Farmer Response to Changes in Climate: The Case of Corn Production

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Abstract. *A test of whether minor production adaptations to climate significantly affect corn yields is the focus of this article Cross-sectional, field-level corn data are used to analyze production across various climates A 6 5°F change in temperature, when both adaptations to climate and the direct effect of weather are included, raised yields by 43 8 percent in areas with average July temperatures of 67°F and reduced yields by 69 6 percent in areas with average July temperatures of 76 5°F*

Keywords. *Plant growth models, corn production, climate changes, greenhouse effect*

Some scientists expect a rise in global temperatures, due to an increased accumulation of carbon dioxide (CO_2), methane, and other greenhouse-effect gases in the atmosphere (*7*) [1] Some researchers estimate that the climatic effects of a doubling of greenhouse gases are likely to appear within 50 to 100 years (*30*) Global climatic change can lead to changes in agricultural production in the United States and the rest of the world, either directly through effects on crop yields, or indirectly as prices of agricultural commodities balance demands with new crop yield potentials

Understanding the effects of climate changes on agriculture is necessary for the development of technologies to mitigate future problems, and for indicating potential costs associated with a rise in the levels of greenhouse gases Uncertainties remain, however, concerning the effects of climate change

First, there is considerable uncertainty about the rate of accumulation of the most significant greenhouse-effect gas, CO_2 (*18*)

Second, changes in weather patterns are uncertain Simulations of weather patterns resulting from greenhouse gas accumulation are estimated using three-dimensional mathematical models called Global Circulation Models (GCM's) Different GCM's, however, provide different climate projections under the same scenario of greenhouse gas accumulation Furthermore, GCM's provide only projections of changes in average seasonal temperature and precipitation and do not include important details on changes in weather variability, extremes of temperature and precipitation, or the amount of cloud cover

Third, researchers are concerned about the accuracy of the estimated direct effects of climate and CO_2 fertilization on crop yields Direct effects (for example, effects before consideration of price changes) have been estimated using computer simulations of crop growth, or crop growth models (*5, 6, 16, 18, 21, 22, 23, 27, 30*) Crop growth models simulate day-by-day crop growth subject to the projected climate (such as precipitation, temperature, and cloud cover), the level of CO_2, the application of irrigation water and fertilizers, and the soil type Analyses of the indirect effects (for example, yields after adjustments to subsequent prices) of climate change result from the direct effects and the subsequent changes in agricultural input and output prices and production levels, given projected output demands (*9*) The indirect effects must account for elasticities of substitution and economies of scale

Crop growth models may not fully reflect the range of farmers' responses to climate change Most crop growth models allow for farmers' adjustments in nitrogen use and irrigation levels and sometimes other major inputs to a new climate Unless crop growth models include all adjustments to climate (or expected weather) that significantly affect yield, their estimated effects of climate change will be biased

This study tests whether there are significant yield effects of production adaptations to climate that are not included in crop growth models The null hypothesis states Adjustments in input use and management practices to climate, which are not included in plant growth models, have no effect on yield This hypothesis is tested using regression techniques on field-level data from the 10 major corn-producing States Cross-sectional data provide a view of production across areas of different climatic conditions, where production practices embody local technologies to maximize profits for the region's climate

Estimation results indicate a rejection of the null hypothesis Thus, minor production adaptations to climate appear to have a significant effect on yield Crop growth models may be producing biased estimates, at least in corn production The results presented here do not specify the adaptations that could improve crop growth models However, the significance of the results suggests that efforts to detail adaptations to climate may be fruitful

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The author thanks the contributors to this article Steve Crutchfield, Daniel Hellerstein, Harry Kaiser, John Reilly, Marc Ribaudo, Rhona Lantin, and David Plante

[1] Italicized numbers in parentheses cite sources listed in the References section at the end of this article

Farm Production Adaptations to Climate

An approach to estimating the yield effect of farm production adaptations to climate under a fixed set of input and output prices follows directly from a characterization of the profit-maximizing farmer For each growing season, in a given field, the farmer determines optimal input application rates based on the marginal physical products, prices of the inputs, and the expected output price That is to say, the farmer attempts to maximize

$$\Pi = P*Y - XC, \tag{1}$$

where

Π = expected economic profit (per acre),
P = expected output (corn) price,
Y = output (yield) and $Y = f(X)$ where $f(X)$ is assumed to be continuously differentiable across all X,
X = a vector of the factors of production, and
C = a vector of input prices associated with X

The first n elements of X, x_1 x_n represent factors of production under the control of the farmer, such as chemical nitrogen, seed choice, crop rotation pattern, and tillage practice The remaining w elements of X, x_{n+1} x_{n+w} are the environmental inputs or factors that the farmer cannot adjust directly, such as the characteristics of the soil, weather, and climate

Weather is actual (observed) temperature and precipitation and thus directly affects yields Webster's New World Dictionary defines climate as "the prevailing or average weather conditions of a place as determined by the temperature and meteorological changes over a period of years " Climate, therefore, indicates what type of weather to expect

Equation 1 is maximized when

$$\partial Y/\partial x_i = c_i/P, \tag{2}$$

for all $i \leq n$, subject to the farmer's knowledge or expectation of x_{n+1} x_w, where c_i represents the price of the i^{th} factor

The yield effect of a change in the environmental factor x_j can be expressed as

$$\partial Y/\partial x_j = \partial f(X)/\partial x_j + \sum_{i=1}^{n} (\partial f(X)/\partial x_i * \partial x_i/\partial x_j), \tag{3}$$

where $n < j \leq n + w$ The first term on the right-hand-side of equation 3 represents the direct effect on yield of the change in the environmental input x_j The second right-hand-side term represents the change in yield as input use is adjusted for the change in the environmental input When x_j represents July weather, the second right-hand-side term will likely equal 0 since there are few production adjustments available to the farmer in July[2] When the environmental input, x_j, represents expected weather or climate, the first right-hand-side term will equal 0 Instead, the adjustments in input use or production technologies to expected weather will result in a nonzero value to the second right-hand-side term Assuming that the yield effects of adjustments in input use and production technologies ascribed to climate can be described by some function G(C), where C represents the set of climate variables from the vector X

$$\partial G/\partial x_j = \sum_{i=1}^{n} (\partial f(X)/\partial x_i * \partial x_i/\partial x_j) \tag{4}$$

When $[\partial f(X)/\partial x_i * \partial x_i/\partial x_j] = 0$ for any i, then $\partial G/\partial x_j = 0$ A test of significant adjustments in input use and management practices relating to climate becomes a test of the significance of climate as a determinant of yield That is, the proposed hypothesis will be rejected if any of the n input adjustment terms for climate are significantly different from zero and those effects are characterized by G(C)

Yield Responses to Weather and Input Use

The relationship between yield and the inputs supplied by man and nature has been examined by agronomists, economists, soil scientists, and others One significant problem in estimating yield functions is determining the correct functional form

Commonly estimated yield functions are linear across most inputs with quadratic or logarithmic measures of particular inputs with nonconstant marginal physical products (*3, 7, 11, 14, 19, 26, 28*) Such a generalized model is applied here[3] Thus, yield (Y) at the j^{th} site (observation) is written as

$$\begin{aligned} Y_j = {} & \alpha_0 + \alpha_1 LOWTIL_j + \alpha_2 NOTILL_j + \alpha_3 IRRIG_j \\ & + \alpha_4 CORN_j + \alpha_5 CORNCORN_j + \alpha_6 ERODE_j \\ & + \alpha_7 NITRO_j + \alpha_8 NITROSQ_j + \alpha_9 LNSEED_j \\ & + \alpha_{10} PLDATE_j + \alpha_{11} SLPLGTH_j + \alpha_{12} TFACT_j \\ & + \alpha_{13} KFACT_j + \alpha_{14} PREJUL_j \end{aligned} \tag{5}$$

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[2] Irrigation is a production adjustment that farmers may be able to make during the July portion of the growing season This production adjustment was tested by including irrigation and weather interaction terms and was found not significant

[3] Also tested was a log-log yield function (or Cobb Douglas) of the form

$$Yield_j = \alpha_0 * e^{\sum_{i=1}^{m} \alpha_i X_{ij}} * \prod_{i=m}^{n} x_{ij}^{\alpha_i} * \delta_j,$$

where the variables x_1 through x_m represent the independent variables that are zero-one dummies x_{m-1} through x_n are the independent variables having continuous values, the α's are estimated as regression coefficients, and δ is an error term assumed to be distributed so that $\ln(\delta) \approx N(0,\sigma^2)$ This model performed poorly, partially due to its inability to adjust for changes in the sign of the output elasticity of some variables

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\begin{aligned}
&+ \alpha_{15}PREJULSQ_j + \alpha_{16}TMPJUL_j \\
&+ \alpha_{17}TMPJULSQ_j + \alpha_{18}PAVGJUL_j \\
&+ \alpha_{19}PAVGJULSQ_j + \alpha_{20}TAVGJUL_j \\
&+ \alpha_{21}TAVGJULSQ_j + \alpha_{22}TJULINT_j \\
&+ \alpha_{23}PJULINT_j + \alpha_{24}TMPPRESQ_j \\
&+ \alpha_{25}PRETMPSQ_j + \epsilon_j,
\end{aligned}
$$

where the α_0 is the intercept, the remaining α's are the coefficients on the independent variables, and ϵ_j is the error term. Six of the variables are zero-one dummy variables (see table 1).

LOWTIL indicates a 30-percent residue cover remaining after tillage,

NOTILL indicates no tillage between harvest of the previous crop and planting.

IRRIG indicates the field was irrigated,

CORN indicates corn was grown on the field in the previous year,

CORNCORN indicates corn was grown on the field in the previous 2 years,

ERODE indicates that more than half of the agricultural land in the county was classified as erodible.

NITRO and NITROSQ represent the pounds per acre of nitrogen applied and pounds squared, respectively. LNSEED is the natural log of the kernels/acre seeding rate. The use of a second-degree term to account for the diminishing marginal product of nitrogen outperformed the log of nitrogen, but the opposite occurred with the seeding rate. PLDATE is the planting date. SLPLGTH is the slope-length (in feet), TFACT is the soil's erosion tolerance factor, and KFACT is the soil's erodibility factor. Both TFACT and KFACT were derived for use in the Universal Soil Loss Equation.

The weather and climate variables include actual July precipitation, PREJUL, PREJUL squared, PREJULSQ, average July temperature, TMPJUL, TMPJUL squared, TMPJULSQ, the 30-year average of July precipitation as one characterization of climate, PAVGJUL, PAVGJUL squared, PAVGJULSQ, the 30-year average of July temperatures, TAVGJUL, and TAVGJUL squared, TAVGJULSQ and interactions among these variables, that include TJULINT (=TMPJUL * TAVGJUL), PJULINT (=PREJUL * PAVGJUL), TMPPRESQ (=TMPJUL * PREJULSQ), and PRETMPSQ (=PREJUL * TMPJULSQ).

While the expectation of significant interactions between temperature and precipitation is self-evident, the interactions between climate and weather were included to account for changes in the marginal impacts of weather with respect to climate. Growing conditions in July are strategic because July is the most common period for corn to pollinate.

To ensure that adaptations to climate in one area were applicable to another, location-specific factors were included in the analysis. ERODE, IRRIG, CORN, CORNCORN, SLPLGTH, PLDATE, TFACT, and KFACT were significant. Also included, but dropped for lack of significance, were variables indicating soil permeability, soil water-holding capacity, growing season cultivations for weed control, land of capability class 1 or 2, previous crop (wheat, soybeans, or alfalfa), the harvest date, and herbicide and insecticide use. If any location-specific factors remained, they were assumed to be orthogonal to the climate variables.

Other climate and weather variables were dropped for lack of significance such as June precipitation as both climate and weather variables, August temperatures as both climate and weather variables, interactive precipitation and temperature variables for climate, and first-degree interactive terms for weather.

Data

Field-level observations on corn yields and the inputs used by farmers came from the 1988 and 1989 Objective Yield Surveys (OYS), which is a random sample of acres in corn production. There are 3,057 of these field-level observations spread across the 10 major corn-producing States (Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Nebraska, Ohio, South Dakota, and Wisconsin). Farmers furnished information on irrigation, seeding rate and timing, crop rotation, nitrogen use, weed and pest control, tillage practices, harvest date, and the consequential yield on the sample field. Thus, variables representing this information come directly from the OYS. The level of remaining crop residue used to determine LOWTIL was derived from OYS tillage and previous crop information (*2*).

The OYS identifies the county where each observation is located. The county identification identifies the soil, weather, and climatic conditions associated with each observation.

The National Oceanic and Atmospheric Administration (NOAA) supplied monthly weather data from data bases. The 3,057 observations spanned 83 different multi-county weather districts. Climate data were derived by averaging 30 years of monthly weather conditions. Climate variability across the sample ranged from 67°F to 80°F in average July temperatures and 1.9-4.5 inches in average July precipitation.

The 1985 National Resource Inventory (NRI) and the Soils-5 survey gave soil information Characteristics of the soil for each observation were determined by their county averages Only NRI sample points on cropland were used Thus, the water-holding capacity, permeability, slope length, TFACT, and KFACT for each observation came from the average across the NRI cropland sample points within the appropriate county

Estimation

A tobit model was used to estimate equation 5 because of a cluster of zero-yield observations (*29*) As first shown by Tobin, analyses of data where the dependent variable is censored must recognize the resulting error distribution and the factors underlying its truncated and continuous values

A tobit estimation procedure is applicable when the censoring of the dependent variable is driven by the same factors that determine the variable's magnitude There is no reason to suggest that this condition does not hold in analyzing corn yields Farmers do not harvest when yields are very low because harvesting costs and any forage value of the corn are not covered This nonzero censoring problem is corrected by subtracting 9 bushels per acre, the lowest nonzero reported yield, from all nonzero values of Y (*4*)

Heteroscedasticity occurs when the variance is correlated with some set of variables, Z Problems of heteroscedasticity in tobit models can be overcome by making reasonable assumptions about the nature or source of the heteroscedasticity (for example, the elements of Z), testing the assumptions, and adjusting the estimation of the model accordingly (*12*) The correcting for heteroscedasticity is especially important in tobit models because the presence of uncorrected heteroscedasticity can result in estimates that are neither efficient nor consistent (*13*)

Heteroscedasticity is tested and adjusted for following a generalized specification of the variance suggested by Rutemiller and Bowers

$$\sigma_k^2 = (\tau + \delta Z_k)^2, \qquad (6)$$

where Z is a vector of variables hypothesized to affect the variance, δ is a vector of coefficients, τ is the homoscedastic component of the variance (for example, when $\delta=0$ then $\tau^2=\sigma^2$), and the k subscript denotes subpopulation (or observation) k

Heteroscedasticity is tested as a function of climatic conditions, the observation year, farmer-applied inputs, and location-specific factors Climate is hypothesized to affect variance because the sensitivity of corn yields to deviations in climatic conditions is expected to be most significant in the most productive climates Observation year serves to account for any differing in variance between years Farmer-applied inputs and location-specific parameters are included, given their possible effect on variance[3]

Results

Equation 5 was estimated subject to equation 6, where variables with t-statistics of less than 1 were dropped from the model (table 1) Despite applying the conservative critical t-value of 1, most of the remaining variables are significant at the 95-percent level The R-square, corrected for degrees of freedom, indicates that the estimated model explains 77 percent of the variation in yield, which is high for field-level data

Signs and magnitudes of the estimated tobit coefficients were as expected (table 1) Because the focus of this article is on the estimated dependency of yield on climate and weather, the implications of the other coefficients are not discussed The listing and discussion of the results of testing and correcting for heteroscedasticity are in the appendix and appendix table 1

Hypothesis Test Results

The indirect effects of climate on yield were significant at the 95-percent level for five of the six climate variables (PAVGJUL, PAVGJULSQ, TAVGJULSQ, TJULINT, and PJULINT), indicating a strong rejection of the null hypothesis (table 1) Acceptance of the alternative hypothesis indicates that the effects of minor production adjustments to marginal changes in climate are significant enough to warrant their inclusion in analyses of yields under changing climatic conditions The direct effects of the weather (PREJUL, PREJULSQ, TMPJUL, TMPJULSQ, TJULINT, PJULINT, PRETMPSQ, and TMPPRESQ) on yield are also significant

The production adjustments to changes in climate do not include the effect of changes in the planting date, irrigation, tillage practices, and nitrogen use These variables are included separately in the analysis, and their effect is often accounted for in plant growth models The effects of these variables are significant and have the expected signs (table 1)

Implications of the Weather and Climate Coefficients

Acceptance of the alternative hypothesis suggests that variations in weather can affect yields more than variations in climate The greater magnitude of the second derivative of actual temperature relative to climatic temperature indicates that the yields are more sensitive to variations in weather than variations in climate

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[3] The software that allows a tobit estimation of equation 5, subject to restrictions in equation 6, was written and provided by Daniel Hellerstein ERS

Table 1—Model estimation results

Variable	Coefficient	t-statistic
LOWTIL	4 60*	2 56
NOTILL	–5 35*	–2 07
IRRIG	22 4**	6 85
CORN	–4 78*	–2 42
CORNCORN	–2 00	– 85
ERODE	–11 9**	–8 23
NITRO	120**	4 76
NITROSQ	000202**	–2 65
LNSEED	72 2**	13 10
PLDATE	275**	–4 45
SLPLGTH	0162**	2 66
TFACT	12 8**	6 38
KFACT	64 7**	2 88
PREJUL	103*	2 51
PREJULSQ	–34 4**	–3 09
TMPJUL	106**	2 77
TMPJULSQ	–2 15**	–4 00
PAVGJUL	66 2**	3 05
PAVGJULSQ	–9 74**	–3 32
TAVGJUL	58 8	1 89
TAVGJULSQ	–1 80**	–5 51
TJULINT	2 84**	3 75
PJULINT	4 41**	3 60
TMPPRESQ	424**	2 87
PRETMPSQ	– 0173*	–2 38
Intercept	–6940**	–7 10

Variable	Definition	Source
LOWTIL	> 30 percent of soil covered by previous crop residue	OYS
NOTILL	no tillage performed since previous crop harvest	OYS
IRRIG	dummy = 1 if field was irrigated	OYS
CORN	dummy = 1 if corn grown on field in previous year	OYS
CORNCORN	dummy = 1 if corn grown on field in previous 2 years	OYS
ERODE	dummy = 1 if soil erosion designated as a problem	NRI
NITRO	lbs/acre nitrogen application rate	OYS
NITROSQ	lbs/acre nitrogen application rate squared	OYS
LNSEED	natural log of the seeding rate	OYS
PLDATE	planting date	OYS
SLPLGTH	slope length used in the Universal Soil Loss Equation (USLE)	NRI
TFACT	soil erodibility factor used in the USLE	NRI
KFACT	soil loss tolerance	NRI
PREJUL	actual July precipitation	NOAA
PREJULSQ	actual July precipitation squared	NOAA
TMPJUL	actual July temperature	NOAA
TMPJULSQ	actual July temperature squared	NOAA
PAVGJUL	30-year average of July precipitation	NOAA
PAVGJULSQ	30-year average of July precipitation squared	NOAA
TAVGJUL	30-year average of July temperature	NOAA
TAVGJULSQ	30-year average of July temperature squared	NOAA
TJULINT	= TMPJUL * TAVGJUL	NOAA
PJULINT	= PREJUL * PAVGJUL	NOAA
TMPPRESQ	= TMPJUL * PREJULSQ	NOAA
PRETMPSQ	= PREJUL * TMPJULSQ	NOAA

*Significant at the 95-percent confidence level
**Significant at the 99-percent confidence level

The extent to which the production adaptations associated with TAVGJUL mitigate the negative impact of higher temperatures can be seen by examining the effect of weather across different climatic areas For example, the yield-maximizing July temperature is 70°, 72 2°, 75°, and 77 5°F for regions where July temperatures average (TAVGJUL) 70°, 74°, 78°, and 82°F, respectively, and given PAVGJUL and PREJUL equal 4 inches [4]

As with temperature, the actual July precipitation (PREJUL) that maximizes yield depends on the minor production adjustments made to the expected level of precipitation (PAVGJUL) The yield-maximizing levels of actual July precipitation are 4 6, 4 2, 3 8, and 3 4 inches, given the production practices associated with July climatic precipitation (PAVGJUL) levels of 4 5, 4, 3, and 2 5 inches, respectively, and average July temperatures of 74°F (TAVGJUL=TMPJUL =74°F) These results indicate that the effect of precipitation on yields can be mitigated by production adjustments In contrast to temperature, the relative magnitudes of the second-order conditions with respect to the climate and weather precipitation variables appear to indicate that the rate of change in yields due to variations in climatic precipitation is greater than the rate of change in yields due to annual variations in July precipitation However, the smaller rate of yield response to annual precipitation likely stems from the importance of carryover soil moisture So, PREJUL does not fully reflect actual variations in moisture availability

The results also suggest production interrelationships between precipitation and temperature The climatic precipitation that maximizes yields varies directly with climatic temperature For example, when TAVGJUL and TMPJUL equal 70°, 74°, and 78°F, yields are maximized at 4 2, 4 5, and 4 9 inches, respectively PAVGJUL ranges from 1 9 to 4 5 inches across the sample area Likewise, the climatic temperature that maximizes yields varies directly with climatic precipitation When July precipitation averages 3 inches, the yield-maximizing climatic temperature is 73 5°F When July precipitation averages 4 5 inches, the yield-maximizing temperature increases to 74 4°F TAVGJUL ranges from 67 1°F to 80 0°F across the sample area (See app table 1 for means and standard deviations of other variables)

A partial effect of climate change, which includes only the effects of weather and the minor production adaptations associated with the climate variables, can be obtained from the estimation results The total effect of climate change on yield must also include the effects of the more major production adjustments to climate that are explicitly included in this and other models The total effect must also include the associated

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[4] Evaluations are made at mean values for the other independent variables

adjustments in input use and acreage in production to future prices, technology, and plant variety development, and the effects of CO_2 fertilization The partial effects are made under the assumption that weather patterns in new climate regimes parallel the patterns observed in the cross-section of climates in this analysis

An Estimation of the Partial Yield Impacts of Climate Change

Farmers' minor production adjustments to climate were found to significantly affect yield Yet, past studies on climate change and yields have overlooked these minor production adjustments The magnitude of the yield effects of climate change and the subsequent minor production adjustments are derived from the estimation results

The effects of weather and minor production adaptations to future climatic conditions are based on projections of the Goddard Institute for Space Science's (GISS) global climate model The GISS model forecasts rises of approximately 6 5°F in July temperature and 1 inch in July precipitation in the midwestern United States for a doubling of carbon dioxide

The 6 5°F temperature rise would increase yields by an estimated 44 5 bushels per acre (43 8 percent) for colder regions of the study area but would reduce yields by about 82 3 bushels per acre (69 6 percent) in warmer regions, given only minor production adaptations (table 2) The 82 3-bushels-per-acre yield decrease is a projection made 3°F outside the range of TAVGJUL and so must be viewed with caution Also, the positive yield effects of the expected increase in precipitation and of the significant production adaptations have been excluded from the reported climatic effects

The effects of precipitation changes are not as dramatic as those of temperatures Yield changes range from 14 2 to 1 5 bushels per acre per half-inch change in average July precipitation (table 2) However, PREJUL provides only a partial measure of variation in growing season moisture availability because soil moisture availability is affected by precipitation in previous months, and actual precipitation can fall above average one month and below average the next Thus, the direct effects of climate change with respect to precipitation are likely underestimated

Table 2—Yield impacts in different climatic regions[1]

Temperature		Yield change		Precipitation		Yield change	
From	To			From	To		
		Bu/acre	*Percent*			*Bu/acre*	*Percent*
Degrees F				*--Inches--*			
67 0	73 5	44 5	43 8	2 5	3 0	13 9	10 7
70 0	76 5	-6 4	-5 0	3 0	3 5	9 8	8 2
73 5	80 0	-52 4	-38 7	3 5	4 0	5 7	4 4
76 5	83 0	-82 3	-69 6	4 0	4 5	1 5	1 1

[1] Evaluated at mean values of all other independent variables

Conclusions

The minor production adaptations to climate significantly affect yield This analysis cannot specify the minor production adaptations and, therefore, cannot offer a specific remedy for improving plant growth models However, the estimated results offer some insight into the magnitude of the effects of minor production adaptations

The significance of the yield effects of the minor production adaptations were tested by modeling yield as a function of the more significant production adaptations, local resource characteristics, and minor production adaptations as proxied by climate Regional soil characteristics and actual weather were included as independent variables to ensure that the climate variables reflected only changes in the less significant farm inputs

The direct effects on corn yields of a projected 6 5°F change in temperature and 1-inch change in precipitation were estimated for a number of climatic conditions The estimated changes in yields exclude the effects of adjustments in the major inputs and responses to any subsequent input/output price change Also excluded are the effects of CO_2 enrichment and improvements in plant varieties and other production technologies Given these limited conditions, only in the coolest areas were corn yields projected to rise For the 6 5°F temperature change alone, yields were projected to increase as much as 44 1 bushels per acre (43 8 percent) in areas with average July temperatures of 67°F and fall by 82 3 bushels per acre (69 6 percent) in areas with average July temperatures of 76 5°F

The importance of production adaptations to climate change depends on farmers' abilities to incorporate them into their operations Unless farmers perceive a change, there will be no adaptations in production

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Appendix

The estimation results of the heteroscedastic component of the estimated yield model is listed in appendix table 1 All right-side variables of equation 5 were included as heteroscedastic terms Variables with t-statistics greater than 1 were dropped from the analysis Six of the remaining variables, IRRIG, ERODE, SLPLGTH, NITRO, TAVGJUL, and TAVGJULSQ, are significant from zero at the 95th percentile

The signs on the coefficients indicate greater variance for irrigated corn, for corn-corn rotations, and for soils classified as erodible, although they constitute less than 1 percent of the total variance Variance also shows a positive correlation with field slope and a negative correlation with the natural log of the seeding rate The contributions of nitrogen, climatic precipitation, and climatic temperature to variance are minimized at a nitrogen application rate of 196 pounds per acre, when July precipitation averages 10 4 inches and temperature averages 74 9°F The nitrogen and average July precipitation values exceed most of those in the sample Thus, variance is a decreasing function across the relevant range of nitrogen use and climatic precipitation In contrast, the effect of temperature on variance is minimized near the average climatic temperature Also, when July precipitation averages 4 5 inches, the yield-maximizing temperature equals 74 4°F So, a significant movement away from the yield-maximizing temperature can also increase the variance of the yield Neither the climate nor the nitrogen coefficients show as much as a 1-percent contribution to the level of total variance However, including the heteroscedastic terms does minimize the possibility that the estimates of the coefficients in equation 5 are biased

Appendix table 1—Estimated coefficients and the standard errors of heteroscedastic variables

Variable	Coefficient	Standard error
IRRIG	4 56	1 80
CORN	2 18	1 23
ERODE	2 26	977
NITRO	- 0475	0242
NITROSQ	000121	0000895
LNSEED	-3 60	2 39
SLPLGTH	00845	00421
PAVGJUL	-4 57	5 49
PAVGJULSQ	219	102
TAVGJUL	-33 1	77 5
TAVGJULSQ	221	118
Intercept[1]	7 590	2,300

[1] Homoscedastic component of the variance

Appendix table 2—Means and standard deviations of variables

Variable	Mean	Standard deviation
LOWTIL	0 145	0 352
NOTILL	0648	246
IRRIG	120	325
CORN	369	483
CORNCORN	238	426
ERODE	420	494
NITRO	129	66 1
NITROSQ	20,900	24,400
LNSEED	10 1	171
PLDATE	126	11 7
SLPLGTH	222	123
TFACT	4 60	402
KFACT	309	0429
PREJUL	2 34	1 46
PREJULSQ	7 63	9 41
TMPJUL	75 4	1 78
TMJULSQ	5,700	266
PAVGJUL	3 77	470
PAVGJULSQ	14 4	3 36
TAVGJUL	74 1	2 28
TAVGJULSQ	5,500	337
TJULINT	5,600	284
PJULINT	8 80	5 64
TMPPRESQ	571	701
PRETMPSQ	13,200	8,120