AgEcon SEARCH
RESEARCH IN AGRICULTURAL & APPLIED ECONOMICS

The World's Largest Open Access Agricultural & Applied Economics Digital Library

This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

Help ensure our sustainability.

Give to AgEcon Search

AgEcon Search
http://ageconsearch.umn.edu
aesearch@umn.edu

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

Crop yield growth along a forty-first parallel transect contributions of factor intensification, irrigation, weather, and technical change

Federico Trindade
Daniel J. Evans School of Public Policy and Governance, University of Washington, Seattle, Washington, USA
ftrindade@gmail.com

Lilyan Fulginiti
Department of Agricultural Economics, University of Nebraska, Lincoln, Nebraska, USA
lfulginiti@unl.edu

Richard Perrin
Department of Agricultural Economics, University of Nebraska, Lincoln, Nebraska, USA
rperrin@unl.edu

Selected Paper prepared for presentation at the 2019 Agricultural & Applied Economics Association Annual Meeting, Atlanta, GA, July 21-23

Copyright 2019 by Trindade, Federico, Fulginiti, Lilyan and Perrin, Richard. All rights reserved. Readers may make verbatim copies of this document for non-commercial purposes by any means, provided that this copyright notice appears on all such copies.

Crop yield growth along a forty-first parallel transect contributions of factor intensification, irrigation, weather, and technical change

Introduction

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 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 (Schlenker and Roberts, 2009, Roberts, Schlenker and Eyer, 2012, Hsiang, et al., 2017, among others). On the other hand, many studies of yield growth suggest that technical change will continue to increase production, while experimental plot studies indicate that CO_2 fertilization will also increase production, so the likely trend of crop yields in the presence of climate change remain poorly understood. Virtually no studies other than this one have attempted to identify simultaneously both the marginal impacts and the recent contributions of weather, technological change, input intensification, and irrigation.

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 N (41st || hereafter) of the U.S. Great Plains. We chose to study this transect because yields there increased dramatically across a wide range of temperate-region growing conditions. We identify the separate contributions and interactions of weather, intensification, irrigation, soil organic matter, and technical change by estimating a general 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 $Y= f(X,e)$, output and input prices and the characteristics of the environment (weather, soil, etc.), 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 environment variables are represented by vector $\boldsymbol{e}$ and non-specific technical change is t. Following Chambers (1988) the yield function $f(\boldsymbol{X}, \boldsymbol{e}, \boldsymbol{t})$ 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:

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

with $j = 1, \dots, J$ and where γ_j is the production elasticity of input j, which under optimizing behavior is it's the 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 given expectations about natural circumstances as reflected by $\boldsymbol{e}$.

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

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

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) (sometimes referred to as Total-Factor Productivity or Multi-Factor Productivity change), is:

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

According to its effects on relative input productivity, the nature of technical change can be further characterized in terms of input biases. We use Chambers' (1988) measure of

overall bias that identifies change in optimal input share, under constant prices, due to technical change, defined as:

$$B_j = \frac{\partial s_j(p, \boldsymbol{w}, \boldsymbol{e}, t)}{\partial t} \quad \forall\ j \tag{5}$$

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 time, we couple these marginal effects with observed changes in the amounts of these factors during the period of analysis in a growth decomposition analysis as:

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

where the first right hand side terms indicate the contribution of inputs to output growth, the second and third indicate the contribution of environmental factors and the fourth is the contribution of non-specific technical change.

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 the output produced and the 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 than 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 functional form to represent the production function in (1) and the corresponding shares in (2).[1] This specification is flexible as it provides a local second order approximation to any production technology, minimizing a priori restrictions on its structure. The following system of equations[2] is estimated:

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

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

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

[1] Production functions with many parameters relative to the number of observations might suffer from low precision and might result in imprecise parameter estimates. The joint estimation of the factor shares and the production function leads to higher efficiency since the higher information present in the joint estimation can compensate for the information inadequacy in the production function alone (Ray, 1982).

[2] We have included only share equations for fertilizers and chemicals because we lack county level information on labor, capital, and cost of irrigation.

where y_{it} is logarithm of observed biomass yield Y (tons per acre) in county i year t; s_{1it} is the share of fertilizer, s_{2it} is the share of chemicals, x_{it} is a vector of the logarithms of quantity indexes of fertilizer and chemicals applied per acre and the fraction of agricultural land irrigated, $\boldsymbol{d}_{iwt}$ is a vector of the number of degree days in three temperature intervals; p_{it} is the logarithm of growing season precipitation in cm; *som* is the logarithm of the level of soil organic matter; r is the region where the county is situated, with $r = 2,\ldots,5$; 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 α_0, β*'s,* ω*'s*, θ*s*, τ*'s*, φ*'s* and ρ*'s* are the parameters to be estimated[3]. 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 take decisions about the desired yield and the amount of fertilizer and chemicals needed to produce it simultaneously, an instrumental variables

[3] Total output, fertilizer and chemicals have been divided by land. An estimation of a yield function is preferable if the data being analyzed are subject to heteroskedasticity (Jacobs, Smith and Street, 2006).

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.[4]

Since the Cobb-Douglas production function is nested in the translog production function when all second order coefficients are zero, 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 γ_{ijt} that, given our assumptions of profit maximization and perfect competition, are equal to the factor shares s_{ijt}. These elasticities vary with time (*t*) and county inputs (*i, j*) in the following way:

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

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:

$$\gamma_{irri,t} = \left(\frac{\partial y_{it}}{\partial X_{irri,t}}\right) = \left(\frac{\partial Y_{it}}{\partial X_{irri,t}}\right) \cdot \left(\frac{1}{Y_{it}}\right) = \beta_j + \sum_{k \neq j}^{3} \beta_{jk} x_{ikt} + \varphi_j t\,, \quad j = irrigation \qquad (9)$$

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 capture the marginal impact of degree days (*dd*):

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

[4] Reg3 command in STATA version 14.0 was used for the econometric estimations.

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

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

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

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*, 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):

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

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. 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 yield contributions of various environmental conditions as well as human inputs. After estimation of equation (7) we calibrate the estimated yield function to average conditions in each of five relatively homogeneous subregions from west to east.

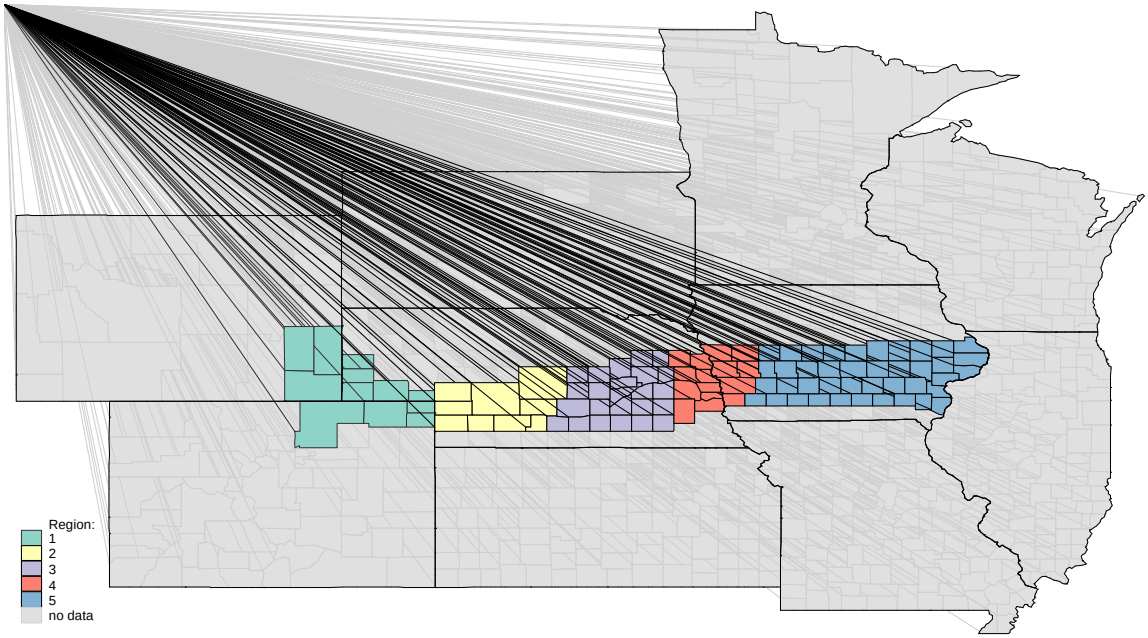

Figure 1. Study counties along the 41st parallel N

Table A.1 - Summary Statistics in Study Counties along the 41st Parallel North, 1960-2008

	All counties (101 counties)				Region 1 (12 counties)			
Variable	Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max
Yield (Mg/ha)	8.59	2.77	1.75	18.17	7.26	3.04	1.75	18.17
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)	8.56	3.36	1.97	17.29	9.05	3.06	2.64	17.99
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)	8.16	2.19	3.46	14.59	8.88	2.40	2.25	15.49
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

Figures 2-4 illustrate how environmental factors vary across the subregions. Table 1 provides basic statistics for these variables. Detailed description of the construction of the variables used is in the Supplementary Material.

The variables used in estimation of the system of equations (7) are: biomass yields, fertilizers, chemicals, share of land irrigated, soil organic matter, temperatures and precipitation. To calculate biomass yields 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, 2001). Figure 2 shows average biomass yield by county, while Figure 3 shows the 41st || transect average yield through time.

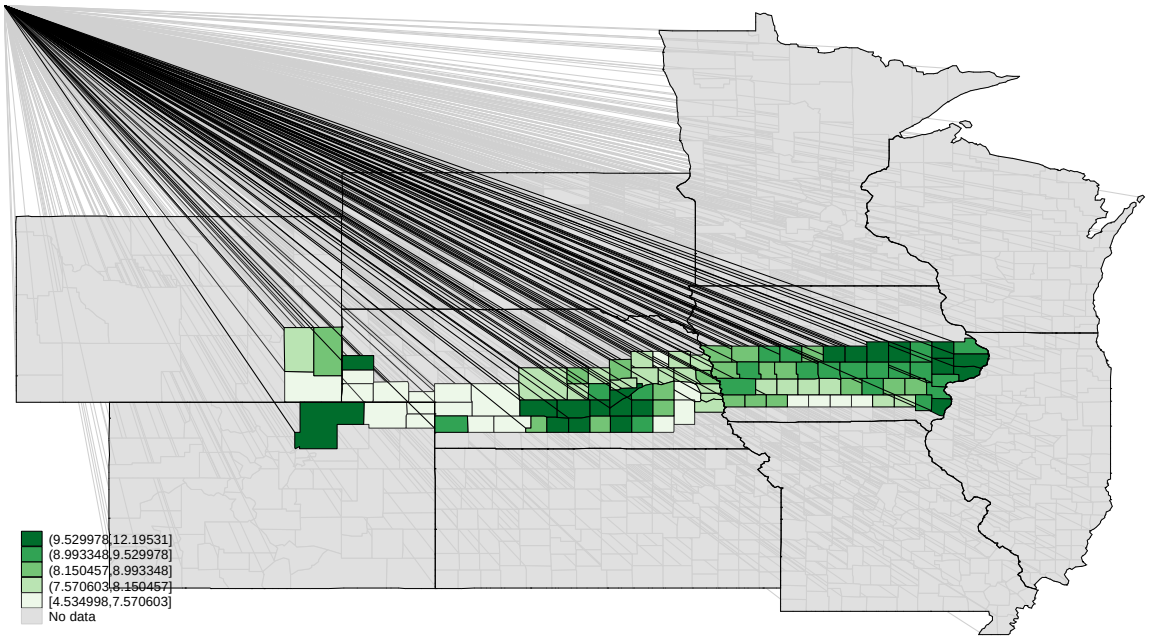

Figure 2. Average dry matter yield by county, 1960-2008

Across the region, average yields increased about 105% from 1960 to 2008, for an average compound rate of 1.5%. This aggregate yield increase masks substantial

variation by subregion: in subregions 2 and 3 with their substantial increases in irrigation yields increased by 170%, compared to 95% in the more humid eastern subregion.

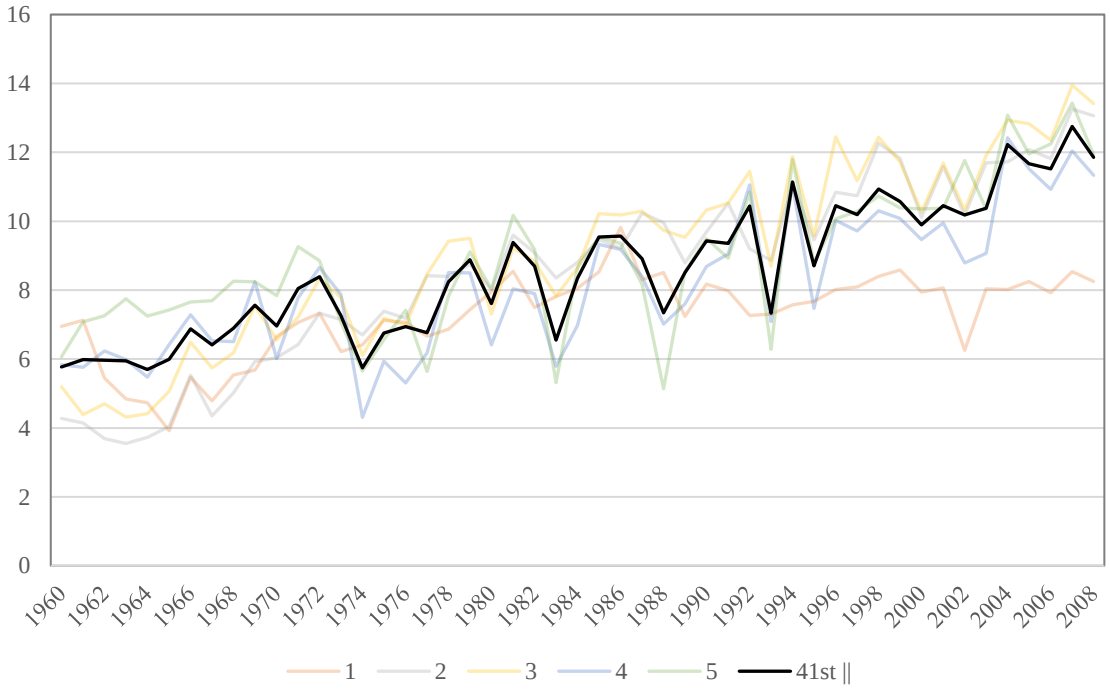

Figure 3. Average 41st || transect dry matter yield (Mg ha^{-1}) by region, 1960-2008

Factor intensification is captured by the 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 as well as exogenous innovations or technical change.

Fertilizer and chemical inputs are expressed as indexes of quantity applied per acre. 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 4.

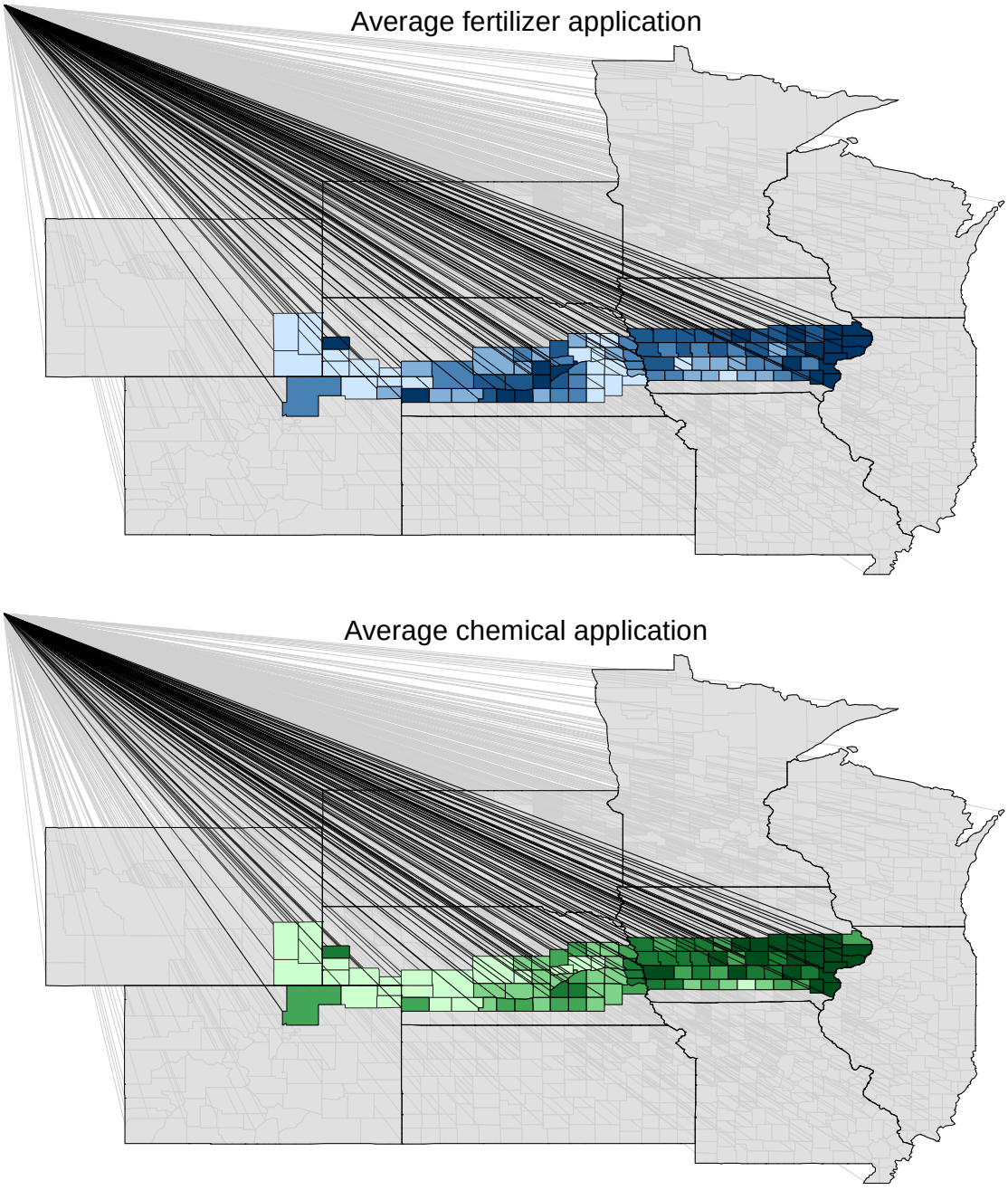

Figure 4. Average fertilizer and chemical application rates (indexes), 1960-2008

Irrigation is expressed as the share of irrigated land in each county. This variable is obtained 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[5].

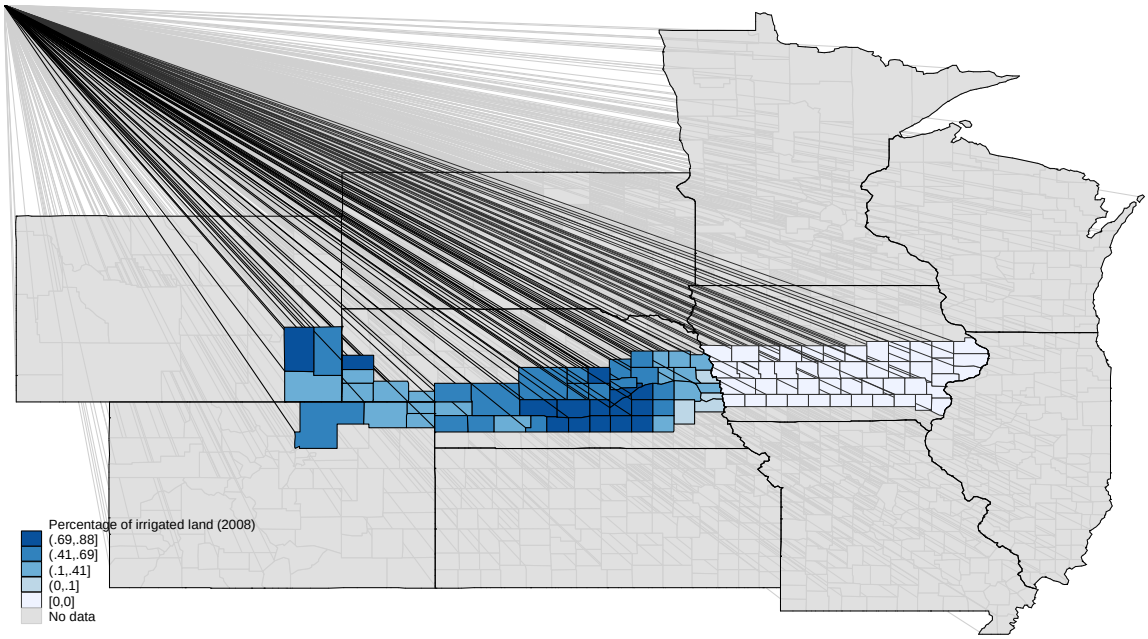

Figure 5. Average share of land irrigated, 1960-2008

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, and decreasing levels through time (Figure 6). The average value of SOM for region 1 (west) was 88 Mg ha^{-1}, while for region 5 (east) it was 178 Mg ha^{-1}.

[5] Given the minimal levels of irrigation present in Iowa, USDA does not report the amount of planted land that was irrigated.

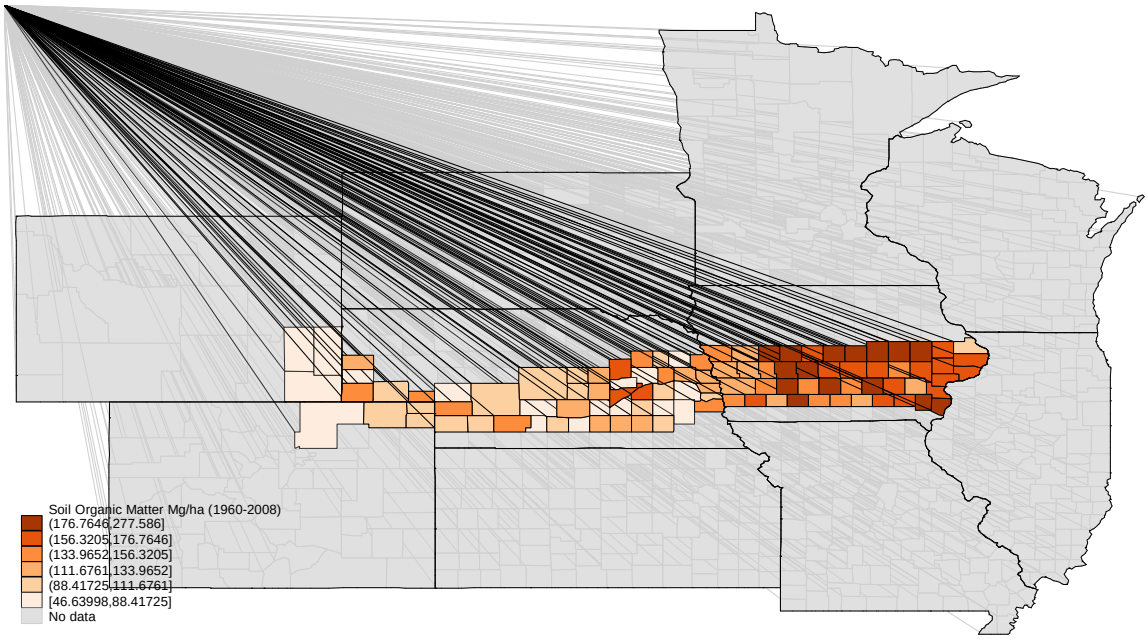

Figure 6 Average soil organic matter, in Mg ha^{-1}

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 value (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 obtained as the weighted average of observations from the five closest weather stations to the center of each county. These observations where weighed using a Shephard inverse distance approach as follows:

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

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", following Schlenker and Roberts (2009). 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. The Supplementary Materials describe 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 increases from east to west.

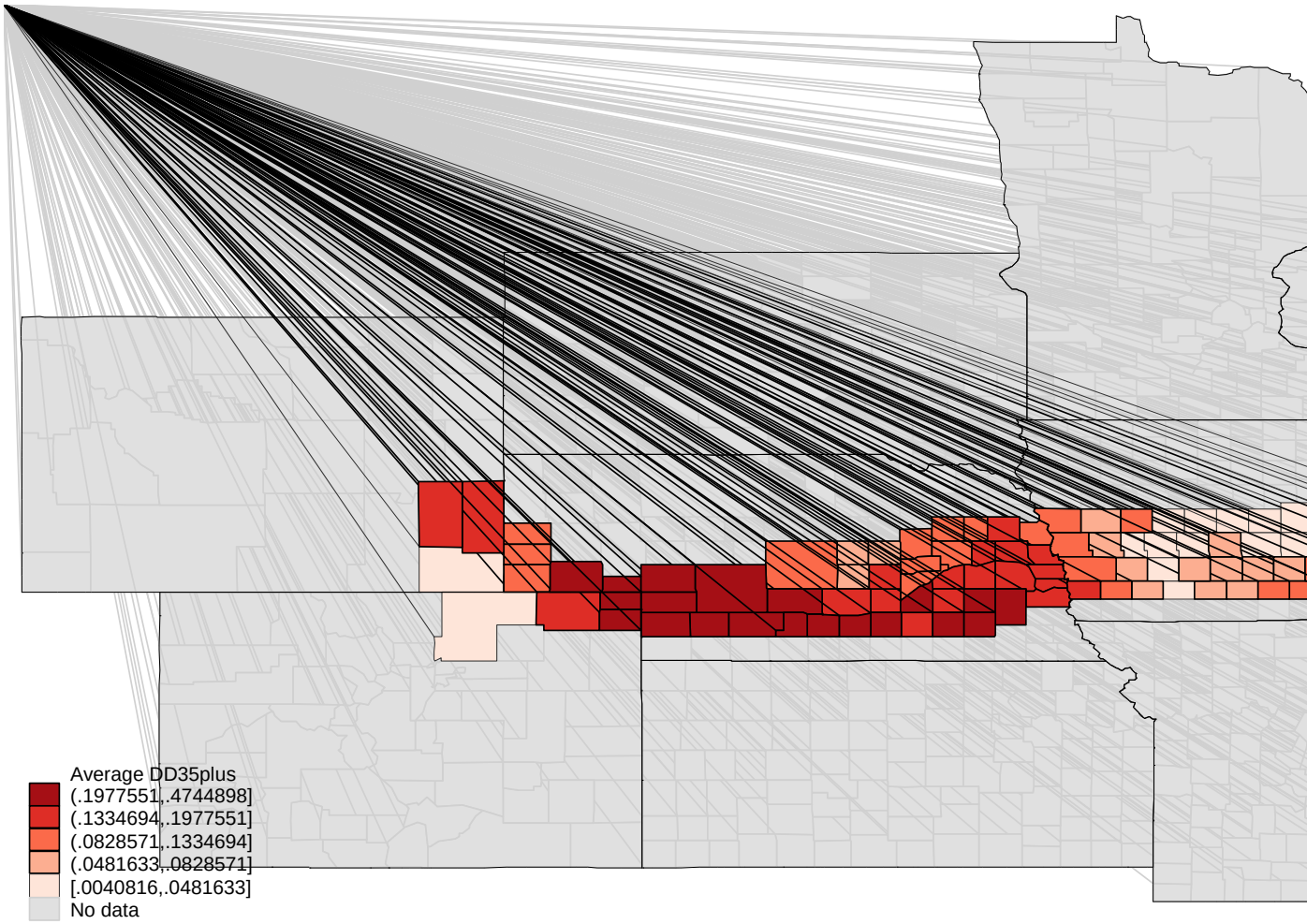

Figure 7 Average number of degree days above 35ºC during the growing season in study counties, 1960-2008

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 west to east. Region 1, in the west, received an average of 29.8 cm, while region 5, in eastern Iowa, the average precipitation was almost twice that much, 57.5 cm.

Finally, exogenous innovations or technical change are captured by a quadratic time trend with 1960=1.

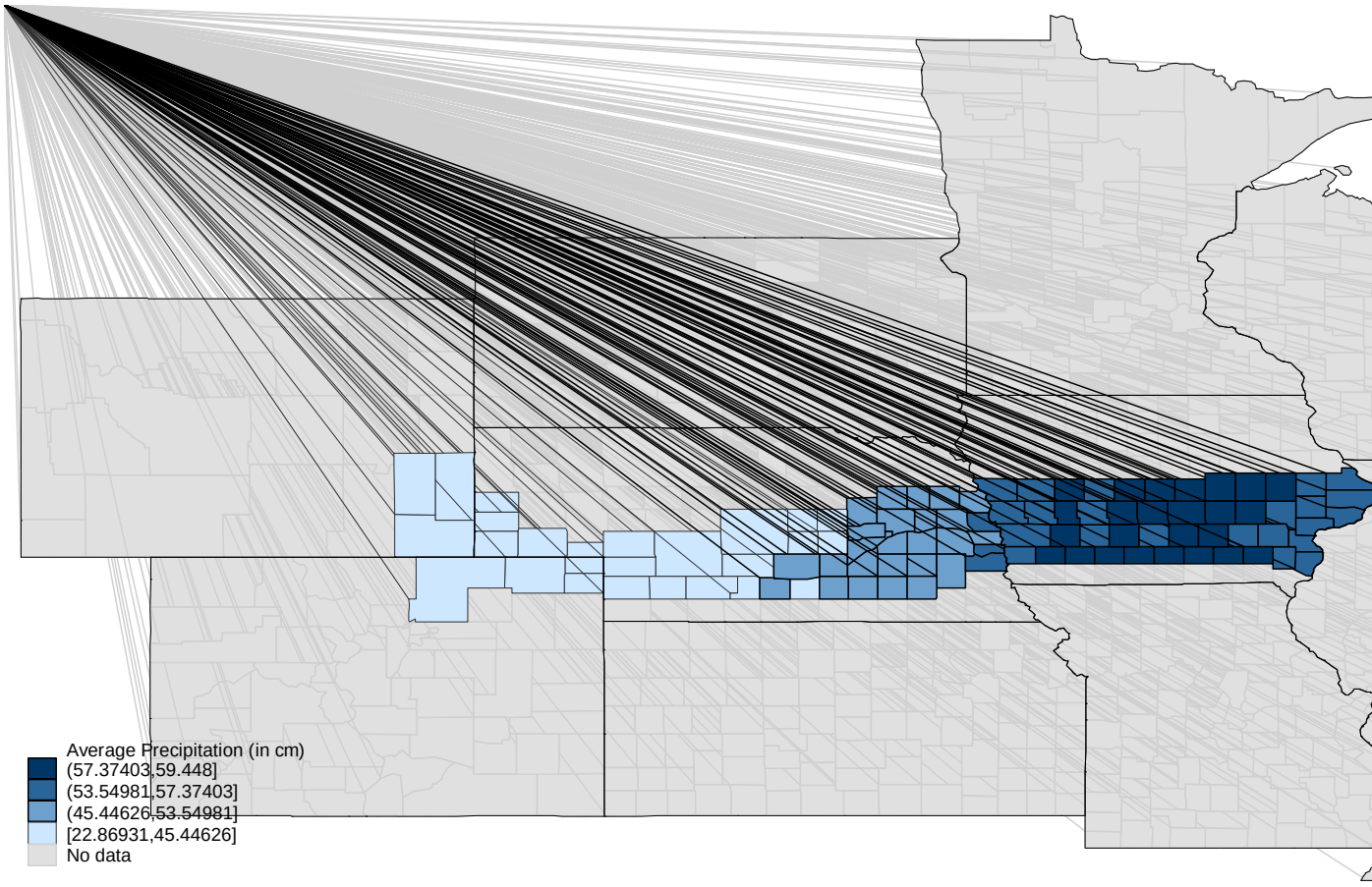

Figure 8. Average growing season precipitation (cm) in study counties, 1960-2008

Results and discussion

We estimated the parameters in the system of equations (7) using Iterated 3-Stage Least Squares. Twenty-four of the twenty-eight parameters estimated are significantly different from zero. A Wald test rejects the nested Cobb-Douglas as a better specification (details of this and other estimation issues are described in the Supplementary Material). Parameter estimates are in Appendix A.

We used the parameter estimates to identify the marginal contributions from factor intensification, irrigation, weather and innovations to biomass yield 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, are reported in Table 2.

Table 2. Estimated transect-wide marginal effects of variables on biomass yield

Variable	type of response	Value	Percentage of obs. signif.*
Fertilizer, quantity index	elasticity	0.111	99.8%
Chemicals, quantity index	elasticity	0.058	99.8%
Irrigation ratio, 0-1	semi-elasticity	0.683	99.4%
Time trend, years	semi-elasticity	0.0066	99.9%
Soil organic matter, Mg/ha	elasticity	0.076	87.4%
DD0030, days	semi-elasticity	0.0031	85.5%
DD3035, days	semi-elasticity	-0.0177	85.3%
DD35plus, days	semi-elasticity	-0.306	88.3%
Precipitation, cm	elasticity	-0.075	80.4%

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

The estimated production elasticity of fertilizer (0.111) 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 (0.683) implies that overall, conversion from rainfed to irrigated land doubles biomass yield[6], but a little more in the central subregions where most conversion to irrigation took place. Part of this benefit of irrigation is achieved by reducing the impact of high temperatures, as indicated by the impact of irrigation on the DD35plus semi-elasticity.

Soil organic matter has been declining since cultivation began on these prairie soils. The average marginal elasticity is 0.076, significantly different from zero at the 5% level. Calculated regional SOM elasticities ranged from 0.015 in the west to 0.134 in the east.

On average, an extra 24 hours (one day) of temperatures above 35°C decreased yields by 26.38%, while the marginal effect of a day between 30°C and 35°C would decrease them by only 1.8%, an important nonlinear effect that supports similar estimates in the literature. In the east, these semi-elasticities rise to 36% and 2.3%, while in region 3 where irrigation is most prevalent they fall to 14.4% and 0.5%. On average across the region, sensitivity to temperatures above 35°C decreased over the period from 31.6% to 29.3% , but in region 3 it declined from 29.5% to 12.7%, all due to increased irrigation. This declining sensitivity to hot weather is somewhat contrary to findings of Lobell, et al (2014), who found that for Iowa, Illinois and Indiana, maize yields (virtually all unirrigated) were becoming more sensitive to vapor pressure deficit during 1995-2012.

A marginal increase of 2.5 cm (1 inch) of precipitation along this transect would on average *decrease* yields slightly[7], by 0.4%. This average response again masks

[6] The relative change in yield is calculated as exp (0.683) = 1.98.

[7] This somewhat surprising result is completely consistent with previous studies by Schlenker and Roberts (2009) whose study of crops east of the 100th longitude (the middle of our transect) revealed optimum

geographical and temporal variations. Evaluated for average conditions in the far west (region 1), an additional inch would increase yields on average by only 1.72% (irrigation buffers yields against drought), while in the far east (region 5), an additional inch would decrease yields by -0.72%. During the wettest decade (the 90s) the region-wide response to an additional inch was -0.57%, while during the driest decade (the 70s) the response was -0.26%. Clearly the concavity of these responses is mild – marginal contributions of precipitation evaluated across the data set are relatively minor.

The estimated residual time trend, our proxy for unidentified, nonspecific technical change, increased yield by an average of 0.66% per year. We intend this variable to capture the marginal effects of new varieties, the quality and quantity of machinery and labor, the improvements in management and similar variables for which we have no data available at the level of county agriculture. The negative coefficient estimate for the variable time squared indicates that, ceteris paribus, this rate of improvement declined over the time period. However, when evaluated at the average values of all variables, the estimated rate of increase was 0.57% per year during the first decade, compared to 0.70% in the 90's and 0.72% per year in the final period, indicating a continuously increasing rate of yield growth due to non-specific technological change, at least through the 2000-08 "decade".

Contributions of factors to yield growth during 1960-2008.

precipitation of 25" for corn and 27" for soybeans. Results are also consistent with Irwin, whose estimates for corn in Iowa, Illinois and Indiana indicated optimum monthly precipitation were close to the average levels.

We use our estimates of regional and transect-level elasticities and semi-elasticities to decompose the observed yield growth, 1960-2008, into contributions of changes in the variables in our analysis: intensification, irrigation, soil organic matter, weather and nonspecific technical change (15).

Estimated 1960-2008 contributions to yield growth of inputs under farmers' control are shown by region in Figure 9, with their contributions by decade shown in Figure 10[8]. Increases in irrigation over this period in regions 1, 2, and 3 contributed to increases of 23-38% in these regions but contributed very little to yield growth in other regions because irrigated areas were stationary or non-existent. Averaged across the **41st ||** transect, irrigation contributed a yield increase of about 12%. Most of these increases in irrigation occurred during the first three decades, as indicated in Fig. 10.

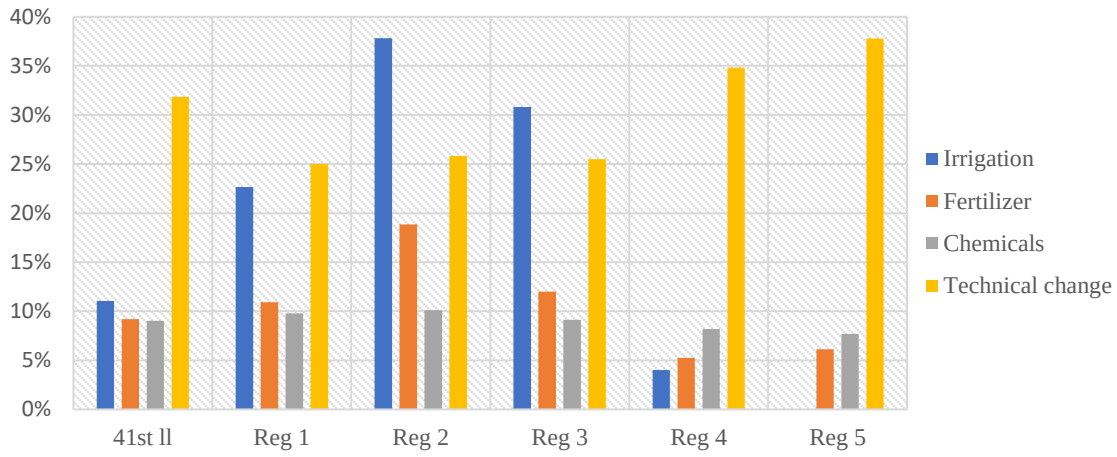

Fig. 9 . Farmer-controlled contributors to yield increases across regions along the 41st ||, 1960-2008

[8] We use the average production elasticity or semi-elasticity between two consecutive decades, multiplied by the percentage change in the corresponding variable between the same two decades to obtain the impact of that variable on decadal yield changes. These changes in yields then are associated with changes in intensification, in irrigation, in weather and other innovations as shown in equation (6).

Intensification in the form of higher input use per hectare contributed to a yield increase of about 18% across the **41st ||** transect, evenly contributed by increased application rates of fertilizers and chemicals, with most of this occurring during the 1960s and 1970s. The fertilizer contribution occurred almost exclusively during the 60s, while chemical contributions continued throughout the 1960-2008 period. Regions 1, 2 and 3 show higher contributions of more intense use of these inputs, consistent with the increased production in these regions due to the increases in irrigation.

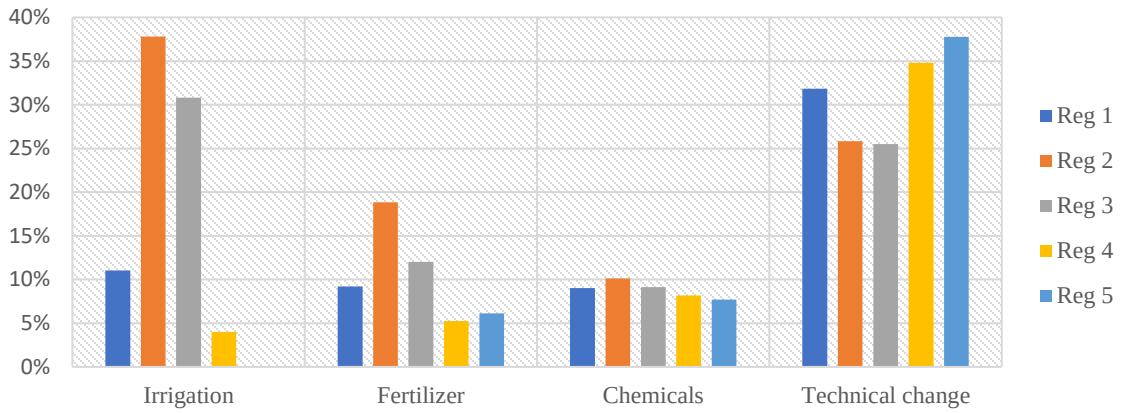

Fig. 10. Farmer-controlled contributors to yield increases across the 41st parallel, by decade, 1960-2008.

Non-specific technological change contributed more to yield change across the transect (32%) than any other factor we measured. The quadratic specification revealed an inverted-U shape for these non-specific technical changes through time, but taking into account other variables, the contributions did not actually decline across periods (the last period is shorter than the others, and the average annual contribution in the final "decade", 0.72%, is higher than the previous decade average of 0.70%). Technological change contributed more to the yield gains in the two eastern subregions, 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, Anderson, et al. (2018) document declining rates of overall farm productivity that they surmise may be related to declines in R&D spending. Thus, the future path of this non-specific technical change remains a crucial issue that we do not explore further in this study.

At the aggregate level across the 41st || transect, weather as we have measured it has made no significant contributions to 1960-2008 yield changes (see the open circles in Figure 11). However, this outcome masks significant positive contributions of precipitation in regions 1 and 3 (3-4% increases) that were offset by the negative contribution (-4%) of precipitation in region 5, where it was just too wet during the last decade. The aggregate outcome also masks some significant temperature contributions through time (note the open circles in Figure 12), where an increase in 35°C+ days in the 70s contributed a 7% decrease in transect average yield, only to have that offset by a 7% yield reduction due to a decrease in such days in the 80s. Note that this pattern of temperature contributions was more dramatic in regions 4 and 5, where negative contributions of 10-14% in the 70's were nullified by 9-17% increases in the 80's. An important insight here for examining the impacts of weather is that aggregate data tend not to reveal the impacts of changes in weather because the very real impacts at local levels tend to be canceled out in the

aggregate data. But analysis of aggregate relationships using local data, as we have done here, reveals the marginal responses to local weather and the aggregate responses as well.

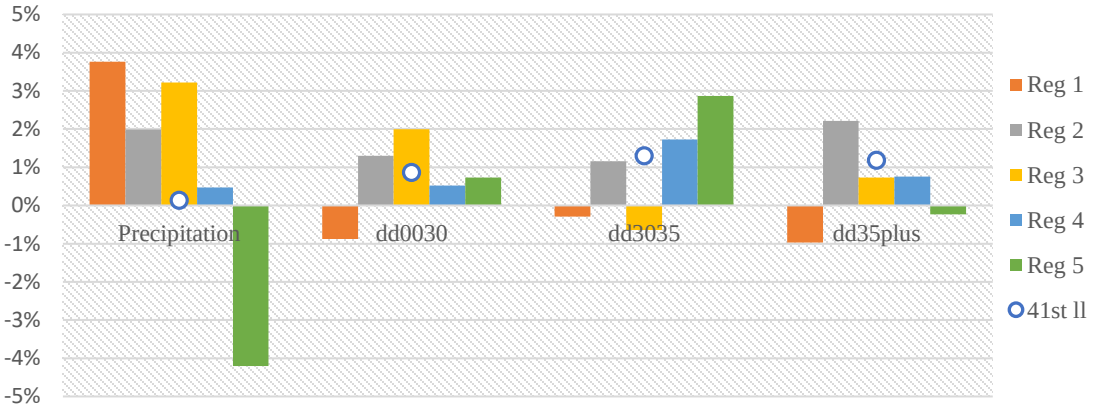

Figure 11. Climatic contributors to yield increases across regions along the 41st ||, 1960-2008.

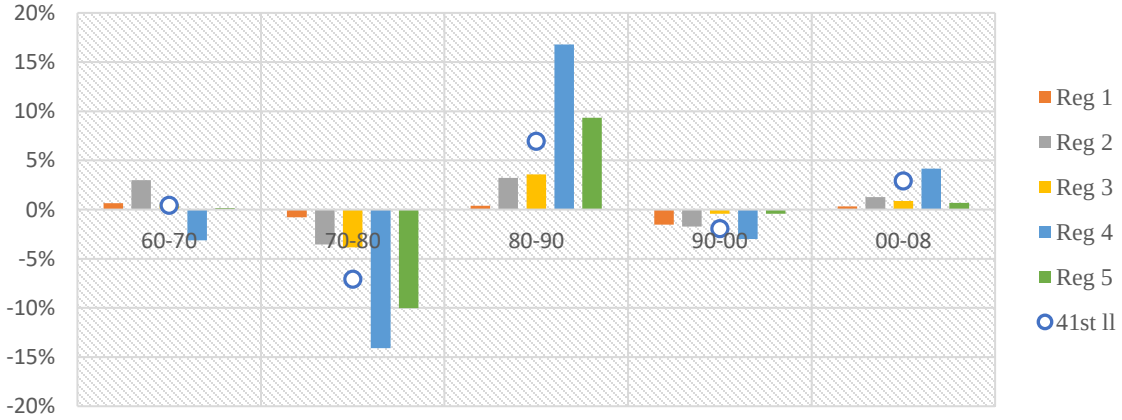

Figure 12. Contributions of temperatures above 35°C to yield increases across regions, along the 41st ||, by decade 1960-2008 .

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, the total contribution to yields was small – a reduction of 1%. In the east SOM reductions decreased yields by about 1.5% in region 4 and 2.8% in region 5, whereas contributions in the western three regions were well under 1%. While losses of soil organic matter through time were small, differences

in SOM levels of 178 Mg/ha in the east vs 88 Mg/ha in the west account for a yield difference of as much as 15%.

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 decade-average yield changes are these: non-specific technical change +32%, irrigation +11%, fertilizer and chemicals +9% each, less time with temperatures over 30°C +2.5%, change in precipitation +0.1% and loss of soil organic matter -1.1%, explaining the 60% biomass yield changes in this period.

We found important departures from those relative contributions across the five regions we examined. In the western regions, irrigation contributed the most to yield gain, 23-38%, while technical change contributed only about 25%. In the eastern regions the contribution of technical change was higher, about 36%, while irrigation contributed nothing. Losses of soil organic matter through time were small at -1.1%, but ranged by region from essentially zero in the western regions to -2.8% in the easternmost region. Furthermore, regional differences in SOM levels of 176 Mg/ha in the east vs 57 Mg/ha in the west account for a yield difference of about 15%.

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 1960-1990. Increases in the time exposed to high temperatures reduced yield growth during the 1970s but those results were completely offset by increased yield growth due to fewer high temperature days in the 80's.

The dramatic yield increases along this transect of the **41st ||** were almost entirely attributable to human 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 average yields by 75% or more in the central subregions, but increased the average yield for the transect by only about 11% because of the lack of response to irrigation in the east. Contributions of additional intensification have been substantial, but in recent decades dwindled in all subregions to less than one-tenth of a percent yield increase per year from fertilizer and less than two-tenths from chemicals.

Non-specific technological change contributed more to yield gains than any other factor we were able to measure, but the negative estimate of the quadratic term suggests that the contribution of unidentified exogenous technological change is declining through time. However, when the rate of technical change is evaluated at current levels of other variables, the average rate for 2000-2008 is 0.72% per year, compared to 0.70% per year for the 1990s, indicating that the yield growth rate from non-specific technological change has continued to climb at least through mid 2000-08.

The lack of environmental contributions to yield growth along this **41st||** transect is not to say that weather and precipitation had no marginal impacts: precipitation

responses *were* small, but temperature responses were quite large. The lack of contributions to yield growth during the period is because these weather variables did not change much between the first and last decades of the study. It is notable, however, that the sensitivity of biomass yield to high temperatures *increases* from the west where the response elasticity is -.09, to the east where it is -.46, and that the transect-wide elasticity *decreased* from -.35 in the 1960's to -.27 in the 2000's. 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 suggest that the periods of hot weather might increase by 10% in this area, which would decrease yields by 3%. It is instructive to note that this decrease, however, is somewhat less than the increase in yields predicted from the CO_2 fertilization effect suggested by experimental data. Projections of precipitation change along this 41st || transect are roughly neutral, but a decrease of 10% would decrease yields by only about 2% in the west, while actually increasing yields in the east by 1-2%.

The potential for additional irrigation is minimal, given concerns about the sustainability of groundwater supplies, and for both environmental and economic reasons there is little prospect that fertilizer and chemical applications will increase. But our results indicate that the yield growth rate from non-specific technological change continued to climb, at least through 2000-08, along this transect. This and other considerations in this paragraph indicate reasonable prospects for continued yield growth along this important food-producing transect, even in the presence of climate change.

References

Ball, V. E. 1985. "Output, Input, and Productivity Measurement in US Agriculture 1948–79." *American Journal of Agricultural Economics*, *67*(3), 475-486.

Chambers, R. G. 1988. *Applied production analysis: a dual approach*. Cambridge University Press.

Griliches, Z. 1964. "Research Expenditures, Education, and the Aggregate Agricultural Production Function." *The American Economic Review*, 961-974.

Hay, R. K. M. 1995. "Harvest index: a review of its use in plant breeding and crop physiology." *Applied Biology*, 126, 197-216.

Hayami, Y. and Ruttan, V. W. 1970. "Agricultural productivity differences among countries." *The American Economic Review*, 895-911.

Hsiang, S., Kopp, R., Jina, A., Rising, J., Delgado, M., Mohan, S. Rasmussen, D. J., Muir-Wood, R., Wilson, P., Oppenheimer, M. and Larsen, K. 2017. Estimating economic damage from climate change in the United States. Science, 356(6345), 1362-1369.

Jacobs, R., Smith, P. C. and Street, A. 2006. *Measuring efficiency in health care: analytic techniques and health policy*. Cambridge University Press.

Lakoh, K. 2012. "Three Essays on Renewable Energy" PhD dissertation, University of Nebraska, Lincoln.

Liska, A. J., Yang, H., Milner, M., Goddard, S. M., Blanco, H., Pelton, M. P., Fang, X. X., Zhu, H. and Suyker, A. 2014. "Biofuels from Crop Residue Can Reduce Soil Carbon and Increase CO2 Emissions." *Nature Climate Change*, 4(May), 398-401.

Lobell, D, M Roberts, W. Schlenker, N Braun, B Little, R Rejesus and G Hammer. 2014. Greater Sensitivity to Drought Accompanies Maize Yield Increase in the U.S. Midwest. *Science*, 344: 516-519.

Loomis, R. S. and Connor, D. J. 1992. *Crop ecology: productivity and management in agricultural systems*. Cambridge University Press.

Prince, Stephen D., Jonathan Haskett, Marc Steininger, Holly Strand, and Robb Wright. 2001. Net Primary Production of U.S. Midwest Croplands from Agricultural Hrvest Yield Data. *Ecological Applications* 11(4):1194-1205.

Ray, S. C. 1982. "A translog cost function analysis of US agriculture, 1939–77. *American Journal of Agricultural Economics*, *64*(3), 490-498.

Ritchie, J.T. and Nesmith, D. S., 1991. "Temperature and Crop Development." In Hanks and Ritchie (ed.) *Modeling plant and soil systems*. *Agronomy. Monograph*. 31, ASA, CSSSA, SSSA, Madison, WI.

Roberts, M. J., Schlenker, W. and Eyer, J. 2012. "Agronomic weather measures in econometric models of crop yield with implications for climate change." *American Journal of Agricultural Economics*, 95(2), 236-243.

Saha A., Shumway, C. and Havenner A. 1997. "Econometrics of Damage Control." *American Journal of Agricultural Economics,* 79 (3) pp: 773-785.

Schlenker, W. and Roberts, M. 2009. "Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change." *Proceedings of the National Academy of Sciences*, September 15, 2009, vol. 106, p 15594-15598.

Snyder, R.L. 1985. "Hand calculating degree-days." *Agricultural & Forest Meteorology*, 35(1), 353-358.

United States Historical Climatology Network, CDIAC, Carbon Dioxide Information Analysis Center. http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn.html (Last accessed December 2012)

USDA National Agricultural Statistics Service - Quick Stats. http://www.nass.usda.gov/QuickStats/ (Last accessed May 2011).

USDA National Agricultural Statistics Service – Agricultural Census. http://www.agcensus.usda.gov/Publications/Historical_Publications/index.php (Last accessed August 2012).

USDA National Agricultural Statistics Service – Table 23 Price indices and implicit quantities of farm outputs and inputs by State, 1960-2004 https://www.ers.usda.gov/data-products/agricultural-productivity-in-the-us/ (Last accessed May 2019).

USDA United States Department of Agriculture, Economic Research Service (ERS), 2017, Summary of recent findings: https://www.ers.usda.gov/data-products/agricultural-productivity-in-the-us/summary-of-recent-findings/ (Last accessed Aug 2018)

USDA Economic Research Service. Fertilizer Price Indexes. http://www.ers.usda.gov/data-products/fertilizer-use-and-price.aspx#26727 (Last accessed May 2019).

Unkovich, M., Baldock, J. and Forbes, M. 2010. "Variability in harvest index of grain crops and potential significance for carbon accounting: examples from Australian agriculture." *Advances in Agronomy*, *105*, 173-219.

Appendix A. Data statistics and estimation.

Table A.1 - Parameters Estimated Using Three-stage Least-Squares Iterated Regression. Study Counties along the 41st Parallel North in Iowa, Nebraska, Colorado and Wyoming, 1960-2008.

Equation	Observations	Parameters	RMSE	R-sq	P
lny	4949	32	0.185017	0.7226	0.0000
sharefert	4949	4	0.0290134	0.3705	0.0000
sharechem	4949	4	0.0161621	0.6046	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	1.8640	0.4905	3.8000	0.0000
ln(Fertilizer)	0.0821	0.0009	94.0600	0.0000
ln(Chemicals)	0.0176	0.0005	34.5900	0.0000
ln(Precipitation)	2.6225	0.5251	4.9900	0.0000
ln(SOM)	0.1343	0.0163	8.2200	0.0000
0.5*Irrigation_sq	0.1795	0.1354	1.3300	0.1850
0.5*ln(Fertilizer)_sq	0.0351	0.0019	18.9200	0.0000
0.5*ln(Chemicals)_sq	0.0246	0.0012	21.2900	0.0000
0.5*ln(Precipitation)_sq	-0.5756	0.0587	-9.8100	0.0000
Irrigation_ln(Fertilizer)	0.0107	0.0022	4.8200	0.0000
Irrigation_ln(Chemicals)	-0.0123	0.0011	-10.6800	0.0000
Irrigation_ln(Precipitation)	-0.0225	0.0531	-0.4200	0.6720
Irrigation_ln(SOM)	-0.2992	0.0471	-6.3600	0.0000
ln(Fertilizer)_ln(Chemicals)	-0.0144	0.0013	-11.2400	0.0000
dd0029	0.0142	0.0129	1.1000	0.2710
dd3035	-0.0897	0.0310	-2.8900	0.0040
dd3640	0.8394	0.2928	2.8700	0.0040
dd0029_Irrigation	0.0012	0.0024	0.4900	0.6270
dd3035_Irrigation	0.0479	0.0073	6.5400	0.0000
dd3640_Irrigation	0.5316	0.0857	6.2000	0.0000
dd0029_Precipitation	-0.0029	0.0032	-0.9100	0.3620
dd3035_Precipitation	0.0161	0.0079	2.0400	0.0410
dd3640_Precipitation	-0.3213	0.0785	-4.1000	0.0000
Time	0.0055	0.0010	5.7200	0.0000
Time_sq	0.0000	0.0000	0.4800	0.6310
Irrigation_Time	-0.0048	0.0010	-5.0500	0.0000
ln(fertilizer)_Time	0.0008	0.0000	15.8000	0.0000
ln(Chemical)_Time	0.0005	0.0000	13.5800	0.0000
Region 2 dummy	-0.0378	0.0157	-2.4200	0.0160
Region 3 dummy	-0.0369	0.0180	-2.0500	0.0400
Region 4 dummy	0.1779	0.0229	7.7700	0.0000
Region 5 dummy	0.1386	0.0255	5.4400	0.0000
Constant	-5.2863	2.0783	-2.5400	0.0110

Supplementary materials

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 year 1960, converting them to a multilateral index with base level being the per hectare application in Adams County, 1960.

Irrigation

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. We do not have data on the actual amount of water applied from irrigation or from the irrigation technology used (center pivot, canal, etc.).

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:

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

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.[9]

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

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, *dd35plus,* 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.