An Econometric Analysis of U.S. Crop Yield and Cropland Acreage: Implications for the Impact of Climate Change

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Introduction

There is growing demands on land to meet not only the needs for food and feed but also biofuels. The Energy Information and Security Act (2007) has mandated that 15 billion gallons of corn ethanol be produced by 2015; this would require about a third of corn produced in the US to be diverted to biofuel production. At the same time, there are concerns about the impact of climate change on agriculture and there has been considerable research examining the impact of climate variables on US crop yields and suitability of land for crop production (Adams et al. 1990). Studies differ in the extent and direction of the impact of climate change on agriculture with Deschenes and Greenstone (2007) showing that US agriculture will benefit from climate change and Schlenker et al. (2006) showing otherwise. The extent to which crop yields can be expected to grow in the future both in response to improved crop production technology as well as in response to higher food prices and the extent to which crop acreage can be expected to change both on the intensive and extensive margins in response to prices will be critical in determining the extent of the competition for land between food and fuel in the US. It will also influence the extent to which expanding biofuel production in the US will lead to indirect land use changes in other parts of the world. The latter arises as higher food prices (due to biofuel production) lead to conversion of non-cropland to cropland in other countries and cause emissions of carbon stocks stored in vegetation, contributing to climate change. Keeney and Hertel (2009) show that yield and acreage responses are critical in predicting indirect land use change arising from large scale biofuel production.

Early studies have sought to estimate the effect of crop prices on corn yields for the pre-1990 period (Houck and Gallagher, 1976; Menz and Pardey, 1983; Choi and Helmberger, 1993). More recent studies on crop yields include climate variables but in general ignore the effect of input and output prices (Lobell and Asner, 2003; Schlenker and Roberts, 2006; Deschenes and Greenstone, 2007; McCarl et al., 2008). Similarly, existing estimates of acreage response are either based on data prior to 1994 (Abler, 2001) or limited to a specific region with no consideration of the climate influence (Lin and Dismukes, 2007).

The purpose of this paper is to undertake a more comprehensive analysis of the impact of climate variables, technology and crop prices on crop yield and on crop acreage in the US using county-specific, historical data for 1977-2007. Specifically, we estimate the yield responses of corn, soybeans and wheat to output prices and to changes in climate and technology over time. We use instrumental variable regression methods to control for endogeneity of prices and county specific fixed effects to control for unobserved location specific effects on yield. We also examine the price responsiveness of total cropland and the own and cross-price elasticities of crop-specific acreage while controlling for climate and other socio-economic factors. Since our empirical framework includes lagged dependent variables and endogenous variables such as crop price, we use the dynamic panel GMM estimation method. We explore the implication of future climate change as projected by the Intergovernmental Panel on Climate Change (IPCC) (2001) for crop yields based on our estimated coefficients on climate variables. The main contributions of this study are to examine the impact of climate variables on crop yield and acreage while controlling for a number of other variables using panel data methods. We also provide updated estimates of various price elasticites and productivity growth trends that are critical to examining the extent to which rising crop yields can mitigate the food vs fuel competition for land and the extensive and intensive margin changes likely as crop prices increase.

Literature review

Early studies focused primarily on yield effects of precipitation, temperature and technological progress with findings suggesting a positive relationship between crop yields and precipitation and a negative relationship between yields and temperature (Oury 1965). Some early studies also argued for the use of less geographically aggregated meteorological data since the relationships between crop yields and climate factors are not monotonic and hence such causal relationships may be nullified when yield and climate variables are averaged at higher levels of spatial aggregation (Shaw 1964).

Recent concerns about the potentially harmful impact of climate change on agricultural production have led to several empirical studies with mixed findings regarding the effects of temperature, growing season degree days and precipitation on crop yields (e.g., Lobell and Asner, 2003; Deschenes and Greenstone, 2007; Kucharik and Serbin, 2008; McCarl et al., 2008; Lobell et al., 2008; Schlenker and Roberts, 2009). By regressing changes in U.S. county-level corn and soybean yields on changes in temperature and a constant for the period 1982-98, Lobell and Asner (2003) conclude that a one degree increase in growing season temperature leads to about 17% decrease in both corn and soybean yields. Using U.S. county-level panel data and a fixed effects model for the periods1987, 1992, 1997 and 2002, Deschenes and Greenstone (2007) find that the impact of growing degree days (GDD) on corn and soybean yields are consistently negative and non-linear. Using county-level data for Wisconsin for 1976-2006 Kucharik and Serbin (2008) find that a one degree increase in temperature during the summer months could reduce corn and soybean yields by 13% and 16%, respectively. More recently, using an extensive 1950-2005 county level panel for the Eastern U.S. and fixed-effects models, Schlenker and Roberts (2009) find that the effect of temperature on U.S. crop yields is nonlinear and negative with a threshold level of 29^{o} C for corn and 30^{o} C for soybeans. They also project that a warmer climate can severely reduce crop yields by 30-82% depending on the speed of global warming by the end of the century.

While most empirical studies are in general agreement that warmer climate can be harmful to crops in the US, McCarl et al. (2008) estimate a fixed-effects model for the U.S.with state level crop yields from 1960 to 2007 and find that higher temperatures have a positive and statistically significant impact on soybean yields but no significant impact on other crops. Lobell et al. (2008) use aggregate data for major regions of the world from 1961-2002 and find that the percentage changes in crop yields can vary between -21% and +8.7% across crops and regions. Similar mixed findings also exist in the literature with regard to the effect of precipitation. Deschenes and Greenstone (2007) and Kucharik and Serbin (2008) find that an increase in precipitation is beneficial for crop and soybean yields while McCarl et al. (2008) suggest that increased precipitation can be harmful for wheat yield, beneficial for cotton yield but have no significant impact on corn, sorghum, or soybean yield.

These studies differ in their scope, in the data they use and in their econometric methods. They also differ in the way they measure the climate variables, in the level of disaggregation of data and the size of the panel data included. For instance, Deschenes and Greenstone (2007), Lobell et al. (2008), and McCarl et al. (2008) use either growing season precipitation or yearly precipitation in their crop yield analysis and do not consider the effects of timing of precipitation. Deschenes and Greenstone (2007) use county-level panel data for the period 1987-2002 but include every fifth year only (1987, 1992, 1997 and 2002). McCarl et al. (2008) use a panel data approach with a time dimension from 1960 to 2007 but their cross-sectional units are U.S. states. Lobell et al. (2008) use time-series data for 1961-2002 but only at the regional level. Schlenker and Roberts (2009) use U.S. county level panel data and control for cross sectional fixed effects and spatial correlation in error terms but their precipitation variables are measured as the growing season total.

Most of the climate and crop yield studies (such as Deschenes and Greenstone, 2007; Lobell et al., 2008; McCarl et al., 2008; Schlenker and Roberts, 2009) also exclude other factors that can also affect crop yields such as crop price and input prices. As noted by Schlenker and Roberts (2009) this can result in biased estimates of the effects of climate variables, since crop and production input prices can be correlated with climate. Several econometric studies provide evidence of the responsiveness of crop yields to prices (Houck and Gallagher 1976; Menz and Pardey 1983; Choi and Helmberger 1993; Kaufmann and Snell 1997). Houck and Gallagher (1976) examine the effect of corn and fertilizer prices on U.S. average corn yields using time series data for 1951-71. Using a model similar to that in Houck and Gallagher (1976) but longer time series for 1951-80, Menz and Pardey (1983) find that the significant response of corn yield to prices for period 1951- 71cannot be extended to the period 1972-80. Choi and Helmberger (1993) investigate the responsiveness of corn, soybean and wheat yields to crop prices and fertilizer application rate using time series for 1964-88 and a two-stage recursive regression model by first estimating the fertilizer use equation and then the crop yield equation. Kaufmann and Snell (1997) include in their corn response model the Commodity Credit Corporation (CCC) loan rate relative to the previous year's corn price in addition to a set of climate variables. Using ordinary least squares and county-level pooled cross-sectional data obtained from the Census of Agriculture for 78 Midwestern counties and for 1969, 1974, 1978, 1982, and 1987, they find that the CCC loan rate relative to previous year's corn price has a significant positive impact on yield. In general the existing literature shows that output prices have a positive effect on crop yields (see Table 4 for a summary of the estimated yield elasticities in the literature and review in Keeney and Hertel, 2009).

Crop yields are expected to increase over time because of technological advances such as the adoption of new varieties, greater application of fertilizers and irrigation, and expansion or contraction of crop acreage. Technological progress is usually represented by a linear or quadratic time trend in empirical studies (e.g., Choi and Helmberger, 1993; Kaufmann and Schnell, 1997; McCarl et al., 2008). Crop yields are found to increase with time though the estimated magnitude of the time effect differs across studies (see Table 4 for more details). It is worth noting that empirical studies show mixed results regarding the effect of crop acreage on yield. Houck and Gallagher (1976) and Kaufmann and Snell (1997) both find that an increase in corn acreage decreases yield, while McCarl et al. (2008) find that an increase in crop acreage increases corn, soybean, wheat, and sorghum yield but decreases cotton yield. The yield effect of crop land use change together with other technological effects dominates the influence of other factors in determining the long-term yield trends (Lobell et al., 2008).

There is a general paucity of empirical research on how crop acreages respond to climate change. Acreage response studies have typically ignored climate factors and used geographically aggregated time series data to represent the behavior of a representative farmer (Chavas and Holt, 1990). Nerlove (1956) shows that farmers' expectations of future prices shape their crop acreage decisions and the Nerlovian adaptive price expectations model has become a useful tool for the estimation of agricultural supply functions (see Askari and Cummings, 1977 for a comprehensive review of early applications of the Nerlovian model; and Tegene et al., 1988 for more recent development of the model). The model leads to a reduced form with acreage in a given year expressed as a function of one-year lagged crop price and one and two-year lagged crop acreages (Braulke, 1982). Others studies have proposed a modified adaptive expectations model that not only includes price expectations but also incorporates the effect of observed deviations of yield from its normal value (Nowshirvani, 1971). More recent studies derived from farmer's expected utility maximization behavior suggest that crop yield risk and price risk, measured by deviations in crop yields and prices from their average values, can also impact crop acreage since they affect the anticipated profit from crop production (Chavas and Holt, 1990; Lin and Dismukes, 2007). Estimating their expected-utility-maximization-derived corn and soybean acreage equations using seemingly unrelated regression methods and aggregate time series data for 1954-85, Chavas and Holt (1990) find that these risk effects on corn and soybean acreage are real though small and crop-specific. Lin and Dismukes (2007) update the Chavas-Holt study with the inclusion of lagged dependent variable and the use of state-level data for the U.S. North Central states for 1991-2001 and find similar results.

Crop acreages are also expected to be influenced by relative rents, proxied by own and substitute crop prices, and by the prices of production inputs such as fertilizers as well as by land characteristics, population growth and climate variables (Tegene et al., 1988; Miller and Plantinga, 1999; Lubowski et al., 2008). These studies show that the acreage of a crop responds positively to its own price and negatively to the price of other crops (see Abler (2001) and Table 4 for detailed estimated acreage elasticities in the literature).

Determinants of Crop yields

Following Choi and Helmberger (1993), a price-taking farmer is assumed to maximize expected profit as below:

$$E_t(\pi_{t+1}) = E_t(P_{t+1})E_t(Y_{t+1} \mid A_t , F_t , W_{t+1})\, A_t - R_t A_t - V_t F_t A_t - TFC \qquad (1)$$

where E is the expectation operator, π is profit, P is crop price, Y is crop yield, A is planted acres, F is the application rate of fertilizer per acre, W is production conditions including climate, soil quality, technological change, etc, R is non-fertilizer cost per acre, V is fertilizer price, TFC is total fixed cost of crop production, and the subscript t is time period. Assuming that Y is decreasing in A but increasing in F, optimization of the expected profits yields the farmer's demand functions for A and F (as in Choi and Helmberger, 1993):

$$A_t = a[R_t, V_t, E(P_{t+1}), E(W_{t+1})] \qquad (2)$$

$$F_t = f[R_t, V_t, E(P_{t+1}) , E(W_{t+1})] \qquad (3)$$

Given the physical relationship for yield:

$$Y_{t+1} = y[A_t, F_t, W_{t+1}] \qquad (4)$$

substituting equations (2) and (3) into (4) suggests that crop yields can be expressed as a function of climate variables, expected crop prices and production input prices. Thus, we specify county-specific yields per acre in county i and year t as a function of climate, prices, technology and land quality, while controlling for other county characteristics through county fixed effects. A general form of a crop yield model using a county level panel data set can be written as:

$$Yield_{it} = f(Climate_{it}, Prices_{i,t-1}, Technology_{it}, Land\ Quality_{it}) + \alpha_i + \varepsilon_{it} \qquad (5)$$

where $Climate_{it}$, $Price_{i,t-1}$, $Technology_{it}$, and $Land\ Quality_{it}$ are independent variable sets representing climate conditions, economic environment, technical progress, and farm land use changes, respectively; i and t are county and time period identifications of the panel data set; and α_i is a county fixed effect and ε_{it} is the error term. Specifically, *Climate* variables include monthly mean precipitation and their squared terms, growing season degree days, and monthly deviation in temperature (maximum – minimum temperature) to control for variability in temperature. *Prices* include a fertilizer price index and lagged crop price. *Technology* variables include the percent of irrigated crop acres, time trends and their squared terms to capture technical progress. Since the crop yield variable is an average for the county, this average is likely to be affected by changes in cropping practices and *land quality*. Expansion of corn production on land previously under other crops is likely to affect average corn yields differently than expansion of land at the extensive margin (on previously idle/non-cropland acres). We capture these effects by constructing two variables; Substitute crop acreage, defined as the minimum of the increase in acreage of a crop (relative to previous year) and the decrease in aggregate acreage of all other crops; and marginal acreage, defined as the difference between the increase in acreage of the crop (relative to previous year) and its own substitute acreage if the difference is positive and zero otherwise. Soil quality variables are not included directly since they are time invariant and hence cannot be distinguished from region-specific effects. This general form of the crop yield model is further specified with minor variations for corn, soybean and wheat yield estimations. We use a linear functional form for the yield model (as in Houck and Gallagher, 1976; Choi and Helmberger, 1993; Kaufmann and Snell, 1997; Deschenes and Greenstone, 2007; McCarl et al, 2008) and examine the validity of a quadratic nonlinear relationship between crop yield and climate and technological change.

To estimate the yield model, a panel data instrumental variable (IV) estimator with county fixed effect is used while correcting for heteroskedasticity. The fixed-effect IV approach is important since explanatory variables such as the share of irrigated acres, substitute and marginal acres, expected crop prices (lagged prices), and fertilizer price index may not be strictly exogenous and the time-invariant county characteristics such as geography and demographics may be correlated to those explanatory variables. Instrumental variables include lagged annual precipitation, growing degree days, state-level major crop stocks, crop price and yield risks, and population density. Crop stocks are included as IV because they are likely to influence price expectations but not yields while crop price risks and yield risks are included because they may affect crop acreage decisions but are unlikely to be correlated with realized yield in a given year. Past weather is included because it is exogenous and varies widely across locations and time and can affect expected prices by affecting inventories (Roberts and Schenkler, 2010).

Determinants of Crop acreage

Assuming that farmers have rational price expectations based on their information set, farmers' crop acreage decisions can be described using a typical Nerlovian adaptive price expectations model of three equations (Braulke, 1982):

$$A_t^D = \alpha_0 + \alpha_1 P_t^e + u_t \qquad (6)$$

$$P_t^e = P_{t-1}^e + \beta(P_{t-1} - P_{t-1}^e) \qquad (7)$$

$$A_t = A_{t-1} + \gamma(A_t^D - A_{t-1}) \qquad (8)$$

where A_t is actual planted acres, A_t^D is desired planted acres, P_t is actual price, P_t^e is expected price, u_t is a disturbance term representing the effect of weather and other factors affecting cropland supply, the subscript *t* is time period, and β and γ are the expectation and adjustment coefficients, respectively. As shown in Braulke (1982), by removing the unobserved variables A_t^D and P_t^e from the model, the reduced form of the actual planted acreage equation can be written as:

$$A_t = b_o + b_1 A_{t-1} + b_2 A_{t-2} + b_3 P_{t-1} + v_t \qquad (9)$$

where b_o, b_1, b_2, and b_3 are parameters determined by $\alpha_o, \alpha_1, \beta$ and γ in equations (6)-(8) and v_t is a disturbance term related to u_t.

Combining equations (2) and (9) and including factors discussed in the previous section, we hypothesize that the crop acreage in each county is a function of the lagged acreage, climate variables, economic variables, risk variables and population density of that county with a general form as follows:

$$Acreage_{it} = g(Acreage_{i,t-1}, Acreage_{i,t-2}, Climate_{i,t-1}, Prices_{i,t-1}, Price\ risk_{i,t-1}, Yield\ risk_{i,t-1}, Population\ density_{it}, Time\ trend_t) + \beta_i + e_{it} \qquad (10)$$

where $Acreage_{i,t-1}$ and $Acreage_{i,t-2}$ are lagged acreage variables to capture unobservable factors that lead to slow transition in land use. $Climate_{i,t-1}$ and $Prices_{i,t-1}$ are as defined above but with some variations. Different from the yield model, $Weather_{i,t-1}$ variables in the acreage model include seasonal total precipitation and growing degree days while $Economic\ environment_{i,t-1}$ include not only a crop's own price, fertilizer price index and fuel oil average prices, but also the prices of other major crops to capture the effect of competition for land use among the major crops. For the total crop acreage model, we construct a composite crop price index for each county using deflated state level prices and county production levels for each crop fixed in 1977 (i.e., the Laspeyres price index). *Price* and $Yield\ risk_{i,t-1}$ are price and yield risks for corn, soybeans and wheat. $Population\ density_{it}$ is population density to capture the effect of population growth and urban development on farmland use. A linear $Time\ trend_t$ is used to describe the overall change in acreage due to unobservable factors that may change over time. β_i is a county fixed effect to capture unobserved time invariant features (such as soil quality) that could influence land use decisions in individual counties. e_{it} is the error term. Again, soil quality variables are left out due to the use of fixed effect estimation. Note that acreage, weather, price, risk and population density variables are in logged values. The above general acreage model is also further adjusted for specific crop acreage estimations (i.e., corn, soybean, and wheat acreage) and the expected composite crop price index is then replaced by individual lagged corn, soybean and wheat prices.

In the existing literature, crop acreage response models are usually specified with a log linear functional form for ease of interpretation (e.g., Lee and Helmberger, 1985; Orazem and Miranowski, 1994; Miller and Plantinga, 1999). We use a log-linear functional form for our acreage models though a simple linear functional form is also tried and found to lead to qualitatively similar results. The inclusion of lagged acreage and input and output price variables as independent variables in the acreage model may create an endogeneity problem for similar reasons as discussed in the estimation of the crop yield models. In addition, the presence of lagged dependent variables also gives rise to autocorrelation. To appropriately take care of the issues inherited in such a dynamic panel data model with a relatively short time dimension and a large cross-section dimension, a fixed-effect Arellano-Bond difference GMM estimator is used

(Arellano and Bond 1991). We also control for serial autocorrelation and heteroskedasticity using the robust estimator. Instrumental variables used in the Arellano-Bond GMM estimation include lagged annual precipitation, growing degree days, monthly temperature deviation and major crop stocks. Major crop stocks and past weather are included due to their potential influence on price expectations and therefore on crop acreage decisions.

Data

Data on cropland acreage, measured by acreage under 15 row crops are obtained from the National Agricultural Statistics Service (NASS). These crops are corn, soybeans, wheat, sorghum, hay/alfalfa, corn silage, rice, oats, barley, cotton, peanuts, sugarbeets, potatoes, tobacco and rye. County-specific planted acres for each crop from 1977 to 2007 are obtained from NASS (USDA/NASS, 2009) and used to calculate the total planted crop acres and the composite crop price index for each county. State level crop prices and stocks and fertilizer and fuel price index data are also obtained from NASS and all prices are converted to 2000 dollars using U.S. GDP Deflator. The composite crop price index is calculated for each county using the deflated crop prices with production fixed in 1977. Crop price risk and yield risk variables are generated as a weighted average of the squared deviations of the price or yield of a crop from its three-year moving average (see Chavas and Holt 1990 and Lin and Dismukes 2007 for more details). Substitute crop acres and marginal acres are calculated for corn and soybeans based on crop acres data obtained from NASS while this calculation is not applied to wheat because data on wheat acres include both winter and spring wheat acres, which make it difficult to track whether a change in wheat acres is from other crop acres or non-crop acres. We also obtain the historical county level irrigated acres for corn, soybeans, and wheat from NASS (USDA/NASS, 2009) to calculate the percentage of irrigated land for each of the three crops.

Monthly mean, minimum and maximum temperature and precipitation variables for each county from January 1977 to December 2007 are derived from the PRISM climate grid developed by the Spatial Climate Analysis service at Oregon State University (PRISM Climate Group 2009). Monthly deviation in temperature is calculated as the monthly maximum minus the minimum temperature. Growing degree days are calculated following the method described in Schlenker et al. (2006). County level data on population density from 1977-2007 are obtained from Population Division at the U.S. Census Bureau (2009). In total, our county level panel data set includes 3015 continental U.S. counties over 31 time years. The summary statistics of the variables included in our analysis are reported in Table 1.

Estimation results

Determinants of Crop Yields

We estimate several alternative specifications for the yield models. Model I includes a simple quadratic time trend and weather and price variables only; Model II includes substitute and marginal acre variables for corn and soybean yield estimation; Model III include more sophisticated time trend variables to provide more flexibility in the dynamics of technical change over the study time period. The estimated coefficients on price and weather variables are found to be robust across these specifications. Similar specifications were estimated for soybeans and wheat but only the results for Model III are reported for brevity (other versions of the estimated results for soybean and wheat yield models are available from the authors on request).

Table 2 shows that the coefficients of the explanatory variables have the expected sign and are statistically significant. The yields of all three crops respond positively to their own prices while the yield of corn and wheat respond negatively to fertilizer prices. More specifically, a one dollar increase in crop prices in terms of dollars per bushel would enhance crop yield by

5.36, 0.27, and 2.66 bushels per acre for corn, soybeans, and wheat, respectively. Based on U.S. average crop prices and yields observed in 2007, the coefficients on crop prices can be translated into yield elasticity of 0.15, 0.06, and 0.43 for corn, soybeans, and wheat, respectively. The estimated coefficients on fertilizer prices show that a one point increase in fertilizer price index reduces corn and wheat yields by 0.21 and 0.11 bushels per acre, respectively, indicating that higher fertilizer prices lead to reduced fertilizer use and hence reduced crop yields. Fertilizer price index is excluded in the soybean yield model because fertilizer use in soybean production is very limited. The estimated coefficients on proportion of irrigated acres indicate that a one percent increase in proportion of irrigated acres increases the average yield of corn and soybeans by about 0.5 and 0.9 bushels per acre, respectively. Substitute acres have a positive effect on corn yield (an extra corn acre planted on acreage under other crop in the previous year in a county increases the average corn yield of the county by 0.002 bushels per acre), but its effect on soybean yield is not significant, consistent with the fact that corn rotated with other crops has a higher yield than continuous corn. In contrast, marginal acres have a negative impact on corn yield but again its negative effect on soybeans is not significant. The estimated coefficient on marginal acres in the corn yield equation is -0.00066, implying an average corn yield of about 100 bushels per marginal acre given the magnitude of marginal acres at the county level on average over the sample period 1977-2007. Compared with an average corn yield of 122 bushels per acre over the same period, our results suggest a ratio of marginal to average yields of 0.82, which is at the upper bound of the estimated range, 0.47-0.82, in literature (Keeney, 2010). The land management effects on soybean yield appear to be negligible because the estimated coefficients on substitute and marginal soybean acres are statistically insignificant. The estimated coefficient on wheat acres shows that a one acre increase at the county level would reduce the average wheat yield by 0.0003 bushels per acre, consistent with our assumption that crop yield is decreasing in planted acres. Similarly, using the sample mean in our data, the yield of wheat on extensive acres is calculated to be 21.6 bushels/acre. Compared with the mean yield of 28.4 bushels/acre, we obtain a ratio of marginal to average yield of 0.76 for wheat, which is within the range of 0.67-0.90 in the literature (Keeney, 2010).

The estimated coefficients on time variables show that corn and wheat yield trends have an inverted U shape over the period 1980 and 1993, suggesting that the rate of increase in corn and wheat yields was declining over this time period. This result is in agreement with the observation of Conway and Toenniessen (1999) who attribute the decline in crop yield increase to the end of the green revolution. However, such an inverted U time trend is not significant for soybean yield, which had a constant increase of 0.23 bushels per acre during the same time period. Over the second time period 1994-2007, the coefficient estimates indicate that corn yield increases at an accelerating rate of 2.30 to 2.92 bushels per acre per year while soybean and wheat yields grow at a relatively smaller but steady rate of 0.29 and 0.64 bushels per acre per year, respectively. McCarl et al. (2008) estimate that the yield trend is 1.88 bushels per acre per year for corn, an ever-increasing trend from 0.14 to 0.43 for soybeans, and from 0.43 to 0.71 for wheat over 1960-2007; our estimated trend for period 1994-2007 are within their ranges for soybean and wheat yields but slightly higher for corn yields, suggesting that recent adoption of new varieties with many genetic improvements together with adjustments in planting management such as increases in corn planting density and rotation have led to renewed increases in corn yields since the mid 1990s.

Determinants of Crop Acreage

We estimate two alternative specifications of the crop acreage model. Model I includes lagged acreage, weather, and input and output prices, population density, and a time trend. In Model II we also include price and yield risks variables. We report the estimates of both versions of the acreage model for total crop acres and corn acres in Table 3.1 and the estimates for soybean acres and wheat acres in Table 3.2. In general, results are qualitatively robust across the two models and the following discussion is based on Model II.

We find that current crop acreage is positively related to the acreages in previous years, providing evidence that unobservable factors lead to slow transition in land use. The acreage of a crop also responds positively to its own price but negatively to the prices of other crops. The estimated acreage elasticities for total crop, corn, soybean, and wheat acreages with respect to their own prices are 0.26, 0.51, 0.49, and 0.07, respectively. The effect of fertilizer price on corn acreage is robustly positive. Recall, in the crop yield models we find that high fertilizer prices lead to reduced crop yields per acre. A possible explanation for the positive association between corn acreage and fertilizer prices is that higher fertilizer prices reduce the intensity of cultivation but leads to changes at the extensive margin and substitute land for fertilizer. The effect of fertilizer price on soybean acreage is not statistically significant which is expected since fertilizer is not applied for soybeans. We do not find robust results for the effect of fertilizer price on wheat acres and on total acres.

Our results also show that fuel prices have a negative impact on total crop and corn and wheat acres but no significant impact on soybean acres, suggesting that the cultivation of corn, wheat, and crops in general might be more energy sensitive than that of soybeans. Similarly, population growth leads to reduced acreage for total crops, corn, and wheat and the most affected crop is corn while its negative effect on soybean acreage is not statistically significant. The response of crop acres to crop price risks is mixed. Higher corn price risks reduce total crop acres and soybean acres and higher wheat price risks reduce both corn and wheat acres, suggesting that farmers might be risk averse to corn and wheat prices. On the other hand, higher soybean price risks lead to increased acreage for all crops. The influence of yield risks on crop acreage decisions appear to be very limited since the estimated coefficients on yield risks in most cases are statistically insignificant (with the exception of soybean yield risks which have a statistically significant positive effect on soybean acres, possibly due to inelastic demand for soybeans). Overall, U.S. total crop acres and corn acres are increasing slightly over time while the time trend for soybean and wheat acreage is negative.

We summarize our estimated crop yield and acreage elasticities in Table 4 and provide elasticity estimates from the literature for comparison. Our corn yield elasticity is 0.15, smaller than the range of 0.22-0.76 reported in other studies. Our crop acreage elasticity estimates are well within the wide range obtained from other empirical studies. We also estimate the crop acreage models using regional data and our results suggest that crop acreage responsiveness to price signals differs across regions (these results are available from the authors on request).

Effects of climate variables on crop yields and acreages

Our results regarding the effects of climate variables on crop yield (see Table 2) show that there exists an inverted U-shaped relationship between corn and soybean yields and growing degree days and a U relationship between wheat yields and degree days. Schlenker and Roberts (2006 and 2009) find similar nonlinear effects of the climate variables for corn and soybean yields though a direct comparison of our finding and theirs is difficult due to the difference in data used, model specification, and estimation methods. The estimated coefficients on the degree days variables suggest that, *ceteris paribus*, corn and soybean yields peak at 1816 and 2156 degree days, respectively; the effect of degree days on wheat yields is negative for the observed range of degree days in the sample. At the observed sample mean of the degree days variable (2248) for the U.S. the effect of a marginal increase in degree days (or temperature) on all crop yields examined is negative. Similar nonlinear effects of temperature on corn yields are also found in Schlenker and Roberts (2006); Deschenes and Greenstone (2007) and McCarl et al. (2008) also provide evidence that temperature has a negative effect on U.S. corn and soybean yields.

It can be seen in Table 2 that monthly precipitation variables and their squared terms generally have a statistically significant impact on corn, soybean, and wheat yields. The nonlinear relationship between precipitation and crop yields differs from month to month and from crop to crop; and in most months precipitation increases yield but at a decreasing rate. Based on the sample mean of monthly precipitation, the total effect of a marginal increase in precipitation each month on yield is 0.15 bushels per acre per mm of precipitation per month for corn. Corresponding figures are 0.06 for soybeans, and -0.004 for wheat. These findings are similar to those in Deschenes and Greenstone (2007) for corn and soybeans and to those in McCarl et al. (2008) for winter wheat. Our results further show that deviation in monthly temperature is generally harmful for corn and soybean yields but beneficial for wheat yields; the total impact of a one degree increase in deviation in temperature in each month is -4.48, -2.39, and 0.14 bushels per acre per year for corn, soybeans and wheat. Our result differs from the finding in McCarl et al. (2008) that variability in temperature has a negative impact on the winter wheat yields; one reason for this could be that we consider winter and spring wheat combined.

Our results regarding the relationship between climate and crop acreages is relatively straightforward given the log-log functional forms used in our crop acreage models. One percent increase in expected growing degree days increases total crop acres by 0.12%, corn acres by 0.09%, and wheat acres by 0.08% but the effect on soybean acres is not significant. The expected precipitation in season 1 would lead to a decrease in soybean and wheat acres with an acreage elasticity of -0.03 and -0.01, respectively, but has a marginally significant positive impact on total crop acres with an acreage elasticity of 0.01 and an insignificant effect on corn acres. The expected precipitation in season 2 has an acreage elasticity of 0.01 for total crop acres, 0.07 for corn, 0.04 for soybeans, and -0.05 for wheat. Acreage elasticity with respect to precipitation in season 3 is -0.01 for total crop, 0.01 for corn, and -0.03 for wheat. Soybean acres appear to be insensitive to expected rainfall in season 3. Lastly, higher expected precipitation in season 4 unanimously reduces the acreage for all crops with an acreage elasticity is -0.02 for total crop, -0.01 for corn, and -0.04 for both soybeans and wheat.

We evaluate the likely effects of future climate change projected by IPCC (2001) on crop yields based on our estimated parameters. According to IPCC (2001), the globally averaged surface temperature is likely to increase by 1.4 to 5.8^{o}C over the period 1990-2100. Average global precipitation is also projected to increase although there could be increases and decreases in precipitation at the regional level. Specific projections regarding precipitation in the U.S. indicate a consensus on a small increase in precipitation (5-20%) in some regions and disagreement on changes in precipitation in most part of the U.S.. In our analysis, we assume that future temperature will increase by 1-6^{o}C while future monthly precipitation will change by $\pm$ 10 - $\pm$ 30 mm per month in each county, about 13 – 39% of the monthly mean precipitation in the sample (76.7 mm per month), to fully reflect possible dramatic changes in precipitation. The projected effect of the likely future change in climate on crop yields is shown in Figure 1. As temperature increases, corn, soybean, and wheat yields all decrease significantly and when temperature increases by $6\,^{o}C$, corn yields would decrease on average by 55 bushels per acre, soybeans by 15 bushels per acre, and wheat by 10 bushels per acre, equivalent to a reduction of 45%, 42%, and 26% relative to the mean yields in the sample for corn, soybeans, and wheat, respectively. In comparison, Lobell and Asner (2003) find that for each degree in growing season temperature, corn and soybean yields will decrease by about 17%; Schlenker and Roberts (2009) predict that by the end of 2100, a $6\,^{o}C$ increase in temperature can lead corn yield to decrease by 55% and soybean yield by 49%.

The effects of future changes in precipitation on corn and soybean yields are easier to interpret: more precipitation mean higher corn and soybean yields while less precipitation means lower yields. Our simulated response of wheat yields to precipitation is more complicated: higher or lower precipitation both could lead to increased or decreased wheat yields (see the last graph in Figure 1). When monthly precipitation increases by 30 mm, corn and soybean yields would increase on average by 3.25 and 1.36 bushels per acre while wheat yields would slightly decrease by 0.34 bushels per acre, implying an increase of 2.2% for corn, 3.3% for soybeans, and -0.1% for wheat compared with their 2007 yield levels. On the other hand, a decrease in monthly precipitation by 30 mm per month would lead to a decrease in corn yield by 5.94, soybean yield by 2.15, and wheat yield by 0.08 bushels per acre, or -3.9% for corn, -5.2% for soybeans, and -0.2% for wheat relative to their 2007 yield levels. In contrast, Schlenker and Roberts (2009) project that a 40% reduction in precipitation will decrease corn yield by 7.43% and soybean yield by 8.52% while a 40% increase in precipitation will decrease corn and soybeans yields by 0.95% and 0.10%, respectively. In Schlenker and Roberts (2009) corn and soybean yields will increase slightly by 0.09-1.07% when precipitation increases between 10-30%. Compared with the effects of temperature, the effects of precipitation are relatively small in size.

Conclusions

We conduct an econometric analysis of the factors influencing U.S. crop yields and acres using U.S. county level data from 1977 to 2007 and evaluate the likely effects of future climate change on U.S. crop yields based on the projected climate changes by IPCC (2001) and our estimated parameters. As compared to other studies, our study includes a more comprehensive set of climate and socioeconomic variables, more recent and less aggregated county level data, and more sophisticated econometric panel data approaches. We find that corn, soybean and wheat yields all respond positively to their own prices and that corn and wheat yields respond negatively to fertilizer prices. Substitute acres have a positive impact on corn yield but no significant impact on soybean yield. Marginal acres have a negative impact on corn yield but its negative impact on soybean yield is insignificant. Corn yield increases with an accelerating rate while soybean and wheat yields grow at a relatively small but steady pace over the second half of our study period. We also find that climate variables have significant impact on the yields for all three crops and high temperature can lead to reduced crop yields while more precipitation will just enhance corn and soybean yields. Our results regarding the impacts of precipitation on wheat yields are inconclusive: changes in precipitation could possibly increase or decrease wheat yields.

Our results show that crop acreage responds positively to its own prices and negatively to the prices of other crops and fuels. Corn acreage would respond positive to fertilizer prices but the effect of fertilizer on total, soybean and wheat acreage is not significant. Population growth would lead to reduced crop acreage in all cases and the most affected crop is corn. Moreover, higher crop stocks would lead to a decrease in crop acreage in general but the size of this impact is very small. The response of crop acreage to crop price risks is mixed and the influence of yield risks on crop acreage decisions appear to be very limited.

Finally, our simulated results regarding the potential impact of future climate change on crop yields clearly indicate that further increases in global temperature would significantly reduce the yields of corn, soybeans, and wheat. Future changes in precipitation would unambiguously affect corn and soybean yields: increases in precipitation would lead to increased corn and soybean yields while decreases in precipitation would lead to reduced corn and soybean yields. Our findings regarding the relationship between precipitation and wheat yields are inconclusive: changes in precipitation in either direction could lead to an increase or decrease in wheat yields.

References

Abler, D. 2001. "Elasticities of Substitution and Factor Supply in Canadian, Mexican, and United States Agriculture." *Market Effects of Crop Support Measures*. OECD. Paris, OECD: 57-88.

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

Askari, H. and J.T. Cummings. 1977. "Estimating Agricultural Supply Response with the Nerlove Model: A Survey." International Economic Review 18(2): 257-292.

Arellano, M. and S. Bond. 1991. "Some Tests of Specification for Panel Data: Monte Carlo Evidence and an Application to Employment Equations." The Review of Economic Studies 58: 277-297.

Braulke, M. 1982. "A Note on the Nerlove Model of Agricultural Supply Response." International Economic Review 23(1): 241-244.

Chavas, J. and M. Holt. 1990. "Acreage Decisions under Risk: the Case of Corn and Soybeans." American Journal of Agricultural Economics 72(3): 27-33.

Chembezi, D.M., and A.W. Womack. 1992. "Regional Acreage Response for US Corn and Wheat: The Effects of Government Programs." Southern Journal of Agricultural Economics 24: 187-198.

Choi, J.-S. and P.G. Helmberger. 1993. "How Sensitive are Crop Yields to Price Changes and farm Programs?" Journal of Agricultural and Applied Economics 25: 237-244.

Conway, G. and G. Toenniessen. 1999. "Feeding the World in the Twenty-First Century." Nature 402 (supp): C55-C58.

Deschenes, O., and M. Greenstone. 2007. "The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations inWeather." American Economic Review 97(1):354–85.

Fargione, J., J. Hill, D. Tilman, S. Polasky and P. Hawthorne (2008). "Land Clearing and the Biofuel Carbon Debt." Science 319(5867): 1235-1238.

Houck, J.P., and P.W. Gallagher. 1976. "The Price Responsiveness of U.S. Corn Yields." American Journal of Agricultural Economics 58:731–734.

IPCC. 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

Kaufmann, R.K. and S.E. Snell. 1997. "A Biophysical Model if Corn Yield: Integrating Climatic and Social Determinants." American Journal of Agricultural Economics 79(1): 178-190.

Keeney, R. and T.W. Hertel. 2008. "Yield Response to Prices: Implications for Policy Modeling." Working Paper #08-13, Department of Agricultural Economics, Purdue University.

Keeney, R. and T.W. Hertel. 2009. "The Indirect Land Use Impacts of United States Biofuel Policies: The Importance of Acreage, Yield, and Bilateral Trade Responses." American Journal of Agricultural Economics 91(4): 895-909.

Keeney, R. 2010. "Yield Response and Biofuels: Issues and Evidence on the Extensive Margin." Paper Presented at the Fourth World Congress of Environmental and Resource Economists, Montreal, Canada, June 28 – July 2, 2010.

Kucharik, C.J. and S.P. Serbin. 2008. "Impacts of Recent Climate Change on Wisconsin Corn and Soybean Yield Trends." *Environmental Research Letters* 3 (3): 034003.

Lee, D.R., and P.G. Helmberger. 1985. "Estimating Supply Response in the Presence of Farm Programs." American Journal of Agricultural Economics 67: 193-203.

Lin, W. and R. Dismukes. 2007. “Supply Response under Risk: Implications for Counter-Cyclical Payments' Production Impact.” Review of Agricultural Economics 29(1): 64-86.

Lobell, D.B. and G.P. Asner. 2003. “Climate and Management Contributions to Recent Trends in U.S. Agricultural Yields.” Science 299: 1032.

Lobell, D.B., M.B. Burke, C. Tebaldi, M.D. Mastrandrea, W.P. Falcon, and R.L. Naylor. 2008. “Prioritizing Climate Change Adaptation Needs for Food Security in 2030.” Science 319: 607-610.

Lubowski, R.N., A.J. Plantinga, and R.N. Stavins. 2008. “What Drives Land-Use Change in the United States? A National Analysis of Landowner Decisions.” Land Economics 84(4):529–550.

Lyons, D.C., and R.L. Thompson. 1981. “The Effect of Distortions in Relative Prices on Corn Productivity and Exports: A Cross-Country Study.” Journal of Rural Development 4:83–102.

McCarl, B.A., X. Villavicencio, and X. Wu. 2008. “Climate Change and Future Analysis: Is Stationary Dying?” American Journal of Agricultural Economics 90(5): 1241-1247.

Menz, K.M., and P. Pardey. 1983. “Technology and U.S. Corn Yields: Plateaus and Price Responsiveness.” American Journal of Agricultural Economics 65:558–562.

Miller, D.J. and A.J. Plantinga. 1999. “Modeling Land Use Decisions with Aggregate Data.” American Journal of Agricultural Economics 81(1): 180-194.

Morzuch, B.J., R.D. Weaver, and P.G. Helmberger. 1980. “Wheat Acreage Supply Response under Changing Farm Programs.” American Journal of Agricultural Economics 62: 29-37.

Nerlove, M. 1956. “Estimates of the Elasticities of Supply of Selected Agricultural Commodities.” Journal of Farm Economics 38(2): 496-509.

Nowshirvani, V.F. 1971. “A Modified Adaptive Expectations Model.” American Journal of Agricultural Economics 51(1): 116-119.

Orazem, P.F., and J.A. Miranowski. 1994. “A Dynamic Model of Acreage Allocation with General and Crop-Specific Soil Capital.” American Journal of Agricultural Economics 76: 385-395.

Oury, B. 1965. “Allowing for Weather in Crop Production Model Building.” *Journal of Farm Economics* 47 (2): 270-283.

Reilly, J.M., J. Graham, D.G. Abler, R. Darwin, S. Hollinger, C. Izaurralde, S. Jagtap, J. Jones, J. Kimble, B. McCarl, L. Mearns, D. Ojima, E.A. Paul, K. Paustian, S. Riha, N. Rosemberg, C. Rosenzweig, and F. Tubiello. 2002. Changing Climate and Changing Agriculture: Report of the Agricultural Sector Assessment Team. Cambridge: Cambridge University Press.

PRISM Climate Group. 2009. Monthly Data, http://www.prism.oregonstate.edu/

Schlenker, W. and M.J. Roberts. 2006. "Nonlinear Effects of Weather on Corn Yields." Review of Agricultural Economics 28(3): 391-398.

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

Roberts, M.J. and W. Schenkler. 2010. "The U.S. Biofuel Mandate and World Food Prices: An Econometric Analysis of the Demand and Supply of Calories." NBER Meeting on Agricultural Economics and Biofuels, Cambridge, MA, March 4 - 5, 2010.

Schlenker, W., W.M. Hanemann and A.C. Fisher. 2006. "The Impact of Global Warming on U.S. Agriculture: An Econometric Analysis of Optimal Growing Conditions." Review of Economics and Statistics 88(1): 113-125.

Searchinger, T., R. Heimlich, R. A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes and T.-H. Yu (2008). "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change." Science 319(5867): 1238-1240.

Shaw, L.H. 1964. "The Effect of Weather on Agricultural Output: A Look at Methodology." *Journal of Farm Economics* 46 (1): 218-230.

U.S. Census Bureau. 2009. Population Estimates, http://www.census.gov/popest/archives/, release date: March 19, 2009.

USDA/NASS (2009) U.S. & All States County Data - Crops, http://www.nass.usda.gov/QuickStats/Create_County_All.jsp.

Wallace, H.A. 1920. "Mathematical Inquiry into the Effect of Weather on Corn Yield in the Eight Corn Belt States." Monthly Weather Review 48 (8): 439-446.

Table 1. County-Level Summary Statistics (1977-2007 Average)

Variable	Obs.	Mean	Std. Dev.	Min	Max
Corn price, $/bushel	93465	3.29	1.16	1.53	7.49
Soybean price, $/bushel	93465	7.82	2.84	3.96	15.01
Wheat price, $/bushel	93465	4.17	1.40	1.79	8.56
Distillate fuel oil price, $/m Btu	93465	9.60	2.61	5.81	17.98
Fertilizer price index	93465	110.61	28.24	72	209
Total crop acres, acres	93465	90930.92	106707.20	0	971500
Planted corn acres, acres	64994	36676.49	49810.07	10	397000
Corn yield, bushel/acre	64994	121.95	32.32	4.5	246
Corn stock, bushels	64994	315924.7	464460.3	0	2345203
Planted soybean acres, acres	49983	40083.18	48780.26	0	540000
Soybean yield, bushel/acre	49983	35.33	9.51	1.7	64.4
Soybean stock, bushels	49983	91494.98	115982.1	0	499598
Planted wheat acres, acres	93465	22684.95	55466.62	0	764400
Wheat yield, bushel/acre	93465	28.4	23.03	0	127.8
Wheat stock, bushels	93465	48375.6	74295.09	0	464093
Substitution corn acres, acres	64994	763.82	2870.22	0	77200
Marginal corn acres, acres	62586	1125.56	4161.17	0	117400
Substitution soybean acres, acres	50238	1004.04	3644.02	0	100000
Marginal soybean acres, acres	48232	7954.66	23278.09	0	269000
Share of irrigated corn acres	64994	0.08	0.24	0	1
Share of irrigated soybean acres	49982	0.03	0.15	0	1
Population density, residents/mile^2	93274	199.65	1591.80	0	70373
Degree days (8-32 ^oC)	93465	2179.73	659.13	63.18	3979.55
Annual precipitation, mm	93465	975.90	390.30	13.67	3925.11
Deviation in temperature Jan (max-min), ^oC	93465	11.31	2.41	2.00	22.17
Deviation in temperature Feb (max-min), ^oC	93465	12.08	2.33	4.83	22.79
Deviation in temperature Mar (max-min), ^oC	93465	12.90	2.21	5.23	22.87
Deviation in temperature Apr (max-min), ^oC	93465	13.83	2.05	5.56	22.24
Deviation in temperature May (max-min), ^oC	93465	13.50	1.96	5.12	22.97
Deviation in temperature Jun (max-min), ^oC	93465	13.19	2.19	5.27	24.44
Deviation in temperature Jul (max-min), ^oC	93465	13.13	2.35	5.24	23.59
Deviation in temperature Aug (max-min), ^oC	93465	13.26	2.29	5.40	24.02
Deviation in temperature Sep (max-min), ^oC	93465	13.61	2.32	5.74	25.04
Deviation in temperature Oct (max-min), ^oC	93465	13.69	2.33	5.61	23.51
Deviation in temperature Nov (max-min), ^oC	93465	12.04	2.62	3.63	23.77
Deviation in temperature Dec (max-min), ^oC	93465	11.19	2.52	3.77	21.38

All dollar figures are in 2000 constant dollars.

Table 2. Fixed-Effect Instrumental Variable Estimates of Crop Yield Models

Independent variable	Dependent variable				
	Corn yield (1)	Corn yield (2)	Corn yield (3)	Soybean yield	Wheat yield
Own price$_{-1}$	2.852***	2.108***	5.356***	0.265***	2.661***
	(0.414)	(0.664)	(1.029)	(0.0489)	(0.273)
Fertilizer price index	-0.483***	-0.580***	-0.207***	-	-0.114***
	(0.0245)	(0.0363)	(0.0346)	-	(0.0163)
Proportion of irrigated acres	55.97***	52.58***	46.46***	90.10***	-
	(4.589)	(5.563)	(4.900)	(10.13)	-
Substitution acres	-	0.00487***	0.00231***	6.98e-05	-
	-	(0.000488)	(0.000385)	(9.65e-05)	-
Marginal acres	-	-0.00138***	-0.000657***	-1.67e-05	-
	-	(0.000231)	(0.000223)	(3.59e-05)	-
Wheat acres	-	-	-	-	-0.000313***
	-	-	-	-	(3.21e-05)
Time (1980-2007)	-2.920***	-3.520***			
	(0.168)	(0.211)			
Time^2 (1980-2007)	0.163***	0.181***			
	(0.00588)	(0.00765)			
Time1 (1980-1993)	-	-	6.396***	0.232**	2.205***
	-	-	(0.669)	(0.116)	(0.234)
Time1^2 (1980-1993)	-	-	-0.238***	-0.000347	-0.0949***
	-	-	(0.0227)	(0.00464)	(0.00900)
Time2 (1994-2007)	-	-	2.248***	0.285***	0.641***
	-	-	(0.341)	(0.0629)	(0.128)
Time2^2 (1994-2007)	-	-	0.0241***	0.000453	-0.000611
	-	-	(0.00677)	(0.00134)	(0.00370)
Degree days	0.101***	0.104***	0.0926***	0.0457***	-0.0122***
	(0.00332)	(0.00401)	(0.00339)	(0.00161)	(0.00153)
Degree days^2	-2.86e-05***	-2.98e-05***	-2.55e-05***	-1.06e-05***	5.88e-07*
	(7.75e-07)	(9.45e-07)	(7.92e-07)	(3.52e-07)	(3.51e-07)
Precipitation January	-	-	-	-	0.00590**
	-	-	-	-	(0.00239)
Precipitation January^2	-	-	-	-	-1.45e-05**
	-	-	-	-	(6.07e-06)
Precipitation February	-	-	-	-	-0.00723***
	-	-	-	-	(0.00273)
Precipitation February^2	-	-	-	-	1.20e-06
	-	-	-	-	(6.88e-06)
Precipitation March	0.0251***	0.0107	0.00724	0.00107	0.00606**
	(0.00574)	(0.00724)	(0.00659)	(0.00246)	(0.00274)
Precipitation March^2	-7.63e-05***	-3.37e-05	-4.32e-05*	4.63e-06	-3.45e-05***
	(2.02e-05)	(2.52e-05)	(2.25e-05)	(8.97e-06)	(8.80e-06)
Precipitation April	0.00715	0.0105	0.00486	-0.00917***	0.0163***
	(0.00580)	(0.00710)	(0.00591)	(0.00197)	(0.00287)
Precipitation April^2	-4.89e-05**	-5.09e-05**	-4.17e-05**	3.49e-05***	-8.63e-05***
	(2.02e-05)	(2.46e-05)	(2.07e-05)	(6.42e-06)	(9.44e-06)
Precipitation May	0.0204***	0.0165*	0.0303***	-0.00692***	0.00214
	(0.00678)	(0.00847)	(0.00758)	(0.00231)	(0.00348)
Precipitation May^2	-0.000230***	-0.000218***	-0.000258***	-1.57e-05**	-6.00e-05***
	(2.12e-05)	(2.58e-05)	(2.20e-05)	(6.82e-06)	(1.08e-05)
Precipitation June	0.109***	0.119***	0.131***	0.0287***	-0.00222
	(0.00709)	(0.00860)	(0.00732)	(0.00244)	(0.00306)
Precipitation June^2	-0.000408***	-0.000415***	-0.000473***	-0.000125***	-2.51e-05***
	(2.35e-05)	(2.83e-05)	(2.43e-05)	(7.39e-06)	(8.86e-06)
Precipitation July	0.207***	0.197***	0.186***	0.0390***	-0.00712**

	(0.00591)	(0.00722)	(0.00615)	(0.00218)	(0.00323)
Precipitation July^2	-0.000506***	-0.000474***	-0.000444***	-0.000107***	-1.12e-05
	(1.72e-05)	(2.10e-05)	(1.78e-05)	(6.25e-06)	(9.58e-06)
Precipitation August	0.0222***	0.0384***	0.0614***	0.0737***	0.00413
	(0.00717)	(0.00898)	(0.00753)	(0.00243)	(0.00376)
Precipitation August^2	-2.61e-05	-0.000149***	-0.000182***	-0.000193***	1.08e-05
	(2.50e-05)	(3.27e-05)	(2.74e-05)	(8.14e-06)	(1.30e-05)
Precipitation September	-0.0115**	-0.0145**	0.00242	0.00846***	-0.00424*
	(0.00448)	(0.00563)	(0.00497)	(0.00154)	(0.00239)
Precipitation September^2	-8.05e-05***	-7.79e-05***	-9.43e-05***	-3.23e-05***	1.37e-05**
	(1.18e-05)	(1.43e-05)	(1.21e-05)	(4.05e-06)	(6.31e-06)
Precipitation October	0.0589***	0.0394***	0.0116*	0.00341*	0.0130***
	(0.00600)	(0.00756)	(0.00636)	(0.00181)	(0.00280)
Precipitation October^2	-0.000140***	-8.34e-05***	-3.73e-05*	-9.85e-06	-1.25e-05
	(2.06e-05)	(2.55e-05)	(2.14e-05)	(6.04e-06)	(8.52e-06)
Precipitation November	-	-	-	-	0.0178***
	-	-	-	-	(0.00217)
Precipitation November^2	-	-	-	-	-2.83e-05***
	-	-	-	-	(5.51e-06)
Precipitation December	-	-	-	-	-0.00711***
	-	-	-	-	(0.00207)
Precipitation December^2	-	-	-	-	3.46e-06
	-	-	-	-	(4.78e-06)
Deviation in temperature January	-	-	-	-	-0.292***
	-	-	-	-	(0.0516)
Deviation in temperature February	-	-	-	-	0.149***
	-	-	-	-	(0.0436)
Deviation in temperature March	0.604***	0.441***	0.173**	-0.0335	-0.0461
	(0.0813)	(0.1000)	(0.0875)	(0.0348)	(0.0454)
Deviation in temperature April	1.449***	1.527***	1.493***	0.0323	-0.0831*
	(0.0896)	(0.111)	(0.0932)	(0.0354)	(0.0502)
Deviation in temperature May	-0.832***	-1.433***	-0.884***	-0.165***	0.457***
	(0.108)	(0.144)	(0.118)	(0.0415)	(0.0557)
Deviation in temperature June	-1.280***	-0.791***	-1.542***	-0.244***	0.0362
	(0.126)	(0.165)	(0.135)	(0.0508)	(0.0676)
Deviation in temperature July	-1.623***	-2.169***	-2.775***	-0.657***	-0.761***
	(0.131)	(0.169)	(0.147)	(0.0520)	(0.0692)
Deviation in temperature August	-1.791***	-1.485***	-1.087***	-1.064***	0.122*
	(0.138)	(0.172)	(0.148)	(0.0521)	(0.0715)
Deviation in temperature September	-1.010***	-1.135***	-0.596***	-0.261***	0.218***
	(0.106)	(0.139)	(0.119)	(0.0379)	(0.0522)
Deviation in temperature October	1.251***	1.081***	0.739***	0.0253	0.367***
	(0.103)	(0.128)	(0.107)	(0.0307)	(0.0503)
Deviation in temperature November	-	-	-	-	0.145***
	-	-	-	-	(0.0384)
Deviation in temperature December	-	-	-	-	-0.184***
	-	-	-	-	(0.0455)
Constant	74.48***	100.7***	9.876	-3.043	45.38***
	(6.228)	(7.959)	(7.894)	(2.055)	(3.549)
Observations	57495	57495	57495	42952	81218
Number of counties	2550	2550	2550	2048	3014

Note: 1. Standard errors in parentheses; 2. *** p<0.01, ** p<0.05, * p<0.1.

Table 3.1 Fixed-Effect Arellano-Bond GMM Estimates of Crop Acreage Models

Independent variable	Dependent variable (logged)			
	Total acres (1)	Total acres (2)	Corn acres (1)	Corn acres (2)
lg(Own acreage)$_{-1}$	0.486***	0.446***	0.484***	0.445***
	(0.0222)	(0.0221)	(0.0167)	(0.0180)
lg(Own acreage)$_{-2}$	0.144***	0.139***	0.0807***	0.0344***
	(0.0148)	(0.0148)	(0.00989)	(0.0102)
lg(Composite price index)$_{-1}$	0.249***	0.257***	-	-
	(0.00982)	(0.0109)	-	-
lg(Corn price)$_{-1}$	-	-	0.378***	0.510***
	-	-	(0.0156)	(0.0182)
lg(Soybean price)$_{-1}$	-	-	-0.0113	-0.118***
	-	-	(0.0117)	(0.0152)
lg(Wheat price)$_{-1}$	-	-	-0.109***	-0.345***
	-	-	(0.0127)	(0.0157)
Fertilizer price index$_{-1}$	-0.000812***	0.000315*	0.00103***	0.00395***
	(0.000160)	(0.000180)	(0.000174)	(0.000214)
lg(Fuel price)$_{-1}$	0.00633	-0.0701***	-0.0247**	-0.143***
	(0.00947)	(0.0109)	(0.0108)	(0.0125)
lg(Population density)	-0.442***	-0.711***	-0.412***	-0.861***
	(0.0902)	(0.120)	(0.104)	(0.155)
Time trend (1978-2007)	0.00525***	0.0108***	0.00529***	0.00648***
	(0.000816)	(0.00112)	(0.000847)	(0.00135)
lg(Degree days)$_{-1}$	0.0640***	0.122***	0.108***	0.0853***
	(0.0208)	(0.0215)	(0.0191)	(0.0186)
lg(Precipitation season 1)$_{-1}$	0.000211	0.00662*	0.0113***	-0.00228
	(0.00353)	(0.00345)	(0.00384)	(0.00383)
lg(Precipitation season 2)$_{-1}$	0.0219***	0.0146***	0.0830***	0.0731***
	(0.00460)	(0.00421)	(0.00561)	(0.00496)
lg(Precipitation season 3)$_{-1}$	-0.0102***	-0.00753**	0.0112**	0.0118***
	(0.00357)	(0.00333)	(0.00450)	(0.00424)
lg(Precipitation season 4)$_{-1}$	-0.0104***	-0.0202***	-0.0159***	-0.0113***
	(0.00303)	(0.00297)	(0.00330)	(0.00350)
lg(Corn price risk)$_{-1}$	-	-0.0735***	-	0.00727
	-	(0.0115)	-	(0.0126)
lg(Soybean price risk)$_{-1}$	-	0.160***	-	0.350***
	-	(0.0150)	-	(0.0146)
lg(Wheat price risk)$_{-1}$	-	0.00451	-	-0.246***
	-	(0.0110)	-	(0.0134)
lg(Corn yield risk)$_{-1}$	-	0.00173	-	-0.00703
	-	(0.00283)	-	(0.00461)
lg(Soybean yield risk)$_{-1}$	-	0.00209	-	-0.000519
	-	(0.00333)	-	(0.00297)
lg(Wheat yield risk)$_{-1}$	-	0.00286	-	-0.00215
	-	(0.00290)	-	(0.00240)
Constant	5.139***	5.743***	3.862***	6.386***
	(0.517)	(0.591)	(0.502)	(0.682)
Observations	73801	68152	57354	52663
Number of counties	2849	2831	2472	2443

Note: 1. Standard errors in parentheses; 2. *** p<0.01, ** p<0.05, * p<0.1.

Table 3.2 Fixed-Effect Arellano-Bond GMM Estimates of Crop Acreage Models

	Dependent variable (logged)			
Independent variable	Soybean acres (1)	Soybean acres (2)	Wheat acres (1)	Wheat acres (2)
lg(Own acreage)$_{-1}$	0.197***	0.192***	0.516***	0.283***
	(0.0178)	(0.0184)	(0.0150)	(0.0191)
lg(Own acreage)$_{-2}$	0.0672***	0.0775***	0.0355***	-0.0176*
	(0.0162)	(0.0173)	(0.0105)	(0.00969)
lg(Corn price)$_{-1}$	-0.164***	-0.295***	0.264***	0.306***
	(0.0457)	(0.0577)	(0.0207)	(0.0218)
lg(Soybean price)$_{-1}$	0.313***	0.487***	-0.0482***	-0.0543***
	(0.0422)	(0.0611)	(0.0156)	(0.0192)
lg(Wheat price)$_{-1}$	0.0202	0.0489	0.124***	0.0668***
	(0.0452)	(0.0525)	(0.0185)	(0.0185)
Fertilizer price index$_{-1}$	0.000470	0.00105	-0.00109***	0.000134
	(0.000604)	(0.000693)	(0.000251)	(0.000285)
lg(Fuel price)$_{-1}$	0.0555	0.0284	0.0649***	-0.0314*
	(0.0356)	(0.0395)	(0.0144)	(0.0169)
lg(Population density)	-0.312	-0.178	-0.170**	-0.348***
	(0.232)	(0.207)	(0.0695)	(0.0767)
Time trend (1978-2007)	-0.0113***	-0.00774*	-0.000440	-0.0107***
	(0.00295)	(0.00416)	(0.00106)	(0.00155)
lg(Degree days)$_{-1}$	-0.157*	-0.0547	0.161***	0.0824***
	(0.0839)	(0.0860)	(0.0280)	(0.0268)
lg(Precipitation season 1)$_{-1}$	-0.0294**	-0.0285**	0.00751*	-0.00691*
	(0.0135)	(0.0140)	(0.00455)	(0.00412)
lg(Precipitation season 2)$_{-1}$	0.0476***	0.0413***	-0.0722***	-0.0502***
	(0.0148)	(0.0148)	(0.00703)	(0.00626)
lg(Precipitation season 3)$_{-1}$	0.0335**	0.0277	-0.0370***	-0.0342***
	(0.0169)	(0.0173)	(0.00589)	(0.00580)
lg(Precipitation season 4)$_{-1}$	-0.0282***	-0.0369***	-0.0593***	-0.0447***
	(0.00929)	(0.00966)	(0.00498)	(0.00456)
lg(Corn price risk)$_{-1}$	-	-0.0848**	-	0.0246
	-	(0.0424)	-	(0.0159)
lg(Soybean price risk)$_{-1}$	-	0.0804*	-	0.0500***
	-	(0.0416)	-	(0.0170)
lg(Wheat price risk)$_{-1}$	-	0.0635	-	-0.0583***
	-	(0.0470)	-	(0.0170)
lg(Corn yield risk)$_{-1}$	-	0.00884	-	0.00370
	-	(0.00767)	-	(0.00346)
lg(Soybean yield risk)$_{-1}$	-	0.0489***	-	0.00266
	-	(0.0164)	-	(0.00331)
lg(Wheat yield risk)$_{-1}$	-	0.000351	-	-0.000508
	-	(0.00940)	-	(0.00743)
Constant	9.008***	6.892***	3.835***	7.716***
	(1.178)	(1.148)	(0.407)	(0.443)
Observations	42080	38783	53666	49179
Number of counties	1918	1866	2502	2459

Note: 1. Standard errors in parentheses; 2. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 4. Comparison of Estimates of Crop Yield and Acreage Elasticities

Crop Yield Elasticities			
Study	***Crop***	***Elasticity***	***Trend (bushel/acre/year)***
Choi and Helmberger (1993)	Corn	0.27	2.98 (1964-88)
	Soybeans	0.13	1.04 (1964-88)
	Wheat	0.03	0.57 (1964-88)
Houck and Gallagher (1976)	Corn	0.24 – 0.76	2.63 (1951-72)
Kaufmann and Schnell (1997)	Corn	-	0.87 (1969-87)
Lyons and Thompson (1981)	Corn	0.22	-
Menz and Pardey (1983)	Corn	0.61	0.95 (1951-80)
McCarl et al. (2008)	Corn	-	1.88 (1960-07)
	Soybean	-	0.28 (1960-07)
	Wheat	-	0.57 (1960-07)
Our study (calculated based on U.S. average crop price and yield in 2007)	Corn	0.15	2.42 (1994-07)
	Soybean	0.06	0.29 (1994-07)
	Wheat	0.43	0.64 (1994-07)
Crop Acreage Elasticities			
Study	***Crop grown on land***	***Own-price elasticity***	***Cross-price elasticity***
Chavas and Holt (1990)	Corn	0.15	-0.15 (Soybeans)
	Soybeans	0.45	-0.30 (Corn)
Chembezi and Womack (1992)	Corn	0.10	-0.05 (Soybeans)
			-0.05 (Wheat)
	Wheat	0.05	-0.05 (Corn)
			-0.10 (Soybeans)
Lee and Helmberger (1985)	Corn	0.05	-0.15 (Soybeans)
	Soybeans	0.25	-0.15 (Corn)
Lin and Dismukes (2007)	Corn	0.17 – 0.35	-
	Soybean	0.30	-
	Wheat	0.25 – 0.34	-
Miller and Plantinga (1999)	Corn	0.95	-0.45 (Soybeans
	Soybeans	0.95	-0.40 (Corn)
Morzuch et al. (1980)	Wheat	0.35	-
Orazem and Miranowski (1994)	Corn	0.05	0.00 (Soybeans)
	Soybeans	0.25	0.00 (Corn)
Tegene et al. (1988)	Corn	0.20	-
Our study	Corn	0.510	-0.118 (Soybeans)
			-0.345 (Wheat)
	Soybeans	0.487	-0.295 (Corn)
			0.00 (Wheat)
	Wheat	0.067	0.306 (Corn)
			-0.054 (Soybeans)
	Total acres	0.257 (Composite crop price index)	

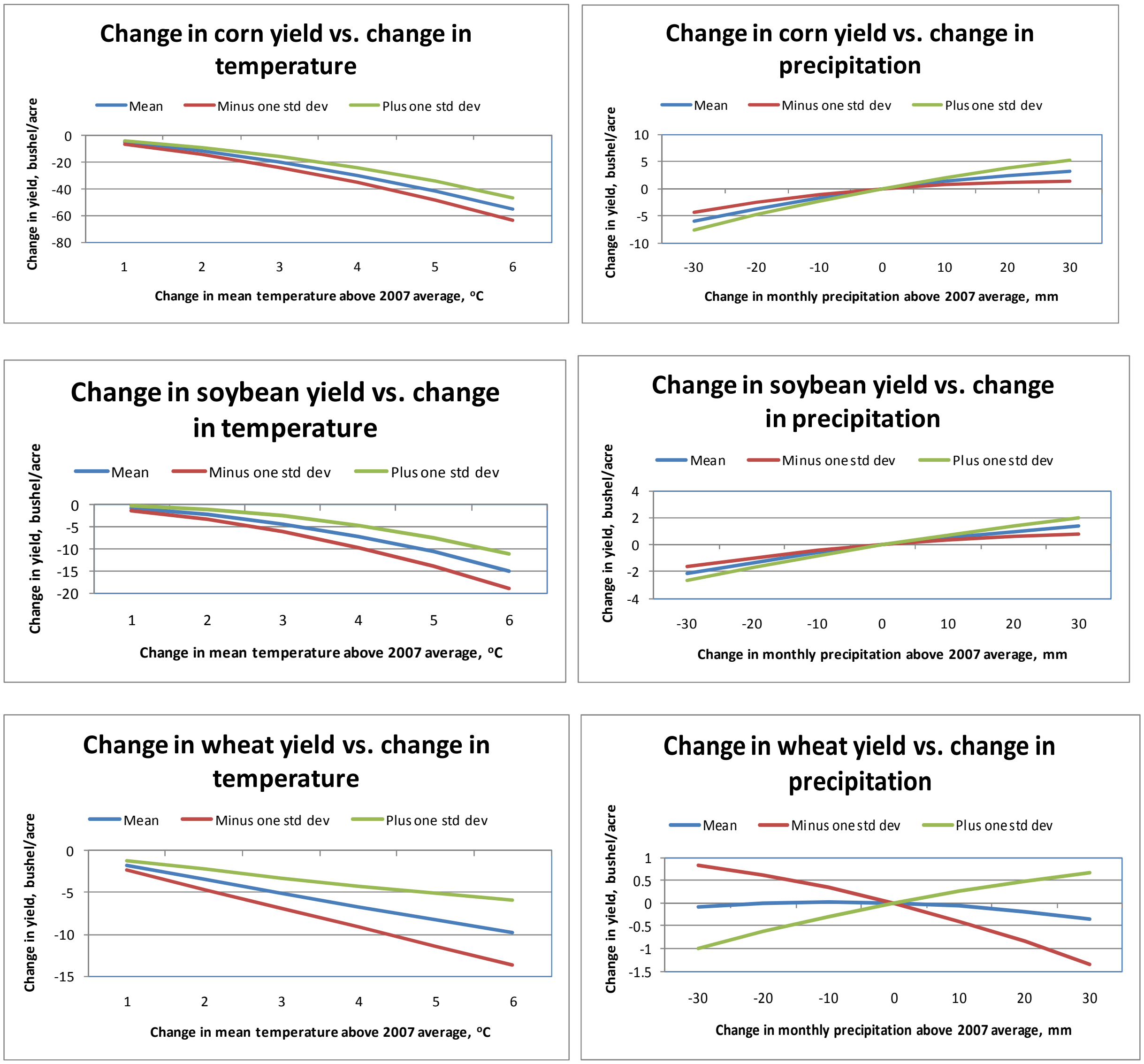

Figure1. The impacts of projected climate change on U.S. crop yields