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The Impact of the Kansas Wheat Breeding Program on Wheat Yields, 1911–2006

Lawton Lanier Nalley, Andrew Barkley, and Forrest Chumley

This paper quantifies advances of the Kansas Agricultural Experiment Station (KAES) wheat breeding program for two time periods: (1) 1911 to 2006 and (2) 1977 to 2006. Using multiple regression, increases in yields of wheat varieties grown in Kansas are quantified, holding growing conditions and other improvements in productivity constant. Differences in KAES variety yields and those released by other public and private breeders are quantified. During the "new age" of wheat breeding (1977–2006), wheat breeding alone is found to have increased yields by 6.182 bushels per acre, or an average increase of 0.206 bushels per year.

Key Words: wheat yield, public wheat breeding, multiplicative heteroscedasticity, economic impact of technological change

JEL Classifications: O13, Q16

This paper quantifies advances of the Kansas Agricultural Experiment Station (KAES) wheat breeding program for two time periods: (1) 1911 to 2006 and (2) 1977 to 2006. The KAES at Kansas State University has collected data on wheat performance test yields since 1911, a natural starting point for our study. The second time period is from 1977 through 2006, since the first semidwarf wheat variety Newton was released in 1977, initiating the "new age" of wheat breeding in Kansas (Figure 1).

KAES has invested a large amount of public expenditures in wheat breeding research each year for several decades. Estimates of the impact of the wheat breeding program on increasing wheat yields provide information to scientists, administrators, and policy makers regarding the efficacy and return to these investments. Quantitative estimates of yield improvements due to the wheat breeding program provide important information for future funding decisions. Estimates of yield improvement also allow for the completion of a cost-benefit analysis of the wheat breeding program and for evaluation and assessment of the impact of the program.

With multiple regression, increases in Kansas wheat variety yields are quantified, holding constant growing conditions and other technological enhancements in productivity. The yield differential for each wheat variety included in the annual wheat performance tests is measured. Differences in yields between KAES wheat varieties and varieties released by other public and private breeders are quantified. The study also quantifies the

Lawton Lanier Nalley is assistant professor, Department of Agricultural Economics and Agribusiness, University of Arkansas, Fayetteville, AR. Andrew Barkley and Forrest Chumley are professor, Department of Agricultural Economics, and Associate Director, Kansas Agricultural Experiment Station, respectively, Kansas State University, Manhattan, KS.

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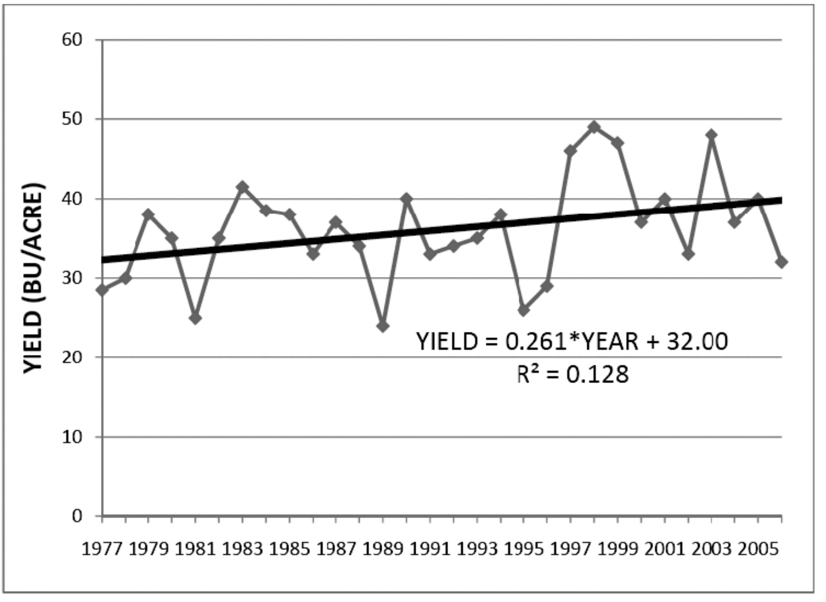

Figure 1. Kansas On-Farm Wheat Yields and Trend, 1977–2006

yield differentials across wheat characteristics, including white, soft, and blended wheat varieties. With the regression results, technological advances in the wheat breeding industry are identified and the contribution of the KAES wheat breeding program to the Kansas economy is summarized.

Measurements of the Benefits of Wheat Breeding Programs

The methodology used to calculate the economic benefits of the Kansas wheat breeding program followed a rich literature on the economic impacts of agricultural research, as summarized by Alston, Norton, and Pardey and Huffman and Evenson. Previous evaluations of wheat breeding programs were conducted by Barkley, Blakeslee and Sargent, Brennan (1984, 1989a, and 1989b), and Byerlee and Traxler.

The first step in evaluating the economic impact of the Kansas wheat breeding program is to measure the increase in yields from the genetic improvement of wheat, holding all other production parameters constant. Gains in wheat yield can be attributed to two types of factors, genetic and agronomic. Agronomic management gains are attributed to improvements in fertilizer, pesticides, fungicides, or other factors that are not embodied in the seed. For example, Foster and Babcock examined the determinants of growth in per acre yields in tobacco, paying careful attention to policy-induced price changes and technology supply shifts. Kaliba, Verkuijl, and Mwangi studied varietal selection of improved maize seeds in Tanzania.

Genetic gains, on which this study is based, are associated with improved wheat breeding or technology that is embodied within the seed. Quantifying the genetic gains, or those associated with breeding programs, was accomplished by applying the methodology of Feyerherm, Paulsen, and Sebaugh to calculate the relative yields for each variety with data from KAES performance tests with wheat varieties. Use of relative yield performance data from nurseries implicitly assumes that actual producer yields are proportional to test plot yields in KAES experiments. Although a gap between experimental and actual yields exists (Figure 2), Brennan (1984) wrote, "The only reliable sources of relative yields are variety trials" (p. 182). Therefore, annual changes in relative yields are measured with performance test data.

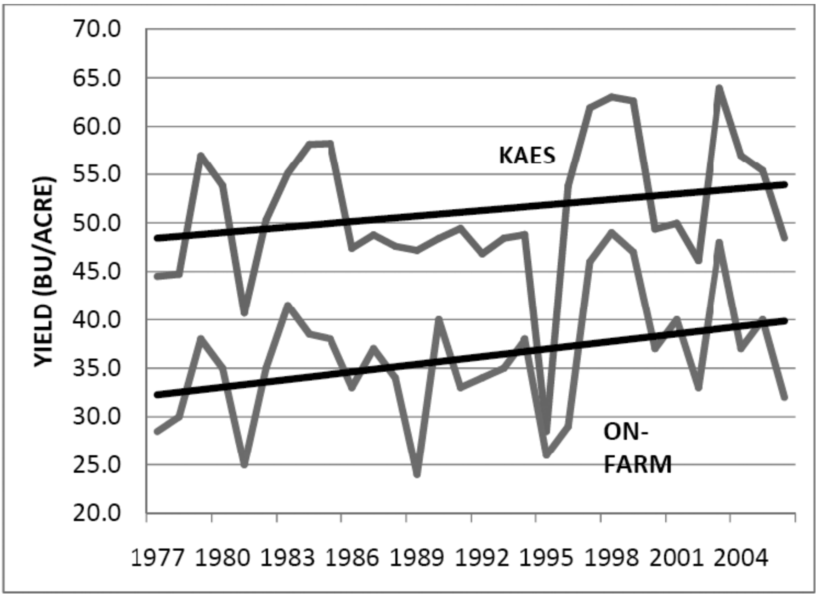

Figure 2. Average Kansas Wheat Yields for KAES Test Plots and On-Farm, 1977–2006

Data

Data were taken from the annual "Kansas Performance Tests with Winter Wheat Varieties," published by the KAES at Kansas State University. The data set included test results for 282 wheat varieties produced by 46 seed companies. The locations of the performance tests throughout the state of Kansas were then assigned a number so that each yield result could be matched with its specific location within the state. Variables were defined for (1) irrigation, (2) public or private varieties, (3) soft varieties, and (4) varietal blends. Lastly, both the year that the wheat was tested and the year that the wheat was released to the public were defined and included in the data set. The data included 14,492 observations for the period 1911–2006, and 9,333 observations for the 1977–2006 period.[1] The breaking point 1977 was used because of the introduction of the semidwarf gene into KAES breeding. As breeding advanced in the 1960s and yield increased, "tall" wheat varieties began to lodge (fall over) due to the heavier yield. Lodging can both reduce yield and increase disease and pests. By introducing the semidwarf gene into wheat varieties, a stronger stouter plant is produced with the magnitude of lodging lessened (Reitz; Reitz and Salmon).

Year Variable

The year variable is the time series component of the panel data, crucial to holding annual changes in growing conditions and technology constant. The year variable captures annual variations in weather, such as a drought, or an atypical amount of rain or subsoil moisture, *ceteris paribus*. The year variable also holds constant nonbreeding technological changes in wheat production practices that have taken place during the two time periods, and their impact on yield per acre. A major change in nonbreeding technology during the 1977–2006 time period in Kansas would be the introduction of no-till practices and the use of precision fertilizer application, both of which are aimed at reducing cost but can also affect yield. The year variables will be used only as a fixed effects component in the subsequent model.

Release Year Variable

After the previous research of Brennan (1984) and Traxler et al., the release year (*RLYR*)

[1] The 1977–2006 observations are a subset of the 1911–2006 database.

variable can be interpreted as the "vintage" of the wheat breeding technology (Traxler et al.). It captures the progression of wheat breeding technology across time, forming the main variable for measurement and analysis of the impact of a wheat breeding program on wheat yields in performance fields. That is, the coefficient on *RLYR* represents the increases in yield due to genetic gains attributable to a wheat breeding program.

Release year is not a time trend variable but is modeled similarly to the way that Arrow's (1962) growth model denoted embodied technology (Traxler et al.). Arrow assigned "serial numbers" of ordinal magnitude to the embodied technology in capital. In this model the variable *RLYR* represents the embodied technology for a given year of release by the KAES breeding program. Therefore, the coefficient on *RLYR* possesses both a cardinal and ordinal significance in defining the spacing as well as the sequencing of releases (Traxler et al.).

Station Variable

The station variable is the cross-sectional component of the panel data and plays a pivotal role in holding growing conditions constant across the growing regions. Growing conditions vary by location. Rainfall and other growing conditions in western Kansas diverge greatly from the eastern Kansas experiment stations. Southeastern Kansas typically gets over twice the rain that western Kansas receives. For example, in 2006 the Parsons experiment station (in Labette county) located in the southeast corner of Kansas received 37.87 inches of rain compared to the Tribune experiment station (in Greeley county) located in western Kansas that received just 19.38 inches (Kansas Weather Library). Another spatial difference would be the presence of rust. Owing to the high rainfall in the central and southeastern part of the state, the exposure of rust is higher than in the dryer western part of the state. Agronomic conditions also vary with soil in the western part of the state, holding water at a much higher rate than the soil in the eastern part of the state.

Where the *Year* variable can determine if a given growing season is abnormally wet or dry for the state as whole, the station variable can determine within a year if a specific location is abnormally wet or dry. These differences in growing conditions across experiment field locations, or stations, are accounted for by inclusion of the station variable in the regression model. In some instances there are both irrigated and dry land test plots within an experiment station. This is accounted for by using a binary variable to represent those plots which are irrigated.

Varieties and Public/Private Variables

A binary variable was assigned to each variety if it was released by a public research university (Kansas State University, Texas A&M, University of Nebraska, etc., *PRIVATE* = 0) or a private research company (*PRIVATE* = 1). The data included a wide diversity of varieties, from Turkey, released in 1911, to the most recently released 2006 variety. This allows for any differences between the yields of privately developed wheat breeds and publicly released varieties. Fuglie and Walker found that competition between private and public breeding programs can occur in applied breeding programs. The importance of varietal selection was recently emphasized by Richards and Green. In 1977, less than 2% of Kansas was planted to private varieties, but in recent years Kansas has seen a rapid increase in adoption of private varieties, reaching nearly 33% in 2006. A separate binary variable was added to analyze those varieties released by Kansas State University (KAES) and to track their performance in comparison with the other varieties. The percentage of acres planted to KAES varieties in Kansas has varied minimally; 35% of wheat planted in 1977 in Kansas was planted to KAES varieties compared to 43% in 2006. The continuing coexistence of public and private varieties demonstrates that wheat seeds from both types of program are economically viable, and yields of each type of variety are extensively planted.

White, Soft, and Blended Variables

White wheat was distinguished with a separate variable because of its increase in popularity among breeders and millers, together with the interest from international buyers. The possible advantages of white wheat over red wheat, however, are associated with end use, and not necessarily agronomic performance. Hard white (HW) wheat is the newest class of wheat to be grown in the United States. It is used for noodles, yeast breads, and flat breads and is grown in California, Idaho, Kansas, and Montana. One advantage of hard white wheat commonly cited is the potential for an increase in the flour extraction rate. Another potential advantage of hard white wheat is that it may increase demand for U.S. wheat, because some importing countries prefer hard white wheat to hard red wheat (Boland and Dhuyvetter). Currently, HW wheat is used primarily in domestic markets with limited quantities being exported. Soft white (SW) wheat is a preferred class of wheat for flat breads, cakes, pastries, crackers, and noodles and is grown primarily in the Pacific Northwest. Soft white is a relatively low-protein wheat, usually about 10% protein. Soft white wheat represents just over 20% of total U.S. exports, primarily to Asia and the Middle East (Kansas Wheat Commission). The data include qualitative (0–1) variables for both white and soft attributes. There is also a qualitative variable defined and included for blended wheat varieties. Blended varieties are mixtures of seeds from two or more different pure varieties. Blends have become increasingly popular in Kansas as a means of increasing yields and decreasing production risk (Bowden et al.). Blended wheat varieties are relatively new entrants into the performance tests, and as a result the sample size was low (0.68%).

Model

An ordinary least-squares (OLS) regression was estimated using LIMDEP 8.0 to identify and quantify the determinants of performance test wheat yields in Kansas. The conceptual regression model is

$$
\begin{aligned}
Yield_{ijt} &= \alpha + \beta_1 White_i + \beta_2 Soft_i \\
&\quad + \beta_3 RLYR_i + \beta_4 Private_i + \beta_5 Blend_i \\
&\quad + \beta_5 KAES_i + \boldsymbol{\delta}_t + \boldsymbol{\theta}_i + \varepsilon_{ijt},
\end{aligned} \tag{1}
$$

where $Yield_{ijt}$ is the yield in bushels per acre for variety i, at station j, in time period t. $White_i$, $Soft_i$, and $Blend_i$ are qualitative variables (0–1) for variety i. $RLYR_i$ is the release year for variety i. The term $\boldsymbol{\delta}_t$ represents a vector of qualitative variables for each year (t), from $t = 1911$ to $t = 2006$, with $t = 2006$ being omitted as the base (default) year, or from $t = 1977$ to $t = 2006$ for the second period under investigation. The variable $Private_i$ is a binary variable that indicates whether a given variety has been released by a private breeder. The term $\boldsymbol{\theta}_j$ is a vector of qualitative variables for each of the 37 locations, or experiment stations, where the variety test performance experiments are conducted during 1911–2006, and 27 locations during 1977–2006. Station 14 (Manhattan) is the omitted, or base, category. The term $KAES_i$ signifies those varieties that were developed and released by the KAES wheat breeding program. The default then is other publicly released excluding KAES lines. That is, KAES is not a subset of public varieties but rather a separate entity in itself. In this manner KAES varieties can be compared to privately released varieties along with other publicly released varieties.

Because of the pooled nature of the data set, special consideration was given to the empirical estimation method. The unbalanced cross-section, time series model reported for 1911–2006 (Table 1) follows Johnston (p. 397). This regression provides historical perspective but is less relevant for economic analysis of the modern Kansas wheat breeding program. The impact of the wheat breeding program for the period 1977–2006 was estimated to capture the yield increases for semidwarf wheat varieties. Regression model 1 reported in Table 2 is the OLS regression without years or locations.

Table 1. Kansas Wheat Yield Determinants, 1911–2006

Variable	Mean	Estimated Coefficient	*t*-stat
Constant	—	−164.563	−11.118***
White	0.056	−2.004	−3.958***
Soft	0.014	−1.605	−1.716*
Release year	1972.66	0.109	14.690***
Private	0.295	0.095	0.338
Blend	0.007	2.175	1.349
KAES	0.304	−0.658	−2.467**
R^2		0.516	
Adjusted R^2		0.511	
Number of observations		14,492	

Notes: Dependent variable is $Yield_{it}$ = wheat yield at location i in year t. Dependent variable mean is 46.875. The level of statistical significance is *** = 0.01; ** = 0.05; * = 0.10. The unbalanced cross-section, time series model reported above included fixed effects (intercept shifters) for all locations and years. These estimated coefficients are not reported. The reported t-statistics are calculated from standard errors that are heteroscedasticity consistent (White).

Model 2 includes fixed effects for both years and locations. The fixed effect estimates for model 2 are reported in Tables 2 and 3 for all years and locations. A Lagrange multiplier (LM) test for fixed effects across locations, as measured by experiment field stations, was estimated to determine whether the vector of fixed effect estimates contributed to the overall model. The high value and statistical significance of the LM statistic indicated that fixed effects were highly statistically significant and should be included in the regression model (Greene).

The 27 locations of the experiment fields (1977–2006) are agronomically diverse. Rainfall, temperature, and subsoil moisture vary greatly across Kansas, and as a result, wheat yields are variable, reflecting these conditions. Since the error structure of the regression model is likely to depend on the location, a Wald statistic was used to determine the presence of multiplicative heteroskedasticity (Greene). With 26 degrees of freedom, the Wald statistic of 49,908 was highly statistically significant, indicating the presence of multiplicative heterocdasticity. The multiplicative heteroscedastic correction is of great importance to this data set because of the variations in both the species and locations of wheat varieties. That is, since varieties within this data set are specifically bred for different climatic and agronomic conditions, the error terms across varieties may be heteroscedastic in nature. By accounting for this multiplicative heteroscedastic error term, comparisons across varieties are more statistically appropriate. The multiplicative heterocdastic regression model was estimated and is reported in model 3 of Table 2.

Regression Results

The overall results of the three estimated regressions for the time period 1977–2006 provided some evidence that the results are robust across model specifications. The large number of observations contributed to the robust results. Over 51% of the variation in wheat yields for the period 1911–2006 was explained by the regression (Table 1). For the modern period, 1977–2006, the simple OLS regression, which does not include fixed effects for years or locations (regression 1, Table 2), explained only 3.5% of the variation in yields. This regression is included in Table 2 for comparison purposes but not discussed in detail below. Inclusion of the fixed effects (model 2) increased the explanatory power to 41.5% for the period 1977–2006 (regression 2, Table 2). The multiplicative heterocdastic regression 3 is highly statistically significant, as indicated by the chi-square test for the model equal to 1,346.035. Regression 3 has the best fit, with the maximum log-likelihood of the three regression models reported in Table 2, equal to −37,003.92. Each of the included variables will be discussed below.

Table 2. Kansas Wheat Yield Determinants, 1977–2006

Variable	Mean	Regression 1 OLS Estimated Coeff. (*t*-stat)	Regression 2 OLS Fixed Effects Estimated Coeff. (*t*-stat)	Regression 3 Multiplicative Heteroskedasticity Estimated Coeff. (*t*-stat)
Constant	—	−516.704 (−14.750)***	−474.403 (−10.803)***	−359.048 (−11.304)***
White	0.086	−1.589 (−2.333)**	−2.624 (−4.777)***	−1.804 (−4.067)***
Soft	0.022	−1.697 (−1.350)	−0.693 (−0.676)	0.762 (0.927)
Release year	1987.464	0.286 (16.213)***	0.265 (12.052)***	0.206 (12.975)***
Private	0.362	0.962 (2.135)**	0.302 (0.819)	0.492 (1.602)
Blend	0.011	3.717 (2.025)*	1.418 (0.974)	1.344 (1.038)
KAES	0.298	−1.153 (−2.461)**	−0.463 (−1.255)	−0.264 (−0.858)
R^2		0.035	0.419	—
Adjusted R^2		0.035	0.415	—
Chi-square		—	—	1,346.05***
Log-likelihood		−40,042.79	−37,676.95	−37,003.92
Number of observations		9,333	9,333	9,333

Notes: Dependent variable is $Yield_{it}$ = wheat yield at location *i* in year *t*. Dependent variable mean is 52.260. The level of statistical significance is *** = 0.01; ** = 0.05; * = 0.10. Regression 2 includes fixed effects for years and locations (not reported), and regression 3 includes fixed effects for years and locations (reported in Table 3, qualitatively identical to those of regression 2). The reported *t*-statistics in regressions 1 and 2 are calculated from standard errors that are heterocdasticity consistent (White).

Table 3. Fixed Effect Regression Results: Stations and Years, 1977–2006

Station	Yield Difference	Year	Yield Difference
Bellvue	9.811***	1977	0.349
Colby	−0.582	1978	−0.241
Garden City	−16.517***	1979	11.285***
Hays	2.596***	1980	7.856***
Ottawa	−3.688***	1981	−6.285***
Powhattan	−3.918***	1982	1.390
Everest	3.891***	1983	8.084***
Parsons	−4.054***	1984	8.946***
Manhattan (default)	—	1985	12.002***
St. John	−0.273	1986	−2.179*
Tribune	−10.713***	1987	−0.448
Hesston	−8.574***	1988	−2.466*
Columbus	−17.636***	1989	−1.291
Hutchinson	−5.733***	1990	0.562
Minneola	−18.868***	1991	0.260
Sumner	−24.120***	1992	−2.037
Phillipsburg	−6.462**	1993	−0.924
Hugoton	10.165***	1994	2.358**
Pittsburg	−12.845***	1995	−16.710***
Smith Center	−26.012***	1996	1.606
Dodge City	−11.674***	1997	12.383***
Concordia	−6.321***	1998	13.903***
Beloit	17.146***	1999	13.681***
Larned	−41.951***	2000	−2.156**
		2001	−0.354
Irrigated Stations (I)		2002	−4.110***
Colby(I)	11.544***	2003	13.161***
Garden City (I)	7.681***	2004	7.393***
	6.966***	2005	6.608***
Tribune (I)		2006 (default)	—

Note: The level of statistical significance is *** = 0.01; ** = 0.05; * = 0.10.

White Wheat

As shown in Table 2, the multiplicative heterocdasticity-consistent model reports the coefficient on $White_i$ during 1977–2006 was −1.804 (Regression 3), statistically significant at the 1% level. This indicates that on average, *ceteris paribus*, white wheat yielded 1.804 fewer bushels per acre over the 1977–2006 period than nonwhite wheat varieties, which in Kansas are typically hard red winter wheat (HRW).

Soft and Blended Wheat

The coefficient on blended wheat varieties ($Blend_i$) was not statistically different from zero at the 10% level in either time period (Table 2). The results of the multiplicative heteroscedastic model (regression 3, Table 2) indicate that yields for blended versus non-blended varieties were not statistically different from each other, when growing conditions (year) and environment (location) were taken into account. This result differs from previous research by Bowden et al., who estimated an average advantage to blends of 0.85 bushels/acre, statistically different from zero. The difference between our results and those of Bowden et al. is the difference in statistical technique: here, multiple regression is used, whereas Bowden et al. compared average yields. Blended varieties had only 98 observations, accounting for 0.68% and 0.11% of all observations for the 1911–2006 and 1977–2006 periods, respectively. Soft wheat ($Soft_i$) was also not statistically significant, at the 10% level, in any of the four regression models, indicating that yields for hard and soft wheat are statistically equivalent.

Release Year and Year Variable

The coefficient on release year ($RLYR_i$) is the main variable of focus in this study, since it captures the "vintage" of each variety, or the technology that is incorporated into each variety of wheat. During 1911–2006, the estimated coefficient on release year was equal to 0.109, statistically significant at the 1% level (Table 1). The OLS fixed effects estimate in Table 1 indicates an increase of 0.109 bushels per acre for each year for newly released varieties over the period 1911–2006. The coefficient of $RLYR_{ijt}$ during 1977–2006 (regression 3, Table 2) was equal to 0.206, statistically significant at the 1% level. The comparison the $RLYR_{ijt}$ coefficients between the two time periods analyzed, 1911–2006 and 1977–2006, demonstrates a larger impact of the KAES wheat breeding program since 1977.[2] Given the average yield of 52.26 bushels per acre, the yield increase due to the KAES program was equal to 0.39% yield increase per year (0.206/52.26, Figure 2). The fixed effects of both the year and station variables can be found in Table 3.

During the 1977–2006 period, the KAES wheat breeding program contributed 6.182 (0.206×30) bushels per acre to wheat yields. Crude estimates of cumulative economic benefits, assuming a perfectly elastic demand for wheat, are equal to $78.9 million per year, in constant 2006 dollars, over the 30-year period (Table 4). The estimated costs of the program are significantly lower, equal to $5.0 million 2006 dollars per year (Table 4).

[2] This comparison is strictly true only if the models are equally valid. Given the specification differences between the two models, this comparison should be considered as an approximation, or rough estimate, of the differences in rates of yield gain between the two time periods.

Kansas State University Varieties and Private Varieties

During the 1911–2006 period, the coefficient on the Kansas State University varieties ($KAES_i$) equaled -0.658, statistically significant at the 5% level (Table 1). Compared to non-KAES varieties, varieties released by KAES yielded on average 0.658 bushels less per acre. However, beginning in 1977, with the release of semidwarf varieties, there was no statistical difference between KAES varieties and other public and privately released varieties, when growing conditions (year) and environment (location) were taken into account (Table 2, regression 3). This is an interesting and relevant result, given the recent release and adoption of a large number of private varieties in Kansas from less than 2% in 1977 to nearly 33% in 2006.

The private variety Jagalene, released in 2003, first tested on Kansas State test plots in 2000, has been the dominant privately released variety in the state. In 2006 over 27% of total wheat acres were planted to Jagalene in Kansas. Jagalene is a cross of a KAES variety Jagger (released in 1994) and an AgriPro variety Abilene (released in 1988). It should be noted that intellectual property rights on wheat are not well defined and that technology spillover is prevalent from public to private firms and vice versa.[3] Therefore, it is not surprising that public and private varieties continue to coexist and be competitive.

Station Variables

The fixed effects (FE) model reported in regressions 2 and 3 (Table 2) holds constant the growing conditions and all other geo-

[3] A wheat breeder can cross two existing breeds which are not their own and claim the new cross as theirs. For example, Texas A&M can cross a Colorado State variety with an AgriPro variety and release it as a A&M variety. Breeders must not back cross however, meaning that if you cross X with Y neither of which are your varieties then you may not cross the hybrid XY with X or Y again. Through this manner technology spillover can mitigate the yield differences between any two firms.

Table 4. Benefits and Costs of Kansas Wheat Breeding Program, 1977–2006

Year	Kansas Harvested Acres	% Kansas acres in KAES Varieties	Wheat Price NC KS (2006$/bu)	Cumulative Genetic Improvement[1] (bu/acre)	Benefits (USD2006)	Costs (USD2006)	Benefit-Cost Ratio
1977	12,100,000	38.3	8.73	0.206	8,334,232	2,387,568	3.49
1978	10,000,000	41.9	7.57	0.412	13,067,940	2,471,913	5.29
1979	10,800,000	46.6	8.94	0.618	27,805,817	2,653,649	10.48
1980	12,000,000	54.4	10.18	0.824	54,758,953	3,484,369	15.72
1981	12,100,000	63.8	9.41	1.03	74,822,618	3,135,956	23.86
1982	13,100,000	65.0	8.29	1.236	87,248,437	3,101,805	28.13
1983	10,800,000	56.6	7.10	1.442	62,584,069	3,582,316	17.47
1984	11,200,000	49.2	6.82	1.648	61,933,369	4,334,680	14.29
1985	11,400,000	46.0	6.33	1.854	61,542,640	5,161,348	11.92
1986	10,200,000	47.7	5.31	2.06	53,220,664	5,943,244	8.95
1987	9,900,000	48.5	4.18	2.266	45,479,232	5,260,772	8.64
1988	9,500,000	49.7	4.45	2.472	51,938,389	7,060,611	7.36
1989	8,900,000	45.4	6.28	2.678	67,954,164	6,789,119	10.01
1990	11,800,000	36.8	5.92	2.884	74,139,011	5,094,902	14.55
1991	11,000,000	37.0	3.77	3.09	47,412,651	4,657,423	10.18
1992	10,700,000	38.5	4.77	3.296	64,766,449	3,382,609	19.15
1993	11,100,000	48.0	4.49	3.502	83,777,365	2,861,950	29.27
1994	11,400,000	52.0	4.26	3.708	93,639,162	3,739,106	25.04
1995	11,000,000	52.1	4.67	3.914	104,753,396	3,730,267	28.08
1996	8,800,000	56.6	6.51	4.12	133,591,033	2,671,361	50.01
1997	10,900,000	60.6	5.81	4.326	166,020,520	2,928,520	56.69
1998	10,100,000	65.6	3.97	4.532	119,208,060	6,351,168	18.77
1999	9,200,000	68.6	3.13	4.738	93,594,717	6,461,687	14.48
2000	9,400,000	68.4	2.74	4.944	87,098,962	7,822,420	11.13
2001	8,200,000	68.4	3.18	5.15	91,855,318	8,449,005	10.87
2002	8,200,000	67.7	3.05	5.356	90,686,560	6,917,227	13.11
2003	10,000,000	68.0	4.04	5.562	152,799,264	7,410,015	20.62
2004	8,500,000	61.2	3.77	5.768	113,119,363	7,259,784	15.58
2005	9,500,000	46.0	3.41	5.974	89,022,756	7,513,147	11.85
2006	9,400,000	43.7	3.58	6.18	90,882,610	7,509,836	12.10
Mean	10,373,333	53.1	5.49	3.19	78,901,924	5,004,259	17.6

[1] Calculated using the RLYR coefficient from regression 3.

graphical or locational differences in wheat production. A subset of the KAES stations is irrigated, and the station variable captures this important difference in production technology. Table 3 reports average yields for each station to that of the Manhattan Experiment Station (the base station). Not surprisingly, relative to the dryland default station located in Manhattan, there were statistically significant higher yields per acre in each of the three irrigated stations. The other station results reflect differences in rainfall, location specific diseases (rust), and other growing conditions.

Wheat Breeding Programs

Taking the average yield of all varieties in all of the KAES test plots, and obtaining the average yield for all varieties of wheat actually planted by farmers in the state of Kansas from 1977 to 2006, the effect on yield exclusively from wheat breeding (both public and private) could be calculated. Figure 2 illustrates how the observed on-farm yield average is related to the KAES test plot yield average. Knowing that the average on-farm wheat yield increased by 7.83 bushels (USDA/NASS) per year from

1977 to 2006, it can then be inferred that 79% of the total increase in on-farm yields can be attributed to wheat breeding programs. Restated, if we assume that the average increase per year in yield attributed to wheat breeding alone on the KAES test plots (0.206 bu/year) is the same as in the average farmers field in Kansas, then approximately 79% (6.182/7.83) of the increased wheat yields attained by farmers in the state of Kansas during the 1977–2006 period can be attributed to genetic improvements from wheat breeding. The remaining 21% can be attributed to other agronomic factors (precision fertilizer, improved harvesting efficiency, etc.).

A crude estimate of the benefits from the KAES breeding program can be calculated using the *RLYR* coefficient from regression 3, together with price and planting data from the state of Kansas. Wheat prices for Kansas from 1977 to 2006 were collected from the internet site, AgManager, and deflated into 2006 prices (U.S. Department of Labor, BLS). Total acreage planted to wheat and percentage of total wheat planted to KAES varieties was gathered from the annual ‘‘Kansas Performance Tests with Winter Wheat Varieties’’ (Table 4). Annual costs of the KAES breeding program were obtained from the Director of the Kansas Agricultural Experiment Station (Nalley, Barkley, and Chumley).

An estimate of the total benefits from the KAES breeding program was made by first multiplying the number of wheat acres in Kansas by the percentage planted to KAES varieties to obtain the number of acres in Kansas planted to KAES varieties. The number of Kansas acres to KAES varieties is then multiplied by the cumulative genetic gain attributed to the KAES breeding program, the *RLYR* coefficient from regression 3.[4] The product of cumulative genetic gains (bu/acre) and number of acres planted KAES lines (acres) yields the number of bushels per year attributed to the KAES breeding program. The number of additional bushels per year associated with the KAES breeding program is then multiplied by that year's respective wheat price per bushel to obtain a total annual benefit. The results as presented in Table 4 show that the average benefits associated with the KAES breeding program from 1977–2006 equaled 78.90 million (2006) dollars. The average cost of the breeding program for the same time period was 5.00 million (2006) USD, yielding a benefit-cost ratio of 17:6.

Conclusions and Implications

This study has shown that in two time periods, 1911–2006 and 1977–2006, white wheat had lower average yields relative to red wheat, by 2.004 bushels per acre and 1.804 bushels per acre, respectively. It must be taken into consideration that this study analyzed only white wheat yield and not milling attributes, demand, or quality, which are selling points for white wheat. The results for white wheat varieties, which millers point out have higher average flour extraction rates, may require more in-depth research to see if its lower yield could be economically mitigated by its milling attributes. It should be noted that white wheat yields are a ‘‘moving target,’’ and the recently released white varieties are closing the gap or in some instances have caught up to red varieties in yield (Kansas Performance Tests with Winter Wheat Varieties, 2007). While the results for white wheat were significantly negative, at the 1% level for the multiplicative regression, the results for soft wheat were statistically insignificant, at the 10% level, for both time periods. The result for blended wheat was found to be statistically insignificant at the 10% level, when growing conditions and environment are taken into account. It should be noted that 48% (47/98) of the blended wheat observations were from the period 2003–2006, so it is a fairly new program that may take time to evolve before significant yield differences can be measured.

No statistical difference was found between KAES, other public, and private varieties yield when fixed effects (location and year) are taken into account. The lack of variance

[4] Cumulative genetic gains are used in the calculation of benefits. Since the 0.206 bushels per acre gain attributed to the KAES breeding program is observed each year, by definition the benefits from year to year are cumulative.

between yield of public and private varieties may be the result of the high degree of information and germplasm sharing that occurs between all wheat breeding programs, given the high amount of mobility between private and public breeders and the weak intellectual property rights assigned to wheat. The KAES varieties during the 1911–2006 period yielded 0.658 bushels per acre less than the average of all varieties. However, when looking at the "new age" of wheat breeding 1977–2006 (characterized by the introduction of the semidwarf gene), there was no statistical difference at the 10% level in KAES released varieties and the average, indicating that KAES has kept pace with all breeding programs, both public and private.

Possibly the most robust results are those of the effect of wheat breeding programs on increases in yield per acre over time. When analyzing yield data from Kansas test performance farms during 1977–2006, 79% (6.182/7.83) of the increase in yields can be attributed to wheat breeding programs, private and public, genetic advances alone. Other increases may be attributed to more efficient harvesting techniques, higher quality inputs, and improvements in technology. When analyzing the "new age" of wheat breeding (1977–2006) wheat breeding is attributed with an increase of 6.182 bushels per acre, or an average increase of 0.206 bushels per year.

A simple, relatively crude estimate of the total economic benefits of the KAES wheat breeding program is approximately $78.90 million per year, in constant 2006 dollars, for the 30-year period (Table 4). The estimated costs of the program are approximately $5.00 million per year (Nalley, Barkley, and Chumley). Given these estimates, the benefits of the wheat breeding program appear to outweigh the costs by 17 to 6 (Table 4), providing some evidence that the investment in Kansas public wheat breeding programs have resulted in a high rate of return.

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