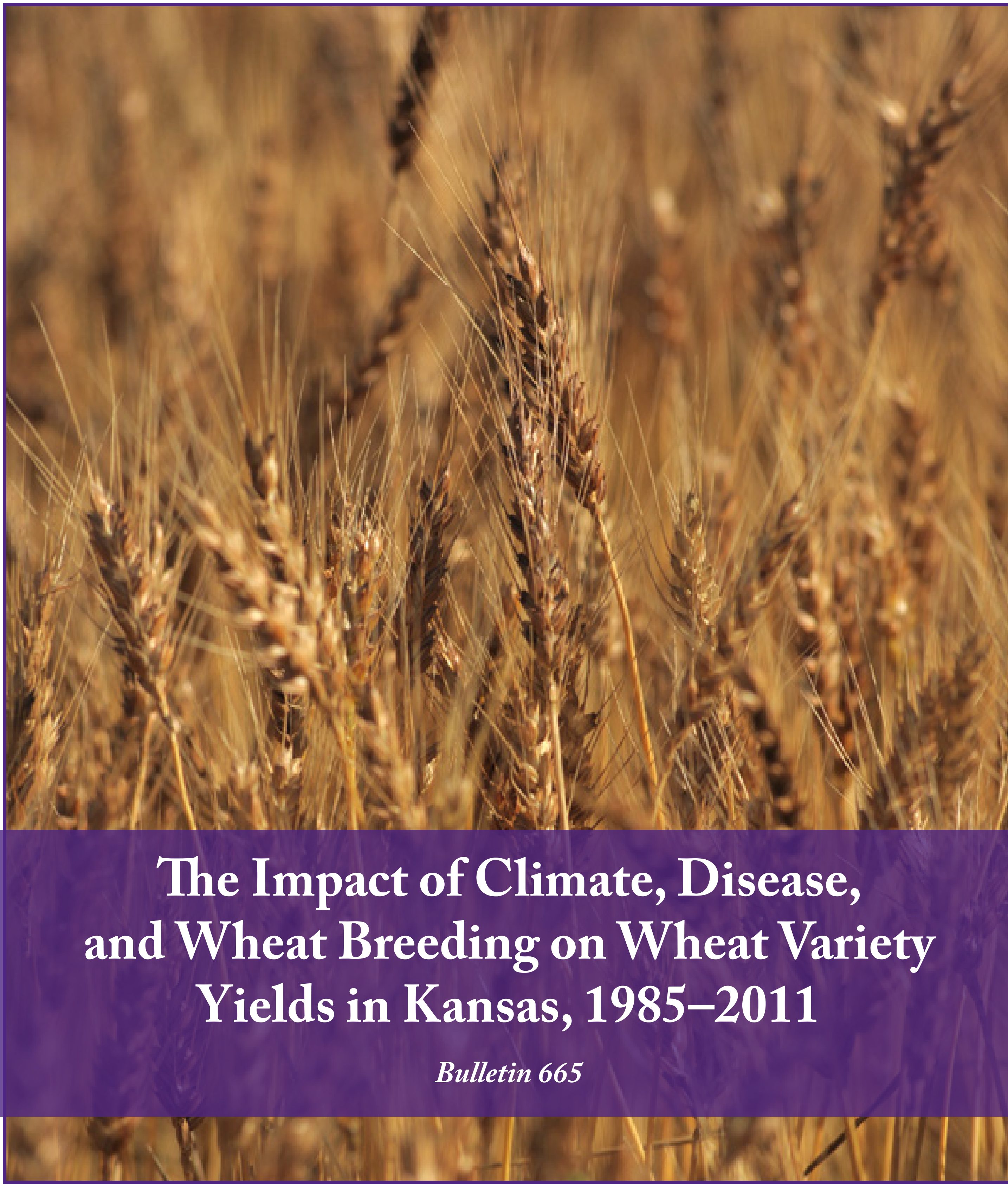

The Impact of Climate, Disease, and Wheat Breeding on Wheat Variety Yields in Kansas, 1985–2011

Bulletin 665

K-STATE
Research and Extension

Kansas State University Agricultural Experiment Station and Cooperative Extension Service

The Impact of Climate, Disease, and Wheat Breeding on Wheat Variety Yields in Kansas, 1985–2011

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Abstract

The overall objective of this research is to quantify the impact of climate change, disease, and genetic improvement on wheat (*Triticum aestivum* L.) yields of varieties grown in 11 locations in Kansas from 1985–2011. Wheat variety yield data from Kansas performance tests were matched with comprehensive location-specific weather and disease data, including monthly temperature, temperature, and solar radiation around anthesis (flowering), and vapor pressure deficit (VPD). The results show that wheat breeding programs increased yield by 0.51 bu/acre each year. From 1985 through 2011, wheat breeding increased average wheat yields by 13 bu/acre, or over 26% of total yield. Weather was found to have a large impact on wheat yields. Simulations found that a 1°C increase in projected mean temperature was found to decrease wheat yields by 10.64 bu/acre, or nearly 21%.

Contents

Climate change is likely to have a major impact on global agricultural production, but its effects on crop yield and yield risk are not well understood (Lobell and Field, 2007). Tubiello et al. (2002) projected that climate change will significantly affect rainfed wheat production in the Great Plains. They projected 10 to 50% decreases in hard winter wheat yields with higher variability in yields in the southern Great Plains (Colo., Kan., Okla., and Texas), thus increasing yield risk to farmers. For spring wheat, yields were projected by Tubiello et al. (2002) to increase by 2030 but decrease by 2090 in the northern Great Plains (N.D., S.D., and Neb.). Ortiz et al. (2008) concluded that as weather patterns such as hotter temperatures, shorter growing seasons, and less rainfall change, cultivar selection will become increasingly important to help mitigate yield risk.

Although climate change is predicted to have a negative impact on future wheat yields in the Great Plains, genetic improvement is likely to offset at least some of the impact. In recent years, private companies and the public sector have made large investments in and improvements to wheat breeding programs (Battenfield et al., 2013). Wheat breeding programs have also made significant contributions to countering the yield-reducing effects of pathogens, particularly wheat rust (*Puccinia triticina* Eriks; Graybosch and Peterson, 2010). Measuring the ability of wheat breeders to offset disease and increase future wheat yields is important given the need to feed the large and increasing global population.

Schmidt (1984) noted that increases in grain yield potential from 1975 to 1984 in the Great Plains were minimal and suggested that the rate of genetic gain was slowing or reaching a plateau. Graybosch and Peterson (2010) concluded that relative grain yields of Great Plains hard red winter wheat may have peaked in the early to mid-1990s.

The aim of this study was to quantify the impact of potential climate change, genetic improvement, and the presence of disease on wheat yields in Kansas. Most previous studies have concentrated on either genetic improvement or the impact of weather on wheat yields. Other studies have quantified the impact of diseases on wheat yields (Bockus et al., 2001). This research extends the previous literature by including all three major determinants (genetic improvement, weather, and disease) of wheat yields in an integrated approach, and our results provide much higher explanatory power and more goodness of fit measures than previous work.

Our study included wheat varieties as separate variables, providing an accurate and up-to-date estimate of the relative yield of each variety and holding constant location, weather, and disease. This approach provides initial estimates of how to construct a portfolio of wheat varieties to reduce risk, which was shown to be important in mitigating the effects of climate change by Collier et al. (2009), Tack et al. (2012), and Tack et al. (2013a and 2013b), and extends previous wheat portfolio research of Barkley et al. (2010) and Nalley and Barkley (2010) and the rice portfolio work of Nalley et al. (2009). Model results for wheat varieties provide wheat breeders initial information about breeding for heat tolerance (Pradhan et al., 2012). Wheat varieties grown in Kansas are described in detail by Watson (various years).

Regression results are used to simulate plausible future climate change scenarios, and the forecasts are compared with previous results. This information is crucial to understanding how climate change could affect yield, profits, and revenue risk for wheat producers in Kansas and the Great Plains as well as for the wheat seed industry. In addition, insurance product designers need this information to be able to offer products that better meet the needs of these farmers.

Literature Review

Climate change may have a significant impact on the Great Plains and central United States. This area of the country may be subject to climatic shifts that could result in crop shifts away from traditional agronomic crops; an increase in the migration of invasive species of plants and animals; an increase in heat stress on livestock; an increase in irrigation demands, thus affecting water conservation; reductions in soil productivity; an increase in risk of flooding and soil erosion; and stress on rural economies (Joyce et al., 2000). A large and rapidly increasing literature charts the impact of weather and climate change on agricultural production, as summarized by Adams et al. (1999) and Mendelsohn et al. (1994). Adams et al. (1998) summarized and interpreted previous research findings on how climate change affects agricultural production, and Schlenker et al. (2005) and Schlenker and Roberts (2006) provided important results on the impact of climate change on crop yields.

Several recent studies provide a reference point for the results of potential climate change on wheat yields and the simulations reported in the current study; for instance, Cabas, Weersink, and Olale (2010) examined the impact of climate and non-climate factors on the mean and variance of corn, soybean, and winter wheat yields in Southwestern Ontario, Canada. Chen et al. (2004) also investigated the impact of climate on yield variability, following Dixon et al. (1994), who measured corn yield response models. Lobell and Asner (2003) presented recent trends in United States agricultural yields, and Lobell and Field (2007) examined changes in global production of major crops due to climate variables. Prior research using the economic approach to the climate/crop relationship provides a solid foundation upon which to expand our knowledge of how weather and climate affect agricultural production in Kansas and the Great Plains (Black and Thompson, 1978; Hansen, 1991; Kaufmann and Snell, 1997; Brown and Rosenberg, 1999; Southworth et al., 2002; Weiss et al., 2003; Long et al., 2006; and Ferrise et al., 2011). These authors estimated the impact of weather on crop yield distributions using aggregate-level data and model simulations.

A recent study by Kunkel et al. (2013) provided an extensive, complete, and targeted synthesis of historical and plausible future climate conditions in the Great Plains region. This study included simulated differences in average annual mean and extreme temperatures and precipitation for three future time points: 2035, 2055, and 2085. The projections showed increases in temperature and extreme weather conditions, providing some evidence of the importance of improving our understanding and estimation of the impact of weather and climate on wheat yield distributions. Semenov et al. (1996) also emphasized the need to account for climatic variability when modeling wheat yields.

Methods

Following the pioneering work of Brennan (1984, 1989a, 1989b), Feyerherm et al. (1984), Byerlee and Traxler (1995), and Traxler et al. (1995), previous research on advances in Kansas wheat yields include Barkley, 1997; Barkley and Porter, 1996; and Nalley, Barkley, and Chumley, 2006 and 2008. We continue this line of research on genetic improvement by expanding the statistical yield model to include a comprehensive accounting of weather, diseases, varieties, and location in pursuit of three specific objectives: (1) to quantify the impact of private and public wheat breeding programs on wheat yields over time, (2) to estimate and forecast the potential impact of climate change on Kansas wheat yields, and (3) to quantify the impact of disease, insects, lodging, and shattering on wheat yields. Previous work on estimating the impact of genetic improvement on wheat yields includes Nalley, Barkley, Crespi, and Sayre (2009) and Nalley, Barkley, and Featherstone (2010).

Following Nalley, Barkley, and Chumley (2008), the econometric model is specified as in equation (1):

(1) $YIELD_{ijt} = \alpha + \beta_1 YR_t + \beta_2 VAR_i + \beta_3 DIS_{jt} + \beta_4 LOC_j + \beta_5 WEA_{jt} + \varepsilon_{ijt}$

where $YIELD_{ijt}$ is yield (bu/acre) for variety i at location j in year t. YR_t is a trend term for the trial year to capture all determinants of yield that are not included in the model; LOC_j is a vector of 11 location variables (listed in Table 1), with Hays (ELDF) omitted as the default category. VAR_i is a vector of qualitative variables for each of the 245 included varieties. Scout 66 was omitted as the default category. The variable DIS_{jt} is a vector of qualitative variable for the presence of diseases, insects, lodging, and shattering. WEA_{jt} is a vector of weather variables, including temperature, precipitation, and vapor pressure deficit (VPD). The error term ε_{ijlt} is assumed to be a normally distributed error term. The model includes a comprehensive number of weather variables, as defined and explained in the next section.

Data

Wheat yield data are from Kansas Performance Tests with Winter Wheat Varieties for the years 1985 through 2011. All yield data are for dryland (non-irrigated, rainfed) Hard Red Winter Wheat (HRWW), with some observations of Hard White Wheat (HWW).[1] All data are in bushels per acre, including 245 varieties in 11 locations throughout Kansas. Summary statistics and descriptions of all included variables are reported in Table 1. Average yields differ significantly across locations due to the diverse weather, soil, and growing conditions in Kansas.

Disease data were also from the Kansas Performance Tests with Winter Wheat publications. Diseases, insects, lodging, and shattering data are qualitative variables (0–1) based on field notes indicating the presence of the disease, insects, lodging, or shattering. Note that these variables are relatively crude and do not measure the degree of severity of these wheat yield determinants. In many cases, the presence of a disease does not reflect yield impacts, as shown in Results. The estimated coefficients of these variables must be interpreted with care because the presence of these diseases in some cases is associated with wet years, and the moisture can lead to higher yields. Leaf rust (LR) was the most prevalent disease, occurring in 24.9% of the location-years (Table 1). Lodging (LODGE) occurs when the wheat plant is knocked down, typically due to strong wind or hail. Shattering (SHAT) occurs when the wheat grains are knocked out of the plant and onto the ground, for the same reasons.

Weather variables include: (1) precipitation, (2) average monthly temperatures, (3) temperatures during anthesis, or flowering, and (4) vapor pressure deficit (VPD). All weather data are from the Kansas Weather Library. Precipitation is included as seasonal totals (Table 1) for fall (September, October, and November), winter (December, January, and February), and spring (March, April, and May). Squared precipitation is included to capture nonlinearities, following Roberts et al. (2013) and Rosensweig et al. (2002).

Previous research has shown that weather around anthesis can have a crucial impact on wheat plant development. Nalley, Barkley, and Sayre (2009) extended previous research and found that average temperature and solar radiation in the period 31 days prior to 1 day after anthesis provided the best fit for wheat yield data from CIMMYT experiment fields in Mexico's Yaqui Valley. This time frame is used here to quantify the impact of temperature and solar radiation on Kansas wheat yields, extending previous literature on wheat yields in Kansas and the Great Plains.

The VPD is included based on the recent work of Roberts et al. (2013), who found a statistically significant relationship between VPD and Illinois corn yields. The authors explained that VPD is related to relative humidity, and influences evaporation, evapotranspiration, and soil moisture. Roberts et al. (2013) provided calculations and explanations for how VPD affects crop yields and concluded, "We might therefore expect an increasing relationship between VPD and yield when soil moisture is adequate and a decreasing relationship between VPD and yield when soils moisture is inadequate." The formula developed by Tetens (1930) and reported by Roberts et al. (2013) is used to approximate each day's VPD (Table 1).

Daily temperature was collected at the specific location of each variety trial, resulting in a location-specific match between variety yield and weather data. This approach is unique in this branch of climate change literature, which typically relies on weather estimates over broad geographical areas. Following Schlenker and Roberts (2009), daily minimum and maximum temperatures are used to estimate the sinusoidal distribution of hours in each degree Celsius during each day. Total hours spent in each degree were summed for each month during the wheat growing season (September through May). Because harvest typically occurs during June, the data do not include weather during the final part of the growing season or during harvest. Following previous work of Schlenker and Roberts (2009), temperature was included in 3° increments. One of the challenges of research on the relationship between wheat yield and weather is the long growing season, which includes warm weather in the fall, cold weather in the winter, and warm weather again in the spring. Weather extremes occur

[1] This study focused on non-irrigated (dryland) wheat variety data to capture the influence of potential climate change on rainfed wheat. The impact of climate change on irrigated wheat is likely to be less severe on wheat yields but will require additional irrigated water due to evaporation.

throughout the growing season but vary enormously in magnitude and impact; for example, cold extremes during winter months do not damage the wheat, but winterkill occurs after the weather has warmed and the wheat plant is in the growing stage.

Monthly temperature data were measured as time spent in all 3° temperature intervals from [-34,-32] to [47,49]. Within each month, intervals capturing "extreme" temperatures were constructed as follows. First, intervals for which non-zero values were recorded at all locations within the data were identified. Observation of non-zero values across locations in all years was not required; rather, a non-zero value had to occur for each location in at least one year. Second, the threshold interval for lower extremes was defined as the lowest interval in this subset, and the threshold interval for the higher extremes was defined as the highest interval in this subset; these threshold intervals are called tmin and tmax. Third, the low temperature extreme interval was defined as the sum across all intervals at or below the tmin interval, and the high temperature extreme interval was defined at or above the tmax interval.

These extreme aggregate intervals were constructed separately for each month in the data (September through May). The construction for March is used as an illustrative example. No location experienced temperatures below -20; four locations experienced temperatures in the [-22,-20] interval; all locations experienced temperatures in the [-19,-17], [-16,-14], ... , [26,28], [29,31] intervals; seven locations experienced temperatures in the [32,34] interval; one location experienced temperatures in the [35,37] interval; and no locations experienced temperatures above 37. Applying our methodology, the low temperature extreme interval is the sum of the [-22,-20] and [-19,-17] intervals, whereas the high temperature extreme interval is the sum of the [29,31], [32,34], and [35,37] intervals. The final set of temperature intervals is then defined by [-∞,-17], [-16,-14], ..., [26,28], [29,∞]. A strength of this approach is that it allows one to safely disentangle extreme temperature outcomes from time-invariant location-specific fixed effects.

A qualitative (0-1) variable was included for each of the 245 wheat varieties to estimate the yield change over the base variety, Scout 66. The estimated coefficients were then used to quantify the impact of genetic improvement on wheat yields for all varieties grown in Kansas.

Results

Overall regression results appear in Table 2, with variety results in Table 3 and temperature results in Table 4. The trend variable YEAR had a statistically significant coefficient equal to 0.317 (Table 2), indicating an increase in wheat yields of nearly 0.32 bu/acre for all reasons excluding weather, genetics, location, and diseases. The result most likely indicates increases in grain harvesting technology, best management practices, and input improvements such as fertilizer and chemicals. This estimated coefficient includes the impact of new precision farming, reduced tillage, and satellite technology on Kansas wheat yields.

The experimental field locations had a large and statistically significant impact on yields (Table 2), with average yields ranging from -26.8 bu/acre in the West (FND, Garden City) to +5.2 bu/acre in the Northeast (RPD, Belleville). These results reflect all non-weather-related differences in growing conditions. Diseases, insects, lodging, and shattering influenced yields, with large negative estimated coefficients for wheat streak mosaic virus (WSM, -17.9 bu/acre), soilborne mosaic virus (SBM, -14.2 bu/acre), *Septoria nodorum* (SN, -13.2 bu/acre), tan spot (TS, -12.3 bu/acre), greenbugs (BUGS, -10.7 bu/acre), and shattering (SHAT, -10.1 bu/acre). Lodging (LODGE) was associated with higher yields, probably due to a relationship between heavy plants with high yields and lodging due to wind. Spindle streak mosaic virus (SSM) was not significant, most likely due to correlation with soilborne mosaic virus (SBM). Unexpected results were Hessian fly (HF) and Russian wheat aphids (RWA), which had positive estimated coefficients. Stem rust (SR) had a positive coefficient equal to 8.0 bu/acre, perhaps due to moist growing conditions that were conducive to both the disease and higher yields.

Varietal yield coefficients were nearly all positive and statistically significant compared with the default variety, Scout 66, with larger values associated with more recently released varieties (Table 3), as summarized in Figures 1 and 2. The impact of genetic improvement on wheat yields can be estimated by estimating a regression (trend) of wheat yield advantages, as measured by the estimated coefficients reported in Table 3, by the year of variety release, as shown in Figures 1 and 2. Genetic improvement has resulted in an increase of 0.5058 bu/acre per year for the wheat varieties grown in Kansas, and because the result includes all tested varieties and only the highest yielding varieties are grown, this is an underestimate. Varieties developed by the Kansas Agricultural Experiment Station (KAES) are shown in Figure 2, with a nearly identical rate of improvement for the varieties grown in experiment fields from 1985 through 2011.[2] The results suggest that when weather, disease, and location are taken into account, genetic improvement has plateaued. These results update the previous work of Battenfield et al. (2013) and Graybosch and Peterson (2010), who used different time periods.

Precipitation had a large and significant effect on wheat yields, as shown in Table 2 and Figure 3. Rainfall in the fall months (September, October, and November) had a negative then positive impact, probably due to the nature of quadratic results; the model fits the data such that these results are not uncommon. Winter precipitation increases, then decreases, and spring precipitation increases (Figure 3). Because each seasonal precipitation variable has a squared term included in the model, the change at the mean is calculated for each of the three seasons. At the mean, a 1-inch increase in fall precipitation resulted in a yield decrease of 0.30 bu/acre; results for winter and spring are 2.51 bu/acre and 0.70 bu/acre, respectively.

Locations reflect diverse growing conditions for wheat in Kansas, as summarized in Figure 4. Compared with Hays (ELDF, the default location), experimental wheat fields in Southwest Kansas had significantly lower yields, and one North Central Kansas location had higher average yields during the 1985–2011 time period. Weather during anthesis has a large impact on wheat yield (Table 2), as found in previous research summarized by Nalley et al. (2009). Temperatures during anthesis have the expected negative impact on yield. The result of solar radiation, however, is unexpectedly negative and statistically significant. The magnitude is small, but this result deserves further research.

Vapor pressure deficit (VPD) was significantly negative in four of the nine months, statistically positive in one month, and insignificant in four months (Table 2). This result most likely reflects adequate soil moisture in October and inadequate moisture during November, December, April, and May. The inclusion of VPD has a large impact on yields, as in Roberts et al. (2013). Further research and interpretation will help to refine this important contribution to climate change research.

Temperature results are reported in Table 4. Nearly all of the 3° temperature interval variables were highly statistically significant compared with the default category of 14 to 16°C. Note that the included temperature distributions vary from month to month as the distribution becomes colder, then warmer, during the course of the growing season. Although the individual coefficients are difficult to summarize, the results allow for simulations of the entire temperature range that forecast the result of a potential increase in mean temperatures during each month.

Simulations

Kunkel et al. (2013) reported that the increase in temperature in the Great Plains in the past 20 years is simulated to continue over time. For 2035, simulated temperature values ranged from 0.8 to 1.9°C. For 2055, warming ranged from 1.9 to 3.6°C. By 2085, the temperature increases were in the 1.9 to 5.3°C range. Given these forecasts, the regression results were simulated for an increase in mean temperatures of 1 and 3°C (Table 5). Changes in wheat yields occur through three sets of variables: monthly temperatures, weather during anthesis, and VPD, as summarized in Table 5. A 1°C increase in temperature from the 1985–2011 mean is simulated to result in a decrease in wheat yields equal to -10.64 bu/acre. The decrease is largely due to decreased yields during anthesis, October, November, January, and March. Vapor pressure deficit also reduced yield, with the

[2] The variety NuWest was excluded from the graph and regression in Figure 1. The estimated coefficient for this 1999 Agripro variety was -11. It is assumed that this variety was not widely planted, so it was omitted due to the large low yield coefficient.

largest effect in April. This yield decrease represents a 21% decrease (=10.64/50.59) in average yields. The magnitudes are larger for a simulated 3°C increase in mean temperature (Table 5). These simulated results are similar to previous research, including Tubiello et al. (2002) and Lobell and Field (2007).

Conclusions

We used a unique dataset that matches varietal wheat yields with location-specific weather data, allowing for estimation of a model that extends previous research in several important directions. The model estimates the impact of a complex and comprehensive set of weather variables on wheat yields, with important implications for potential climate change on wheat yields in the Great Plains. A rise in average temperatures of 1°C is simulated to reduce wheat yields by 21%, or 10.64 bushels per acre. Results also suggest that further study of weather during anthesis and VPD will likely further our understanding of the complex determinants of wheat yields.

The unique approach of including location-specific weather data, together with genetic improvement and disease data, has improved our ability to understand changes in wheat yields over time. The model results presented here advance understanding of the determinants of wheat yields. Further research is needed to replicate, refine, and expand our model.

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Table 1. Summary statistics for included variables in wheat variety yield model, 1985–2011

Variable	Definition	Mean	SD[1]	Min	Max
Dependent variable					
Yield	Wheat yield (bu/acre)	50.591	18.07	2.40	121.33
Independent variables					
Intercept	–	1.000	–	0	1
Year	Year wheat harvested	1997	7.222	1985	2011
Experiment trial location					
ELDF	Hays, Ellis County	0.115	–	0	1
FND	Garden City, Finney County	0.104	–	0	1
FRD	Ottawa, Franklin County	0.070	–	0	1
GRD	Tribune, Greeley County	0.106	–	0	1
HVD	Hesston, Harvey County	0.094	–	0	1
LBD	Parsons, Labette County	0.078	–	0	1
RLD	Manhattan, Riley County	0.064	–	0	1
RND	Hutchinson, Reno County	0.075	–	0	1
RPD	Belleville, Republic County	0.108	–	0	1
STD	St. John, Stafford County	0.066	–	0	1
THD	Colby, Thomas County	0.120	–	0	1
Disease presence					
SBM	Soilborne mosaic	0.033	–	0	1
SSM	Spindle streak mosaic	0.020	–	0	1
WSM	Wheat streak mosaic	0.047	–	0	1
BYD	Barley yellow dwarf	0.115	–	0	1
LR	Leaf rust	0.249	–	0	1
SR	Stem rust	0.020	–	0	1
STRIPE	Stripe rust	0.073	–	0	1
SLB	Speckled leaf blotch	0.043	–	0	1
GB	Glume blotch	0.020	–	0	1
TS	Tan spot	0.071	–	0	1
PM	Powdery mildew	0.081	–	0	1
HF	Hessian fly	0.014	–	0	1
RWA	Russian wheat aphid	0.027	–	0	1
BUGS	Greenbugs	0.018	–	0	1
LODGE	Lodging	0.148	–	0	1
SHAT	Shattering	0.022	–	0	1
SN	*Septoria nodorum*	0.042	–	0	1
AW	Army worms	0.012	–	0	1

continued

Table 1. Summary statistics for included variables in wheat variety yield model, 1985–2011

Variable	Definition	Mean	SD[1]	Min	Max
Precipitation					
Fall: Sept./Oct./Nov.	Fall precipitation (in.)	5.090	3.610	0	23.73
Fall squared		38.943	66.090	0	563.11
Winter: Dec./Jan./Feb. Winter precipitation (in.)		2.011	1.847	0	10.1
Winter squared		7.454	13.928	0	102.01
Spring: March/Apr./May Spring precipitation (in.)		7.151	3.719	0.29	23.31
Spring squared		64.967	73.752	0.08	543.36
Weather variables 32 days before to 2 days after anthesis					
AnthTemp	Average daily temp (°C)	14.67	-16.27	8.14	20.35
AnthSolar	Solar radiation (Langleys)	470.894	78.637	229.434	626.12
Vapor pressure deficit (VPD)					
September	VPD (kPa)	2.057	0.502	0.211	3.056
October	VPD (kPa)	1.445	0.362	0.122	2.416
November	VPD (kPa)	0.879	0.308	0.112	1.651
December	VPD (kPa)	0.586	0.185	0.079	1.131
January	VPD (kPa)	0.601	0.182	0.302	1.169
February	VPD (kPa)	0.709	0.224	0.318	1.344
March	VPD (kPa)	1.015	0.213	0.460	1.532
April	VPD (kPa)	1.390	0.253	0.959	2.227
May	VPD (kPa)	1.788	0.299	0.969	2.617

[1] Standard deviation.

Table 2. Regression results for wheat varieties grown in Kansas, 1985–2011

Variable[1]	Estimated coefficient	Robust SE[2]	t-value
Dependent variable			
Yield (bu/acre)	121.33	–	–
Independent variable			
Intercept	-522.274	158.693***	-3.29
Year	0.317	0.075***	4.23
Location			
ELDF	–	–	–
FND	-26.821	0.910***	-29.49
FRD	-1.367	1.906	-0.72
GRD	-24.591	1.580***	-15.56
HVD	-9.644	1.878***	-5.14
LBD	-6.837	2.987**	-2.29
RLD	-0.511	1.759	-0.29
RND	-6.635	1.710***	-3.88
RPD	5.237	1.022***	5.12
STD	-0.255	1.459	-0.18
THD	-12.127	1.304***	-9.30
Disease presence			
SBM	-14.201	1.374***	-10.33
SSM	1.745	1.543	1.13
WSM	-17.931	1.041***	-17.23
BYD	0.941	0.711	1.32
LR	1.616	0.578***	2.79
SR	8.005	1.372***	5.84
STRIPE	-3.739	1.259***	-2.97
SLB	6.467	1.229***	5.26
GB	-0.150	1.994	-0.07
TS	-12.289	1.063***	-11.57
PM	-2.863	1.275**	-2.25
HF	19.629	2.300***	8.54
RWA	17.750	1.448***	12.26
BUGS	-10.713	2.232***	-4.80
LODGE	2.712	0.665***	4.08
SHAT	-10.069	1.270***	-7.93
SN	-13.194	1.393***	-9.47
AW	3.069	2.197	1.40

continued

Table 2. Regression results for wheat varieties grown in Kansas, 1985–2011

Variable[1]	Estimated coefficient	Robust SE[2]	t-value
Precipitation			
Fall: Sept./Oct./Nov.	-0.709	0.189***	-3.74
Fall sqared	0.040	0.008***	4.89
Winter: Dec./Jan./Feb.	4.143	0.492***	8.42
Winter squared	-0.406	0.057***	-7.09
Spring: March/April/May	0.991	0.189***	5.25
Spring squared	-0.020	0.009**	-2.19
Weather variables 32 days before to 2 days after anthesis			
Temperature	-1.572	0.145***	-10.85
Solar radiation	-0.023	0.005***	-4.87
Vapor pressure deficit (VPD)			
September	-1.669	1.153	-1.45
October	6.967	1.499***	4.65
November	-14.164	1.804***	-7.85
December	-10.880	2.910***	-3.74
January	8.414	7.119	1.18
February	6.275	4.990	1.26
March	1.369	3.108	0.44
April	-24.671	1.964***	-12.56
May	-8.648	2.397***	-3.61
R^2	0.8130		
Adjusted R^2	0.8005		
RMSE[3]	8.3515		
Observations	6680		

[1] Temperature variables and variety variables were included and are reported in Tables 3 and 4. Anthesis day ranges are taken from Nalley, Barkley, and Sayre (2009).

[2] Standard error.

[3] Root mean squared error.

Table 3. Regression results for wheat varieties grown in Kansas, 1985–2011

Variety	Freq.	%	Release year	Breeder	Est. coef.	Robust SE[1]	t-value
ROBIDOUX	3	0.04	2011	Nebraska	20.80	7.22***	2.88
SY WOLF	3	0.04	2011	Drussel	15.49	2.18***	7.1
WB-CEDAR	7	0.1	2011	WestBred	17.51	4.31***	4.06
CJ	5	0.07	2010	AgriPro	19.40	4.08***	4.76
Greer	3	0.04	2010	AgriPro	17.25	5.74***	3
McGill	4	0.06	2010	Nebraska	14.90	4.17***	3.57
Stout	5	0.07	2010	AMIGO	13.45	3.00***	4.49
Tiger	7	0.1	2010	AgriPro	14.78	3.31***	4.46
WB-STOUT	7	0.1	2010	Nebraska	17.29	3.77***	4.59
Billings	6	0.09	2009	Oklahoma	24.04	3.70***	6.5
Everest	12	0.18	2009	Kansas	20.32	3.26***	6.22
Snowmass	7	0.1	2009	WestBred	15.28	2.76***	5.53
T158	7	0.1	2009	Drussel	22.50	2.95***	7.62
Armour	26	0.39	2008	WestBred	22.22	1.95***	11.39
Camelot	3	0.04	2008	Nebraska	12.63	5.30***	2.38
Hitch	26	0.39	2008	WestBred	18.60	2.01***	9.24
JackPot	5	0.07	2008	AgriPro	26.97	2.96***	9.1
RustBuster-N	2	0.03	2008	AgriPro	29.04	2.72***	10.66
RustBuster-S	3	0.04	2008	AgriPro	23.31	3.63***	6.42
Settler CL	3	0.04	2008	AGSECO	9.30	6.51	1.43
Spartan	8	0.12	2008	AgriPro	16.08	2.38***	6.76
T113	1	0.01	2008	DC Seed	8.85	1.28***	6.93
T-151	3	0.04	2008	Drussel	16.99	2.70***	6.29
Thunder CL	7	0.1	2008	AgriPro	16.40	3.29***	4.98
Art	22	0.33	2007	AgriPro	19.09	2.02***	9.44
Aspen	11	0.16	2007	WestBred	20.06	1.71***	11.76
Bill Brown	13	0.19	2007	Colorado	19.12	1.87***	10.24
Hawken	14	0.21	2007	AgriPro	14.69	2.21***	6.66
Overland	8	0.12	2007	Nebraska	23.68	2.47***	9.58
Ripper	14	0.21	2007	Colorado	16.42	2.31***	7.12
TAM 203	1	0.01	2007	TAMU	23.47	1.63***	14.35
TAM 304	10	0.15	2007	WestBred	20.26	2.07***	9.79
Winterhawk	21	0.31	2007	AgriPro	19.52	1.56***	12.53
Centerfield	9	0.13	2006	Oklahoma	11.99	1.90***	6.31
Duster	18	0.27	2006	Oklahoma	18.20	2.25***	8.07
Fuller	37	0.55	2006	Kansas	16.59	1.63***	10.2
NuDakota	11	0.16	2006	AgriPro	17.55	1.98***	8.88
NuGrain	16	0.24	2006	AgriPro	11.97	1.89***	6.35
Postrock	37	0.55	2006	AgriPro	16.61	1.65***	10.06

continued

Table 3. Regression results for wheat varieties grown in Kansas, 1985–2011

Variety	Freq.	%	Release year	Breeder	Est. coef.	Robust SE[1]	t-value
RonL	15	0.22	2006	Kansas	11.74	3.09***	3.8
Shocker	21	0.31	2006	AgriPro	15.44	1.86***	8.28
Smoky Hill	13	0.19	2006	Colorado	16.98	3.57***	4.76
Tarkio	5	0.07	2006	Colorado	16.30	5.48***	2.97
Bond CL	14	0.21	2005	Colorado	16.89	2.04***	8.27
Danby	50	0.75	2005	Kansas	16.08	1.48***	10.88
Guymon	8	0.12	2005	Oklahoma	13.10	1.97***	6.64
Hallam	12	0.18	2005	Nebraska	17.66	2.24***	7.9
Hatcher	22	0.33	2005	Colorado	20.55	1.63***	12.6
Infinity CL	14	0.21	2005	AGSECO	20.19	2.69***	7.51
Keota	18	0.27	2005	AGSECO	13.95	1.70***	8.2
Neosho	17	0.25	2005	AgriPro	13.88	2.26***	6.13
OK Bullet	21	0.31	2005	Oklahoma	13.29	1.90***	6.99
Okfield	11	0.16	2005	Oklahoma	14.64	2.88***	5.08
Protection CL	27	0.4	2005	AGSECO	14.96	1.48***	10.13
T-136	1	0.01	2005	Trio-Research	12.91	1.25***	10.3
TAM 112	19	0.28	2005	TAMU	20.95	1.67***	12.53
Deliver	22	0.33	2004	Oklahoma	10.40	1.87***	5.57
Endurance	27	0.4	2004	Oklahoma	18.66	1.59***	11.76
Grazit	2	0.03	2004	Star	11.69	8.23	1.42
Sturdy-2K	17	0.25	2004	AgriPro	13.73	2.16***	6.34
T-140	3	0.04	2004	DC Seed	13.26	2.20***	6.03
W99-194	5	0.07	2004	Nebraska	13.69	3.42***	4.01
Goodstreak	8	0.12	2003	Nebraska	4.68	2.46*	1.91
Overley	61	0.91	2003	Kansas	16.03	1.53***	10.47
PrairieWhite	8	0.12	2003	Farmer Direct	16.40	2.46***	6.68
Santa Fe	29	0.43	2003	AGSECO	19.49	1.82***	10.72
TAM 111	26	0.39	2003	Watley	20.44	1.69***	12.08
Burchett	12	0.18	2002	Farmer Direct	15.22	1.71***	8.89
Cisco	13	0.19	2002	Goertzen	5.58	2.82**	1.98
Gem	19	0.28	2002	AGSECO	10.65	1.92***	5.55
Harry	8	0.12	2002	Nebraska	10.36	3.74***	2.77
Ok102	24	0.36	2002	Oklahoma	11.56	1.90***	6.07
Above	25	0.37	2001	Colorado	13.32	1.54***	8.63
Ankor	12	0.18	2001	Colorado	13.45	2.40***	5.61
AP502CL	19	0.28	2001	AgriPro	11.58	1.58***	7.33
Avalanche	21	0.31	2001	Colorado	12.33	1.72***	7.16
Cutter	45	0.67	2001	AgriPro	13.55	1.54***	8.78
Golden Spike	9	0.13	2001	AgriPro	4.44	3.87	1.15

continued

Table 3. Regression results for wheat varieties grown in Kansas, 1985–2011

Variety	Freq.	%	Release year	Breeder	Est. coef.	Robust SE[1]	t-value
Jagalene	69	1.03	2001	AgriPro	15.79	1.43***	11.04
Ok101	22	0.33	2001	Oklahoma	8.50	1.79***	4.74
Wahoo	20	0.3	2001	WestBred	14.33	2.18***	6.58
2145	66	0.99	2000	Kansas	12.45	1.38***	9.02
Dumas	4	0.06	2000	AgriPro	7.68	2.15***	3.58
GM10003	4	0.06	2000	AgriPro	5.60	2.73**	2.05
Intrada	21	0.31	2000	Oklahoma	8.49	1.73***	4.9
Millennium	25	0.37	2000	Nebraska	13.55	1.46***	9.25
NuFrontier	49	0.73	2000	AgriPro	10.97	1.37***	8
NuHills	29	0.43	2000	AgriPro	14.35	2.22***	6.46
NuHorizon	37	0.55	2000	AgriPro	7.48	1.79***	4.18
Prowers 99	3	0.04	2000	Colorado	-1.43	2.50	-0.57
T111	1	0.01	2000	Drussel	27.27	1.54***	17.68
XH7463	7	0.1	2000	Colorado	17.76	2.33***	7.61
Culver	24	0.36	1999	Nebraska	8.74	1.91***	4.58
Kalvesta	25	0.37	1999	Goertzen	10.64	1.67***	6.38
Lakin	46	0.69	1999	Kansas	11.10	1.41***	7.9
Nuplains	8	0.12	1999	Nebraska	10.53	1.51***	6.99
NuWest	20	0.3	1999	AgriPro	-11.07	1.71***	-6.48
Prairie Red	22	0.33	1999	Colorado	11.85	1.63***	7.26
TAM 302	21	0.31	1999	Scott Seed	8.64	1.99***	4.34
Thunderbolt	32	0.48	1999	Kansas	13.73	1.29***	10.65
Venango	41	0.61	1999	AgriPro	12.16	1.56***	7.81
Betty	61	0.91	1998	Kansas	9.03	1.16***	7.78
Enhancer	40	0.6	1998	Goertzen	10.49	1.25***	8.39
Heyne	39	0.58	1998	Kansas	8.68	1.68***	5.17
Hondo	23	0.34	1998	AgriPro	7.31	1.88***	3.88
HR 217	14	0.21	1998	Terra	11.39	2.03***	5.6
Stanton	64	0.96	1998	WestBred	9.77	1.35***	7.23
Trego	63	0.94	1998	Danne	13.81	1.23***	11.18
Wesley	42	0.63	1998	Nebraska	16.32	1.50***	10.87
560	3	0.04	1997	Star	1.01	2.48	0.41
2174	89	1.33	1997	Oklahoma	10.95	1.14***	9.6
7588	13	0.19	1997	Quantum	18.88	1.88***	10.03
7853-D	8	0.12	1997	AGSECO	7.89	1.87***	4.21
7853-VRTU	8	0.12	1997	AGSECO	6.47	2.04***	3.17
Cossack	22	0.33	1997	Goertzen	7.63	1.50***	5.08
Exp 2139	5	0.07	1997	AGSECO	12.76	2.37***	5.39
Onaga	46	0.69	1997	AGSECO	10.89	1.48***	7.36

continued

Table 3. Regression results for wheat varieties grown in Kansas, 1985–2011

Variety	Freq.	%	Release year	Breeder	Est. coef.	Robust SE[1]	t-value
T91	1	0.01	1997	TAMU	7.93	1.35***	5.89
TAM 301	8	0.12	1997	Rinck	0.35	2.36	0.15
Windstar	25	0.37	1997	AgriPro	7.47	1.69***	4.41
Yumar	14	0.21	1997	Colorado	9.72	1.34***	7.25
566	3	0.04	1996	Quantum	18.64	1.65***	11.3
579	7	0.1	1996	Quantum	13.04	2.48***	5.25
7406	14	0.21	1996	Quantum	15.17	1.69***	8.96
7504	6	0.09	1996	Quantum	14.68	4.20***	3.5
Big Dawg	29	0.43	1996	AgriPro	6.69	1.99***	3.36
Champ Extra	5	0.07	1996	Star	26.88	5.12***	5.25
Dominator	60	0.9	1996	Polansky	12.31	1.23***	9.97
G1878	13	0.19	1996	Goertzen	6.41	1.64***	3.9
HR 153	20	0.3	1996	Terra	10.51	1.57***	6.71
TAM 110	50	0.75	1996	TAMU	11.98	1.23***	9.77
2137	150	2.25	1995	Kansas	14.02	1.02***	13.7
AP 7510	28	0.42	1995	Quantum	17.57	1.39***	12.68
T81	1	0.01	1995	Drussel	15.87	1.16***	13.62
T83	1	0.01	1995	Drussel	12.73	1.29***	9.84
Akron	30	0.45	1994	Colorado	12.30	1.25***	9.87
Alliance	40	0.6	1994	Nebraska	11.47	1.37***	8.4
AP 7501	7	0.1	1994	Quantum	12.41	2.26***	5.5
AP 7601	2	0.03	1994	Quantum	11.87	2.18***	5.43
Champ	27	0.4	1994	Star	12.24	1.94***	6.32
Colby 94	14	0.21	1994	AGSECO	11.32	1.37***	8.26
Coronado	37	0.55	1994	AgriPro	8.19	1.38***	5.94
Custer	51	0.76	1994	Oklahoma	8.75	1.63***	5.36
Halt	16	0.24	1994	Colorado	8.86	1.92***	4.62
Hickok	19	0.28	1994	AgriPro	5.40	2.01***	2.68
Jagger	150	2.25	1994	Kansas	12.41	1.07***	11.58
Jules	7	0.1	1994	Colorado	14.74	2.23***	6.62
Mankato	35	0.52	1994	AGSECO	12.80	1.53***	8.39
Nekota	17	0.25	1994	Nebraska	9.72	1.79***	5.44
Niobrara	38	0.57	1994	Nebraska	11.38	1.29***	8.81
Oro Blanco	42	0.63	1994	AWWPA	8.61	1.21***	7.14
Rowdy	10	0.15	1994	AgriPro	6.33	2.47***	2.57
Salute	6	0.09	1994	Star	4.91	3.84	1.28
Tonkawa	27	0.4	1994	AgriPro	3.91	1.77**	2.21
Voyager	38	0.57	1994	AgriPro	-1.33	1.43	-0.93
Ike	112	1.68	1993	Kansas	11.58	1.04***	11.1

continued

Table 3. Regression results for wheat varieties grown in Kansas, 1985–2011

Variety	Freq.	%	Release year	Breeder	Est. coef.	Robust SE[1]	t-value
577	21	0.31	1992	Quantum	12.19	1.84***	6.64
Arlin	48	0.72	1992	Farmer Direct	5.86	1.49***	3.93
Colby	11	0.16	1992	AGSECO	11.30	2.33***	4.84
Karl 92	135	2.02	1992	Kansas	10.07	1.04***	9.67
Karl 92-G	10	0.15	1992	Kansas	7.74	1.82***	4.25
Ogallala	23	0.34	1992	AgriPro	9.67	1.48***	6.53
Ponderosa	21	0.31	1992	AgriPro	3.61	1.75**	2.07
Vista	55	0.82	1992	Colorado	9.59	1.40***	6.84
578	3	0.04	1991	Quantum	4.37	2.61*	1.68
9001	23	0.34	1991	AGSECO	10.00	1.49***	6.72
Discovery	42	0.63	1991	Century II	4.46	1.35***	3.31
Kleo Red	10	0.15	1991	Pharaoh	-1.23	2.59	-0.48
Kleo White	8	0.12	1991	Pharaoh	1.70	3.05	0.56
Laredo	16	0.24	1991	AgriPro	7.57	1.81***	4.17
Pecos	32	0.48	1991	AgriPro	7.95	1.78***	4.46
Rawhide	29	0.43	1991	Nebraska	3.42	1.58**	2.16
TAM 109	4	0.06	1991	AGSECO	1.05	2.39	0.44
TAM 202	9	0.13	1991	TAMU	0.63	1.98	0.32
Yuma	34	0.51	1991	Colorado	10.53	1.20***	8.78
561	8	0.12	1990	Quantum	7.41	2.84***	2.61
562	29	0.43	1990	Quantum	8.77	1.45***	6.04
574	14	0.21	1990	Quantum	7.41	2.30***	3.22
2158	11	0.16	1990	Pioneer	2.04	1.42	1.44
Cimarron	49	0.73	1990	Oklahoma	7.20	1.31***	5.51
Longhorn	16	0.24	1990	AgriPro	4.69	1.62***	2.89
Tomahawk	57	0.85	1990	Oklahoma	9.48	1.38***	6.85
2163	119	1.78	1989	Pioneer	10.37	1.10***	9.41
7853	101	1.51	1989	AGSECO	8.18	1.07***	7.62
Bronco	22	0.33	1989	AgriPro	3.51	1.31***	2.69
Sierra	38	0.57	1989	Nebraska	6.89	1.45***	4.74
Siouxland 89	11	0.16	1989	AGSECO	4.27	2.66	1.61
Tut	9	0.13	1989	Goertzen	1.59	3.15	0.5
2180	49	0.73	1988	Pioneer	7.45	1.61***	4.63
7833	28	0.42	1988	AGSECO	3.79	1.85**	2.05
Arapahoe	69	1.03	1988	Nebraska	9.17	1.20***	7.63
Karl	87	1.3	1988	Kansas	7.75	1.25***	6.21
Lamar	8	0.12	1988	Colorado	5.75	1.92***	2.99
Rio Blanco	50	0.75	1988	AWWPA	2.26	1.25***	1.81
7805	30	0.45	1987	AGSECO	7.24	1.47***	4.92

continued

Table 3. Regression results for wheat varieties grown in Kansas, 1985–2011

Variety	Freq.	%	Release year	Breeder	Est. coef.	Robust SE[1]	t-value
7846	61	0.91	1987	AGSECO	6.44	1.23***	5.23
Abilene	44	0.66	1987	AgriPro	7.34	1.45***	5.05
Mesa	38	0.57	1987	AgriPro	5.49	1.56***	3.52
TAM 200	79	1.18	1987	TAMU	6.95	1.16***	6.01
2154	10	0.15	1986	Pioneer	1.07	2.20	0.48
7837	41	0.61	1986	AGSECO	2.67	1.31**	2.04
Carson	7	0.1	1986	Colorado	0.11	2.54	0.04
Century	55	0.82	1986	Oklahoma	5.71	1.43***	3.98
Cody	10	0.15	1986	Nebraska	0.81	1.90	0.43
Dodge	34	0.51	1986	Kansas	-2.84	1.36**	-2.09
Norkan	46	0.69	1986	Kansas	1.36	1.34	1.01
Redland	25	0.37	1986	Nebraska	6.33	1.57***	4.02
205	25	0.37	1985	Bounty	10.35	2.13***	4.85
2172	47	0.7	1985	Pioneer	7.24	1.35***	5.38
HR-48	18	0.27	1985	Garst	5.53	2.22**	2.5
Pony	18	0.27	1985	RHS	4.90	2.16**	2.27
Stallion	10	0.15	1985	Kansas	3.84	3.00	1.28
Thunderbird	62	0.93	1985	AgriPro	6.07	1.25***	4.87
Trailblazer	6	0.09	1985	Kansas	1.95	3.65	0.53
Victory	56	0.84	1985	Nebraska	6.87	1.15***	5.97
301	25	0.37	1984	Bounty	10.04	1.90***	5.29
Siouxland	55	0.82	1984	Nebraska	5.39	1.36***	3.96
TAM 107	168	2.51	1984	TAMU	7.38	0.98***	7.55
TAM 108	54	0.81	1984	TAMU	5.76	1.48***	3.88
202	18	0.27	1983	Bounty	6.19	3.17**	1.95
203	9	0.13	1983	Bounty	16.51	2.40***	6.87
2157	39	0.58	1983	Pioneer	1.56	1.40	1.11
Centura	24	0.36	1983	Nebraska	5.23	2.20***	2.38
Chisholm	38	0.57	1983	Oklahoma	5.35	1.57***	3.4
Colt	29	0.43	1983	Nebraska	2.67	1.57*	1.7
Mustang	37	0.55	1983	AgriPro	4.24	1.55***	2.74
Ram	7	0.1	1983	AgriPro	9.88	2.32***	4.25
Wrangler	10	0.15	1983	Quantum	8.03	2.52***	3.18
310	9	0.13	1982	Bounty	9.72	2.58***	3.77
Arkan	97	1.45	1982	Kansas	1.32	1.09	1.22
HR-64	18	0.27	1982	Garst	2.42	2.40	1.01
Brule	12	0.18	1981	Nebraska	2.34	1.94	1.21
Hawk	20	0.3	1981	AgriPro	3.70	2.02***	1.84
Sandy	8	0.12	1980	Colorado	0.90	1.77	0.51

continued

Table 3. Regression results for wheat varieties grown in Kansas, 1985–2011

Variety	Freq.	%	Release year	Breeder	Est. coef.	Robust SE[1]	t-value
TAM 105	33	0.49	1979	TAMU	0.55	1.69	0.32
Centurk 78	12	0.18	1978	Nebraska	0.82	2.87	0.29
Newton	161	2.41	1977	Kansas	2.00	0.93**	2.16
Payne	1	0.01	1977	Oklahoma	6.06	1.22***	4.96
Wings	1	0.01	1977	WestBred	13.44	1.65***	8.14
Larned	124	1.86	1976	Kansas	2.89	0.98***	2.95
Parker 76	3	0.04	1976	Kansas	1.61	1.81	0.89
Vona	22	0.33	1976	Century II	1.43	2.38	0.6
Eagle	6	0.09	1970	Kansas	1.33	2.55	0.52
Scout 66	170	2.54	1967	Nebraska	(default)	–	–
Triumph 64	35	0.52	1964	Pharaoh	2.47	1.61	1.53

[1] Standard error.

Table 4. Regression results for temperature effects on Kansas wheat yields

Variable	Mean	Est. coef.	Robust SE[1]	t-value
September				
< +1	2.306	0.354	0.083***	4.28
+2 to +4	7.206	-0.335	0.054***	-6.18
+5 to +7	18.843	0.488	0.039***	12.49
+8 to +10	39.208	0.008	0.034	0.25
+11 to +13	66.922	0.252	0.027***	9.41
+17 to +19	104.098	0.176	0.029***	6.18
+20 to + 22	106.136	-0.044	0.027*	-1.65
+23 to +25	93.960	-0.098	0.024***	-4.06
+26 to +28	79.766	0.204	0.026***	7.86
+29 to +31	60.991	0.378	0.032***	11.93
+32 to +34	36.379	-0.051	0.022**	-2.31
+35 to +37	12.893	0.153	0.048***	3.16
> +38	2.745	0.605	0.065***	9.33
October				
< -8	0.979	0.908	0.087***	10.46
-7 to -5	2.917	0.411	0.077***	5.32
-4 to -2	9.506	0.109	0.049**	2.22
-1 to +1	28.941	0.458	0.028***	16.25
+2 to +4	55.258	0.374	0.033***	11.32
+5 to +7	80.514	0.282	0.027***	10.65
+8 to +10	96.821	0.308	0.029***	10.75
+11 to +13	102.085	0.124	0.034***	3.64
+17 to +19	90.368	0.314	0.035***	9.08
+20 to + 22	75.132	0.424	0.037***	11.40
+23 to +25	49.788	0.138	0.029***	4.75
+26 to +28	29.776	0.293	0.038***	7.75
+29 to +31	14.968	-0.069	0.039*	-1.76
+32 to +34	4.755	-0.532	0.065***	-8.16
> +35	0.849	2.471	0.110***	22.49

continued

Table 4. Regression results for temperature effects on Kansas wheat yields

Variable	Mean	Est. coef.	Robust SE[1]	t-value
November				
< -11	8.039	-0.616	0.039***	-15.67
-10 to -8	14.888	-0.208	0.048***	-4.30
-7 to -5	31.997	-0.114	0.033***	-3.46
-4 to -2	62.370	-0.223	0.029***	-7.68
-1 to +1	97.513	-0.234	0.028***	-8.48
+2 to +4	112.399	-0.188	0.026***	-7.35
+5 to +7	100.538	-0.135	0.026***	-5.19
+8 to +10	86.947	-0.507	0.031***	-16.28
+11 to +13	71.922	-0.262	0.037***	-7.07
+17 to +19	38.008	-0.452	0.042***	-10.75
+20 to + 22	23.542	-0.164	0.043***	-3.85
+23 to +25	12.513	0.152	0.047***	3.27
> +26	3.451	-1.150	0.074***	-15.44
December				
< -26	0.959	1.221	0.104***	11.71
-25 to -23	1.663	0.774	0.119***	6.48
-22 to -20	4.277	-0.199	0.070***	-2.84
-19 to -17	8.206	0.727	0.049***	14.68
-16 to -14	14.891	0.427	0.047***	9.01
-13 to -11	26.821	0.215	0.043***	4.98
-10 to -8	46.691	0.384	0.034***	11.45
-7 to -5	78.247	0.358	0.032***	11.01
-4 to -2	113.663	0.499	0.033***	14.99
-1 to +1	125.685	0.353	0.033***	10.57
+2 to +4	101.752	0.323	0.035***	9.18
+5 to +7	80.222	0.410	0.035***	11.79
+8 to +10	60.549	0.654	0.035***	18.78
+11 to +13	39.754	0.347	0.041***	8.55
+17 to +19	11.623	0.553	0.054***	10.28
> +20	4.544	0.266	0.066***	4.03

continued

Table 4. Regression results for temperature effects on Kansas wheat yields

Variable	Mean	Est. coef.	Robust SE[1]	t-value
January				
< -20	4.341	-0.104	0.067	-1.56
-19 to -17	9.013	-0.398	0.052***	-7.62
-16 to -14	19.893	0.267	0.049***	5.42
-13 to -11	37.891	-0.348	0.042***	-8.22
-10 to -8	61.660	0.073	0.044*	1.68
-7 to -5	92.102	-0.163	0.039***	-4.18
-4 to -2	113.365	-0.062	0.038*	-1.61
-1 to +1	114.838	-0.292	0.044***	-6.59
+2 to +4	90.997	-0.075	0.042*	-1.78
+5 to +7	70.212	-0.083	0.042**	-1.98
+8 to +10	53.359	-0.039	0.038	-1.01
+11 to +13	37.455	-0.110	0.055**	-1.98
+17 to +19	11.128	-0.633	0.064***	-9.91
+20 to + 22	4.235	1.312	0.083***	15.78
> +23	1.130	-0.773	0.119***	-6.50
February				
< -17	11.408	0.086	0.040**	2.17
-16 to -14	12.187	0.164	0.059***	2.80
-13 to -11	20.467	0.135	0.038***	3.60
-10 to -8	35.778	-0.080	0.034**	-2.36
-7 to -5	61.532	-0.039	0.029	-1.34
-4 to -2	89.415	0.177	0.032***	5.57
-1 to +1	104.833	-0.028	0.033	-0.87
+2 to +4	93.866	0.011	0.033	0.32
+5 to +7	78.419	0.299	0.032***	9.27
+8 to +10	59.488	-0.030	0.032	-0.97
+11 to +13	45.259	0.326	0.041***	7.90
+17 to +19	19.823	-0.415	0.053***	-7.85
+20 to + 22	10.034	-0.156	0.062***	-2.54
+23 to +25	3.266	-0.010	0.089	-0.11
> +26	0.609	1.531	0.168***	9.09

continued

Table 4. Regression results for temperature effects on Kansas wheat yields

Variable	Mean	Est. coef.	Robust SE[1]	t-value
March				
< -17	0.873	-0.762	0.108***	-7.08
-16 to -14	2.623	-0.054	0.064	-0.85
-13 to -11	5.746	-0.171	0.060***	-2.87
-10 to -8	13.173	-0.356	0.046***	-7.75
-7 to -5	26.776	-0.086	0.039**	-2.18
-4 to -2	52.673	0.060	0.034*	1.79
-1 to +1	93.867	-0.231	0.027***	-8.68
+2 to +4	108.736	-0.088	0.029***	-3.05
+5 to +7	102.126	-0.150	0.025***	-6.00
+8 to +10	88.121	-0.253	0.037***	-6.91
+11 to +13	77.114	0.211	0.032***	6.50
+17 to +19	49.218	-0.275	0.042***	-6.52
+20 to + 22	31.236	-0.437	0.043***	-10.25
+23 to +25	17.743	-0.057	0.048	-1.18
+26 to +28	7.477	-0.076	0.059	-1.27
> +29	1.914	-0.412	0.098***	-4.19
April				
< -5	3.872	-0.023	0.040	-0.57
-4 to -2	12.352	-0.254	0.039***	-6.60
-1 to +1	35.445	-0.136	0.028***	-4.85
+2 to +4	64.796	-0.162	0.025***	-6.61
+5 to +7	89.731	-0.112	0.030***	-3.69
+8 to +10	101.985	-0.124	0.025***	-5.05
+11 to +13	102.015	-0.246	0.034***	-7.34
+17 to +19	79.740	-0.302	0.033***	-9.12
+20 to + 22	58.691	0.051	0.037	1.35
+23 to +25	39.468	-0.146	0.044***	-3.33
+26 to +28	23.721	-0.041	0.044	-0.95
+29 to +31	10.476	-0.287	0.048***	-5.95
> +32	3.946	-0.101	0.050**	-2.05

continued

Table 4. Regression results for temperature effects on Kansas wheat yields

Variable	Mean	Est. coef.	Robust SE[1]	t-value
May				
-1 to +1	2.694	-0.218	0.075***	-2.93
+2 to +4	10.072	0.091	0.051*	1.79
+5 to +7	26.591	-0.187	0.036***	-5.22
+8 to +10	60.330	-0.100	0.026***	-3.87
+11 to +13	93.616	-0.059	0.028**	-2.12
+17 to +19	121.085	-0.171	0.027***	-6.44
+20 to + 22	109.295	-0.188	0.028***	-6.82
+23 to +25	88.843	-0.112	0.027***	-4.13
+26 to +28	62.568	-0.060	0.026**	-2.29
+29 to +31	35.226	0.345	0.033***	10.36
+32 to +34	14.129	0.128	0.036***	3.60
> +35	5.118	-0.177	0.056***	-3.19

[1] Standard error.

Table 5. Simulation results for potential increases in temperature on Kansas wheat yields

Variable	Yield change	
	1° (C)	3° (C)
	------------------------- (bu/acre) -------------------------	
Average temperature during anthesis		
Anthesis	-0.87	-2.62
Monthly temperatures		
September	0.16	0.49
October	-3.07	-9.21
November	-5.57	-16.71
December	1.66	4.98
January	-2.06	-6.18
February	-0.95	-2.86
March	-2.67	-8.00
April	0.15	0.46
May	5.52	16.56
Vapor pressure deficit (VPD)		
September	-0.18	-0.58
October	0.57	1.79
November	-0.74	-2.35
December	-0.40	-1.28
January	0.33	1.03
February	0.28	0.89
March	0.09	0.27
April	-2.01	-6.34
May	-0.86	-2.72
Total change	-10.64	-32.36

Figure 1. Yield Advantage of Wheat Varieties Grown in Kansas, 1976-2012 [Check Variety: Scout 66]

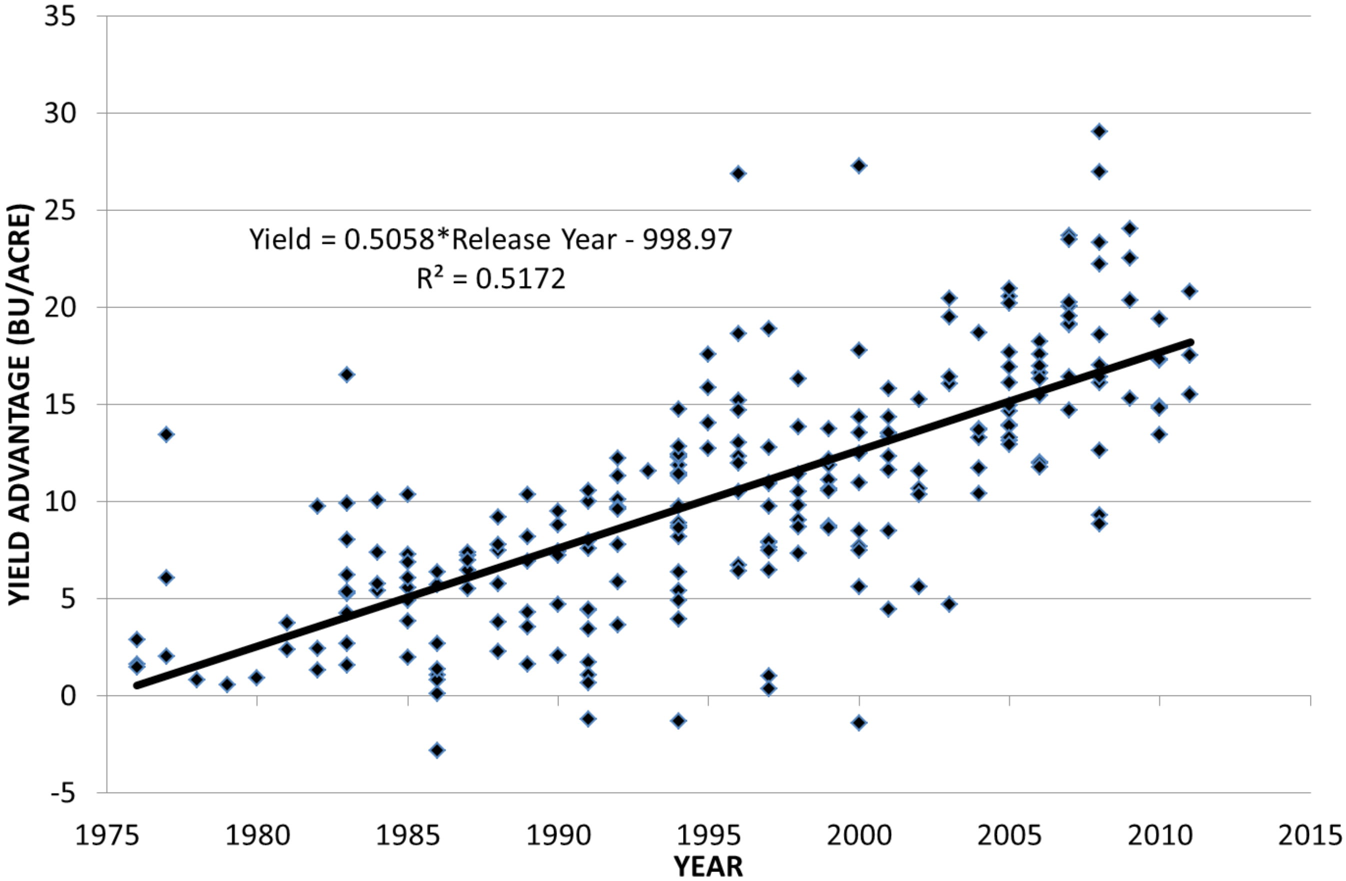


Figure 2. Yield Advantage of Kansas Wheat Varieties, 1976-2012 [Check Variety: Scout 66]

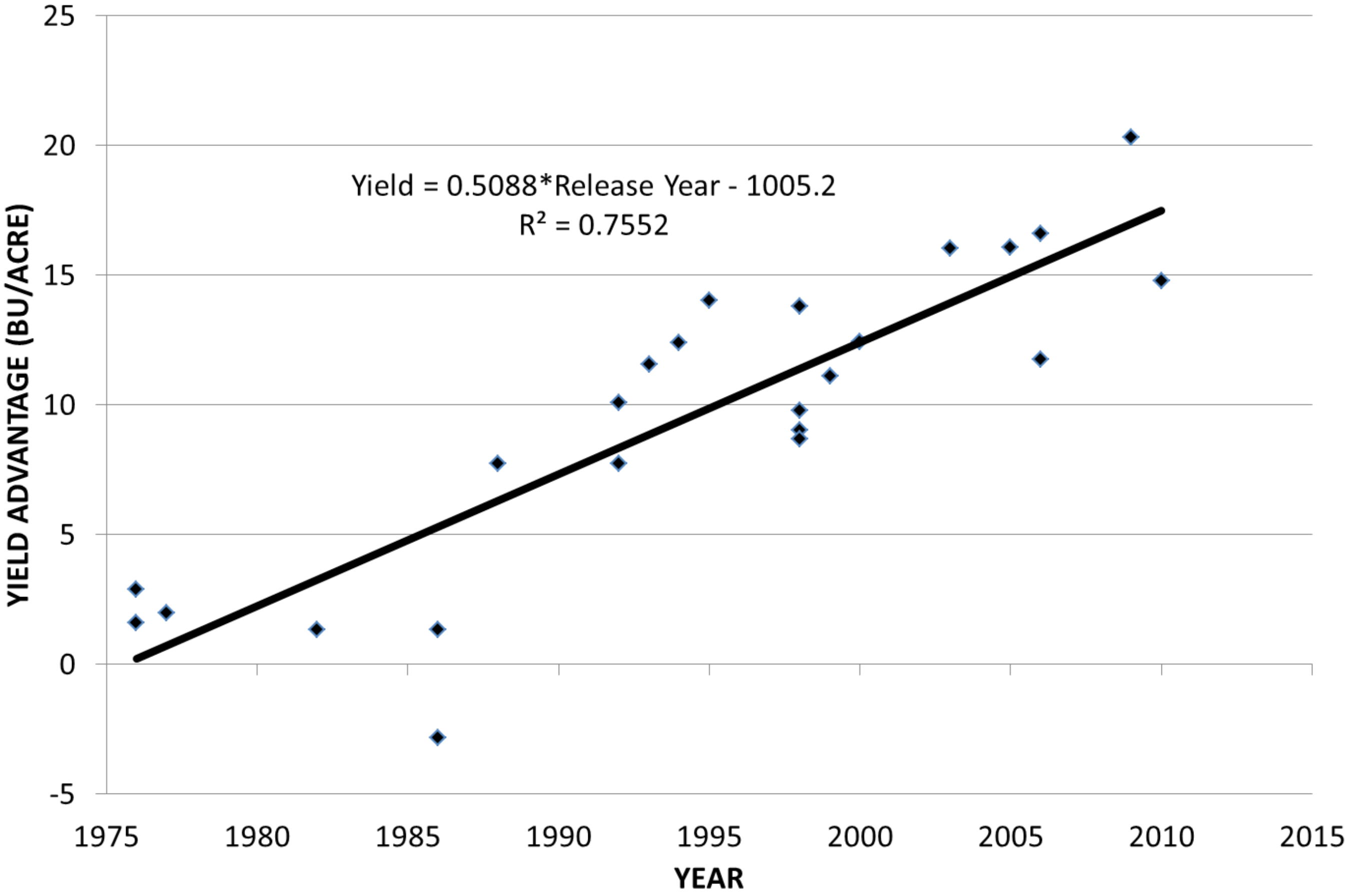


Figure 3. Precipitation Impact on Kansas Wheat Yields, 1985-2012

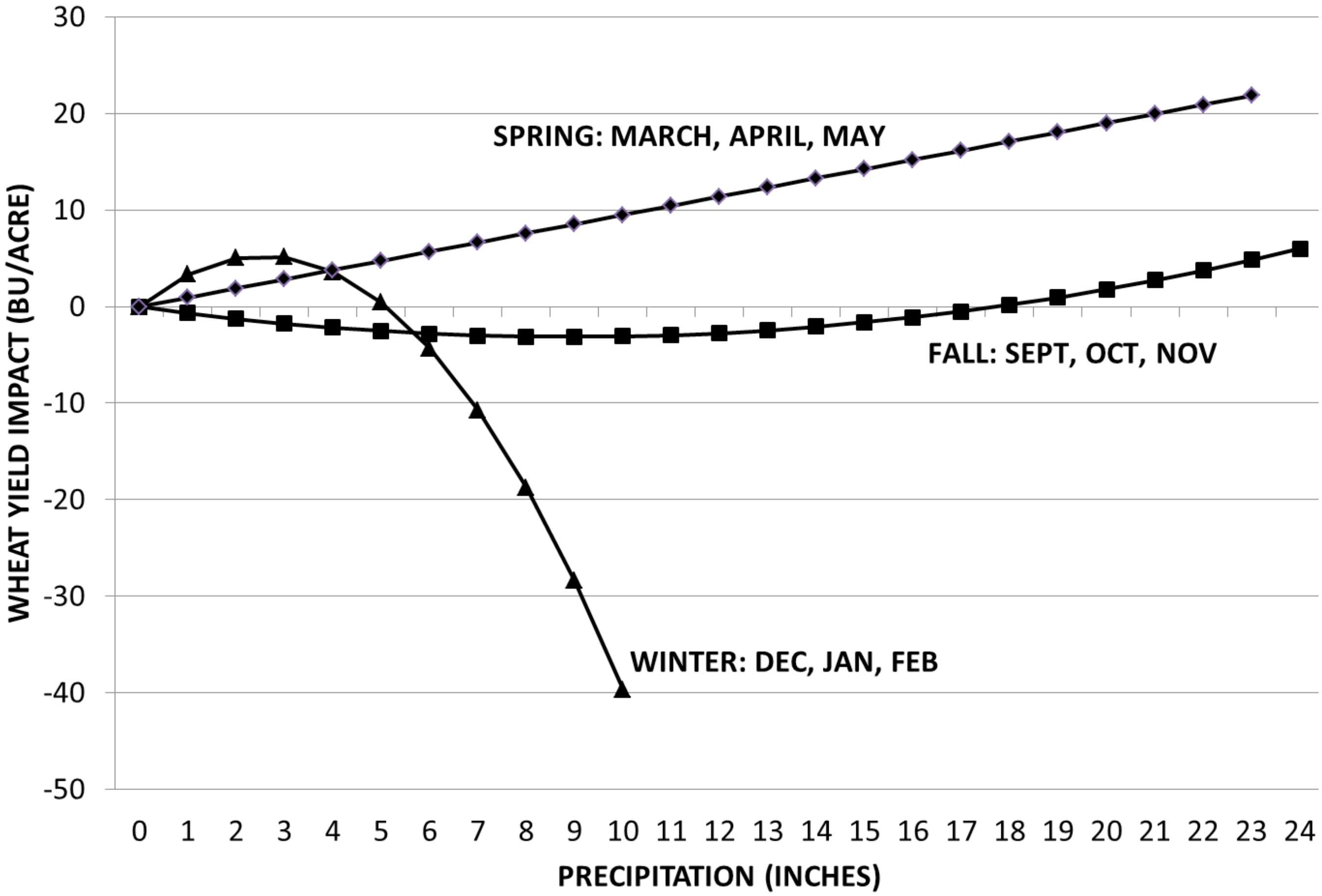
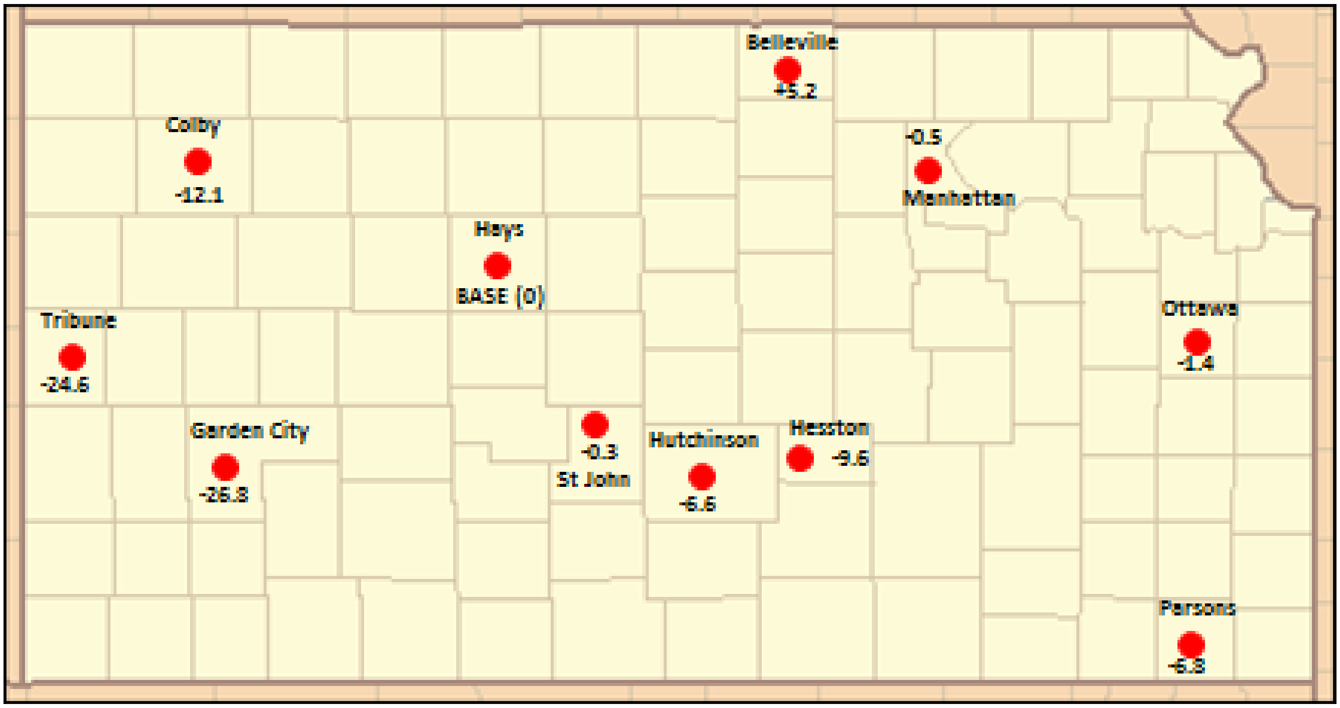


FIGURE 4. KANSAS WHEAT YIELDS BY LOCATON, 1985-2012.



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SB665 August 2013