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# A half century of yield growth along the forty-first parallel of the Great Plains: factor intensification, irrigation, weather, and technical change

The potential for crop production to support the burgeoning world population, in the face of climate change, has motivated dozens of studies reported during the new millennium. Many of these, including this one, have been statistical studies examining the sources of the dramatic increase in aggregate crop yields since the 1950s. They have examined the impacts on yields of such factors as weather, management intensification, irrigation, and non-specific technical change.

What can be said of these efforts? Most of them have measured the response to factors mentioned, but few have gone the step further to estimate the contribution of these factors to observed yield increases. Temperate zone studies have generally found substantial negative yield responses to high temperature, but only modest response to precipitation. Because climate changes are predicted to increase temperatures in most areas of the globe, the general conclusions have been that climate change will decrease crop yields (Zhao et al. 2017). On the other hand, many global studies of yield growth suggest that technical change will continue to increase production (Fuglie, K. 2012), while experimental plot studies indicate that $CO_2$ fertilization will also increase production (Long et al. 2004), so the likely trend of crop yields in the presence of climate change remains poorly understood.  Virtually no studies other than this one have attempted to identify simultaneously both the marginal impacts and the recent contributions of input intensification, irrigation, technological change, and weather in this highly productive transect of the U.S. Great Plains at this level of aggregation.

Studies of changes in *aggregate* crop yields face a scale paradox: it is local weather, soil, and management conditions that actually determine yield changes, but it is yields aggregated to the regional and global scale that will determine food supply. Pixel-level data are available to examine yield growth at only a tiny sample of any country's crop production surface, but pixel-level crop growth models and experimental plots can reveal a fundamental understanding of how plants grow and respond to stimuli. Aggregate yield response, on the other hand, represents an amalgam of pixel-level responses that may not closely resemble that for individual pixels, or may as in the current study mask micro-level response and contribution phenomena. Nonetheless, analyses of country-level and global-level yields have provided estimates of the effects of temperature and precipitation anomalies when measured at similar scale. Aggregate yield analysis is irreplaceable for inferences about aggregate food supplies, but such analyses have been and should be tempered by principles of crop growth as revealed by micro-level studies.

In this study, we examine a half-century of crop yield growth along an 800-mile transect of the forty-first parallel North in the U.S. Great Plains (41st || hereafter). We chose to study this transect because, during the last half-century, yields there increased dramatically across a wide range of temperate-region growing conditions. We identify the separate contributions and interactions of input intensification, irrigation, soil organic matter, weather, and technical change by estimating a general biomass yield response function for the 41st|| transect, from which we draw inferences for segments along the transect by calibrating the resulting model with appropriate weather and soil conditions.

## Theoretical framework

We assume that production decisions are made by profit-maximizing farmers who operate under perfect competition in all commodities and factor markets. Farmers choose their optimum production and input requirements, subject to the production function $Y = f(\boldsymbol{X}, \boldsymbol{e}, t)$, output and input prices, the characteristics of the environment (weather, soil, etc.) and of technical change as the solution to the following problem

$$\max_{X} \pi = \ p \cdot Y - \boldsymbol{w} \cdot \boldsymbol{X} \ \ ; Y = \ f(\boldsymbol{X}, \boldsymbol{e}, t); \ p \gg 0, \boldsymbol{w} \gg 0 \ , \qquad (1)$$

where output per hectare is $Y$ with price $p$, the variable input vector is $\boldsymbol{X}$ with corresponding price vector $\boldsymbol{w}$, the environmental variables are represented by vector $\boldsymbol{e}$ and non-specific technical change is $t$. The yield function $f(\boldsymbol{X}, \boldsymbol{e}, t)$ is assumed to be finite, nonnegative, real valued, and single valued for all nonnegative and finite $\boldsymbol{X}$, everywhere twice-continuously differentiable, non-decreasing in $\boldsymbol{X}$, and quasi-concave, fulfilling the weak essentiality condition.

The first order interior conditions for profit maximization are

$$\frac{\partial \pi}{\partial X_j} = p \cdot \frac{\partial Y(\boldsymbol{X}, \boldsymbol{e}, t)}{\partial X_j} - w_j = 0, \qquad j = 1, \dots, J \qquad (1.a)$$

From equations (1) and (1.a) the marginal impact of input variables, expressed in logarithms, is:

$$\frac{\partial \ln f(\boldsymbol{X}, \boldsymbol{e}, t)}{\partial \ln X_j} = \frac{\partial f(\boldsymbol{X}, \boldsymbol{e}, t)}{\partial X_j} \cdot \frac{X_j}{f(\boldsymbol{X}, \boldsymbol{e}, t)} = \gamma_j = \frac{w_j}{p} \cdot \frac{X_j}{Y}\bigg|_{\boldsymbol{X}^*} = s_j \qquad (2)$$

with $j = 1, \dots, J$ and where $\gamma_j$ is the production elasticity of input $j$, which when evaluated at optimum input levels ($\boldsymbol{X}^*$) is its share in total revenue, $s_j$. Thus, under the conditions of this model, the production elasticity of input $j$ is equal to the revenue share of that input, capturing the essence of the firm's choice of input levels.

The marginal effect on yields of an environmental variable $\boldsymbol{e}$ measured in elasticity terms is:

$$\frac{\partial \ln f(\boldsymbol{X}, \boldsymbol{e}, t)}{\partial e_v} = \mu_v \qquad v = 1, \ldots, V \qquad (3.a)$$

where $e_v$ is an environmental variable measured in logarithms. If the environmental variable is measured in levels rather than logs, the marginal effect can be expressed as the following semi-elasticity:

$$\frac{\partial \ln f(\boldsymbol{X}, \boldsymbol{e}, t)}{\partial e_u} = \mu_u \qquad (3.b)$$

which is the change in logarithm of output (approximately the proportional change) per one-*unit* change in $e_u$, whereas the elasticities in (3a) are standard elasticities (approximately the percentage change in yield per *one percent* change in $e_v$).

Different from the estimates in previous crop yield studies, our estimates of the impact of environmental variables are thus obtained from a model that controls for the simultaneous decisions made by the farmer given market prices as well as natural and technological conditions.

The rate of technical change (TC) is:

$$\frac{\partial \ln f(\boldsymbol{X}, \boldsymbol{e}, t)}{\partial t} = TC \qquad (4)$$

According to its effects on relative input productivity, the nature of technical change can be further characterized in terms of input biases. The bias measure we use identifies change in optimal input share, under constant prices, due to technical change, defined as:

$$B_j = \frac{\partial s_j}{\partial t} \quad \forall\ j \qquad (5)$$

Technical change is said to be unbiased if all biases are zero, i.e, if it does not affect revenue shares. Hence, Hicks neutrality implies share neutrality. If $B_j > 0$ the technical change is said to be biased toward input *j*, or *j*-using; if $B_j < 0$ the technical change is said to be biased against input *j*, or *j*-saving.

Equations (2), (3) and (4) indicate *marginal* effects on yields of inputs, environmental variables, and non-specific technical change, respectively. To study the contributions of each of these factors to yield growth over a given period of time, we couple these marginal effects with observed changes in the amounts of these factors during the period in a growth decomposition analysis as:

$$d \ln Y \quad = \sum_{j=1}^{J} \gamma_j \cdot d \ln X_j + \sum_{v=1}^{V} \mu_v \cdot d \ln e_v + \sum_{u=1}^{U} \mu_u \cdot d\, e_u + TC \qquad (6)$$

where the first right hand side term is output growth attributed to changes in inputs, the second and third are growth attributed to changes in environmental factors and the fourth is output growth attributed to non-specific technical change. (In our application below, we evaluate equation (6) for annual changes.)

**Empirical Specification**

Single equation estimates of the production function will be affected by identification issues due to the simultaneity in firms' choices of output and inputs. A system of equations that estimates jointly the production function and the inverse input demand equations implied by equation (2) allows for endogeneity of input choice and makes it obvious that output produced and inputs used are manifestations of a single decision-making process tempered by expectations about natural phenomena. The estimates of the environmental impact in (3) control for the farmers' behavior given expectations about these environmental factors (weather for example) and will, in general, be different from pure technical environmental responses measured on experimental plots. Models that do not explicitly account for this behavior will err in measuring the impact of each factor on yields because they do not account for adaptive decision-making.

We chose the transcendental logarithmic (translog) functional form to represent the production function in (1) and the corresponding shares in (2). This specification is flexible as it provides a local second order approximation to any production technology, minimizing a priori restrictions on its structure. After adding random errors and assuming contemporaneous correlation the following system of equations is estimated:

$$\begin{aligned} y_{it} = \alpha_0 &+ \sum_{j=1}^{3} \beta_j x_{ijt} + \frac{1}{2}\sum_{j=1}^{3}\sum_{k=1}^{3} \beta_{jk} x_{ijt} x_{ikt} + \theta_1\, p_{it} + \frac{1}{2}\theta_{11}\, r_{it}^2 + \theta_{13} r_{it} x_{i3t} + \sum_{w=1}^{3} \omega_w d_{iwt} \\ &+ \sum_{w=1}^{3} \omega_{wx} d_{iwt} x_{i3t} + \sum_{w=1}^{3} \omega_{rw3} d_{iwt} r_{it} + \theta_2\, som_{it} + \theta_{23} som_{it} x_{i3t} + \tau_1\, t + \frac{1}{2}\tau_2\, t^2 \\ &+ \sum_{j=1}^{3} \varphi_j t x_{ijt} + \rho_k \end{aligned} \qquad (7)$$

$$s_{1it} = \beta_1 + \beta_{11} x_{i1t} + \beta_{12} x_{i2t} + \beta_{13} x_{i3t} + \varphi_1 t$$

$$s_{2it} = \beta_2 + \beta_{21} x_{i1t} + \beta_{22} x_{i2t} + \beta_{23} x_{i3t} + \varphi_2 t$$

where $y_{it}$ is logarithm of observed biomass yield $Y$ (tons per hectare) in county $i$ year $t$; $s_{1it}$ is the share of fertilizer; $s_{2it}$ is the share of chemicals[1]; $\boldsymbol{x}_{it}$ is a vector of the logarithms of quantity indexes of fertilizer (for $j=1$) and chemicals (for $j=2$) applied per hectare and the fraction of agricultural land irrigated (for $j=3$); $\boldsymbol{d}_{iwt}$ is a vector of the number of degree days in three temperature intervals; $r_{it}$ is the logarithm of growing season precipitation in centimeters; *som* is the logarithm of the level of soil organic matter in megagrams per hectare; $k$ is the region where the county is situated, with $k = 1,\ldots,5$; and the variable $t$ is a proxy for non-specific technical change measured as years since the beginning of the analysis starting with 1960 = 1. The coefficients $\alpha_0$, $\beta$*'s*, $\omega$*'s*, $\theta$*s*, $\tau$*'s*, $\varphi$*'s* and $\rho$*'s* are the parameters to be estimated. We included all the interactions between variables that represent farmer's choices of inputs (fertilizer, chemicals, and irrigation), and technology (time trend). In addition, we account for the environmental variables (soil organic matter, degree days, and precipitation) that condition farmers' choice, adding interactions of irrigation with precipitation, which allows us to examine how irrigation mitigates water stress and to account for the substitutability between them. We also add interactions of irrigation with degree-days, to study how irrigation mitigates heat stress; and of irrigation with soil organic matter, to examine the benefits of irrigation on different types of soils.

Equality of coefficients across equations as well as symmetry were imposed during estimation while monotonicity was checked at each data point after estimation. Equations (7) were jointly estimated using an iterated three-stage least squares approach. Since the farmers make decisions about the desired yield and the amount of fertilizer and chemicals needed to produce it simultaneously, an instrumental variables approach was used to avoid endogeneity issues. For this purpose, indexes of prices of these inputs were used as instruments. Given that the interactions of the instrumented inputs, fertilizer and chemicals, with themselves and with the other variables are also endogenous, instruments for these interactions were also created[2].

Since the Cobb-Douglas production function is nested in the translog production function, we use a Wald test to check if the former is as good as the latter in capturing this technology.

As established in equation (2), the first derivative of the translog production function with respect to the logarithm of each input corresponds to the production elasticities $\gamma_{ijt}$ that, given our assumptions of profit maximization and perfect competition, are equal to the factor shares $s_{ijt}$ for input *j* in county *i* in year *t*. These elasticities vary with time (*t*) and county inputs ($i$, $j$) in the following way:

$$\gamma_{ijt} = \left(\frac{\partial y_{it}}{\partial x_{ijt}}\right) = \left(\frac{\partial Y_{it}}{\partial X_{ijt}}\right) \cdot \left(\frac{X_{ijt}}{Y_{it}}\right) = \beta_j + \textstyle\sum_{k=1}^{3} \beta_{jk} x_{ikt} + \varphi_j t \tag{8}$$

One of these factors is irrigation, which we measure as share of irrigated land. In this case the impact of irrigation is represented by the following semi-elasticity:

$$\gamma_{i,3,t} = \left(\frac{\partial y_{it}}{\partial X_{i,3,t}}\right) = \left(\frac{\partial Y_{it}}{\partial X_{i,3,t}}\right) \cdot \left(\frac{1}{Y_{it}}\right) = \beta_3 + \sum_{k=1}^{3} \beta_{3k} x_{ikt} + \varphi_3 t\,, \quad j = 3 = irrigation \tag{9}$$

For the impact of the natural environment, ***e***, on yields, as per equations (3), elasticities or semi-elasticities are estimated, depending on how the variable is defined. The following semi-elasticities identify the marginal impact of degree days (*dd*) in county *i* in year *t*:

$$\mu_{wit} = \frac{\partial y_{it}}{\partial d_w} = \omega_w + \omega_{wx} x_{i3t} + \omega_{rw} r_{it} \qquad w = dd0030, dd3035, dd35 \tag{10}$$

while the soil carbon (*SOM*) and precipitation (*r*) elasticities are:

$$\mu_{som,it} = \frac{\partial y_{it}}{\partial som_{it}} = \theta_2 + \theta_{23} x_{i3t} \tag{11}$$

$$\mu_{rit} = \frac{\partial y_{it}}{\partial r_{it}} = \theta_1 + \theta_{11} r_{it} + \theta_{13} x_{i3t} \tag{12}$$

As indicated in equation (4), the first derivative of the production function with respect to the time trend *t* can be interpreted as the rate of technical change in county *i* in year *t*:

$$\frac{\partial y_{it}}{\partial t} = TC = \tau_1 + \tau_2\, t + \sum_{j=1}^{3} \varphi_j x_{ijt} \tag{13}$$

The biases in technical change (5) are:

$$B_j = \frac{\partial s_j}{\partial t} = \varphi_j\,, \quad \forall\, j \tag{14}$$

If $B_j > 0$ the technical change is biased toward input *j*; if $B_j < 0$ the technical change biased against input *j*.

The contributions of intensification, environment and non-specific technical change to year-to-year yield changes (*i.e.*, yield growth decomposition) are obtained using equation (6) and equations (8)-(13):

$$dy = \sum_{j=1}^{2} \gamma_j d\left(x_j\right) + \gamma_{irrigation} d(X_{irr}) + \mu_{0030} d(dd0030) + \mu_{3035} d(dd3035) + \mu_{35} d(dd35) + \mu_{som} d(som) + \mu_r d(r) + TC \qquad (15)$$

where for simplicity, we have omitted subscripts for time and county. This decomposition allows identification of the variables that have mattered the most in understanding the impressive crop yield increases in the U.S. central plains during the half century under study.

## Data description

Most of the variables used are unique to this analysis, so in the supplementary material we describe how we generated them in some detail. The units of analysis consist of 101 counties between two and four deep along the 41st || N in the U.S. Midwest (Figure 1), examined over the period 1960-2008[3]. This transect was chosen because it encompasses an 800-mile agroclimatic gradient from the Rocky Mountains to the Mississippi River, including highly irrigated farms with low precipitation and moderate soil carbon in the west to rain-fed crops with high precipitation and high soil carbon in the east. The range of conditions allows us the opportunity to identify the contribution of various environmental conditions as well as farmer-chosen inputs to yield growth. After estimation of equations (7) we calibrate the estimated yield function to annual conditions in each county and group them in five relatively homogeneous subregions from west to east. Table A.1 in Appendix A provides basic statistics for the variables used. Figures 2-3 illustrate how input use vary across the subregions, Figures 4-6 illustrate how environmental variables vary across subregions.

The variables used in the estimation of the system of equations (7) are biomass yields, fertilizers, chemicals, share of land irrigated, soil organic matter, a time trend, temperatures, and precipitation. To calculate average county biomass yield we sum the biomass produced by all crops in a county, measured in bone-dry megagrams (Mg), then divide that by total hectares planted. The biomass produced includes both the harvested crop and the residual above-ground biomass left in the field. Hence, we are examining a more general measure of production than any individual crop, a measure that corresponds closely to the notion of net primary agricultural production (Prince et al., 2001). Figure A.1 in Appendix A shows average biomass yield by county, while Figure A.2 shows the 41st || transect average yield through time.

Across the region, average yields increased about 124% from 1960 to 2008, for an average compound rate of 1.66%. This aggregate yield increase masks substantial variation by subregion: in subregions 2 and 3 with their increases in irrigation, yields increased by 190%, compared to 96% in the more humid eastern subregion.

Factor intensification is measured by the amount of fertilizers and chemicals used. Those variables, as well as irrigation, are under farmers' control. Environmental variables, not under farmers' control, are soil organic matter, precipitation, and temperatures. Non-specific technical change, which we represent with the passage of time, is not under the control of farmers, but is certainly under human control.

Fertilizer and chemical inputs are expressed as indexes of quantity applied per hectare. These are obtained using expenditures from the Census of Agriculture and state level price indexes from USDA-ERS productivity accounts. They are expressed as indexes relative to the quantity used in Adams County, Nebraska, in 1960. Average levels by county are shown in Figure 2.

Irrigation we express as the share of irrigated land in each county. This variable we obtain as the ratio of irrigated planted land to total planted land in the county. While it would have been desirable to use quantity of water actually applied, this information is not available. The simple measure that we use, though, has a useful interpretation: it is an approximation of the increase in biomass yield for irrigated relative to non-irrigated production. As illustrated by figure 5, the percentage of irrigated land varies considerably across the transect, with higher values in the center of Nebraska and zero values in Iowa[4].

To account for the differences in soil quality across space and time, we include average megagrams (Mg) of soil organic matter (SOM) per hectare for each county. We observe increasing quantities of SOM as we move from west to east (Figure 6), and decreasing levels through time. The average value of SOM for region 1 (west) was 94 Mg ha$^{-1}$, while for region 5 (east) it was 183 Mg ha$^{-1}$.

County-level weather variables (temperatures in degree-days and precipitation in centimeters) were estimated from individual weather station data collected from the United States Historical Climatology Network. From these data, county average daily precipitation (in centimeters) and county average daily maximum and minimum temperatures were obtained for each day during the growing season (March to August). County-level values for precipitation and temperatures were constructed as the weighted average of observations from the five closest weather stations to the center of each county. These observations were weighted using a Shephard inverse distance approach as follows:

$$q_k = \sum_{i=1}^{5} \frac{b_{ik}\, q_i}{\sum_{j=1}^{5} b_{jk}} \ , \ \text{where } \ b_{ik} = \frac{1}{{d_{ik}}^2} \qquad (13)$$

where $q_k$ denotes the weighted value for county $k$, $q_i$ is the measurement at weather station $i$, and $d_{ik}$ is the distance from weather station $i$ to the center of county $k$. Daily averages at county level were then used to construct the growing season precipitation and degree days variables for each county, explained further in the next paragraph.

To measure the impact of temperatures on yield we use an adaptation of the agronomic measure “growing degree days”. We measure the amount of time, expressed in 24-hour days, the crop is exposed to temperatures in one of three ranges: 0ºC to less than 30ºC; 30ºC to less than 35ºC; and 35ºC or higher. Appendix B describes in more detail how these variables were constructed from weather reporting stations in each county. The average amount of time crops were exposed to temperatures above 35ºC by county is shown in Figure 7. This measure of high temperatures mostly increases from east to west.

Precipitation we measure as the total amount of precipitation during the growing season measured in centimeters. As shown in Figure 8 there is a substantial decrease in average precipitation as we move from east to west. Region 1, in the west, received an average of 30.8 cm, while in region 5, in eastern Iowa, the average precipitation was almost twice that much, 59.1 cm.

Finally, we represent non-specific technical change as a quadratic time trend with 1960=1.

## Results and discussion

We estimated the parameters in the system of equations (7) using Iterated 3-Stage Least Squares (I3SLS). Twenty-three of the thirty-four parameters estimated are significantly different from zero at the 99% confidence level, while one is different from zero at the 95% confidence level.

The pseudo R squared is 0.774, although this standard goodness of fit cannot be interpreted as the proportion of the variance explained when estimating a three-stage least squares system of equations, it still provides a useful indication of the overall predictive power of the estimators (Toft and Bjørndal, 1997). A Wald test rejects the nested Cobb-Douglas form as a better specification. The Wald test on the $\beta_{jk}$ coefficients equal to zero ($\forall\ j, k$ ) rejects the hypothesis that all the inputs are additively separable, and strongly separable ($\forall\ j \neq k$), indicating that the translog specification is preferred to a Cobb-Douglas specification. A Wald test on the $\varphi_j$ coefficients equal to zero rejects the hypothesis of Hicks neutrality.

We employ a "pairs bootstrap" methodology (Freedman 1981) for the estimation of the standard errors. Following MacKinnon (2002) and Flachaire (2005), pairs bootstrapping gives robust estimates under heteroskedasticity. Additionally, we estimated the system using standard 3SLS to check for robustness of results and found minimal qualitative changes in the significance of the estimated parameters. The Wu-Hausman endogeneity test on fertilizer and chemicals rejected the null hypothesis that these variables are exogenous, thus we instrumented these variables and their interactions using price indexes. Parameter estimates are in Table A.3 in Appendix A, first-stage regressions and statistics are available upon request.

We used the parameter estimates to identify the marginal contributions to biomass yield from factor intensification, irrigation, weather, and technical change using equations (8)-(13). Elasticities and semi-elasticities were evaluated at each data point, then averaged across observations for the five regions of interest. The marginal contributions of the variables, averaged across all observations by region, are reported in Table 2.

The estimated average production elasticity of fertilizer (0.111) for the region is consistent with previous estimates by Griliches (1964), Hayami and Ruttan (1970), Antle (1983) and Saha, Shumway and Havenner (1997). The estimated production elasticity of chemicals (0.058) is virtually identical to the 0.057 estimated by Ball (1985). These elasticities indicate that, on average and at the margin, a 1% increase in fertilizer increased biomass yield by 0.11% and a 1% increase in chemicals resulted in a yield increase of approximately 0.06%.

The transect-wide estimate of the irrigation semi-elasticity (0.679) implies that on average, conversion from rainfed to irrigated land can be expected to double biomass yield[5], but more in the central subregions where most conversion to irrigation took place. García-Suárez, Fulginiti and Perrin (2018) irrigation semi-elasticity for the High Plains aquifer region is 0.511, slightly lower than ours. Part of the benefit of irrigation is achieved by reducing the impact of high temperatures, as indicated by the impact of irrigation on the DD35plus semi-elasticity[6].

Soil organic matter (SOM) has been declining since cultivation began on these prairie soils. Its average marginal elasticity is 0.13, significantly different from zero at the 5% level for 88% of the observations. Calculated regional SOM elasticities ranged from 0.10 in the west to 0.18 in the east.

On average, an extra 24 hours (one day) of temperatures above 35°C decreased yields by 26.6%, while the marginal effect of a day between 30°C and 35°C would decrease yields by only 1.5%, an important nonlinear effect that supports similar estimates in the literature. In the east, the comparable negative impacts rise to 37.6% and 2.5%, while in region 3 where irrigation is most prevalent they fall to 12.8% and 0.1% respectively. On average across the region, between 1960 and 2008, sensitivity to temperatures above 35°C decreased from 32.3% to 28.0%. If we disaggregate 1960-2008 trends in heat sensitivity estimates by region (see Figure A.3 in the Appendix), results are not homogeneous. Regions in the west saw a considerable decrease in sensitivity with marginal damage decreasing from 23.0% to 8.2%, mainly due to increased irrigation. Region 4, which has low irrigation, saw a much smaller decrease from 38.8% to 35.5%. On the other hand, region 5, which has no irrigation, saw an increase in the marginal damage from 39.0% to 42.7%. Ortiz-Bobea, Knippenberg and Chambers (2018) also find increased climatic sensitivity in rainfed agricultural areas in the U.S. Our estimates additionally indicate that irrigation is a successful means to reduce heat stress, consistent with findings in Kukal and Irmak (2018).

A marginal increase of 2.5 cm (1 inch) of precipitation along this transect would on average *decrease* yields slightly[7] by 0.46%. This average response again masks geographical and temporal variations. In the drier far west (region 1), an additional centimeter of precipitation would increase yields on average by 1.05%, while in the more humid far east (region 5), an additional centimeter would decrease yields by -0.28%. During the wettest decade (the 90s) the region-wide response to an additional centimeter was -0.15%, while during the driest decade (the 70s) the response was -0.05%. Clearly, the concavity of these responses with respect to precipitation is mild – marginal contributions of precipitation evaluated across the data set are relatively minor.

The estimated time trend, our proxy for unidentified, nonspecific technical change, increased yield by an average of 0.99% per year[8]. We interpret this variable to capture the marginal effects of such changes as new varieties, higher quality and quantity of machinery and labor, improvements in management, and similar variables for which we have no data available at the level of county agriculture. The negligible coefficient estimate for the variable time squared indicates that, ceteris paribus, this rate of improvement remained stable over the time period. In terms of technical change biases, we find them to be irrigation-saving, and fertilizer-and chemical-using. This is consistent with an increased efficiency of irrigation and with an increased reliance on commercial inputs.

### *Contributions of human controlled factors to yield growth during 1960-2008*

We use our estimates of regional and transect-level elasticities and semi-elasticities to decompose the observed yield growth, 1960-2008, into contributions from intensification, irrigation, soil organic matter, weather, and nonspecific technical change (using equation 15) [9].

Estimated human-controlled contributions to yield growth for 1960-2008 are shown by region in Figure 9. Estimated contributions across the transect by decade shown in Figure 10. Figure 9 shows that human-controlled factors explain most of the change in observed yields during this half-century. Increases in irrigation over this period contributed to yield increases of 22%, 52% and 44% in regions 1, 2 and 3, but contributed very little to yield growth in regions 4 and 5 because irrigated areas were stationary or virtually non-existent. Across the **41st ||** transect, irrigation contributed an average yield increase of about 17%. Most of these increases in irrigation occurred during the first two decades, as indicated in Fig. 8.

Intensification in the form of higher fertilizer and chemical use per hectare contributed to yield increases of about 13% and 11%, respectively, across the **41st ||** transect (Fig 7), with most of this occurring during the 1960s and 1970s (Fig 8). The fertilizer contributions occurred almost exclusively during the 60s, while chemical contributions continued throughout the 1960-2008 period. Regions 1, 2 and 3 show higher contributions of fertilizer than do regions 4 and 5, consistent with the increases in irrigation, as they are complementary inputs.

Non-specific technological change contributed more to yield change across the transect (62%) than any other factor we measured (Figure 10). We employed a quadratic specification of time to represent this technological change, which revealed an approximately constant rate of non-specific technical change contributions to yield through time. Technological change contributed more to the yield gains in the two eastern subregions (Figure 7), where there was no prospect for increases from irrigation, and little incentive to increase rates of application of fertilizer and chemicals. What does *this unspecified technological change* consist of? In a widely-cited summary of growth in maize yields, Duvick (2005) notes that yield per plant has been nearly constant, but technological progress has allowed more plants to be grown per hectare, due to genetic changes along with complementary advances in chemicals and machinery. While Duvick expresses confidence that similar gains will continue for at least a few decades, Andersen et al. (2018) document declining rates of overall farm productivity that they surmise may be related to declines in R&D spending. The future path of this non-specific technical change remains a crucial issue that we do not explore further in this study.

### *Contributions of environmental factors to yield growth during 1960-2008.*

At the aggregate level across the **41st ||** transect, environmental factors have contributed about 0.7% to 1960-2008 yield change (Figure 9)[10]. This includes a negative impact of 2.2% due to a depletion of soil organic matter (SOM) and a small positive impact of 1.5% of weather as we have measured it. However the weather outcome masks significant geographical and temporal variation.

Geographically, a positive contribution of precipitation change in region 1 (18%) was partially offset by very small or negative contributions of precipitation change in regions 2, 3, 4, and 5 where it was a little too wet during the last decade. The aggregate outcome also masks some significant variations in temperature contributions through time. For example, very hot weather (temperatures over 35°C) abated across the entire period of analysis in regions 1 and 2, contributing a positive 6-8% yield increase, while hot weather increased in regions 3-5, reducing yields 6-7% there (Figure 10). An increase in 35°C+ days across the transect during the 1980s contributed a 6% decrease in transect average yield, only to have half of that offset by yield increases due to a reduction in such days in the 1990s and 2000s. Note from Figure 11 that the net weather contributions were more dramatic in region 1 (the west) than elsewhere, due to net weather improvements in that region over the period. An important insight here for examining the impacts of weather is that aggregate data (i.e. for the 41st ||) do not reveal the very real impacts of changes in weather at the subregion level, because these impacts tend to be canceled out across areas. But analysis of aggregate relationships using local data, as we have done here, can reveal the marginal responses to local weather and the muted aggregate responses as well.

The final environmental variable we considered was soil organic matter (SOM). The data revealed a steady reduction of SOM through time and a steady reduction across space from east to west. For the full **41st ||** transect across the entire period, changes in yield due to changes in SOM were small – a biomass yield reduction of about 2.2%. In the east SOM reductions decreased yields by about 2.4% in region 4 and 4% in region 5, whereas contributions in the western three regions were well under 1%. While these effects of soil organic matter loss through time were small, differences in SOM levels of 182 Mg/ha in the east vs 94 Mg/ha in the west account for a yield difference of as much as 17%.

## Conclusions

This research examined crop yield growth during 1960-2008 on an 800-mile transect of the Great Plains along the **41st ||** between the Rocky Mountains and the Mississippi River, to determine the relative contributions of natural factors and human factors to this growth. The range of agroecological conditions along this transect is large, with potential implications for crop yield growth in other temperate zone producing regions.

In order of importance, our estimates of contributors to the transect-wide half-century yield increases are these: non-specific technical change +62%, irrigation +17%, fertilizer +13%, chemicals +11%.  Weather changes contributed to an increase in yields of just  1.5%, while reductions in soil organic matter contributed to a decrease in yields of 2.2%.

While unspecified technical change was the main source of yield growth in every region, the contribution of the remaining factors of production varies substantially across subregions. Irrigation was almost as important as technical change for high plains regions 2 and 3, where it produced increases in yields of 52% and 44% respectively. In the east, where irrigation is virtually nonexistent, greater use of fertilizer and chemicals were the second most important reasons for yield growth, each of which contributed yield increases of about 10%.

Losses of soil organic matter through time, our proxy for soil fertility, were small, contributing to yield reductions of about -2% across the entire transect, but ranged from essentially zero in the western regions to -4% in the easternmost region. Furthermore, regional differences in average SOM levels of 182 Mg/ha in the east versus 94 Mg/ha in the west account for a yield difference of about 17%.

We also found that the pattern of yield contributions varied considerably by decade, with fertilizer contributions occurring almost entirely during the 1960s and irrigation contributions mostly during the 1960s and 1970s. Increases in the time crops were exposed to high temperatures reduced yield growth during the 1980s but those results were halved by increased yield growth due to fewer high-temperature days in the 1990s and 2000s.

The dramatic biomass yield increases along this transect of the **41$^{st}$ ||** were almost entirely attributable to human-controlled interventions rather than environmental changes. The fraction of crop area irrigated in the western half of this transect increased dramatically between the 1960s and 2000s, from about a quarter of all cropland to about half. This increased yields by about 48% in the central subregions but increased the average yield for the transect by only about 17% because of the absence of irrigation in the east. Intensification, in terms of additional quantities of fertilizers and chemicals, contributed to yield increases of about 25%, but in the last decade the contribution declined to less than 2%, except in region 2 where application rates continued to increase.

The lack of environmental contributions to yield growth along this **41$^{st}$**|| transect does not imply that temperature and precipitation had no marginal impacts: precipitation responses at the county level *were* small, but temperature responses were quite large. The lack of weather contributions to yield growth over the half-century is due to the fact that there was little change in weather between the beginning and end of the period, even though the marginal effects of temperature are quite significant. It is notable, however, that the sensitivity of biomass yield to the amount of time exposed to temperatures over 35°C *increases* from the west, where the response semielasticity is -.11, to the east where it is -.37, and that the transect-wide semielasticity *decreased* from -.32 in the 1960s to -.28 in the 2000s. Both of these trends are due to irrigation.

What do our results portend for yield growth during the coming decades? Projections of climate change in this region, due to increased atmospheric $CO_2$, suggest that periods of hot weather might increase by 10% in this area, which would decrease average yields by 4%. It is instructive to note that this decrease may be too pessimistic, both because it could be partially or totally offset by the increase in yields predicted from the $CO_2$ fertilization effect suggested by experimental data and because it does not account for some aspects of farmer adaptation (like changes in planting and harvesting dates). Projections of precipitation change along this 41st || transect are roughly neutral, but a decrease of 10% would decrease yields by only about 3% in the west, while actually increasing yields in the east by 1-2%. The potential for additional irrigation to increase average yield is minimal, given concerns about the sustainability of groundwater supplies. For both environmental and economic reasons, there is little prospect that fertilizer and chemical applications will increase. Our results also indicate that along this transect the yield growth rate from non-specific technical change has stabilized at around 1% per year. This and other considerations in this paragraph indicate reasonably good prospects for continued yield growth along this important food-producing transect, even in the presence of climate change.

**Footnotes**

1. We have included only share equations for fertilizers and chemicals because we lack county level information on labor, capital, and cost of irrigation.
2. Reg3 command in STATA version 15.0 was used for the econometric estimations.
3. Counties in each region listed in Table A.2 in the Appendix
4. Given the minimal levels of irrigation present in Iowa, USDA does not report the amount of planted land that was irrigated.
5. The relative change in yield is calculated as exp(0.679) = 1.97.
6. The parameter of the interaction term between irrigation and DD35plus is statistically significant and equal to 0.6205.
7. This somewhat surprising result is completely consistent with Tannura, et al (2008), whose estimates for corn in Iowa, Illinois and Indiana indicated optimum monthly precipitation levels were close to the average levels.
8. Njuki, Bravo-Ureta & O'Donnell (2018) using state level data estimate a 1.2% growth rate for the U.S. agricultural sector during 1960-2004.
9. To calculate year-to-year contributions of each input we multiply the change in the log of the input times the average production elasticity of that input between two consecutive years, a discrete approximation to equation (15). The percent change in $y$ attributable to a change in one input $x_i$ between period $t_1$ and $t_n$ is estimated as: $[(1 + \text{mean contribution}(x_{i1}, \ldots, x_{in}))^n] - 1$. Log changes are converted to percentage changes using the equation: *Percent change in y = exp(dlny)-1*.

10. Njuki, Broavo-Ureta and O’Donnell (2018), using state level data, estimate an annual growth rate of an environmental index (weather effects) for U.S. agriculture of -0.012% for 1960-2004. This is a rate of -0.41% for the whole period.

## Tables and Figures

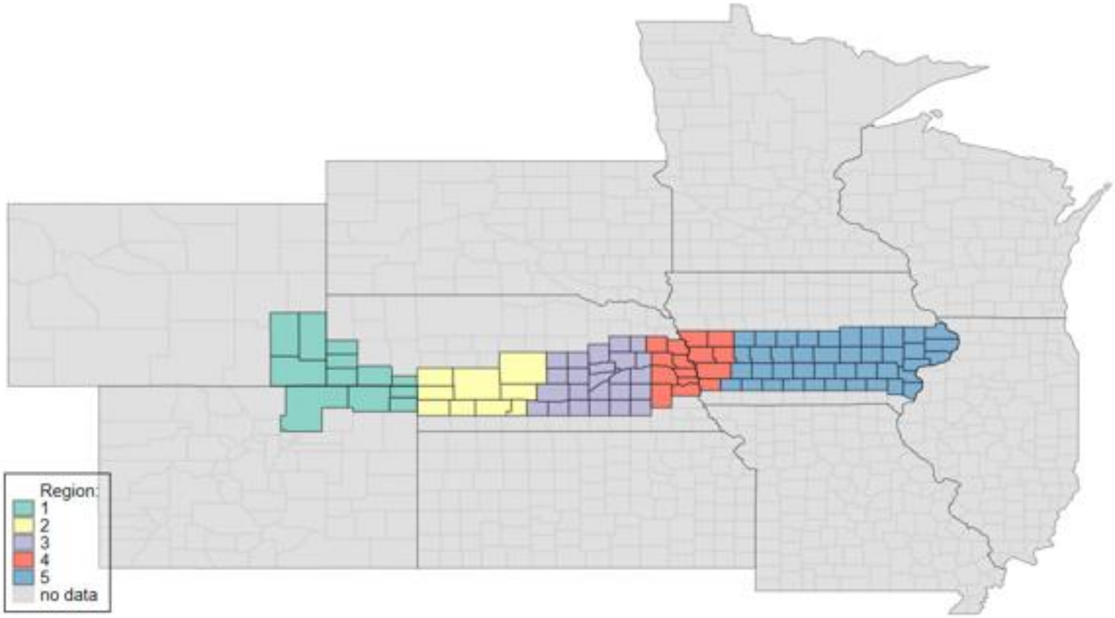

**Figure 1. Study counties along the 41st parallel N**

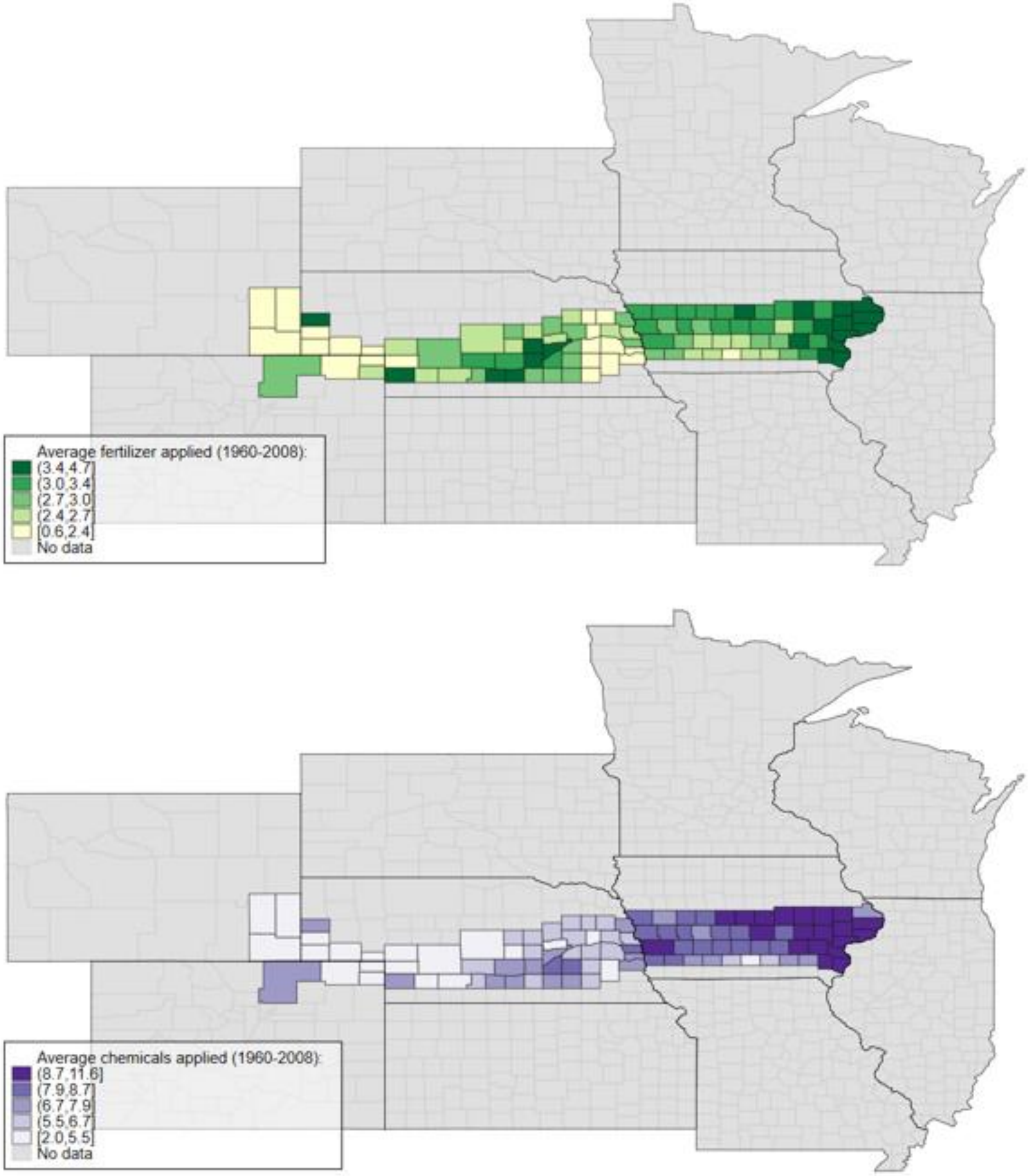

**Figure 2. Average fertilizer and chemical application rates (indexes), 1960-2008**

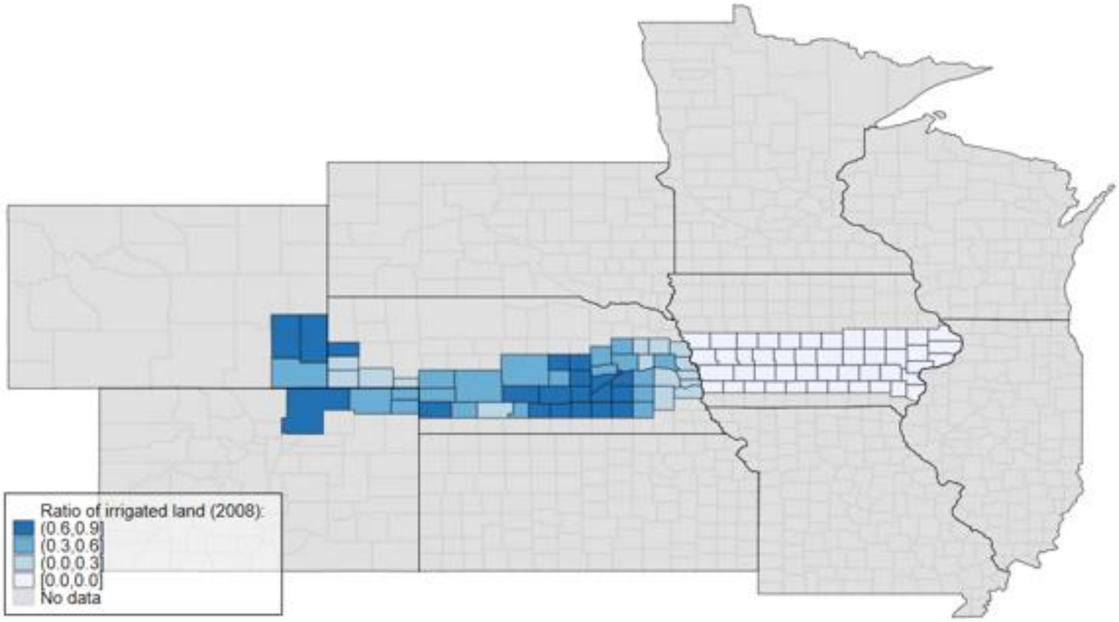

Figure 3. Average share of land irrigated, 1960-2008

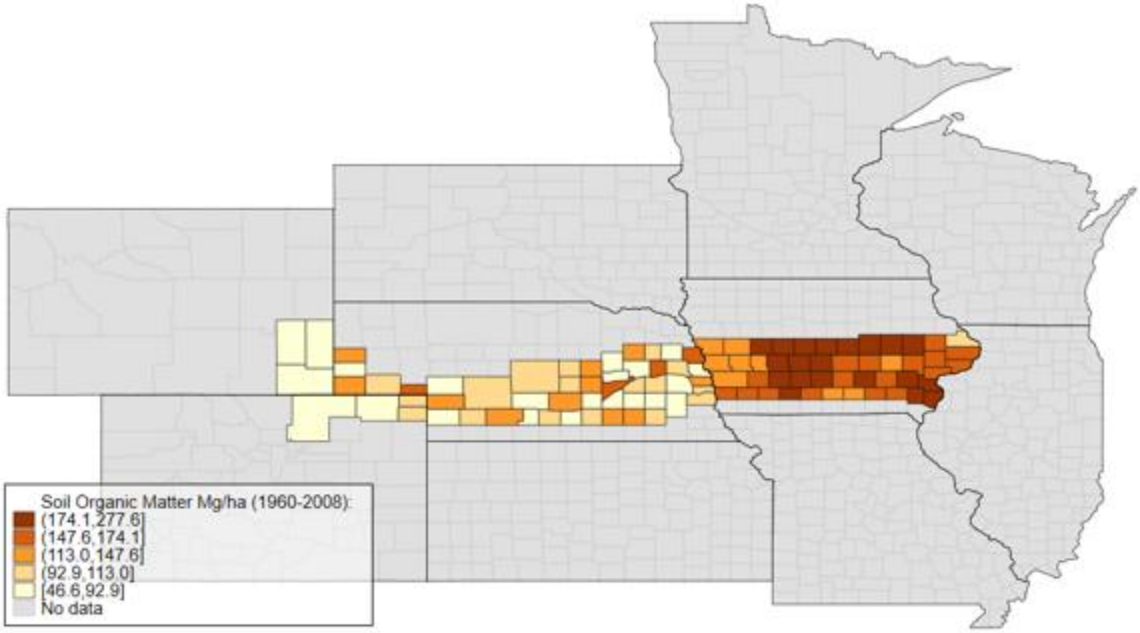

Figure 4 Average soil organic matter (Mg $ha^{-1}$)

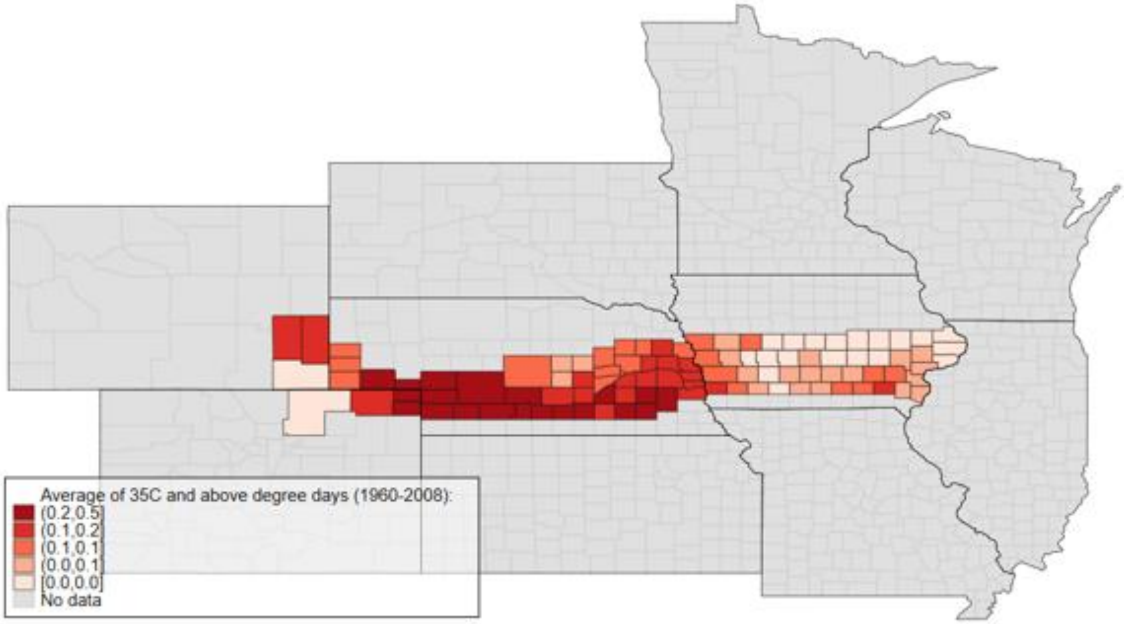

**Figure 5. Average number of degree days above 35ºC during the growing season in study counties, 1960-2008**

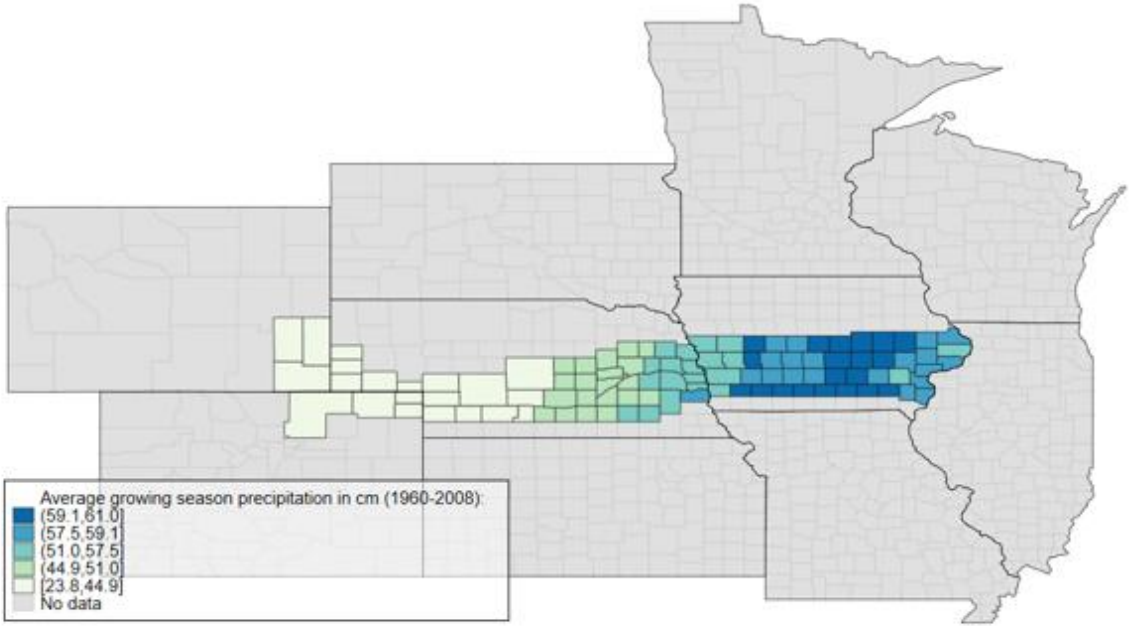

**Figure 6. Average growing season precipitation (cm) in study counties, 1960-2008**

## Table 2. Estimated Average Transect-wide Marginal Effects of Variables on Biomass Yield, by Region

| Variable | Type of response | Region | | | | | |
|---|---|---|---|---|---|---|---|
| | | 41st ‖ | 1 | 2 | 3 | 4 | 5 |
| Fertilizer, quantity index | elasticity | 0.112 | 0.106 | 0.123 | 0.119 | 0.108 | 0.109 |
| Chemicals, quantity index | elasticity | 0.058 | 0.050 | 0.047 | 0.052 | 0.062 | 0.065 |
| Irrigation ratio, 0-1 | semi-elasticity | 0.679 | 0.782 | 0.979 | 0.847 | 0.738 | 0.462 |
| Time trend, years | semi-elasticity | 0.010 | 0.009 | 0.009 | 0.009 | 0.010 | 0.011 |
| Soil organic matter, Mg/ha | elasticity | 0.131 | 0.103 | 0.072 | 0.062 | 0.162 | 0.182 |
| DD0030, days | semi-elasticity | 0.003 | 0.005 | 0.004 | 0.004 | 0.003 | 0.002 |
| DD3035, days | semi-elasticity | -0.015 | -0.008 | -0.003 | -0.001 | -0.021 | -0.025 |
| DD35plus, days | semi-elasticity | -0.309 | -0.113 | -0.121 | -0.137 | -0.408 | -0.472 |
| Precipitation, cm | elasticity | -0.046 | 0.323 | 0.057 | -0.015 | -0.131 | -0.163 |

Note: P-values for the 41st ‖ region are in Table A.4 in the Appendix

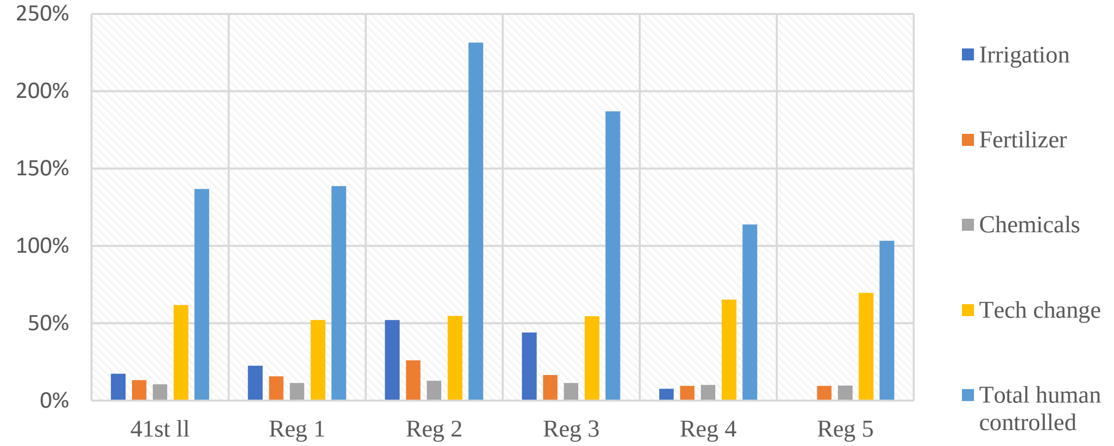

**Fig. 7 . Human-controlled contributions to biomass yield increases and observed biomass yield changes across regions along the 41st parallel, 1960-2008**

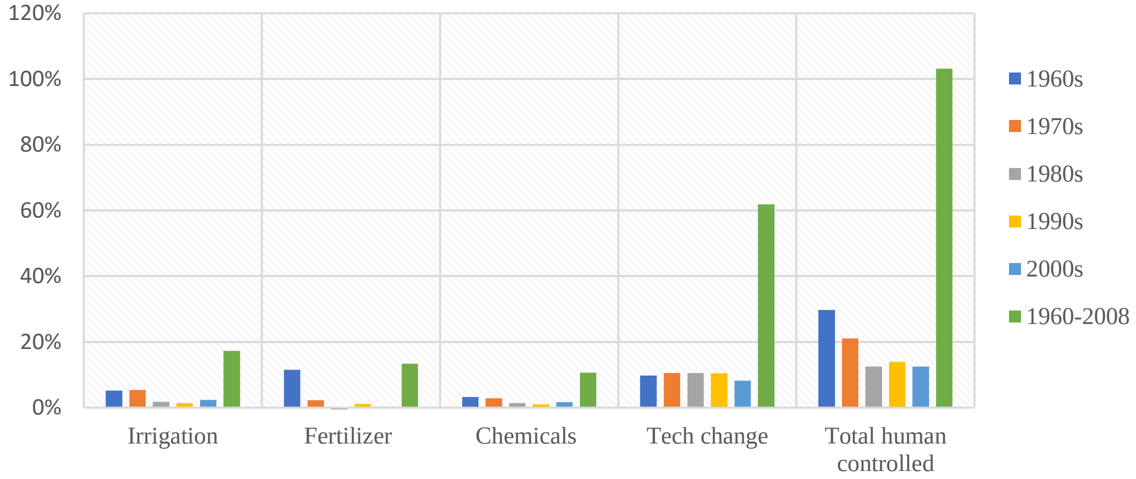

**Fig. 8. Human-controlled contributions to biomass yield increases across the 41st parallel, by decade, 1960-2008**

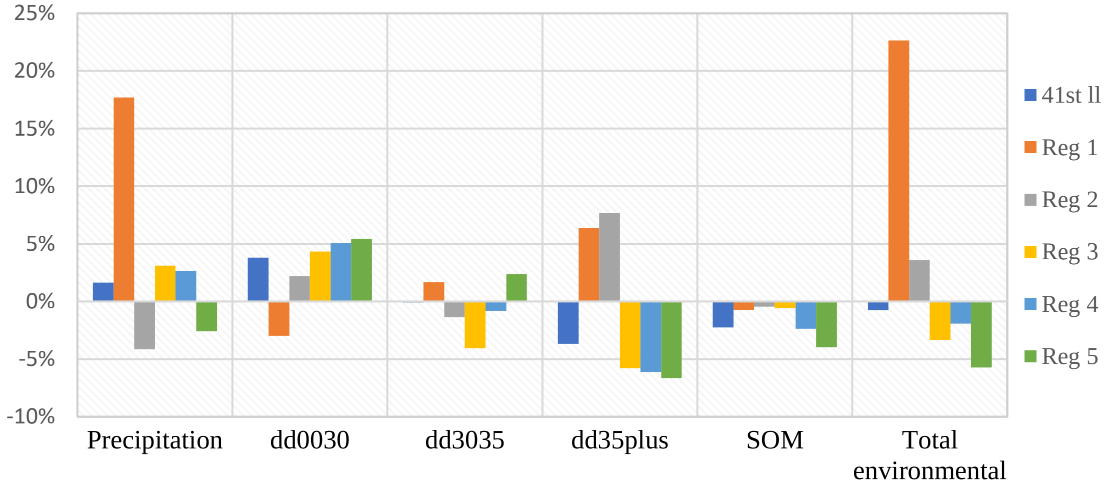

**Figure 9. Environmental contributions to yield increases across regions along the 41st ||, 1960-2008**

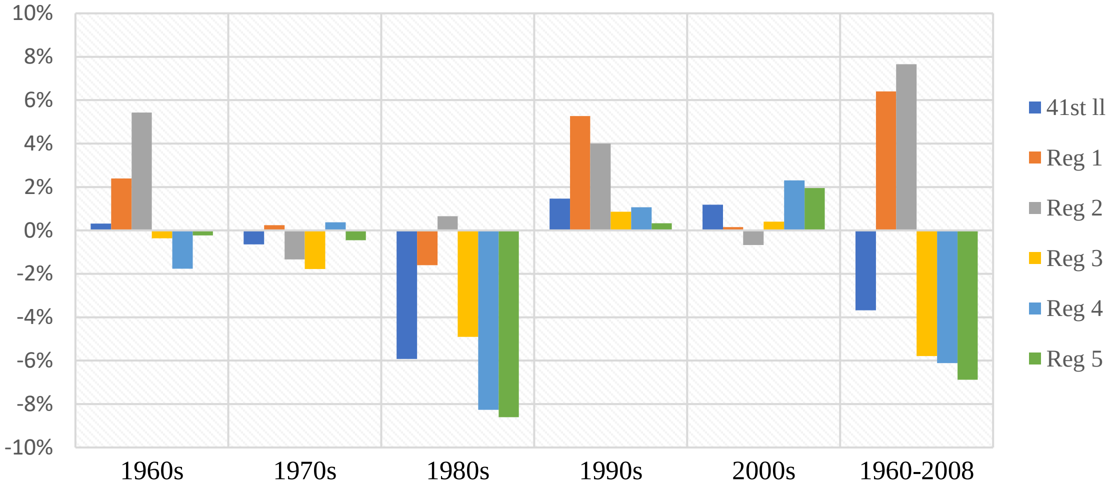

**Figure 10. Contributions of temperatures above 35°C to yield changes across regions, along the 41st ||, by decade 1960-2008**

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## Appendix A - Estimation and additional tables.

**Table A.1 - Summary Statistics in Study Counties along the 41st Parallel North in Iowa, Nebraska, Colorado and Wyoming, 1960-2008**

| | All counties (101 counties) | | | | Region 1 (12 counties) | | | |
|---|---|---|---|---|---|---|---|---|
| Variable | Mean | Std. Dev. | Min | Max | Mean | Std. Dev. | Min | Max |
| Yield (Mg/ha) | 8.39 | 2.83 | 1.20 | 17.91 | 5.71 | 2.24 | 1.20 | 12.49 |
| Fertilizer (quantity index) | 2.83 | 1.07 | 0.03 | 6.82 | 1.80 | 1.17 | 0.03 | 6.55 |
| Chemicals (quantity index) | 7.08 | 3.74 | 0.13 | 23.10 | 3.94 | 2.99 | 0.13 | 14.88 |
| Irrigation (ratio 0-1) | 0.19 | 0.24 | 0.00 | 0.90 | 0.30 | 0.21 | 0.00 | 0.90 |
| SOM (Mg/ha) | 136.52 | 49.18 | 46.53 | 317.35 | 93.69 | 32.10 | 46.53 | 162.39 |
| Time period (1960=1) | 25.00 | 14.14 | 1.00 | 49.00 | 25.00 | 14.15 | 1.00 | 49.00 |
| Precipitation (cm) | 51.20 | 15.68 | 11.94 | 125.21 | 30.79 | 7.66 | 11.94 | 51.94 |
| dd0030 (days) | 164.44 | 5.54 | 147.68 | 178.83 | 160.96 | 4.94 | 147.69 | 174.28 |
| dd3035 (days) | 4.05 | 2.26 | 0.14 | 12.78 | 4.01 | 1.96 | 0.26 | 9.53 |
| dd35 (days) | 0.13 | 0.22 | 0.00 | 1.90 | 0.17 | 0.19 | 0.00 | 0.96 |
| Share Fertilizer | 0.11 | 0.04 | 0.00 | 0.38 | 0.10 | 0.06 | 0.00 | 0.38 |
| Share Chemicals | 0.06 | 0.03 | 0.00 | 0.18 | 0.05 | 0.03 | 0.00 | 0.14 |

| | Region 2 (9 counties) | | | | Region 3 (24 counties) | | | |
|---|---|---|---|---|---|---|---|---|
| Variable | Mean | Std. Dev. | Min | Max | Mean | Std. Dev. | Min | Max |
| Yield (Mg/ha) | 8.44 | 3.41 | 1.86 | 17.34 | 9.00 | 3.10 | 2.46 | 17.91 |
| Fertilizer (quantity index) | 3.04 | 1.33 | 0.30 | 6.75 | 2.84 | 1.07 | 0.16 | 6.82 |
| Chemicals (quantity index) | 5.69 | 3.72 | 0.26 | 17.46 | 6.24 | 3.37 | 0.30 | 16.95 |
| Irrigation (ratio 0-1) | 0.42 | 0.20 | 0.03 | 0.89 | 0.46 | 0.20 | 0.01 | 0.88 |
| SOM (Mg/ha) | 96.73 | 20.25 | 62.80 | 139.77 | 108.83 | 22.50 | 68.72 | 175.91 |
| Time period (1960=1) | 25.00 | 14.16 | 1.00 | 49.00 | 25.00 | 14.15 | 1.00 | 49.00 |
| Precipitation (cm) | 42.06 | 10.81 | 14.59 | 101.49 | 48.75 | 12.00 | 16.95 | 92.76 |
| dd0030 (days) | 162.32 | 5.11 | 148.83 | 174.64 | 164.07 | 5.20 | 150.96 | 177.27 |
| dd3035 (days) | 5.40 | 2.22 | 0.33 | 11.12 | 4.81 | 2.12 | 0.26 | 12.05 |
| dd35 (days) | 0.31 | 0.29 | 0.00 | 1.90 | 0.16 | 0.23 | 0.00 | 1.67 |
| Share Fertilizer | 0.13 | 0.04 | 0.03 | 0.28 | 0.11 | 0.03 | 0.01 | 0.22 |
| Share Chemicals | 0.05 | 0.03 | 0.01 | 0.14 | 0.05 | 0.02 | 0.00 | 0.12 |

| | Region 4 (15 counties) | | | | Region 5 (41 counties) | | | |
|---|---|---|---|---|---|---|---|---|
| Variable | Mean | Std. Dev. | Min | Max | Mean | Std. Dev. | Min | Max |
| Yield (Mg/ha) | 8.15 | 2.20 | 3.45 | 14.60 | 8.88 | 2.40 | 2.24 | 15.54 |
| Fertilizer (quantity index) | 2.64 | 0.81 | 0.81 | 6.69 | 3.15 | 0.84 | 0.65 | 6.23 |
| Chemicals (quantity index) | 7.28 | 3.23 | 0.78 | 14.59 | 8.72 | 3.45 | 1.42 | 23.10 |
| Irrigation (ratio 0-1) | 0.07 | 0.09 | 0.00 | 0.40 | 0.00 | 0.00 | 0.00 | 0.00 |
| SOM (Mg/ha) | 113.91 | 26.90 | 68.03 | 169.02 | 182.28 | 37.30 | 101.49 | 317.35 |
| Time period (1960=1) | 25.00 | 14.15 | 1.00 | 49.00 | 25.00 | 14.15 | 1.00 | 49.00 |
| Precipitation (cm) | 55.28 | 13.53 | 25.53 | 112.17 | 59.12 | 14.11 | 23.10 | 125.21 |
| dd0030 (days) | 164.69 | 5.13 | 152.28 | 176.88 | 166.05 | 5.49 | 147.68 | 178.83 |
| dd3035 (days) | 4.78 | 2.14 | 0.34 | 11.26 | 3.04 | 2.04 | 0.14 | 12.78 |
| dd35 (days) | 0.14 | 0.22 | 0.00 | 1.27 | 0.06 | 0.17 | 0.00 | 1.56 |
| Share Fertilizer | 0.10 | 0.03 | 0.05 | 0.20 | 0.11 | 0.03 | 0.02 | 0.29 |
| Share Chemicals | 0.06 | 0.02 | 0.02 | 0.13 | 0.07 | 0.02 | 0.02 | 0.18 |

**Table A.2 - List of counties**

| | | | | |
|---|---|---|---|---|
| Region 1 | | | | |
| Banner, NE | Cheyenne, NE | Deuel, NE | Goshen, WY | Kimball, NE |
| Laramie, WY | Logan, CO | Phillips, CO | Platte, WY | Scotts Bluff, NE |
| Sedgwick, CO | Weld, CO | | | |
| Region 2 | | | | |
| Chase, NE | Custer, NE | Dawson, NE | Frontier, NE | Gosper, NE |
| Hayes, NE | Keith, NE | Lincoln, NE | Phelps, NE | |
| Region 3 | | | | |
| Adams, NE | Boone, NE | Buffalo, NE | Butler, NE | Clay, NE |
| Colfax, NE | Fillmore, NE | Greeley, NE | Hall, NE | Hamilton, NE |
| Howard, NE | Kearney, NE | Madison, NE | Merrick, NE | Nance, NE |
| Perkins, NE | Platte, NE | Polk, NE | Saline, NE | Seward, NE |
| Sherman, NE | Stanton, NE | Valley, NE | York, NE | |
| Region 4 | | | | |
| Burt, NE | Cass, NE | Crawford, IA | Cuming, NE | Dodge, NE |
| Douglas, NE | Harrison, IA | Lancaster, NE | Mills, IA | Monona, IA |
| Pottawattamie, IA | Sarpy, NE | Saunders, NE | Shelby, IA | Washington, NE |
| Region 5 | | | | |
| Adair, IA | Adams, IA | Audubon, IA | Benton, IA | Boone, IA |
| Carroll, IA | Cass, IA | Cedar, IA | Clarke, IA | Clinton, IA |
| Dallas, IA | Des Moines, IA | Greene, IA | Guthrie, IA | Henry, IA |
| Iowa, IA | Jackson, IA | Jasper, IA | Jefferson, IA | Johnson, IA |
| Jones, IA | Keokuk, IA | Linn, IA | Louisa, IA | Lucas, IA |
| Madison, IA | Mahaska, IA | Marion, IA | Marshall, IA | Monroe, IA |
| Montgomery, IA | Muscatine, IA | Polk, IA | Poweshiek, IA | Scott, IA |

Story, IA Tama, IA Union, IA Wapello, IA Warren, IA
Washington, IA

## Table A.3 - Parameters Estimated (I3SLS) for Counties along the 41st Parallel North in Iowa, Nebraska, Colorado and Wyoming, 1960-2008

Three-stage least-squares regression, iterated

| Equation | Observations | Parameters | RMSE | R-sq | P |
|---|---|---|---|---|---|
| lny | 4949 | 32 | 0.1810456 | 0.7742 | 0.0000 |
| sharefert | 4949 | 4 | 0.0304064 | 0.3136 | 0.0000 |
| sharechem | 4949 | 4 | 0.0163848 | 0.5787 | 0.0000 |

Constraints

( 1) - [sharefert]ln(Chemicals) - [sharechem]ln(Fertilizer) = 0
( 2) - [lny]ln(Fertilizer)_sq + [sharefert]ln(Fertilizer) = 0
( 3) - [lny]ln(Fertilizer)_ln(Chemicals) + [sharefert]ln(Chemicals) = 0
( 4) - [lny]Irrigation_ln(Fertilizer) + [sharefert]Irrigation = 0
( 5) - [lny]ln(Fertilizer)_Time + [sharefert]Time = 0
( 6) - [lny]ln(Chemicals)_sq + [sharechem]ln(Chemicals) = 0
( 7) - [lny]Irrigation_ln(Chemicals) + [sharechem]Irrigation = 0
( 8) - [lny]ln(Chemicals)_Time + [sharechem]Time = 0
( 9) - [lny]ln(Fertilizer) + [sharechem]Constant = 0
(10) - [lny]ln(Chemicals) + [sharechem]Constant = 0

| Variable | Observed Coefficient | Bootstrap Std. Err. | z | P>\|z\| |
|---|---|---|---|---|
| Irrigation | 1.1788 | 0.4674 | 2.5200 | 0.0120 |
| ln(Fertilizer) | 0.0878 | 0.0011 | 81.3900 | 0.0000 |
| ln(Chemicals) | 0.0199 | 0.0006 | 35.3400 | 0.0000 |
| ln(Precipitation) | 3.4205 | 0.5309 | 6.4400 | 0.0000 |
| ln(SOM) | 0.1815 | 0.0178 | 10.2000 | 0.0000 |
| 0.5*Irrigation_sq | 0.2352 | 0.1484 | 1.5800 | 0.1130 |
| 0.5*ln(Fertilizer)_sq | 0.0309 | 0.0015 | 20.5200 | 0.0000 |
| 0.5*ln(Chemicals)_sq | 0.0238 | 0.0010 | 23.8700 | 0.0000 |
| 0.5*ln(Precipitation)_sq | -0.7291 | 0.0514 | -14.1900 | 0.0000 |
| Irrigation_ln(Fertilizer) | 0.0163 | 0.0024 | 6.8700 | 0.0000 |
| Irrigation_ln(Chemicals) | -0.0095 | 0.0013 | -7.4000 | 0.0000 |
| Irrigation_ln(Precipitation) | -0.2597 | 0.0425 | -6.1000 | 0.0000 |
| Irrigation_ln(SOM) | 0.0703 | 0.0490 | 1.4400 | 0.1510 |
| ln(Fertilizer)_ln(Chemicals) | -0.0158 | 0.0012 | -13.5400 | 0.0000 |
| dd0029 | 0.0170 | 0.0140 | 1.2100 | 0.2250 |
| dd3035 | -0.0119 | 0.0281 | -0.4200 | 0.6710 |
| dd3640 | 0.5769 | 0.3070 | 1.8800 | 0.0600 |
| dd0029_Irrigation | 0.0015 | 0.0022 | 0.6700 | 0.5050 |
| dd3035_Irrigation | 0.0506 | 0.0072 | 7.0600 | 0.0000 |
| dd3640_Irrigation | 0.6205 | 0.0831 | 7.4700 | 0.0000 |
| dd0029_Precipitation | -0.0036 | 0.0035 | -1.0300 | 0.3010 |
| dd3035_Precipitation | -0.0033 | 0.0072 | -0.4500 | 0.6500 |
| dd3640_Precipitation | -0.2589 | 0.0837 | -3.0900 | 0.0020 |
| Time | 0.0092 | 0.0008 | 11.0900 | 0.0000 |
| Time_sq | 0.0000 | 0.0000 | -0.4700 | 0.6390 |
| Irrigation_Time | -0.0033 | 0.0007 | -4.6100 | 0.0000 |
| ln(fertilizer)_Time | 0.0008 | 0.0001 | 15.5700 | 0.0000 |
| ln(Chemical)_Time | 0.0005 | 0.0000 | 15.9100 | 0.0000 |
| Region 2 dummy | 0.1331 | 0.0134 | 9.9400 | 0.0000 |
| Region 3 dummy | 0.1370 | 0.0126 | 10.9000 | 0.0000 |
| Region 4 dummy | 0.3605 | 0.0167 | 21.5400 | 0.0000 |
| Region 5 dummy | 0.3096 | 0.0205 | 15.1400 | 0.0000 |
| Constant | -7.6853 | 2.1840 | -3.5200 | 0.0000 |

### Table A.4 Estimated transect-wide marginal effects of variables on biomass yield for counties along the 41 Parallel North in Iowa, Nebraska, Colorado and Wyoming, 1960-2008

| Variable | Type of response | Value | Percentage of obs. signif.* |
|---|---|---|---|
| Fertilizer, quantity index | elasticity | 0.112 | 99.9% |
| Chemicals, quantity index | elasticity | 0.058 | 100.0% |
| Irrigation ratio, 0-1 | semi-elasticity | 0.679 | 99.8% |
| Time trend, years | semi-elasticity | 0.010 | 100.0% |
| Soil organic matter, Mg/ha | elasticity | 0.131 | 88.3% |
| DD0030, days | semi-elasticity | 0.003 | 79.9% |
| DD3035, days | semi-elasticity | -0.015 | 84.0% |
| DD35, days | semi-elasticity | -0.309 | 87.7% |
| Precipitation, cm | elasticity | -0.046 | 82.0% |

*P-values calculated using the delta method. Significance levels at 95%.

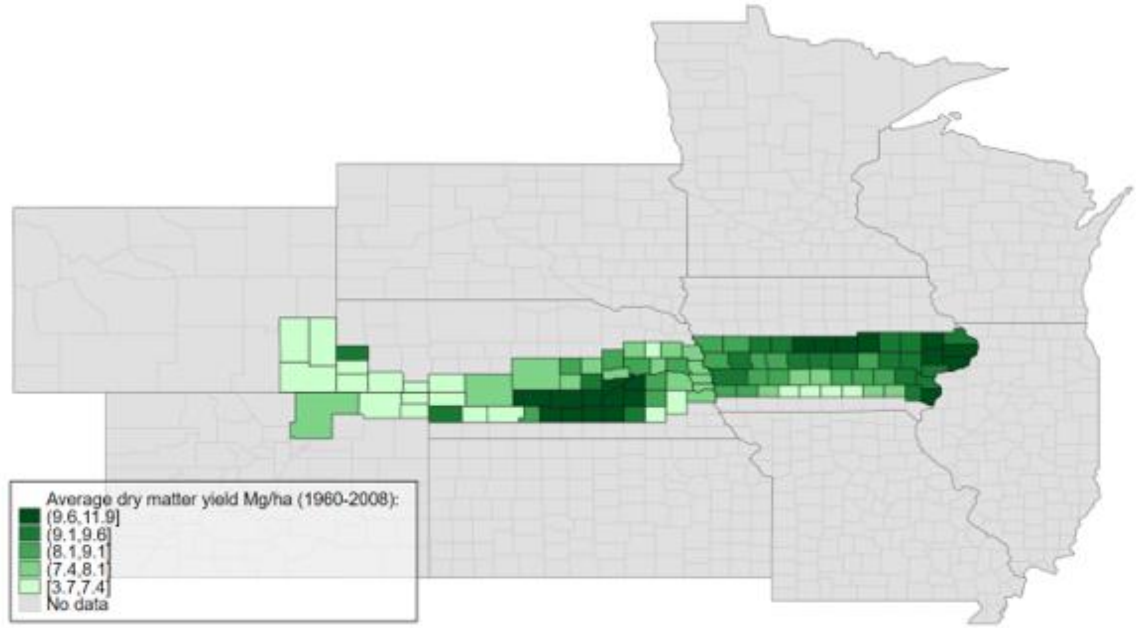

**Figure A.1. Average dry matter biomass yield by county (Mg ha$^{-1}$), 1960-2008**

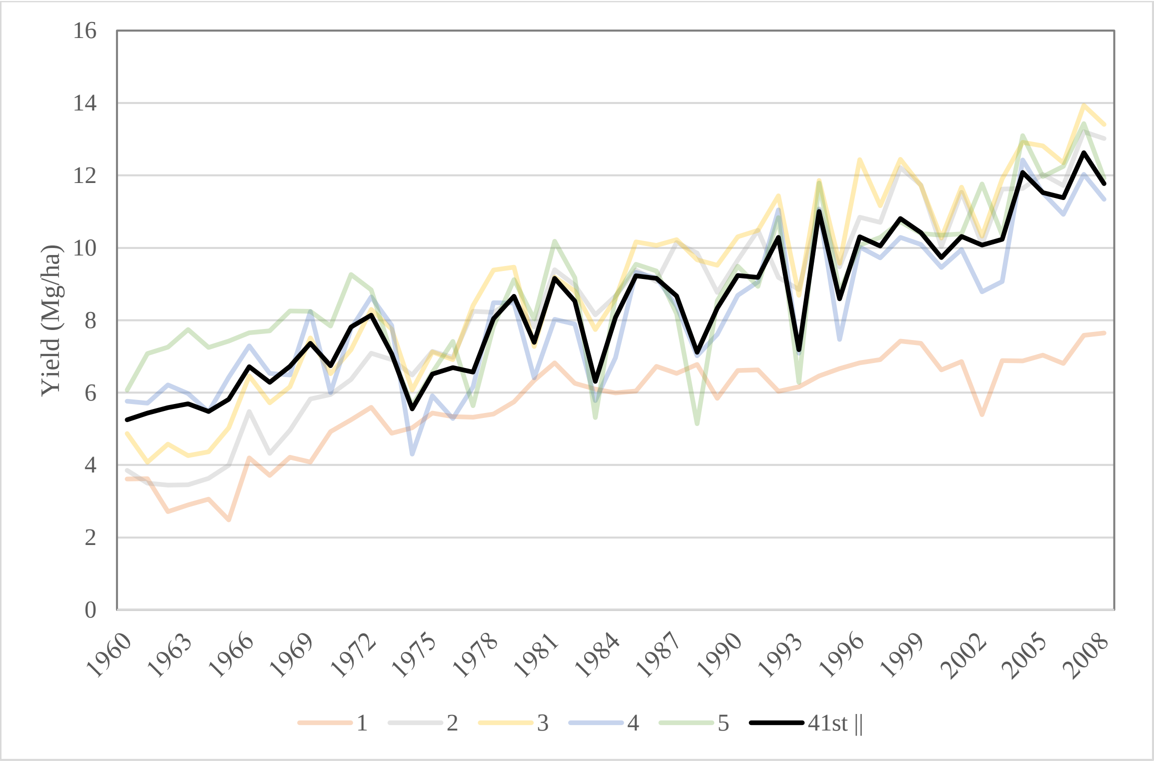

**Figure A.2. Average 41$^{st}$ || transect dry matter yield (Mg ha$^{-1}$) by region, 1960-2008**

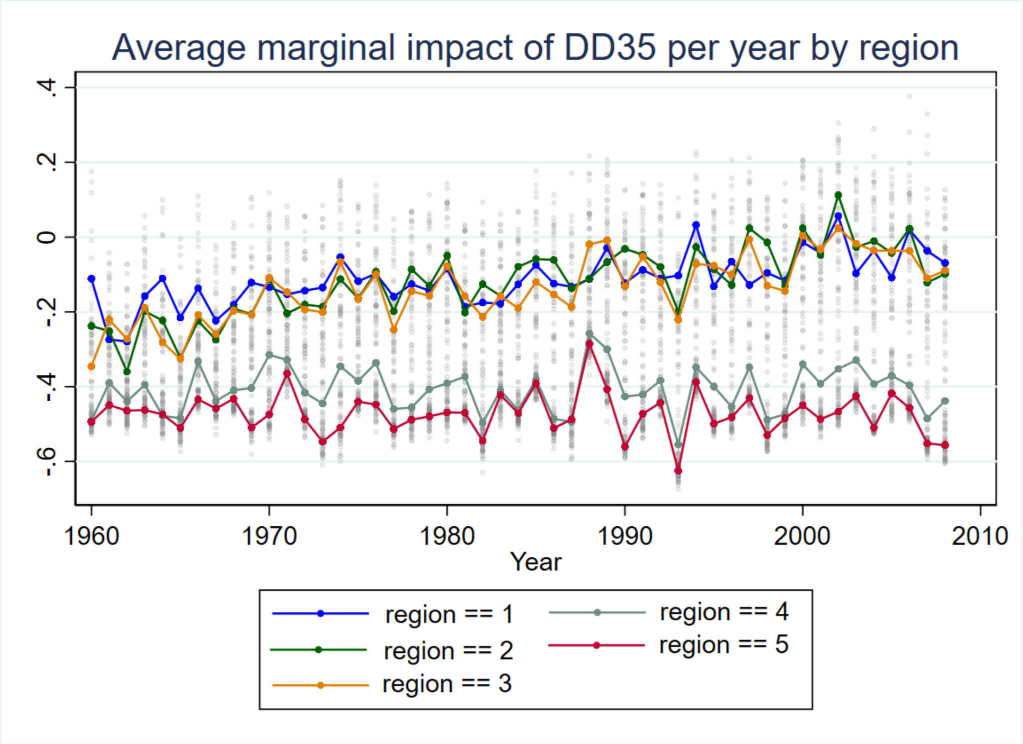

**Figure A.3 – Average marginal impact of an extra 24 hours (a day) of temperatures above 35ºC for counties along the 41 Parallel North in Iowas, Nebraska, Colorado and Wyoming, 1960-2008**

## Appendix B

### *Calculation of biomass yields*

Coefficients used to convert from bushels to megagrams were 0.0254 for corn, sorghum and rye and 0.0272 for wheat and soybeans. The unharvested biomass for each crop was estimated by multiplying the reported harvested production times one minus the harvest index for the crop as reported in the agronomic literature: 0.50 for corn and sorghum for grain; 1.00 for corn and sorghum for silage and hay; 0.40 for soybeans, and 0.35-0.85 for rye and barley and other minor crops (Hay, 1995; Unkovich et al., 2010). The estimated dry matter produced by each crop was converted to dry matter (DM) by multiplying production by one minus the estimated average moisture content of that crop: 0.145 for corn and sorghum for grain, 0.145 for barley and rye; 0.55 for corn and sorghum for silage; 0.135 for wheat; 0.13 for soybeans and beans and 0.10-0.78 for other minor crops (Loomis and Connor, 1992). The county-level yields were obtained by dividing the biomass produced by the total planted area for all crops for each county. Annual harvested production and planted land data were obtained from the U.S. Department of Agriculture's National Agricultural Statistical Service (USDA-NASS).

### *Construction of fertilizer and chemicals indexes*

Fertilizer and chemical inputs are measured as implicit indexes of quantity per hectare planted, calculated as follows. County expenditures on these inputs were taken from the Census of Agriculture as reported by USDA-NASS. Implicit total quantity indexes were constructed for each census year by dividing the reported total expenditure by country-wide price indexes obtained from USDA-ERS for fertilizers and USDA-NASS for chemicals (base 1990-1992=100). These implicit total quantities were then divided by total planted area to obtain indexes of quantities applied per hectare by county and census year. Since the census is taken generally every five years, the missing years were estimated by linear interpolation of these per-hectare quantity indexes between census years. Finally, these indexes were divided by the index in Adams County, Nebraska, for the year 1960, converting them to a multilateral index with the base level being the per hectare application in Adams County, 1960.

### *Irrigation*

We do not have data on the actual amount of water applied from irrigation or from the irrigation technology used (center pivot, canal, etc.). Thus, irrigation is measured as the ratio of irrigated planted area to total planted area. When reported irrigated harvested land was higher than planted land we used the former.

### *Soil organic matter*

This variable was obtained from Lakoh (2012), whose calculations are described in the Supplementary Materials. Using 2010 data on Soil Organic Carbon (SOC) from the Soil Survey Geographic Database (SSURGO), Lakoh estimated average SOC levels per county for 2010, then estimated levels for the period 1960-2008 retroactively from 2010 initial values using modified versions of the DK model as described by Liska et al. (2014). An approximate SOC to soil organic matter (SOM) conversion factor of 2.0 was then applied to convert the series to SOM (Liska et al., 2014).

### *Weather*

Data on degree days and precipitation were estimated from weather station data collected from the United States Historical Climatology Network. From these data, a county average daily precipitation value (in centimeters) and county average daily maximum and minimum temperatures were constructed from temperature and precipitation results for each day during the growing season (March to August). To obtain county-level values for these daily observations, we used a weighted average of data from the 5 closest stations to the center of each county. For weighting, we used a Shephard inverse distance approach:

$$q_k = \sum_{i=1}^{5} \frac{b_{ik}\, q_i}{\sum_{j=1}^{5} b_{jk}} \ , \ \text{where } \ b_{ik} = \frac{1}{{d_{ik}}^2} \tag{13}$$

where $q_k$ denotes the weighted value for county $k$, $q_i$ is the measurement at weather station $i$, and $d_{ik}$ is the distance from weather station $i$ to the center of county $k$. These daily data at the county level were then used to construct the yearly precipitation and degree days data for each county.

### *Temperature*

To measure the impact of temperatures on yield we use an adaptation of the agronomic measure “growing degree days.” Following this literature, a growing degree day is defined as the amount of time (in days) during which the temperature is above a certain threshold; one degree-day is accumulated when the temperature is one degree above the threshold for 24 hours (Ritchie and Nesmith, 1991). Our measure of a degree day is the amount of time the temperature was within a given interval. To estimate degree days we adapt Snyder’s (1985) method, which uses a bell-shaped curve to estimate from maximum and minimum daily temperatures the number of hours during the day that the temperature was within a specific interval. We convert these values into fractions of a day, then sum the fractions over the growing season to provide the variables for this analysis.[1]

We constructed growing season degree-day variables for three intervals that cover all the temperatures higher than 0ºC. The lower temperature interval, *dd0030,* covers the degree days from 0ºC to less than 30ºC, the next interval, *dd3035,* covers the range 30ºC to less than 35ºC and the higher temperatures interval, *dd35,* covers temperatures equal to or higher than 35ºC.

### *Precipitation*

The precipitation variable used is the logarithm of the total amount of precipitation during the growing season, in centimeters, accumulated during the growing season (March to August). To construct these values, the estimated daily values for each county (weighted averages constructed using equation 13) were added for March through August. As shown in figure 3, there is a substantial decrease in average precipitation towards the West. For region 5, located in eastern Iowa the average growing season precipitation was 57.47 cm, while for region 1, located in the west, the average yearly precipitation was 29.78 cm.

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[1] This is necessary because of the area under the approximation curve.