.135	0.00	34.523	0.00	21.048	0.00
Temp×D2	-0.499	0.00	-1.789	0.00	-1.208	0.00	-0.971	0.00
Temp×D3	-0.230	0.00	-0.627	0.00	-2.194	0.00	-0.589	0.00
Temp×D4	0.109	0.03	0.888	0.00	-0.253	0.01	-0.455	0.00
Temp×D5	0.461	0.00	-0.280	0.02	-2.014	0.00	0.052	0.59
Temp×D6	-0.013	0.72	-0.541	0.00	-1.184	0.00	-0.542	0.00
Temp×D7	-0.278	0.00	-0.987	0.00	-0.794	0.00	-0.516	0.00
Constant	-38.433	0.00	-175.953	0.00	90.851	0.00	-139.366	0.00

Table 31 Continued

	Soybeans		Wheat, Spring		Wheat, Durum		Wheat, Winter	
	Coef.	P>|z|	Coef.	P>|z|	Coef.	P>|z|	Coef.	P>|z|
Trend	0.048	0.00	0.026	0.00	0.044	0.00	0.036	0.00
TMP	0.966	0.00	2.011	0.00	-2.580	0.00	1.014	0.00
TMP^2	-0.003	0.14	-0.029	0.00	0.021	0.00	-0.002	0.18
DT32	0.077	0.00	-0.068	0.00	-0.061	0.00	0.054	0.00
DT90	-0.033	0.00	0.026	0.05	0.032	0.04	-0.038	0.00
PCP	0.324	0.00	-0.231	0.00	0.318	0.04	0.023	0.34
PCP^2	-0.002	0.00	0.002	0.00	-0.007	0.04	0.000	0.65
PDSI	-0.123	0.00	0.122	0.00	-0.081	0.10	0.016	0.38
Prec.Intensity	-2.282	0.00	-4.037	0.00	-3.338	0.09	-1.032	0.03
Irrigation rate	1.223	0.00	-2.327	0.00	-9.286	0.00	-0.467	0.02
D2	5.923	0.00	-35.115	0.00	-18.408	0.02	24.883	0.00
D3	-8.779	0.00	-76.087	0.00	-7.427	0.46	2.992	0.24
D4	-2.028	0.37	-11.925	0.00	-7.389	0.33	-15.454	0.00
D5	-29.234	0.00	-77.474	0.00	-3.877	0.78	3.118	0.45
D6	-19.899	0.00	-6.582	0.05	-17.395	0.03	9.111	0.00
D7	16.416	0.22	-17.519	0.01	-70.371	0.00	20.927	0.00
Temp×D2	-0.224	0.00	0.368	0.00	0.163	0.37	-0.564	0.00
Temp×D3	0.045	0.34	1.142	0.00	0.030	0.89	-0.148	0.00
Temp×D4	0.037	0.47	0.280	0.00	0.266	0.15	0.312	0.00
Temp×D5	0.435	0.00	1.175	0.00	-0.090	0.74	-0.082	0.26
Temp×D6	-0.040	0.32	0.128	0.11	0.493	0.01	-0.234	0.00
Temp×D7	-0.813	0.00	0.345	0.01	1.375	0.00	-0.452	0.00
Constant	-54.528	0.00	-16.282	0.15	75.355	0.00	-48.743	0.00

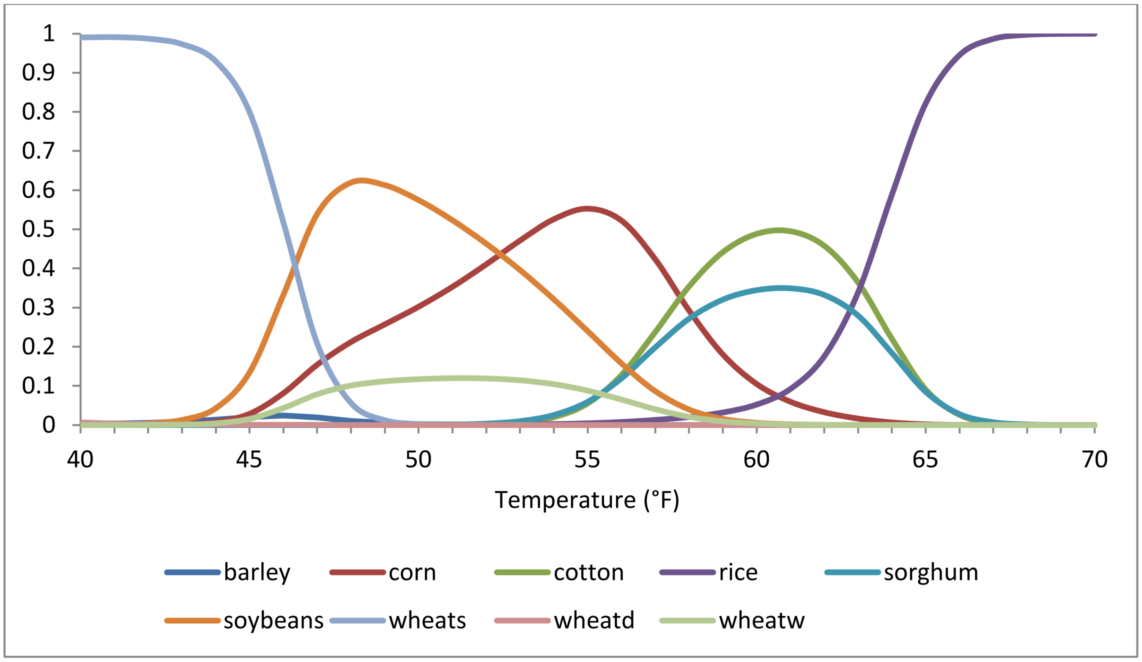


Figure 19 Estimated probability of selecting species given annual mean temperature

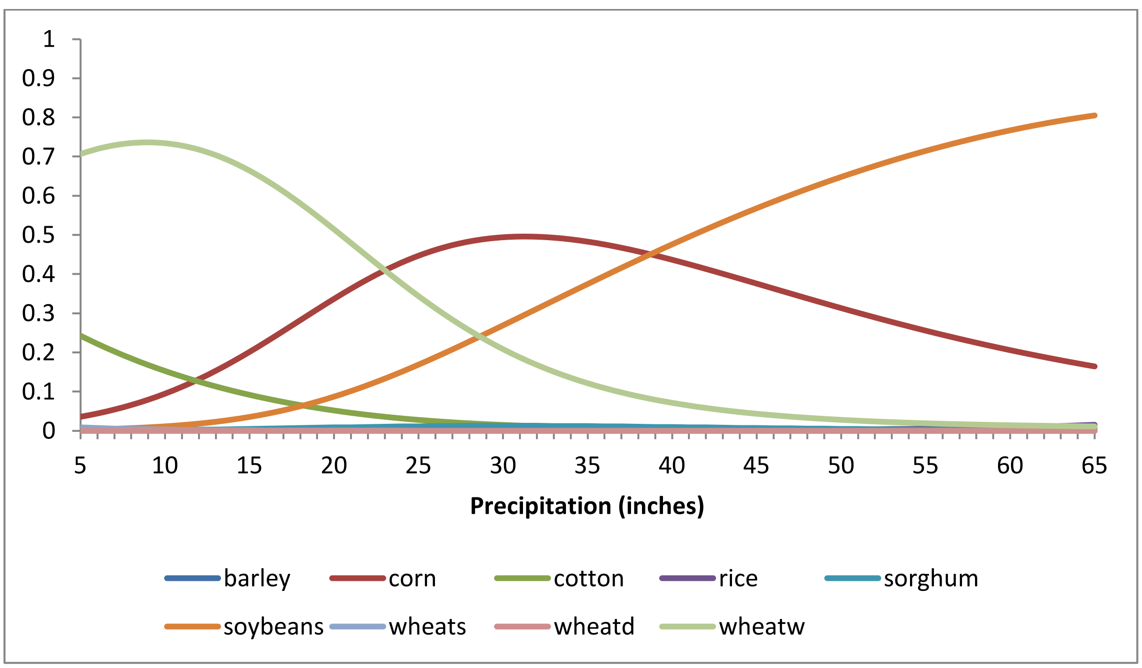


Figure 20 Estimated probability of selecting species given annual total precipitation

wheat. This implies that spring wheat and durum wheat, which are planted in northern states having higher incidence of extremely low temperature, are more likely to be chosen if the incidence of extremely low temperature decreases or the incidence of extremely high temperature increases, and vice versa for other crops except rice. Probability of choosing rice is not affected by the incidence of days with extreme temperatures.

Except for winter wheat, the coefficients of precipitation for all crops are statistically significant. That implies precipitation has significant impacts on the probability of choosing crops. Figure 20 shows the estimated relationship between the probability of choosing crops and annual total precipitation under the ceteris paribus assumption. Other variables are constant at the national average level. Figure 20 also shows that under the moderate temperature, the national average temperature, 53 °F, corn, soybeans, and winter wheat are mostly chosen as stated above. We found that barley, upland cotton, spring and winter wheat are most chosen in dry condition. In contrast, producers tend to choose more rice and soybeans with high precipitation. This finding is consistent with the fact that in the dry states such as Arizona, Montana, Nevada, Texas, and Wyoming, cropland share of barley, upland cotton, spring and winter wheat are higher than that in other states. In addition, in states with high precipitation such as Arkansas and Louisiana, rice and soybeans are cultivated more than other crops. Corn and sorghum are chosen most often in moderate precipitation range. Corn and sorghum have their peaks at 31 and 30 inches of annual precipitation, respectively.

PDSI is positively correlated with the possibility of choosing upland cotton, sorghum, and spring wheat and negatively with rice and soybeans. Producers are more likely to choose soybeans, spring and winter wheat with uniform precipitation pattern (low precipitation intensity), and vice versa for upland cotton. The coefficients on irrigation are positive for corn, upland cotton, rice, and soybeans, and are negative for wheat. It implies that producers tend to choose more corn, upland cotton, rice, and soybeans and less wheat when more irrigation is available.

In eastern regions, probability of choosing corn, upland cotton, rice and sorghum is higher and less affected by temperature than that in other regions, while probability of spring wheat is lower and more affected by temperature. In North and South Plains, corn and spring wheat are less chosen and the choices response more to temperature changes. In Pacific region, producers tend to plant more corn, upland cotton, rice, sorghum and winter wheat and are less sensitive to changes in temperature, and vice versa for spring and durum wheat.

We use time trend variable as a proxy of technical improvement. Coefficients for time trend are positive and statistically significant for all crops. Because if a cropland share of one crop increases, the others' cropland shares should decrease, even though all crops' coefficients on trend are positive, that does not mean all cropland shares will be increased as trend increases. Under the ceteris paribus condition at the national average level, crops with relatively large coefficients like cotton and soybeans are more chosen than crops with relatively small coefficients like sorghum and spring wheat as time trend increases (figure 21).

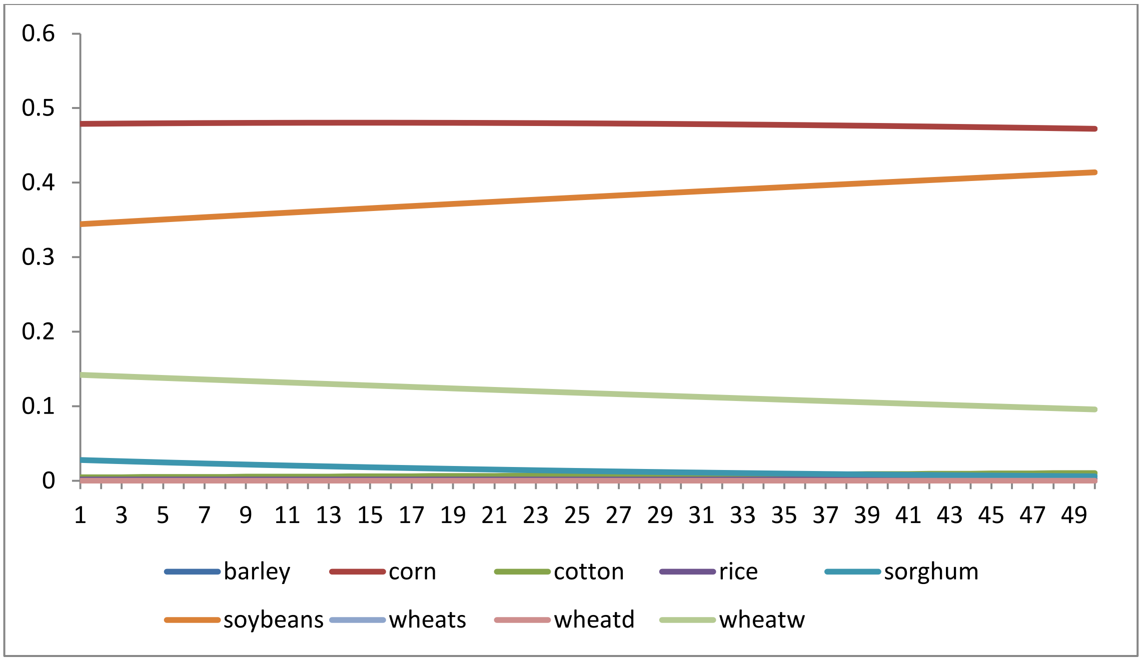


Figure 21 Estimated probability of selecting species given time trend

Simulation

In this section, we simulate the impacts of climate change on producers' choice of crops using parameter estimated in the previous section. Climate change scenarios are projected by General Circulation Models (GCM's). We employ the climate change scenarios which are generated from the Centre National de Recherches Météorologiques Coupled Model version 3 (CNRM: CM3) and the Geophysical Fluid Dynamics Laboratory Coupled Model version 2.1 (GDFL: CM2.1) under the A1B emission scenario. The A1B emission scenario from the Special Report on Emission Scenarios (SRES) of IPCC assumes very rapid economic growth, low population growth and rapid introduction of new and more efficient technology in future (IPCC, 2000). We use state level climate change scenarios in 2040-2069 and 2070-2099. As presented in table 32, in 2040-2969, the national average temperature is projected to increase by 3.9% and 0.9%, and the national average precipitation is predicted to increase by 9.2% and 2.2% from CNRM and GDFL2.1 scenarios respectively. In 2070-2099, the projected changes in temperature and precipitation are greater than that in 2040-2969. All national average changes are positive, but that does not mean that all states will be warmer and wetter. Some states are projected to experience decrease in temperature or precipitation or both. In addition, we assume that there is no adaptation by changing growing period and cropland acreage is not changed.

Tables 33 and 34 and figures 22 and 23 display the simulation results. Because both GCM project increase in temperature and precipitation, most direction of changes

Table 32 Temperature and Precipitation Changed under Alternative Climate Change Projections from Global Circulation Models (GCMs)

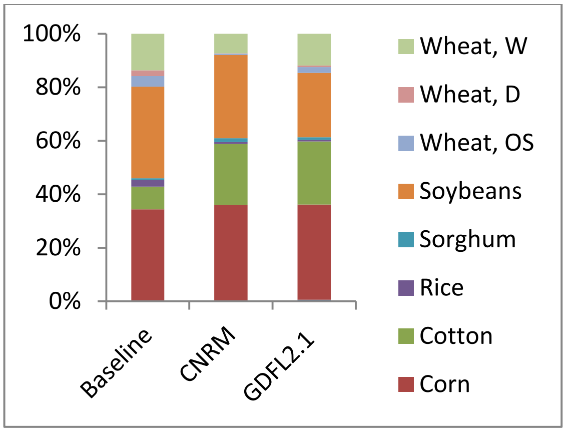
	Baseline		CNRM: CM3		GDFL: CM2.1	
	TMP	PCP	TMP	PCP	TMP	PCP
2040-2069						
D1-Central	48.6	37.0	51.2	37.0	50.0	31.9
D2-Northeast	51.7	44.5	53.7	49.3	50.5	45.2
D3-Southeast	59.7	50.1	61.5	46.8	59.9	40.3
D4-North Plains	47.6	23.3	51.7	33.2	51.6	25.0
D5-South Plains	63.2	46.9	66.3	30.7	65.4	26.8
D6-Mountains	48.9	14.0	49.7	20.9	47.0	22.4
D7-Pacific	52.4	29.2	51.9	26.3	51.3	30.1
U.S. Total	53.1	35.3	55.2	35.4	53.5	31.9
2070-2099						
D1-Central	48.6	37.0	54.5	35.8	51.9	34.1
D2-Northeast	51.7	44.5	55.9	49.0	52.5	46.8
D3-Southeast	59.7	50.1	64.1	46.5	61.7	42.2
D4-North Plains	47.6	23.3	54.8	31.9	53.0	24.8
D5-South Plains	63.2	46.9	69.6	28.9	66.9	27.5
D6-Mountains	48.9	14.0	52.0	20.8	48.6	22.1
D7-Pacific	52.4	29.2	53.8	27.4	52.3	29.0
U.S. Total	53.1	35.3	57.9	34.7	55.2	32.8

Table 33 Cropland Share under Alternative Climate Change Projections from Global Circulation Models for 2040-2069

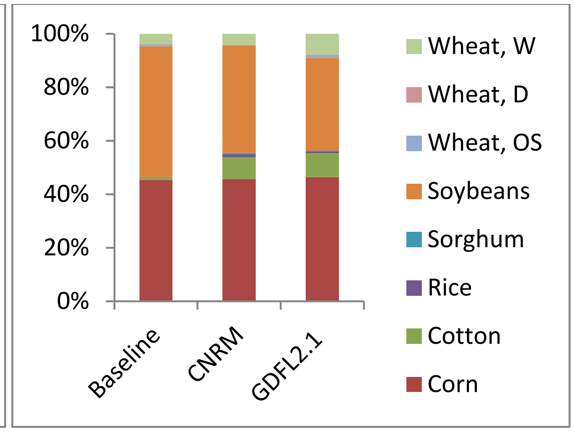
Region	Barley	Corn	Cotton, Upland	Rice	Sorghum	Soybeans	Wheat, Spring	Wheat, Durum	Wheat, Winter
Baseline									
Central	0.0004	0.4535	0.0075	0.0018	0.0008	0.4892	0.0070	0.0001	0.0397
Northeast	0.0019	0.5702	0.0000	0.0000	0.0001	0.3491	0.0000	0.0000	0.0788
Southeast	0.0004	0.2545	0.2437	0.0000	0.0011	0.4196	0.0000	0.0000	0.0806
N. Plains	0.0053	0.3479	0.0010	0.0000	0.0163	0.2804	0.0918	0.0720	0.1852
S. Plains	0.0000	0.0582	0.4620	0.1564	0.0132	0.1610	0.0000	0.0000	0.1491
Mountains	0.0303	0.1953	0.0399	0.0000	0.0041	0.0000	0.1657	0.0396	0.5251
Pacific	0.0154	0.0617	0.1761	0.0658	0.0001	0.0000	0.0645	0.0040	0.6124
CNRM: CM3									
Central	0.0001	0.4561	0.0808	0.0128	0.0042	0.4019	0.0005	0.0000	0.0435
Northeast	0.0014	0.5340	0.0000	0.0000	0.0001	0.4050	0.0000	0.0000	0.0596
Southeast	0.0003	0.2376	0.3655	0.0000	0.0016	0.3346	0.0000	0.0000	0.0604
N. Plains	0.0002	0.2678	0.2969	0.0000	0.0092	0.3761	0.0020	0.0007	0.0470
S. Plains	0.0000	0.2184	0.6398	0.0173	0.0558	0.0410	0.0000	0.0000	0.0277
Mountains	0.0261	0.5250	0.0334	0.0000	0.0369	0.0000	0.0305	0.0203	0.3278
Pacific	0.0226	0.0645	0.1166	0.0009	0.0000	0.0000	0.1212	0.0002	0.6739
GDFL: CM2.1									
Central	0.0004	0.4643	0.0878	0.0069	0.0031	0.3471	0.0109	0.0001	0.0794
Northeast	0.0034	0.5871	0.0000	0.0000	0.0000	0.3188	0.0000	0.0000	0.0907
Southeast	0.0033	0.2651	0.3001	0.0000	0.0015	0.3130	0.0000	0.0000	0.1169
N. Plains	0.0012	0.3210	0.2911	0.0000	0.0125	0.2242	0.0297	0.0065	0.1138
S. Plains	0.0000	0.1220	0.7469	0.0138	0.0246	0.0281	0.0000	0.0000	0.0647
Mountains	0.0636	0.3624	0.0124	0.0000	0.0395	0.0000	0.0923	0.0717	0.3580
Pacific	0.0382	0.0652	0.0261	0.0043	0.0000	0.0000	0.1532	0.0000	0.7128

Table 34 Cropland Share under Alternative Climate Change Projections from Global Circulation Models for 2070-2099

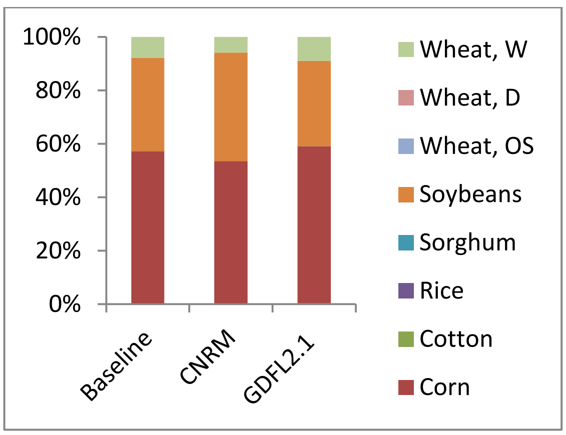
Region	Barley	Corn	Cotton, Upland	Rice	Sorghum	Soybeans	Wheat, Spring	Wheat, Durum	Wheat, Winter
Baseline									
Central	0.0001	0.4293	0.0126	0.0021	0.0002	0.5242	0.0037	0.0001	0.0276
Northeast	0.0004	0.5628	0.0000	0.0000	0.0000	0.3804	0.0000	0.0000	0.0564
Southeast	0.0001	0.2146	0.3396	0.0000	0.0003	0.3953	0.0000	0.0000	0.0501
N. Plains	0.0013	0.3697	0.0021	0.0000	0.0059	0.3324	0.0569	0.0830	0.1487
S. Plains	0.0000	0.0409	0.5844	0.1505	0.0030	0.1333	0.0000	0.0000	0.0879
Mountains	0.0091	0.2653	0.0499	0.0000	0.0014	0.0000	0.1207	0.0439	0.5097
Pacific	0.0044	0.0732	0.2144	0.0489	0.0000	0.0000	0.0461	0.0024	0.6108
CNRM: CM3									
Central	0.0000	0.3199	0.3868	0.0664	0.0041	0.1955	0.0000	0.0000	0.0272
Northeast	0.0002	0.4949	0.0000	0.0000	0.0000	0.4722	0.0000	0.0000	0.0327
Southeast	0.0000	0.1810	0.6059	0.0000	0.0006	0.1918	0.0000	0.0000	0.0206
N. Plains	0.0000	0.3210	0.3164	0.0000	0.0063	0.2598	0.0002	0.0002	0.0961
S. Plains	0.0000	0.4800	0.4663	0.0129	0.0269	0.0119	0.0000	0.0000	0.0021
Mountains	0.0029	0.6008	0.0816	0.0000	0.0206	0.0000	0.0067	0.0101	0.2774
Pacific	0.0021	0.1306	0.3320	0.0012	0.0000	0.0000	0.0069	0.0005	0.5266
GDFL: CM2.1									
Central	0.0000	0.4352	0.1525	0.0140	0.0019	0.3483	0.0004	0.0000	0.0477
Northeast	0.0003	0.5252	0.0000	0.0000	0.0000	0.4246	0.0000	0.0000	0.0499
Southeast	0.0001	0.2044	0.4625	0.0000	0.0005	0.2858	0.0000	0.0000	0.0468
N. Plains	0.0001	0.3402	0.3143	0.0000	0.0052	0.2064	0.0084	0.0026	0.1228
S. Plains	0.0000	0.2181	0.7305	0.0096	0.0121	0.0168	0.0000	0.0000	0.0129
Mountains	0.0117	0.4732	0.0820	0.0000	0.0176	0.0000	0.0346	0.0461	0.3348
Pacific	0.0081	0.0992	0.1523	0.0050	0.0000	0.0000	0.0566	0.0001	0.6786



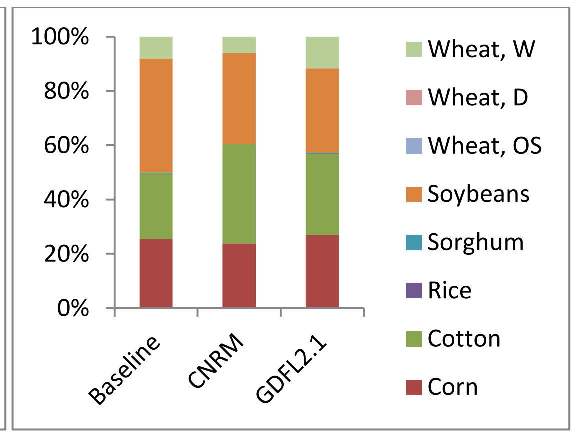
(a) U.S. Total



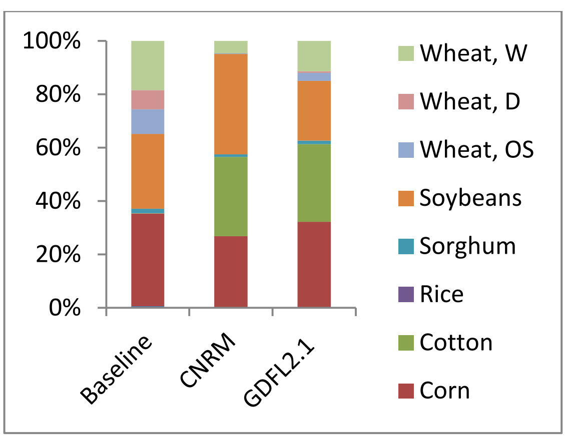
(b) Central



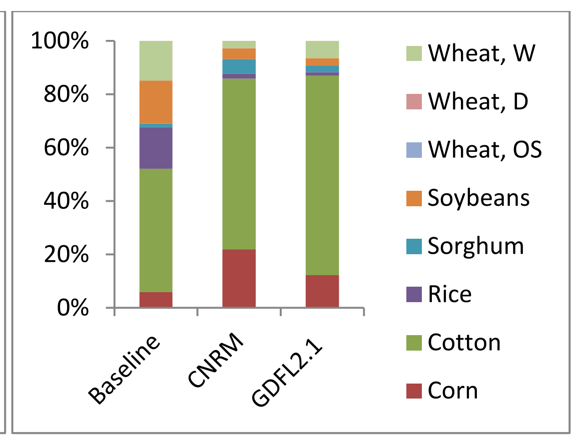
(c) Northeast



(d) Southeast

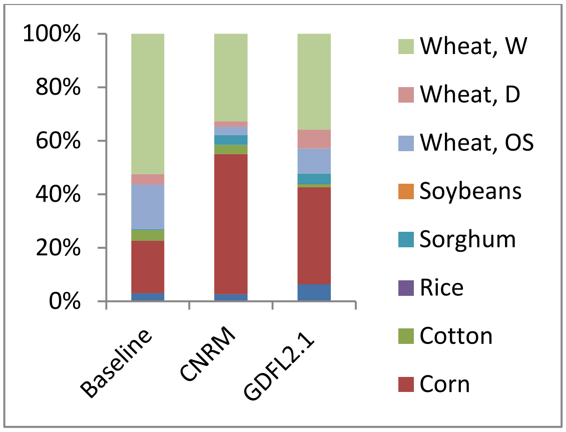


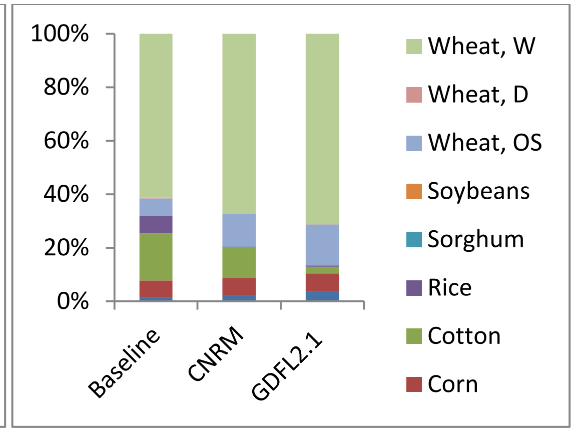
(e) North Plains



(f) South Plains

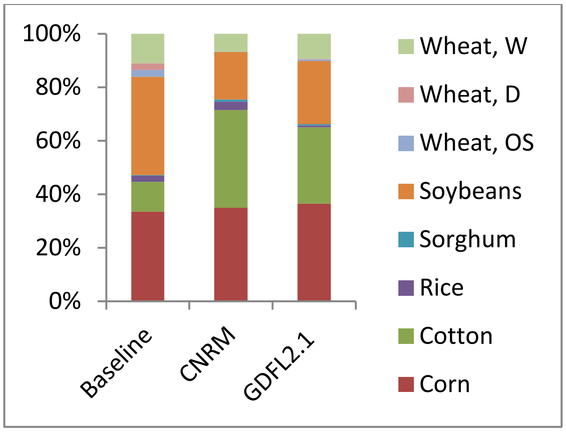
Figure 22 Cropland share under alternative climate change projections from Global Circulation Models (GCMs) for 2040-2069



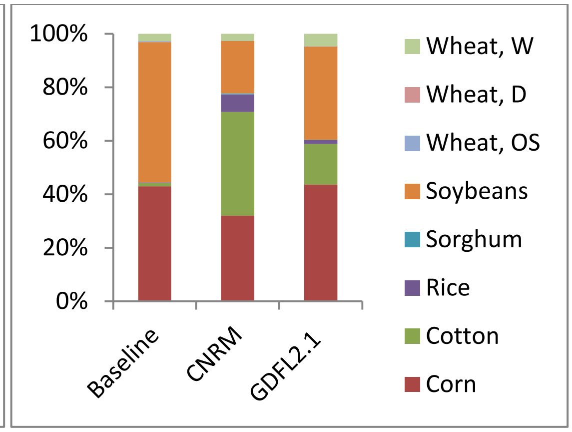


(g) Mountains (h) Pacific

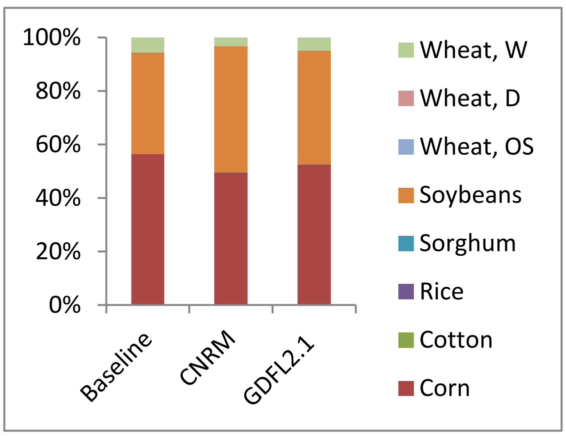
Figure 22 Continued



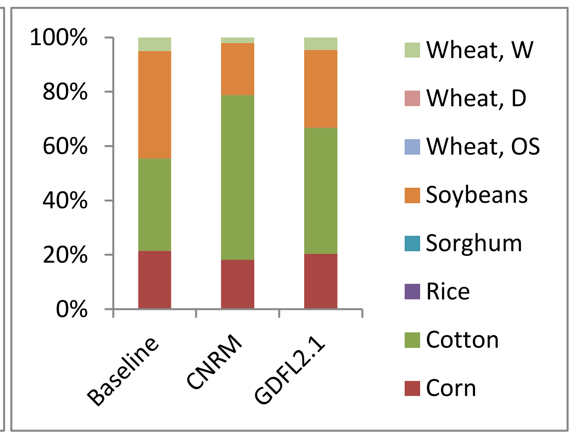
(a) U.S. Total



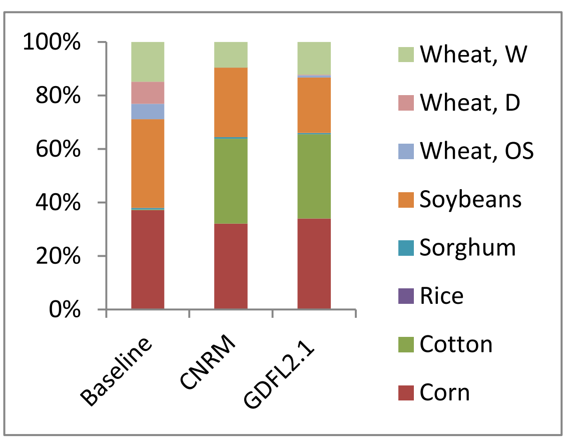
(b) Central



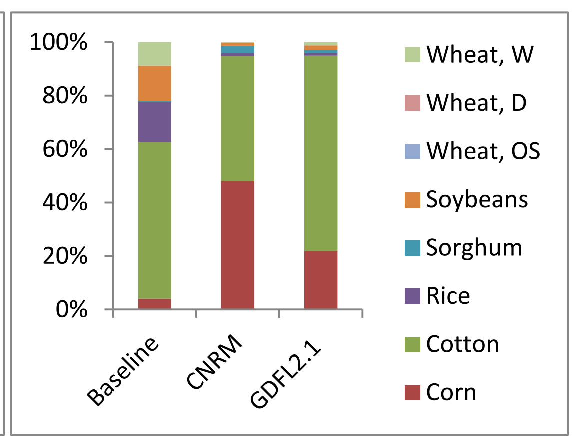
(c) Northeast



(d) Southeast

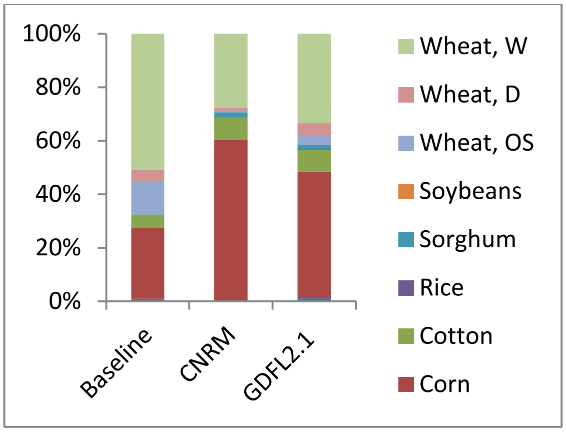


(e) North Plains

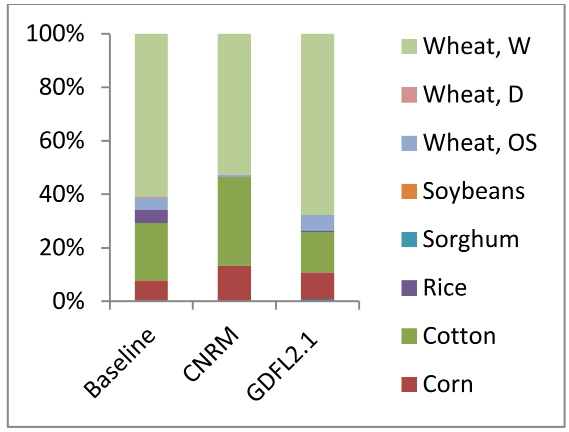


(f) South Plains

Figure 23 Cropland share under alternative climate change projections from Global Circulation Models (GCMs) for 2070-2099



(g) Mountains



(h) Pacific

Figure 23 Continued

in cropland are consistent. However, CNRM projects greater changes in temperature and precipitation, so the magnitude of changes under CNRM is also greater than that under GDFL2.1. In a baseline scenario, we assume that climate change is not occurred and climate condition is consistent in the present level.

National Level

In the simulation for 2040-2069, the most notable is the change in upland cotton. The share of upland cotton is increased from 9% in the baseline to 23% in both GCMs. Sorghum and corn are also chosen more often in higher temperature and precipitation condition than they are in the baseline. In contrast, despite increase in temperature, the share of rice is decreased from 2% to 0.5%. For soybeans and all wheat which are preferred in relatively low temperature, compared with the baseline, their cropland shares are decreased in both GCMs.

In the simulation for 2040-2069, the share of upland cotton is increased from 2040-2069. In CNRM, upland cotton is the crop that has the largest cropland share in U.S, and it has the second largest share in GDFL2.1. Both GCMs predict that producers will switch barley, soybeans, and all wheat to corn, upland cotton, and sorghum. About rice, simulation results are not consistent. CNRM predicts that cropland share of rice will increase from 2.2% to 3.1%, while GDFL2.1 predicts that it will decrease to 0.8%.

Regional Level

In the simulation for 2040-2069, producers in Central region will pick upland cotton, rice and winter wheat more, and soybeans less often. In Northeast, there is no change expected in GDFL2.1, but in CNRM, producers will tend to choose soybeans more often instead of corn and winter wheat. In Southeast, they will switch soybeans to upland cotton. The simulation results of North Plains vary by GCMs. In CNRM, upland cotton and soybeans are expected to be chosen more often and corn and all wheat less. In GDFL2.1, soybeans and all wheat will be switched to upland cotton. Producers in South Plains will tend to choose more corn, upland cotton and sorghum and less rice, spring and winter wheat. In Mountains, spring and winter wheat will be switched to corn and sorghum, and in Pacific, producers will cultivate more barley and wheat and less cotton and rice.

In the simulation for 2070-2099, producers in Central region will be like to switch corn and soybeans to upland cotton and rice. The crop mix in Northeast region is expected not to change much. In Southeast, soybeans will be switched to upland cotton, and in North Plains, upland cotton will be one of the major crops like corn and soybeans, while spring and durum wheat will be almost not cultivated. Because of warmer and drier climate condition, producers in South Plains tend to choose corn more and rice, soybeans, and winter wheat less often. In Mountains, all wheat will be switched to corn and upland cotton. In CNRM, producers will cultivate more rice and winter wheat and less corn and upland cotton, while in GDFL2.1, they will have more rice and cotton but less winter wheat and corn.

To sum up, we find that under climate change projected;

- there will be no significant national change in corn cropland. The share of corn fields will remain at present level or baseline level, and most of corn fields will be in the Corn Belt;
- more upland cotton will be cultivated and Kansas and Missouri, which is to the north of Texas, will become new major cotton producing states (Texas is the major cotton producing state and 47% of cotton fields are located in Texas in 2010);
- the major rice producing state will be shifted to the north from Arkansas to Missouri;
- cropland in soybeans will decrease because of increase in temperature. Illinois and Iowa, Minnesota and North Dakota will be major soybeans producing states;
- total wheat acreage will fall. This will be especially true for spring wheat and durum wheat, which are cultivated in the northern states like Montana and North Dakota particularly in 2070-2099;
- in northern area, the share of corn, sorghum, soybeans, and winter wheat will be increased, while the share of spring and durum wheat will be decreased;
- in middle area, the share of upland cotton and rice will be increased, while the share of corn, soybeans, and winter wheat will be decreased;
- in southern area, the share of corn, upland cotton, and sorghum will be increased, while the share of rice, soybeans, and winter wheat will be decreased.

Conclusion

In this essay, we estimate effects of climate variables on crop selection behaviors. This is accomplished by estimating a fractional multinomial logit model using a panel data set by state for the years 1981 to 2010. We also investigate the impacts of projected climate change on crop choice. Our regression results show that the choice among nine crops, barley, corn, upland cotton, rice, sorghum, soybeans, spring wheat, durum wheat, and winter wheat, is affected by climate condition. In particular, we find that producers in cooler regions are more likely to choose spring wheat, and producers in warmer regions tend to choose upland cotton, rice, and sorghum more often. Producers in dryer regions are more likely to choose winter wheat and upland cotton, while producers in wetter regions choose soybeans more often. The estimation result is consistent with practical adaptation patterns. Upland cotton, rice, and sorghum are concentrated in the southern states such as Arkansas, Louisiana, and Texas, and spring wheat, and durum wheat are concentrated in the northern states like Montana and North Dakota. Corn, soybeans and winter wheat which have a moderate temperature range are cultivated throughout the U.S.

We simulate climate change impacts for the GCM scenarios based on the parameter estimates from the choice model. Simulation over climate change projections presents how future projected climate change may influence crop choice. Under the projected climate change of increasing temperature and precipitation, wheat and soybeans cropland are switched to upland cotton. The major producing locations of upland cotton, rice, and soybeans are shifted to the north. However, most of corn is still cultivated in the Corn Belt and changes in acreage planted are not significant.

The simulation in this essay has limitations.

- The analysis does not take into account the cost of adaptation. When producer changes crop species to adapt to climate change, this adjustment requires a capital investment. We do not consider the effects of the capital investment on change in crop choice.
- We do not consider effects of carbon dioxide. Previous studies indicate that carbon dioxide affects on crops and the effects vary by crops.
- The analysis does not include effects of extreme events and change in climate variance. IPCC warns the possibility of increasing extreme events and change in climate variance, and these changes might alter the crop choice.
- The choice model does not include information about producers. Characteristics of producers like age and education level can affect on crop choice. But due to the limitation of data, we did not estimate the effects of characteristics of the producer.

To estimate more accurate climate change effects, future studies should consider these issues.

CHAPTER V

GENERAL CONCLUSION

This study investigates the impacts of climate change on agricultural sector in the U.S. The study is composed of three essays each looking at different aspects of the issue.

The first essay explores the impacts of climate on crop yield distribution, means, variance, and higher moment by estimating a flexible moment approach productivity function. In the first essay, we find that the climate variables affect in a statistically significant way on not only average crop yields but on their variability, skewness, and kurtosis. In particular, we find that that the effects of temperature on mean yields are inconsistent by crop and for some crops, insignificant. Extremely low or high temperatures cause damage to the crop yields. Most of the mean crop yields initially positively respond to increasing precipitation but at a decreasing rate. The climate effects on variability vary by crops. Except upland cotton and winter wheat, the skewness of crop yields is affected by temperature or precipitation or both. The effect of precipitation on skewness is non-linear and convex, while the effect of precipitation is non-linear and convex. We also investigate the impacts of projected climate change on future crop yield distributions in terms of the mean, variance, skewness, and kurtosis. Our study shows that climate change increases future mean yields for the most crops excluding winter wheat, while decreases future variability of yield for all crops excluding soybeans. Changes in skewness and kurtosis differ by crop, region, and scenario.

The second essay explores the impacts of climate on the irrigation effects on crop yields by estimating productivity functions with or without interactive terms between irrigation and climate variables. In the second essay, we find that irrigation contribute in a statistically significant way to crop yields in both Model 1 with irrigation dummy and Model 2 with irrigation dummy and interactive terms. The estimated irrigation effects from Model 1are constant regardless of climate conditions, while the irrigation effects estimated from Model 2 are affected by external climate factors. In Model 2, as temperature increases, the irrigation effects are decreased and irrigation reduces damages from extreme temperature conditions. Precipitation and PDSI effects are also diminished under irrigation. We also investigate the impacts of projected climate change on future crop yields and irrigation effects. In the simulation, we find that climate change limits irrigation effects for corn, upland cotton, and winter wheat, while for sorghum and soybeans, irrigation mitigates the climate change impacts.

The third essay explores the impacts of climate on crop mix among nine field crops, barley, corn, upland cotton, rice, sorghum, soybeans, spring wheat, durum wheat, and winter wheat, in the U.S. by estimating a fractional multinomial logit model. In this essay, we find that crop mix is affected by exogenous climate conditions. In particular, we find that producers in cooler locations tend to choose spring wheat, and producers in warmer locations tend to choose upland cotton, rice, and sorghum. Producers in dry conditions tend to choose winter wheat and upland cotton, while producers in wet conditions tend to choose soybeans. These cross-sectional results suggest that producers have adjusted crop mix to fit their climate conditions. We also investigate the impacts of projected climate change on crop choice. Under the projected climate change of increasing temperature and precipitation, wheat and soybeans cropland are switched to upland cotton. The major producing locations of upland cotton, rice, and soybeans are shifted to the north. However, most of corn is still cultivated in the Corn Belt and changes in acreage planted are not significant.

These three essays find that climate have significant impacts on agriculture sector in the U.S. and expected climate change will alter crop yield distribution and crop choice behavior. Such data are likely to prove useful in policy making regarding diverse thing as returns to agricultural investments, appropriate setting of crop insurance premium, analysis of climate change effects and greenhouse gas mitigation actions planning.

REFERENCES

Adams, R.M., C. Rosenzweig, R.M. Peart, J.T. Ritchie, B.A. McCarl, J.D. Glyer, R.B. Curry, J.W. Jones, K.J. Boote, and L.H. Allen, Jr. 1990. "Global Climate Change and US Agriculture." *Nature* 345:219-224.

Antle, J.M. 1983. "Testing the Stochastic Structure of Production: A Flexible Moment-based Approach." *Journal of Business and Economic Statistics* 1:192-201.

Atwood, J., S. Shaik, and M. Watts. 2002. "Can Normality of Yields Be Assumed for Crop Insurance?" *Canadian Journal of Agricultural Economics* 50:171-184.

Baker, T.G., and B.A. McCarl. 1982. "Representing Farm Resource Availability over Time in Linear Programs: A Case Study." *North Central Journal of Agricultural Economics* 4(1):59-68.

Beck, N., and J.N. Katz. 1995. "What to Do (and Not to Do) with Time-series Cross-sectional Data." *American Political Science Review* 89:634-647.

Chen, C., B.A. McCarl, and D.E. Schimmelpfenning, 2004. "Yield Variability as Influenced by Climate: A Statistical Investigation." *Climate Change* 66:239-261.

Deschenes, O., and M. Greenstone. 2007. "The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather." *American Economic Review* 97:354-85.

Frees, E.W. 1995. "Assessing Cross-sectional Correlations in Panel Data." *Journal of Econometrics* 69:393-414.

Friedman, M. 1937. "The Use of Ranks to Avoid the Assumption of Normality Implicit in the Analysis of Variance." *Journal of the American Statistical Association* 32:675-701.

Gallagher, P. 1986. "U.S. Corn Yield Capacity and Probability: Estimation and Forecasting with Nonsymmetric Disturbances." *North Central Journal of Agricultural Economics* 8:109-122.

—. 1987. "U.S. Soybean Yields: Estimation and Forecasting with Nonsymmetric Disturbances." *American Journal of Agricultural Economics* 69:796-803.

Im, K.S., M.H. Pesaran, Y. Shin. 2003. "Testing for Unit Roots in Heterogeneous Panels." *Journal of Econometrics* 115:53-74.

IPCC. 2000. *Emissions Scenarios*. N. Nakicenovic, and R. Swart, eds. Cambridge, UK: Cambridge University Press.

IPCC WGI. 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*eds. New York: Cambridge University Press.

IPCC WGII. 2007. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*eds. New York: Cambridge University Press.

Irmak, S., D.Z. Hamana and R. Bastugb. 2000. "Determination of Crop Water Stress Index for Irrigation Timing and Yield Estimation of Corn." *Agronomy Journal* 92:1221-1227.

Just, R. and R.D. Pope. 1978. "Stochastic Specification of Production Function and Economic Implications." *Journal of Econometrics* 7:67–86.

—. 1979. "Production Function Estimation and Related Risk Considerations." *American Journal of Agricultural Economics* 61:277–284.

Levin, A., C.F. Lin, and C.S.J. Chu. 2002. "Unit Root Tests in Panel Data: Asymptotic and Finite-sample Properties." *Journal of Econometrics* 108:1–24.

McCarl, B. A., and U. A. Schneider. 2001. "Greenhouse Gas Mitigation in U.S. Agriculture and Forestry." *Science* 294(5551): 2481-2482.

McCarl, B.A., X. Villavicencio, and X. Wu. 2008. "Climate Change and Future Analysis: Is Stationarity Dying?" *American Journal of Agricultural Economics* 90:1241-1247.

Mu, J., B.A. McCarl., and A.M. Wein. 2012. "Adaptation to Climate Change: Land Use and Livestock Management Change in the U.S." *Mitigation and Adaptation Strategies for Global Warming*, in press.

Papke, L.E., and J.M. Wooldridge. 1996. "Econometric Methods for Fractional Response Variables with an Application to 401(k) Plan Participation Rates." *Journal of Applied Econometrics* 11:619-632.

—. 2008. "Panel Data Methods for Fractional Response Variables with an Applicaiton to Test Pass Rates." *Journal of Econometrics* 145:121-133.

Pesaran, M. H. 2004. “General Diagnostic Tests for Cross Section Dependence in Panels.” Working Papers, Dept. of Economics, University of Cambridge, Cambridge, UK.

Reilly, J.M., J. Graham, D.G. Abler, R.Darwin, S. Hollinger, C. Izaurralde, S. Jagtap, J. Jones, J. Kimble, B.A. McCarl, L. Mearns, D. Ojima, E.A. Paul, K. Paustian, S. Riha, N. Rosemberg, C. Rosenzweig, and F. Tubiello. 2002. *Changing climate and changing agriculture: Report of the agricultural sector assessment team*. Cambridge, UK: Cambridge University Press.

Sammis, T.W. 1981. “Yield of Alfalfa and Cotton as Influenced by Irrigation.” *Agronomy Journal* 73:323-329.

Schlenker, W., and M.J. Roberts. 2009. “Nonlinear Temperature Effects Indicate Severe Damages to U.S. Crop Yields under Climate Change.” *PNAS expand* 106(37):15594-15598.

Seo, S.N., and R. Mendelsohn. 2008a. “Animal Husbandry in Africa: Climate Change Impacts and Adaptations.” *African Journal of Agricultural and Resource Economics* 2:65-82.

—. 2008b. “Measuring Impacts and Adaptations to Climate Change: A Structural Ricardian Model of African Livestock Management.” *Agricultural Economics* 38:151-165.

Seo, S.N., B.A. McCarl, and R. Mendelsohn. 2010. “From Beef Cattle to Sheep under Global Warming? An Analysis of Adaptation by Livestock Species Choice in South America.” *Ecological Economics* 69:2486-2494.

Solow, A.R., R.F. Adams, K.J. Bryant, D.M. Legler, J.J. O'Brien, B.A. McCarl, W. Nayda and R. Weiher. 1998. The Value of Improved ENSO Prediction to U.S. Agriculture. *Climate Change* 39:47-60.

Stone, L.R., A.J. Schlegelb, R.E. Gwin Jr., and A.H. Khana. 1996. “Response of Corn, Grain Sorghum, and Sunflower to Irrigation in the High Plains of Kansas.” *Agricultural Water Management* 30:251–259.

Zhang, H., and T. Oweis. 1999. “Water–yield Relations and Optimal Irrigation Scheduling of Wheat in the Mediterranean Region.” *Agricultural Water Management* 38:195–211.

VITA

Name: Jiyun Park

Address: Department of Agricultural Economics
College of Agriculture and Life Sciences
Texas A&M University
2124 TAMU
College Station, TX 77843-2124

Email Address: zyoun72@gmail.com

Education: B.A., Horticultural Science, Konkuk University, 2004

M.A.B., Agricultural Economics, Texas A&M University, 2007

Ph.D., Agricultural Economics, Texas A&M University, 2012