Estimation and Imputation of Crop Yield Advances by States and Regions

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CONTENTS

SUMMARY

The objectives of this study were: (a) to estimate the proportions of crop yield change attributable to crop variety improvement, higher rates of fertilization, regional specialization and other crop yield variables and (b) to determine how the relative economic yield level per acre changed over a 20-year period.

The analysis covers major crops on a state, regional and national basis. Based on time-series data, over 80 state crop-production functions were estimated for corn, wheat, oats, barley, grain sorghum, soybeans, flax, cotton and tame hay. Annual state crop yields were considered a function of inherent soil fertility, weather, crop variety improvement, fertilizer application, short-run changes in acreage, and time.

Estimated regression equations were linear in logarithms. Variables of crop yield technology were highly correlated. To avoid problems of multicollinearity between trends in variety improvement and fertilizer application, effects of these two variables on crop yields were estimated independently by using experimental data. Crop variety indexes were computed from 88,000 yield tests of individual crop varieties and corn hybrids. Fertilizer response was estimated from 200 yield-response functions. State crop yields were deflated by estimated variety indexes and fertilizer response and then regressed on the variables of weather indexes, short-run changes in acreage, and time.

From the estimated regression equations, expected yields were computed by assuming normal weather and acreage conditions. According to this analysis, expected yields of all crops, except flax, increased over time. Expected corn yields, for example, increased from 30.0 bushels in 1939 to 55.8 bushels in 1961. Annual crop yield change was attributed to variables of crop-yield technology by applying Taylor's expansion. For example, 8.1 bushels of the 25.8-bushel change in corn yield was attributed to higher rates of fertilizer application, 9.2 bushels to the use of improved seed, 4.6 bushels to regional specialization and 3.9 bushels to other crop yield variables. Total gain in estimated wheat yields was 7.6 bushels, with 3.3 bushels attributed to fertilizer, 2.1 bushels to variety improvement, 0.1 bushel to location of production and 2.1 bushels to other variables related to yield technology. Total gain in estimated yields was 175.2 pounds for cotton, with 41.8 attributed to fertilizer, 32.5 to variety improvement and 104.7 to other yield variables. However, cotton declined 3.8 pounds because of location changes. Similar figures are summarized in the text for oats, barley, soybeans, flax and tame hay. Estimated annual yield gains in crop yields added over 3.5 billion dollars to the gross product of United States agriculture annually between 1939 and 1961.

Yield supply functions were derived from state crop-production functions. Estimated yields and economic optimum yield comparisons showed that differences between estimated and optimum yields had diminished over time. Thus, it appears that the incentive to produce more per acre should have declined by the end of the period analyzed. Changes in technology and prices, or both, depending on their direction and rate of change, however, can restore this incentive for the future.

This study stresses methods of analysis used. The procedures used are explained in detail in order that other research workers may extend them and so that the limitations of the procedures may be clearly understood. Limitations of the analysis arise because ideal data for the types of estimates desired are not available, and the procedures had to be adapted accordingly. Limitations that should be emphasized include the facts that the yield effect of increased fertilizer application and variety improvement were estimated before fitting the regression estimates as a means of eliminating problems of multicollinearity, that the variable used to reflect weather was perhaps overly simple, that aggregation procedure used in estimating extent and effects of variety improvement were imperfect because of data limitations and that the production-function form used introduced certain rigidities. The analysis can be used by other research workers, however, as a foundation for eventual steps in improving estimates of technological change over time.

Estimation and Imputation of Crop Yield Advances by States and Regions[1]

by Ludwig Auer and Earl O. Heady[2]

Crop production in the United States has increased rapidly over the last 3 decades. The sources of these increases are important for several reasons. They are of particular interest with respect to the economic development and growth in agriculture's productivity. The estimated sources of increased crop yields and production are significant to numerous groups of decision makers, including farmers, processors of agricultural products, suppliers of farming inputs, government program administrators and persons concerned with the world food situation. Finally, the extent and means of public policies can be adapted to the variables related to increases in crop production and yields. For example, the magnitudes of acreage-control and crop-storage programs should differ, depending on whether production changes are due to weather or to variables more nearly related to crop-production technology. Or, depending on upcoming needs, shifts in relevant variables can help to meet export needs.

OBJECTIVES

The major or over-all objective of this study is to estimate yield gains for corn, wheat, soybeans, flax, barley, oats, grain sorghum and tame hay and to impute these gains to particular variables expressing crop technology. These estimates and imputations are made by states, by producing regions and for the United States. To attain our over-all objective, however, these supplementary objectives or prior steps were necessary: (a) Devise and measure variables or indexes to represent major technologies and influences affecting crop yields and production. (b) Estimate crop-production functions by states and regions that allow derivation of estimated yields and the imputation of yield changes to the various crop-yield technologies or variables. (c) Interpret the relative importance of variables giving rise to differential rates of yield change among states and regions. (d) Analyze the extent to which profit incentive for increasing crop yields has been exploited. (e) Summarize relevant data on estimated yields and yield imputations for the nation.

Since data were not directly available for the analysis, it was necessary to devise methods of aggregating and expressing many of the different variables or indexes that relate to changes in crop yields. The following sections are devoted to their explanation.

Time-series production functions are used to impute changes in the United States crop production to resource inputs and technology advances over the past 2 decades. Yield production functions are estimated for wheat, oats, barley, flax, soybeans, grain sorghum and corn in each of the states that provide the major portion of the nation's supply of these crops. Estimates are presented of the aggregate contribution of crop variety improvement, fertilizer application, regional specialization and other crop yield variables.

To an important extent, the study presents methods of analysis. Because of data inavailablility, procedures are used that allow certain estimates within the framework of information currently available, multicollinearity among certain of the major variables and the time and fund restraints of the study. In order that the procedures and limitations of the analysis will be obvious, the steps in the background methods are outlined in detail. Although these details suggest limitations in the methods used, a summary of the limitations is included at the end of this report.

DATA AND ESTIMATION PROCEDURES

Ideally, the agricultural production function could be viewed as in equation 1, where Y is output, and $x_1, \ldots, x_u$ are the inputs or variables that produce Y. There are, of course, hundreds of specific input categories that may be represented as variables, x_1 to x_k,

$$(1)\ Y = f(cx_1, x_2, \ldots, x_k, x_{k+1}, \ldots, x_u)$$

land of particular quality, labor in 1 month and one quality, crop variety on a given acreage and many others. Over time, new production processes, say $x_{k+1}, \ldots, x_u$, may be uncovered that change the original input combinations by partial substitution or perhaps complete replacement. Although this production function exists, data are not available for estimating it.

In this study, a large number of specific inputs are aggregated into manageable categories that serve as variables. For estimating the production functions, a simple algebraic form, a power function, is used because of its convenience and utility. The production function in all cases is of the form of equation 2.

$$(2)\ Y = b\, V^v F^f W^w A^a T^t\, e$$

where Y is yield per acre of a particular crop and

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[1] Project 1405 of the Iowa Agriculture and Home Economics Experiment Station, Center for Agricultural and Economic Development, cooperating.

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state, b is a constant, V is an index of crop varieties grown in the state, F is the rate of fertilizer application, W is a weather index, A is an index of crop acreage, T is a time-trend variable to represent other aspects of technology, e is the error term, and the other small letters are the exponents of the variables.

In estimating yield-production functions for the various crops and states, there is considerable multicollinearity among such variables as the crop-variety index, fertilization rates and the time-trend variables. Although singular moment matrices do not occur, regression coefficients estimated by ordinary least-squares methods are likely to be highly unstable. Therefore, the effects of variety improvement and fertilizer response are estimated separately and then incorporated into production functions estimated by least-squares methods for acreage, weather and time variables.

Annual changes in crop-yield technology, or variables that represent them, are estimated separately for each crop and each state and then aggregated to furnish the regional and national effect on crop production. States in the analysis are located in the five major producing regions; the Corn Belt, the Lake States, the Northern Plains, the Southern Plains and the Delta States.

Estimation of Crop Yield Variables

Even though data limitations impose restrictions, an attempt is made in this study to quantify the major crop-yield variables. These variables relate to crop-variety improvement, fertilization, weather, acreage and regional specialization.

CROP VARIETY IMPROVEMENT

To estimate effects of new crop varieties on state crop yields, two sets of basic information were analyzed, and corresponding variables were formulated and used in estimating production functions.

The first set was the yield results of crop variety tests. Research workers at agricultural experiment stations have tested yield performance of numerous crop varieties for nearly 3 decades. Results from 88,000 of these crop variety tests were incorporated in this analysis. A 20-year summary of hard, red winter wheat variety tests in the Plains States has been published by the United States Department of Agriculture.[3] This summary, containing annual yield results for more than 30 experiment stations and representing the type of information used in this study, constitutes only a fraction of the data analyzed. Most of the data on crop variety tests were obtained from USDA or directly from agricultural experiment stations, and the sources are summarized elsewhere.[4]

The second set of data analyzed was acreage distribution of crop varieties. Data on the distribution of wheat varieties and the seeding of hybrid corn by states have been published at regular intervals by USDA.[5] Most information on annual acreage distribution of crops used in this study was obtained from research workers engaged in crop-variety improvement programs of individual states.[6] We now use examples to indicate how these two sets of information were used to complete yield indexes.

Crop variety index: Crop variety indexes were estimated from results of crop variety tests and acreage distributions. Annual test yields of individual crop varieties were compared with yields of check varieties at experiment stations. Relative test yields obtained in this manner were aggregated to form state crop-variety indexes by using variety-acreage weights. All variety indexes then were converted to 1947-49 average values to allow comparable indexes over states, crops and time.

To estimate relative test yields of crop varieties, annual yield ratios of individual varieties were averaged over experiment station years as indicated by equation 3. The ratio Y_{ijl}/Y^*_{jl}

$$(3)\quad V = \sum_{i}^{n} p_i v_i = \sum_{i}^{n} p_i \Big(\sum_{j}^{m} \sum_{l}^{k} (Y_{ijl}/Y^*_{jl})/m\,k \Big)$$

is the yield comparison between the test variety Y_{ijl} and check variety Y^*_{jl} in year j at station location l. Relative test yields of individual varieties v_i are estimated by averaging the yield comparisons, Y_{ijl}/Y^*_{jl}, over the test years $(j = 1, \ldots, m)$ and all station locations $(l = 1, \ldots, k)$. In estimating annual state crop variety indexes V, we recognize that some varieties are adopted widely, while others occupy only a small portion of each state. The acreage distribution of varieties also changes over time as superior varieties replace others. Accordingly, relative test yields of individual varieties are aggregated by weighting them with their state acreage as in equation 3, where p_i is the percentage of state acreage planted to variety i in a given year. Finally, to make state crop variety indexes comparable among states, the annual indexes V are divided by their 1947-49 values.

Computational procedures used in estimating the Kansas wheat variety index illustrate the method for all states and crops. Wheat variety tests were conducted for more than 20 years at four Kansas locations: Hays, Colby, Manhattan and Garden City. Results of these tests are summarized in columns 1 and 2 of table 1. Yields of individual varieties were compared with yields of check variety Kharkof at each location.[7] These yield comparisons were expressed as ratios and averaged over locations and years. For

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[3] L. P. Reitz and S. C. Salmon. Hard, red winter wheat improvement in the plains. U. S. Dept. of Agr. Tech. Bul. 1192. 1959.

[4] L. Auer. Impact of crop-yield technology on United States crop production. Ph.D. thesis. Iowa State University, Ames. Order No. Mic. 64-3852, Univ. Microfilms. Ann Arbor, Mich. 1963

[5] Ibid.

[6] Ibid.

[7] For yield comparisons of varieties grown at Garden City, Turkey variety was used as the check variety before 1955. Yield differences between Kharkof and Turkey were considered insignificant.

example, the Pawnee yields averaged 19 percent higher than Kharkof yields in 71 tests. Accordingly, the relative test yield of Pawnee is listed as 1.19 in table 1.

Percentage estimates of acreages planted to these varieties are also listed in table 1. For example, in 1929 (column 3) Kanred, Turkey and Blackhull varieties occupied 12.0, 48.0 and 33.4 percent, respectively, or 93.4 percent aggregatively of Kansas wheat acreage. The remaining 6.6 percent was planted to other varieties.

To derive the wheat variety index for 1929, the relative test yields of Kanred (1.04), Turkey (1.01) and Blackhull (1.08), were multiplied by the corresponding acreage-percentages 12.0, 48.0 and 33.4. The result, 97.03, was then multiplied by 1.071 (100 ÷ 93.4 = 1.071) to adjust for the remaining 6.6 percent of the acreage occupied by other varieties. This adjustment was based on the assumption that the yielding ability of other varieties was the same as the average of the specified varieties. The resulting index is 97.03 x 1.071 = 103.9 and implies that 1929 Kansas yields were 3.9 percent higher than if the total acreage had been planted to Kharkof (table 1, column 3). By 1959, the newer varieties had almost completely replaced the older varieties. The corresponding index (base Kharkof) for 1959 amounts to 118.3 (column 9). As mentioned, annual state crop variety indexes were divided by 1947-49 values to provide interstate comparability. The resulting Kansas winter wheat variety indexes are listed in the bottom row of table 1 for 5-year intervals. Estimates for wheat variety indexes of the intervening years, were derived by simple interpolation. For all other crops, variety indexes were computed for each year by using annual estimates of acreage-variety distributions.

Corn hybrid index: Differing somewhat from computations for other crop variety indexes, the hybrid corn index computations measured changes in state corn yields due to (a) hybrid corn as compared with open-pollinated corn and (b) replacing older hybrids by newer ones. If hybrids and open-pollinated varieties had been tested together over the same period, hybrid corn indexes could have been constructed in the same manner as other crop variety indexes. But yield test of open-pollinated varieties were discontinued in the major corn-producing states 10 to 20 years ago.

Average yields of corn tests have greatly increased since 1940. Yet advances in corn test yields cannot be attributed alone to using and improving hybrid corn. Increases have also resulted from using higher fertilizer rates and other practices. Rapid variety turnover and the local adaptation of hybrids added to the problem of constructing reliable state hybrid corn indexes. Therefore, a technique was required that could (a) estimate yields of hybrid corn relative to open-pollinated varieties, even after the latter had been dropped from yield tests, (b) effectively separate variety-yield effects from fertilizer-yield effects and (c) incorporate the differential features of hybrid corn improvements among state regions.

State hybrid corn indexes were measured by this procedure. Test data were grouped by corn maturity groups and crop reporting districts within states. Comparisons for each of these subgroups were made among open-pollinated varieties, check hybrids and

Table 1. Wheat test yields, estimated percentage of wheat acreage planted to specified varieties and Kansas wheat variety index at 5-year intervals, 1929 to 1959.

	Kansas test yields			Estimated percentage of acreage planted to specified varieties					
Variety	No. of tests[a]	Relative test yields[b]	1929	1934	1939	1944	1949	1954	1959
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Kanred	49	1.04	12.0	10.4	4.5	2.7	0.2	[c]	[c]
Turkey	87	1.01	48.0	44.3	28.9	14.7	1.7	0.3	0.3
Blackhull	60	1.08	33.4	34.9	31.0	15.5	3.6	0.5	0.2
Early Blackhull	63	1.13	[c]	0.6	1.6	9.0	4.6	2.2	
Tenmarq	72	1.15		1.3	19.6	36.6	8.5	0.1	1.2
Kawvale	17	1.20		0.3	6.4	4.4	0.7	0.5	
Chiefkan	41	1.20			2.8	8.6	1.3	6.1	[c]
Red Chief	53	1.09				4.4	3.9	29.0	0.2
Pawnee	71	1.19				[c]	36.0	7.4	11.2
Triumph	37	1.18				0.1	6.4	11.1	14.8
Comanche	73	1.20				0.1	20.8	3.3	8.9
Blue Jacket	23	1.14					0.7	24.3	[c]
Wichita	64	1.17					9.4	2.4	22.7
Ponca	43	1.16						8.1	11.6
Kiowa	44	1.20							13.8
Bison	21	1.17							9.8
Concho	22	1.33							2.0
All others			6.6	8.2	5.2	3.9	2.2	4.2	3.3
Total			100.0	100.0	100.0	100.0	100.0	100.0	100.0
Winter wheat variety index									
Base: Kharkof			103.9	104.2	107.6	108.4	111.7	117.0	118.3
Base: 1947-49			0.896	0.899	0.935	0.963	1.009	1.014	1.020

[a] Includes tests conducted at Hays, Colby, Manhattan and Garden City from 1931 to 1960.
[b] Yield ratios of individual varieties over check variety Kharkof.
[c] Less than 0.5 percent.

other hybrids. The superiority of check hybrids over open-pollinated varieties during this period then was used to express the superiority of other hybrids over open-pollinated varieties after the latter were dropped from trials. As an example, suppose that corn yield tests were conducted at a location representative of corn-yield conditions of a crop district within a state. Hypothetical corn-test yields are shown in table 2, columns 1 to 6. Relative hybrid corn test yields are listed in column 1 next to annual yields of open-pollinated varieties shown in column 2.[8]

In the example, open-pollinated corn varieties are not grown in yield tests after 1940. Therefore, yields of open-pollinated corn varieties are estimated by relative yields of successsive check hybrids. Yields of check hybrids 1-4, tabulated in columns 3 to 6, table 2, are depicted in fig. 1 as curves intersecting the average yield line of all corn hybrids. The yield for hybrid 1 is 1.150 times the yield of open-pollinated varieties during the test years, 1935 to 1940. From 1940-43 the yield for hybrid 2 is 1.087 times that of hybrid 1, the yield for hybrid 3 is 1.080 times that for hybrid 2, and the yield for hybrid 4 is 1.074 times that of hybrid 3. Since hybrid 2 has a yield 1.087 times that of hybrid 1, it is estimated to yield 1.25 (1.150 x 1.087) times that of open-pollinated varieties. Correspondingly, hybrids 3 and 4 are estimated to yield 1.35 (1.25 x 1.080) and 1.45 (1.35 x 1.074) times as much as open-pollinated varieties.

These estimates are then used to compute the relative test yields of corn hybrids shown in column 7, table 2. If relative hybrid corn test yields were identical in all crop districts, then state hybrid corn indexes could be computed by combining relative test yields with the adoption rate of hybrid corn. In the state used for our example, corn hybrids were first grown by 1933, and two-thirds of the corn acreage was planted to corn hybrids by 1939 and occupied the total state corn acreage by 1948.

In computing the state hybrid corn index, 1939 can be used as an example. The relative 1939 hybrid corn test yield was 1.14 (column 7), and 66 percent of the state corn acreage was planted to hybrid corn (column 3). The state hybrid corn index for 1939, therefore, was (1.14 x 0.66) + (1.00 x 0.34) = 1.09; this figure was smaller than the relative hybrid corn test yield of 1.14, and the other 34 percent was still planted to open-pollinated corn (relative test yield 1.00). Annual state hybrid corn indexes for the example are listed in column 9, table 2, and depicted in fig. 2. They remained nearly constant at 1.00 during the early 1930's, increased rapidly during the time of adoption, paralleled the rate of change of relative hybrid corn test yields during the mid 1940's and reached a value of 1.50 by 1960. Hence, we estimate that corn yield was 1.50 greater than would have been realized with open-pollinated corn.

Although average yields of all hybrids increased from 50 bushels in 1930 to 100 bushels in 1960, only part of this 100-percent increase was due to hybrid corn because yields of open-pollinated varieties also increased (from 50 bushels per acre to 66.6 bushels). Annual hybrid corn indexes were based on yield ratios of hybrid corn over open-pollinated corn varieties rather than on actual changes in corn test yields.

Emperical estimation procedures of state hybrid corn indexes conformed to those of the hypothetical

Table 2. Data and method for computing annual state hybrid corn indexes (hypothetical data).

Year	Average yields (bu.) All hybrids	Average yields (bu.) O-p[a] var.	Yields of check hybrids (bu.) 1	Yields of check hybrids (bu.) 2	Yields of check hybrids (bu.) 3	Yields of check hybrids (bu.) 4	Relative hybrid corn test yield[b]	% of acres in hybrid corn	Corn hybrid index
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1930	50.0	50.0					1.00	0	1.00
1931	51.7	51.0					1.01	0	1.00
1932	53.3	51.9					1.03	0	1.00
1933	55.0	52.7					1.04	1	1.00
1934	56.7	53.5					1.06	2	1.00
1935	53.3	54.4	62.6				1.07	4	1.00
1936	60.0	55.1	63.4				1.09	10	1.01
1937	61.7	55.8	64.2				1.11	25	1.03
1938	63.3	56.5	65.0				1.12	48	1.06
1939	65.0	57.2	65.8				1.14	66	1.09
1940	66.7	57.9[c]	66.6	72.4			1.15	78	1.12
1941	68.3	58.6[c]	57.4	73.2			1.17	87	1.15
1942	70.0	59.3[c]	68.2	74.1			1.18	93	1.17
1943	71.7	59.9[c]	68.9	74.9			1.20	96	1.19
1944	73.3	60.5[c]	69.6	75.6			1.21	98	1.21
1045	75.0	61.1[c]	70.3	76.4	82.5		1.23	98	1.23
1946	76.7	61.7[c]		77.1	83.3		1.24	99	1.24
1947	78.3	62.2[c]		77.8	84.0		1.26	99	1.26
1948	80.0	62.7[c]		78.4	84.6		1.28	100	1.28
1949	81.7	63.2[c]		79.0	85.3		1.29	100	1.29
1950	83.4	63.7[c]		79.6	86.0	92.4	1.31	100	1.31
1951	85.0	64.1[c]			86.5	92.9	1.33	100	1.33
1952	86.7	64.5[c]			87.1	93.5	1.34	100	1.34
1953	88.3	64.9[c]			87.6	94.1	1.36	100	1.36
1954	90.0	65.2[c]			88.0	94.5	1.38	100	1.38
1955	91.6	65.5[c]			88.4	95.5	1.40	100	1.40
1956	93.3	65.8[c]			88.8	95.4	1.42	100	1.42
1957	95.0	66.0[c]			98.1	95.7	1.44	100	1.44
1958	96.7	66.2[c]			89.4	96.0	1.46	100	1.46
1959	98.3	66.4[c]			89.6	93.3	1.48	100	1.48
1960	100.0	66.6[c]			89.9	96.6	1.50	100	1.50

[a] O-p denotes open-pollinated.

[b] Relative test yields in column 7 are found by dividing values in column 1 by those in column 2.

[c] Estimated by yield comparisons between open-pollinated corn varieties and check hybrids.

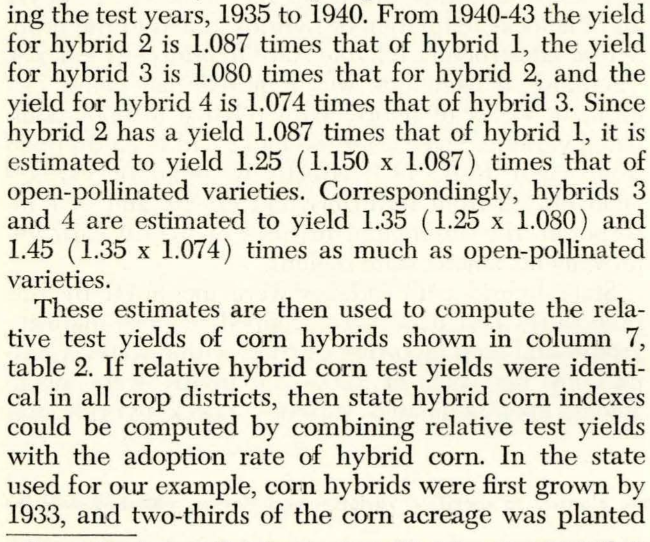

Fig. 1. Hypothetical example of estimation of annual yields of open-pollinated corn varieties.

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[8] We assume that yield tests of open-pollinated corn continued to rise over time because of gradual replacement of older by newer varieties as well as by higher rates of fertilizer application and other improved cultural practices. We also assume that yield ratios between open-pollinated corn and hybrid corn were constant, irrespective of yield levels.

example. First, relative state yields of hybrid corn were computed for each district. Second, annual relative corn test yields were weighted according to district corn acreages and then aggregated to form the individual state's total. This aggregation was necessary because relative test yields and corn acreages differed between corn test districts within a state. Third, a time-trend line was fitted to aggregated test yields so that annual random variations were excluded from state index computations. Finally, the relative test yields derived in this manner were combined with state adoption rates for hybrid corn use as described in the hypothetical example. In Iowa, for example, relative corn test yields were aggregated by years over 11 corn test districts; these are shown in the plot diagram of fig. 3. The line also shown in fig. 3 was fitted by regressing aggregate relative corn test yields on time for 1926 to 1961. The linear regression indicates that hybrid corn test yields advanced at a constant rate relative to yields of open-pollinated corn varieties. This advance might be realistic since research in hybrid corn improvement was intensified over the years. Adoption rates for hybrid corn use and the estimated hybrid corn indexes of Iowa are illustrated by figs. 4 and 5. Hybrid corn acreage increased rapidly during the late 1930's and early 1940's, expanding from less than 20 percent to over 90 percent of the total acreage. By 1960, the state hybrid corn index exceeded 1.40, indicating that Iowa corn yields had increased by more than 40 percent over the past 3 decades because of genetic development and adoption of higher-yielding hybrid corn.

The estimates just described assume that yield improvements on farms due to hybridization paralleled those on experimental test plots. Corn hybrids entered in experiment station tests were usually tested for several years before being released to farmers. Because of this lag, we could not expect yields of hybrids grown by farmers to have greater yielding ability than those grown in tests. On the other hand, newly developed test hybrids were probably far superior; on the average, entries in hybrid corn yield tests outyielded hybrid corn commonly grown on farms. The estimated state hybrid corn indexes would have some bias under these conditions.

To determine if yields differed between corn hybrids entered in yield tests and hybrids commonly grown on farms, the Iowa Agricultural Experiment Station conducted an extensive testing program in 1953. On the basis of 12,000 mail questionnaires, 26 hybrids widely grown by Iowa farmers were entered in the 1953 Iowa corn yield test. At each location, 10 of the farmers' hybrids were planted together with 71 other test variety entries. Evidently, test yields of widely grown hybrids did not differ significantly from test entries (table 3). Yield differences between the 10 widely grown hybrids and the 71 other test hybrids amounted to 3 percent or less and favored hybrids grown by farmers. This result may be because only superior-yielding hybrids

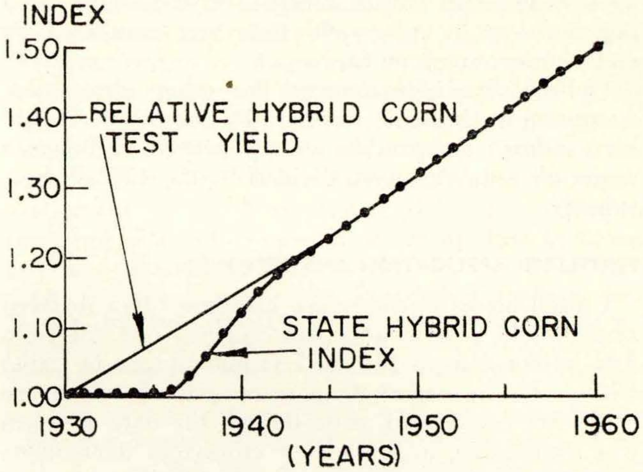

Fig. 2. Hypothetical state hybrid corn index, 1930-1960.

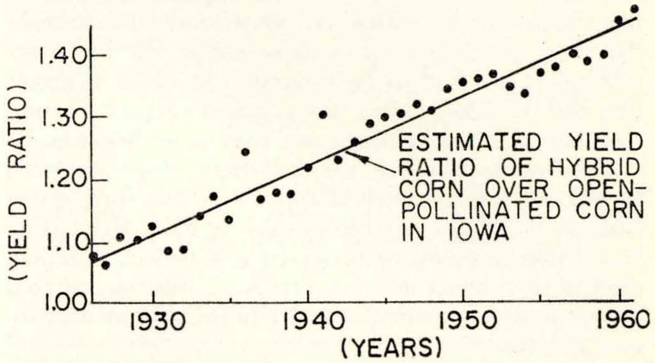

Fig. 3. Relative corn test yields, Iowa, 1926-1961.

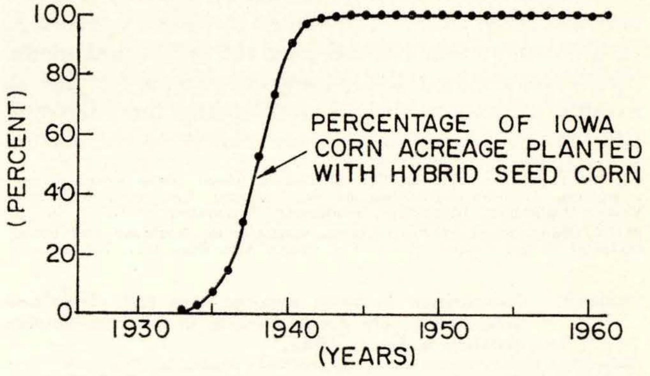

Fig. 4. Adoption of hybrid corn use, Iowa, 1926-1961.

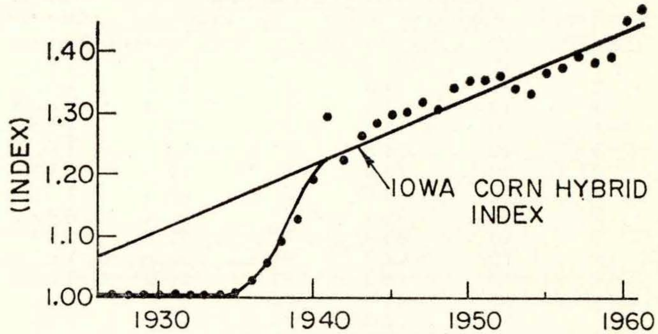

Fig. 5. Estimated hybrid corn index, Iowa, 1926-1961.

have widespread farmer acceptance. Evidently, yield improvement in corn yield tests was paralleled by yield improvement on farms.

Hybrid corn improvements for other states were computed in the same manner. To make state hybrid corn indexes comparable among states and between crops, all estimates were divided by the 1947-49 base values.

FERTILIZER APPLICATION AND RESPONSE

United States fertilizer use has more than doubled since World War II, and plant nutrient use rose from 2.64 million tons in 1945 to 7.35 million tons in 1960.[9] Obviously, the impact of more intensive fertilizer use could not be ignored, even though the data problem was formidable, in a study of crop-yield technology. To estimate the impact of greater fertilizer use, we had to (a) quantify the annual application rates of plant nutrients by states and crops and (b) estimate the corresponding crop yield response. Fertilizer application rates had to be estimated in plant nutrients (N, P_20_5 and K_20) since the nutrient content of commercial fertilizers has increased over time. Because the study deals with annual yield changes, it was essential to estimate *annual* nutrient application by crops, quantities not readily available in existing data. Estimating crop yield response to fertilizer application, independent of the impact of other variables, was necessitated by problems of multicollinearity in subsequent statistical analysis.

Fertilizer application: Estimates of state fertilizer consumption have been published by USDA at regular intervals since 1930.[10] The annual estimates were made on a calendar-year basis during the 1930's and in the early 1940's. Since 1944, they have been for the 12 months starting on July 1 and ending the following June 30, thus conforming more closely to the annual use pattern of commercial fertilizers. These data were available by states in terms of total use N, P_20_5 and K_20, but not for individual crops. Estimates of fertilizer use have been published at regular intervals. For example, the National Fertilizer Association published survey results for 1927, 1938 and 1944,[11] and USDA estimates were available for 1950, 1954 and 1959.[12]

Table 3. Comparisons between average corn test yields and yields of widely grown hybrids in 12 corn testing districts in Iowa, 1953.[a]

	Number of entries and test yields				Yield comparisons
	Widely grown hybrids		Test hybrids		widely grown hybrids ÷ test hybrids
Corn test district	No.	Yield in bushels	No.	Yield in bushels	
1	10	102.5	71	101.6	1.01
2	10	84.3	71	82.5	1.02
3	10	107.4	71	109.3	0.98
4	10	113.7	71	113.9	1.00
5	10	104.8	71	104.7	1.00
6	10	74.8	71	77.3	0.97
7	10	88.9	71	88.3	1.01
8	10	95.1	71	96.4	0.99
9	10	85.4	71	82.5	0.99
10	10	97.7	71	96.2	1.02
11	10	115.3	71	115.9	1.00
12	10	83.9	71	81.8	1.03
Av.	10	96.2	71	95.9	1.00

[a] J. L. Robinson and C. D. Hutchcroft. 1953 Iowa corn yield test. Iowa Agr. Exp. Sta. and Agr. Ext. Serv. Bul. P-116. 1954.

Estimates of annual application rates of N, P_20_5 and K_20 by states and crops were made as follows: Estimates of application rates of nitrogen (N), phosphoric oxide (P_20_5, later denoted as P), and potash (K_20, later denoted as K), were adjusted to annual estimates of total state-use data.[13] These application rates for individual crops were then multiplied by harvested acreages, and the sums were compared with annual state consumption data. If the sum for individual crops exceeded annual state use, all application rates were reduced proportionately. Conversely, if the sum of nutrient use on individual crops was less than annual state consumption, all application rates were proportionally increased. These comparisons and adjustments were made for each plant nutrient, states and survey year.

The earlier surveys, conducted by the National Fertilizer Association in the years 1927, 1938 and 1944, were made largely among fertilizer users. Therefore, adjustments of application rates for the earlier survey years were generally greater than those for later surveys when the sample included both fertilizer users and nonusers.[14] Data in table 4 exemplify adjusted application rates of plant nutrients for specified crops in Indiana for 6 survey years. Evidently, application rates varied greatly between crops and plant nutrients and over time. Corresponding estimates of nutrient application were made for other states.

Finally, annual fertilizer application rates were estimated for the intervening years between survey years. In the long run, fertilizer application rates changed significantly for all crops. Superimposed on these long-run trends were short-run fluctuations in fertilizer use caused by annual changes in farm income, capital rationing, acreage adjustment, price variation and weather conditions. Because of both long-run and short-run changes, estimation of annual application rates by linear interpolation between successive survey years was considered insufficient. Instead, estimates of *annual* application rates were based on: (a) long-run changes in application rates of each nutrient and rela-

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[9] J. R. Douglas and R. D. Crisso. United States plant nutrient consumption. (Mimeo.) Division of Agricultural Relations, Tennessee Valley Authority. Knoxville, Tennessee. November 1961.

[10] U.S. Department of Agriculture. Statistics on fertilizer and liming material in the United States. U.S. Dept. Agr. Stat. Bul. 191. 1957.

[11] J. B. Abbot, C. P. Blackwell, W. F. Pate and W. A. Shelton. American fertilizer practices (first survey). The National Fertilizer Association Inc., Washington, D.C., December 1928; H. R. Smalley, R. H. Engle and H. Willet. American fertilizer practices (second survey). The National Fertilizer Association, Inc., Washington, D.C. December 1939; The National Fertilizer Association. The third national fertilizer practice survey. The Fertilizer Review. January-February-March 1946: pp. 7-10.

[12] H. H. Shepherd. Fertilizer used on crops and pasture in the United States, 1950 estimates. Agricultural Stabilization and Conservation Service, Food and Materials Division. (Mimeo.) U.S. Dept. of Agr. 1951; D. B. Ibach and J. R. Adams. Fertilizer used on crops and pasture in the U.S., 1954 estimates. U.S. Dept. Agr. Stat. Bul. 216. 1957; D. B. Ibach. Fertilizer used on crops and pasture in the U.S. 1959 estimates (prelim.), (Mimeo.) U.S. Dept. Agr. E.R.S. 1962.

[13] The conventional notations P_2O_5 and K_2O have been changed to P and K, respectively, for simplicity and consistency among tables, figures and text.

[14] Ibach (1959). op. cit., pp. 54-64.

tive use on each crop between survey years, (b) short-run changes in annual acreage of each crop and (c) annual changes in total state use of each nutrient. Preliminary estimates of annual rates of application were made by linear interpolation of rates between survey years. For any one year, the preliminary rates were multiplied by their respective crop acreages, summed over all crops and compared with total state consumption of each nutrient as explained previously.

As an illustration, annual estimates of fertilizer application for Indiana crops are shown in figs 6 and 7. In fig. 6, annual N, P and K rates for corn are shown for each nutrient and for all three nutrients combined as estimated for the years 1927 to 1961. Fertilizer application on corn in Indiana decreased during the early 1930's, then increased during the 1940's and rose rapidly after World War II. Application rates of individual nutrients followed a somewhat similar pattern, but their relative quantities changed over time. Nitrogen use was insignificant before 1940, increased gradually during the 1940's and advanced rapidly over the last decade. As shown in fig. 7, the rate of increase has varied greatly among crops.

Corresponding estimates of annual application rates of principal plant nutrients were made for crops in other states. In most cases, this analysis covered the years 1927 to 1961, but started later for crops that received little or no fertilizer in earlier years.

Table 4. Estimated application rates per acre for specified crops in pounds of principal plant nutrients in Indiana for 1927, 1938, 1944, 1950, 1954 and 1959.

		Pounds of nutrients applied to crop[a]			
Year	Crop	N	P	K	N, P and K
1927	Corn	0.9	5.8	3.6	10.3
	Wheat	2.3	16.5	6.4	25.2
	Oats	0.2	1.3	0.5	2.0
	Soybeans	0	0	0	0
	Tame hay . . .	0.1	1.0	1.2	2.3
1938	Corn	0.7	6.0	4.4	11.1
	Wheat	2.1	14.4	7.2	23.7
	Oats	0.2	1.0	0.5	1.6
	Soybeans	0	0	0	0
	Tame hay . . .	0.1	1.2	0.8	2.0
1944	Corn	1.9	12.0	8.5	22.4
	Wheat	2.7	14.8	9.4	26.9
	Oats	0.8	6.6	3.6	11.0
	Soybeans	0.4	3.7	3.2	7.3
	Tame hay . . .	0.2	3.2	1.8	5.2
1950	Corn	6.3	19.9	19.2	45.5
	Wheat	9.6	30.8	19.4	59.8
	Oats	3.3	14.5	10.0	27.9
	Soybeans	1.0	9.2	10.2	20.4
	Tame hay	0.2	3.5	1.9	5.6
1954	Corn	20.1	34.8	39.1	94.0
	Wheat	20.5	31.0	33.0	86.5
	Oats	9.4	28.2	28.6	66.2
	Soybeans	0	9.8	10.7	20.5
	Tame hay . . .	1.2	5.6	5.5	12.2
1959	Corn	34.5	40.5	47.5	122.4
	Wheat	30.6	39.1	40.9	110.6
	Oats	12.2	22.8	23.1	58.1
	Soybeans	1.2	10.5	11.4	23.0
	Tame hay . . .	3.9	5.1	5.6	14.6

[a] In this and other tables, equations and figures in this report, P represent P_2O_5, and K represents K_2O. See text footnote 13.

Fertilizer response: Regression estimates of fertilizer response were derived for each crop and state on the basis of prior knowledge. Data on crop fertilizer response collected by the Fertilizer Work Group of the National Soil and Fertilizer Research Committee were used as the source of information. This data collection consisted of a nationwide summary of state fertilizer response described as follows: [15]

> All pertinent published and unpublished fertilizer data through 1950 were summarized by principal crops, usually according to soils or geographic regions within a state. Yield response data were selected for individual nutrients where yields were not limited by lack of other nutrients. From these, weighted summary curves (Form A response curves) were prepared on a state wide basis for each principal crop . . . The Form A curves thus were a close expression of the data from field experiments.
>
> The Form A curves from each state usually were reviewed by all state representatives within a region. This review frequently showed inconsistencies within the curves or omissions of certain crops and nutrients. In order to present a complete picture, the inconsistencies were corrected and gaps filled by making a second set of curves called Form B curves. The Form B curves thus were based on available data, plus experience, observations and combined judgment of the technical specialists of the state and region. Where experimental data were adequate, the Form A and Form B curves were interchangeable. In some states, where data on particular crops were lacking, Form B curves for parallel situations elsewhere were used to complete the tables.

In this summary, fertilizer response was presented by crops and states in terms of (a) estimated average yields with 1950 application rates and (b) estimated percentage changes in yields resulting from variation of 1950 nutrient application rates. Regression estimates of crop yield response to individual nutrients were derived first, but before the regression equations were fitted, all crop yield data were converted to relative yield relationships (referring to the ratio of crop yields attained *with* nutrient application divided by

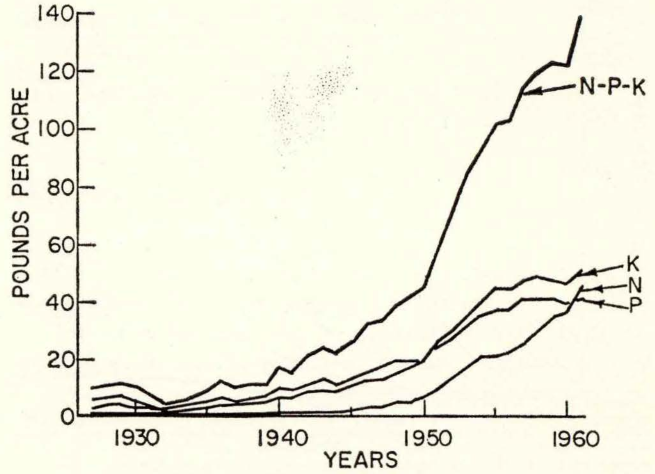

Fig. 6. Estimated annual fertilizer application per acre of corn, Indiana, 1947-1961 (P = P_2O_5; K = K_2O).

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[15] R. Z. Parks, K. C. Berger, W. E. Colwell, J. P. Conrad, M. Drake and D. B. Ibach. Fertilizer use and crop yields in the United States. U. S. Dept. Agr. Agricultural Handbook 68. Washington, D.C. 1954. p. 1.

crop yields attained *without* nutrient application). In addition, all nutrient application rates were coded by adding unity. These coding procedures permitted fertilizer yield relationships to be expressed analogously to crop variety-yield relationships discussed earlier.

Relative crop yield response is defined by equation 4, where crop yield Y_i is functionally related to a nutrient application of x_i pounds per acre,

$$(4) \quad Y_i/Y_o = (x_i + 1.0)^b$$

Y_o is the base yield attained without nutrient application and b is the exponent. If no fertilizer is used, crop yield Y_i equals Y_o and the ratio Y_i/Y_o is unity, a condition satisfied by adding one to the rate of nutrient application x_i on the right hand side of equation 4. If fertilizer is applied, the value of x_i is positive and relative crop response exceeds unity. Since the regression estimates serve merely to algebraically duplicate the graphic response curves, we assume that all b coefficients of individual nutrients, logarithms of the Y_i/Y_o ratios, are regressed linearly on logarithms of the coded application rates $(x_i + 1.0)$ by least-squares methods. To conform with equation 4, regression lines are forced through the origin requiring that relative yield response Y_i/Y_o was unity without fertilization.

Table 5. Corn yields from varying rates of N, P and K application in Indiana, 1950.

Corn yields and application rates per acre					
Yield (bu.)	N rate (lb.)	Yield (bu.)	P rate[a] (lb.)	Yield (bu.)	K rate[a] (lb.)
52.4	0	43.4	0	57.8	0
55.3	3.0	50.0	10.0	63.2	9.5
55.9	4.5	61.6	11.0	64.0	10.0
56.5	5.4	65.8	16.5	65.3	14.2
57.0	6.0	68.6	19.8	67.3	17.1
57.2	6.6	70.0	20.0	68.0	19.0
57.6	7.5	70.0	22.0	69.0	20.0
58.1	9.0	70.7	24.2	68.7	20.9
59.0	10.0	72.8	27.5	69.4	23.8
59.3	12.0	74.2	33.0	71.4	28.5
62.1	18.0	77.0	40.0	74.8	38.0
63.0	20.0	77.7	44.0	76.0	40.0
68.0	40.0	81.2	66.0	78.2	57.0
78.0	80.0	82.0	80.0	81.0	80.0
82.0	120.0	[b]	120.0	82.0	120.0

[a] $P = P_2O_5$; $K = K_2O$.

[b] Corresponding yield estimate not available.

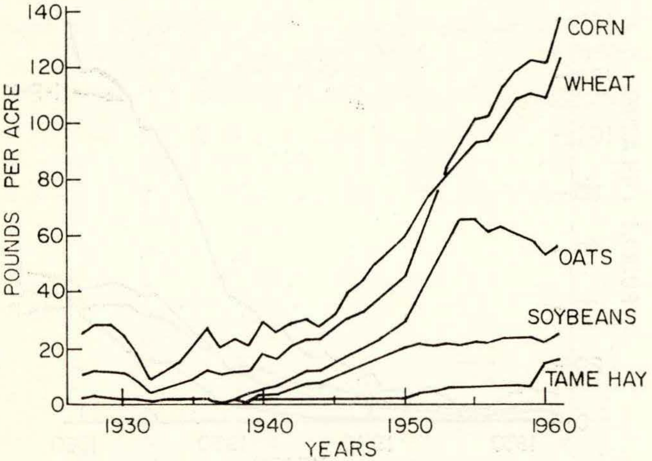

Fig. 7. Estimated annual application per acre of plant nutrients for major crops, Indiana, 1927-1961.

The procedure for estimating fertilizer response coefficients may be illustrated by using Indiana corn-yield data. Data in table 5 represent Indiana corn yields with varying rates of application of the three nutrients. They were derived from information published by the National Soil and Fertilizer Research Committee[16] and are used here to estimate relative corn yield response to varying rates of nutrient application. The estimated single nutrient response functions for nitrogen, phosphoric oxide and potash are represented by equations 5, 6 and 7, respectively, where N, P and K refer to application of nitrogen

$$(5) \quad Y_n/52.4 = (N + 1.0)^{0.068}$$

$$(6) \quad Y_p/43.4 = (P + 1.0)^{0.150}$$

$$(7) \quad Y_k/57.8 = (K + 1.0)^{0.064}$$

phosphoric oxide and potash; Y_n, Y_p and Y_k denote corresponding estimates of corn yields. The constants, 52.4, 43.4 and 57.8, are corn yields attained without fertilizer use and are equivalent to the yield values listed in the first row of table 5. Differences in nutrient response are reflected by estimated exponents of response equations 5, 6 and 7. According to table 5, an application of 80 pounds of nitrogen raises the corn yield from 52.4 to 78.0 bushels per acre, an increase of 25.6 bushels; 80 pounds of phosphoric oxide raises the yield by 38.6 bushels and the same amount of potash raises the yield by 23.2 bushels. Evidently, response to the phosphoric oxide was stronger than response to nitrogen or potash; hence, the larger exponent of P in equation 6. The estimated equations had r^2 values of 0.92, 0.99 and 0.97, respectively, indicating a close fit between fertilizer response data and regression estimates. Corresponding estimates for other crops and states displayed similar relationships, with r^2 values ranging from 0.80 to 0.99.

Single-nutrient response equations required adjustments before they could be used as an estimate of combined nutrient response. The exponents 0.068, 0.150 and 0.064 in equations 5, 6 and 7 were valid if response to any one nutrient was not limited by lack of other nutrients. In practice, however, farmers apply fertilizer mixtures containing two or three nutrients because of this nutrient interaction. For estimating nutrient response, we assumed that combined response could be neither greater than the maximum nor smaller than the minimum response of one nutrient. This assumption was justifiable because estimated maximum yield response to a single nutrient, characterized by the largest exponent among the N, P and K response equations, could be attained only if other nutrients were plentiful. Conversely, combined nutrient response could not be smaller than response to the least-productive single nutrient. A function of combined nutrient response that satisfies these assumptions is equation 8, where the ratio Y/Y_o' repre-

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[16] Ibid., p. 27.

sents relative yield response to application of nutrient mix, value Y_o' refers

$$(8)\ Y/Y_o' = (N+1.0)^{nn/(n+p+k)} (P+1.0)^{pp/(n+p+k)} (K+1.0)^{kk/(n+p+k)}$$

to the yield attained without fertilizer application, N, P and K are application rates of nitrogen, $P_2 0_5$ and $K_2 0$, and n, p, k denote the exponents of the single nutrient response functions.

Taking Indiana corn as an example, yield response to individual nutrients was estimated by n, p and k coefficients of 0.068, 0.150 and 0.064, respectively. Combined nutrient response of Indiana corn to N, P and K application was computed according to equation 8 by using equations 9 and 10. The sum of the three exponents in equation 10, 0.111, represented

$$(9)^{17}\ Y/Y_o = (N+1.0)^{f}\ (P+1.0)^{g}\ (K+1.0)^{h}$$

$$(10)\ Y/Y_o = (N+1.0)^{0.016} (P+1.0)^{0.080} (K+1.0)^{0.015}$$

the estimate of combined nutrient response. It was larger than 0.064 but smaller than 0.150, the minimum and maximum values of the exponents of the single-nutrient equations 5, 6 and 7, as explained previously.

In some cases, there was no response to one or two of the three principal nutrients. For example, there was no yield response to nitrogen for Iowa soybeans, with yield response for N, P and K being estimated in terms of exponents 0.000, 0.023 and 0.010, respectively. In accordance with adjustment equation 8, the combined nutrient response equation then was estimated as in equations 11 and 12. Hence, with Iowa farmers not using nitrogen on soybeans, equation 12 did not discount against nonuse. In this fashion, adjustment formula 8 was used to accommodate use or

$$(11)^{*}\ Y/Y_o = (N+1.0)^{f}\ (P+1.0)^{g}\ (K+1.0)^{h}$$

$$(12)\ Y/Y_o = 1.0\ (P+1.0)^{0.016}\ (K+1.0)^{0.003}$$

nonuse of nutrients in cases of single nutrient, zero-response functions. After being adjusted in this manner, all single nutrient response coefficients could be inserted in the state crop-production functions.

Had they occurred at random, annual weather variations could have been ignored in the analysis of long-run trends in crop-yield technology. However, prolonged periods of drought have occurred in the past. Also, it has been suggested that an important part of corn yield increases in recent years can be largely attributed to "runs" of above-average weather conditions. Prolonged periods of abnormal weather might well bias estimates of yield trends, and, therefore, a weather index was incorporated into our study.

CROP WEATHER INDEX

Indexes for measuring the effect of weather variations on crop yields have been computed by other research workers.[18] Unfortunately, these weather indexes were either incomplete or based on estimational techniques that could not be combined with this study's procedures. Two methods of constructing weather indexes were considered for this study; one based on multiple-regression analysis of weather variables, the other based on phenological crop-yield data. Because of its simplicity and because weather is not the major focus of this study, the latter approach was used.

A phenological crop-weather index is characteristically based on year-to-year variations of crop appearance. Crop appearance is conditioned by weather, soil, variety, fertilizer and disease. A reliable phenological weather index requires estimation of that part of the annual yield variations attributable to annual weather changes. It can be constructed readily only by using simplifying assumptions. We assume that annual yield variations on given experiment station test plots can be attributed to weather fluctuations if fertilizer, variety and other variables are constant. In using test-plot yields as the basic data for deriving weather indexes, we also suppose that experiment station weather effects are correlated with those of the region in which the stations are located.

Yield data of crop nursery tests and crop variety tests, uniform with respect to fertility level, were used for constructing the phenological crop weather indexes of this study. Aside from weather fluctuations, year-to-year changes in test plot yields were caused primarily by replacing older varieties by newer varieties. Therefore, state crop weather indexes were constructed by (a) comparing annual test plot yields of given crop varieties with their respective long-run average yields, (b) averaging these yield comparisons over crop varieties at particular test locations, (c) aggregating and averaging yield comparisons over test locations.

Formally, this estimation procedure is represented by equations 13 and 14, where subscripts i, j and L denote variety, years and location, respectively. In equation 13, w_{ijL} refers to yield variety, in

$$(13)\ w_{ijL} = Y_{1jL}/(\sum_{j}^{n} Y_{jiL}/n_{iL}) \quad \text{where } i = 1, \ldots, m \text{ and } j = 1, \ldots, n$$

$$(14)\ W_{jL} = \sum_{i}^{m} w_{ijL}/m_{jL}$$

year j, at location L, relative to the average yield of the same variety, over a period of n years. In equation 14, W_{jL} refers to the average of such yield comparisons over m varieties, in year j, at station location L, and

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[17] In this equation $f = (0.068/0.282)^2$, $g = (0.150/0.282)^2$, and $h = (0.064/0.282)^2$.

* In this equation $f = (0.000/0.033)^2$, $g = (0.023/0.033)^2$ and $h = (0.010/0.033)^2$.

[18] J. L .Stallings. Indexes of the influence of weather on agricultural output. Ph.D. thesis. Michigan State University, East Lansing. Order No. Mic. 58-5479, Univ. Microfilms, Ann Arbor, Mich. 1958; L. M. Thompson. Weather variability and the need for a food reserve. (Mimeo.) CAED Report 26, Center for Agr. and Econ. Dev. Iowa State Univ., Ames, Iowa. 1966; L. H. Shaw and D. D. Durost. Measuring effects of weather on agricultural output. (Mimeo.) U.S. Dept. of Agr., Econ. Res. Serv., E.R.S. 72. 1962.

may be interpreted as the station weather index of the crop in question. To estimate crop weather indexes of the state, the annual station weather indexes are aggregated and averaged.

The estimation of crop weather indexes may be further illustrated by the derivation of the North Dakota wheat weather index. North Dakota indexes were calculated for Fargo, Langdon, Edgeley, Dickinson, Mandan, Williston and Minot station locations. Wheat yield tests were not conducted at all seven locations each year, but at least four locations were used for index computations of any one year. At each station location, test yields of three wheat varieties (Ceres, Thatcher and Mida) were included, and weather indexes were computed for each variety. As an example, Fargo variety test yields and annual indexes of each variety are tabulated in columns 1 to 6 of table 6. The station weather index, listed in column 7, was computed by averaging annual indexes over varieties for the years of available data. The North Dakota wheat weather index was then derived by averaging individual station indexes.

A graphic illustration of the North Dakota wheat weather index is presented in fig. 8, and estimates of North Dakota wheat yields for the same year are depicted in fig 9. A comparison between figs. 8 and 9 discloses resemblance between the computed weather index and annual state wheat yields. However, there is a marked difference between the long-run trends of the two graphs. During the early period the annual wheat weather index of North Dakota exceeded the long-run average line, an indication of above-normal, better-than-average weather conditions. By contrast, annual yields of North Dakota were below the long-run average yields throughout the early years, reflecting a long-run, positive yield trend. Much of this yield increase was due to introduction of newer and higher-yielding wheat varieties. This yield increase did not affect estimates of annual weather indexes because variety-yield effects were practically eliminated in weather index computations. This elimination was accomplished by considering yield variations of individual varieties rather than annual yield changes of all varieties.

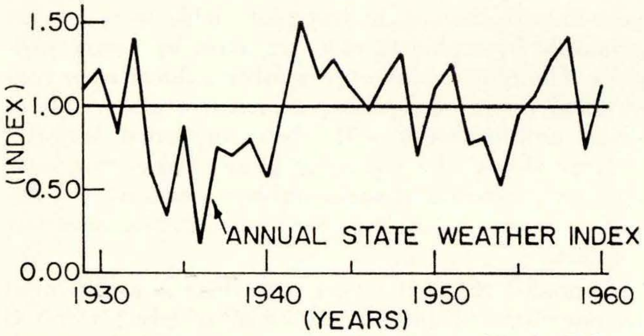

Fig. 8. Estimated wheat weather index, North Dakota, 1929-1960.

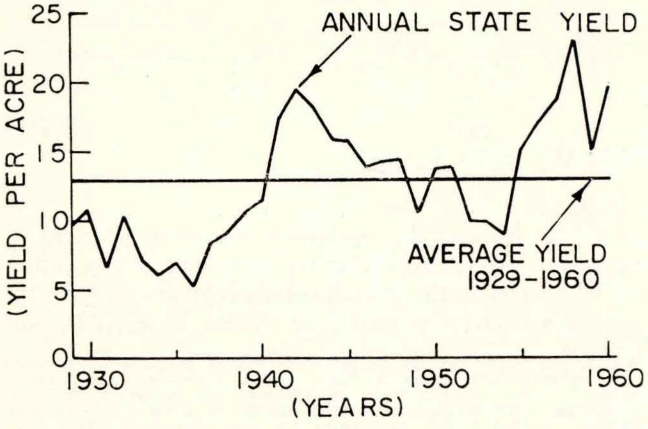

Fig. 9. Wheat yield per harvested acre, North Dakota, 1929-1960.

Essentially, the same procedure was used for constructing state crop weather indexes of other crops and states. As a rule, all station indexes received identical weights when aggregated annually. For soybeans, however, acreage weights were used for aggregating station indexes over maturity groups. State hay-wea-

Table 6. Wheat weather index and related data, Fargo, North Dakota, 1929 to 1960.

	Test yields of spring wheat varieties						Fargo Spring wheat[b]
Year	Ceres[a]		Thatcher[a]		Mida[a]		Weather
	Bushel	Index	Bushel	Index	Bushel	Index	Index
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
1929	31.2	1.42					1.42
1930	41.4	1.65					1.65
1931	35.0	1.39					1.39
1932	33.3	1.33					1.33
1933	29.9	1.19					1.19
1934	17.3	0.69	14.2	0.54			0.62
1935	20.3	0.81	31.6	1.20			1.00
1936	9.8	0.39	10.0	0.38			0.38
1937	20.2	0.80	30.1	1.14			0.97
1938	23.2	0.92	30.7	1.17			1.04
1939	26.1	1.04	26.3	1.00			1.02
1940	17.5	0.70	19.4	0.74	19.7	0.71	0.72
1941	23.6	0.94	22.0	0.84	28.0	1.01	0.93
1942	42.6	1.70	38.3	1.46	48.0	1.73	1.63
1943	17.2	0.69	21.1	0.80	24.0	0.87	0.79
1944	18.2	0.73	22.4	0.85	23.1	0.83	0.80
1945	24.3	0.97	26.7	1.02	27.7	1.00	1.00
1946	27.1	1.08	26.5	1.01	24.6	0.89	0.99
1947	22.5	0.90	22.7	0.86	23.2	0.84	0.87
1948	27.2	1.08	28.6	1.06	27.1	0.98	1.05
1949	28.9	1.15	26.6	1.01	29.2	1.05	1.07
1950	25.8	1.03	32.5	1.24	32.2	1.16	1.14
1951	37.7	1.50	38.2	1.45	35.3	1.27	1.41
1952	18.7	0.75	16.9	0.64	17.7	0.64	0.68
1953	16.6	0.66	21.5	0.82	17.4	0.63	0.70
1954	12.6	0.50	16.6	0.63	14.5	0.52	0.55
1955	19.9	0.79	19.1	0.73	24.0	0.87	0.80
1956	32.8	1.31	36.9	1.40	33.8	1.22	1.31
1957	33.0	1.31	39.9	1.52	41.1	1.48	1.44
1958	29.9	1.19	31.4	1.19	28.3	1.02	1.13
1959	16.9	0.67	22.1	0.84	23.8	0.86	0.79
1960	31.2	0.84	37.9	1.44	39.9	1.44	1.24
Average	25.1	1.00	26.3	1.00	27.7	1.00	

[a] Index is the ratio of annual yield over average yield of variety.
[b] Index is the average value of columns 2, 4 and 6.

ther indexes were derived from data on pasture conditions published annually by the United States Department of Agriculture. In deriving state hay-weather indexes, the average of the June 1 and Sept. 1 pasture conditions were used for 1927 through 1960. Annual state hay-weather indexes were then computed as the ratio, annual pasture condition divided by average condition over the period.

CORN WEATHER INDEX

Corn weather indexes were estimated somewhat differently. Annual average yields of all corn hybrid test entries were calculated for each corn test district, the number of districts ranging from 2 in Ohio to 12 in Iowa. For computing state corn weather indexes, annual average yields of all hybrid corn tests were aggregated by weighting average yields of individual corn test districts by their relative acreages. These acreage weights were usually based on 10 to 20-year averages of individual crop districts, but in some cases, acreage weights were based on shorter periods because of lack of data. Linear time trends were fitted to aggregated corn test yields and annual average corn test yields were divided by estimated trend values. The resulting yield ratios were taken as estimates of state corn weather indexes. The assumption of constant fertility of test plots was dropped. We assumed that corn test yields advanced over time at a constant rate because of gradual increases in fertilizer, replacement of older corn hybrids by newer hybrids and improvements in other cultural practices. This assumption applicable to *test plots* did not imply that *state* corn yields advanced at a constant rate. It did, however, assure that yield effects of abrupt *statewide* changes in fertilizer practices, in corn acreage and government programs were not confounded with state corn weather indexes.

Data released for construction of the Iowa corn weather indexes are illustrated in figs. 10, 11 and 12. Annual corn test yields and the corresponding time-trend line are shown in fig. 10. These data extended from 1926 to 1962 and were based on annual average corn test yields, aggregated and averaged over 12 corn test districts in Iowa. The corresponding annual Iowa corn weather indexes (fig. 11) were computed as ratios of annual corn test yields divided by the trend-line values shown in fig. 10. Iowa corn yields over the same period are shown in fig. 12. Annual state yields varied from less than 20 bushels per acre in 1936 to over 60 bushels in 1961. Aside from annual yield variations, there was a pronounced rise in yields over time, particularly after 1935. Annual corn yields were consistently below long-run average yields during the early period but rose far above these in later years. Hence, the question arises: How much of this yield increase was due to weather variations, and how much was due to other improved practices? The answer to this question could be provided only if the impact of other crop yield variables, discussed later, was specified.

CORN ACREAGE AND OTHER CROP-YIELD VARIABLES

As acreage of any one crop is expanded, yield per acre can be expected to decline because the crop is planted in areas less suited for its production. Yields of certain crops (e.g., corn and soybeans) are known to be especially sensitive to geographic location.

Crop acreage index: To measure the importance of acreage effects on state crop yields, a state crop-acreage index was devised. Acreage trends were computed for all states and crops included in the present study. They were estimated by fitting time-trend lines to harvested crop acres of individual crops and states. In most instances, the analysis started with 1939, but sometimes extended back to earlier years. Time-trend lines were fitted to harvested crop acres over 1939 to 1960 in all cases, but a second trend line was fitted to crop acreages of earlier years whenever required. The 1939 end-point of the trend line of earlier years was made to coincide with the 1939 starting point of

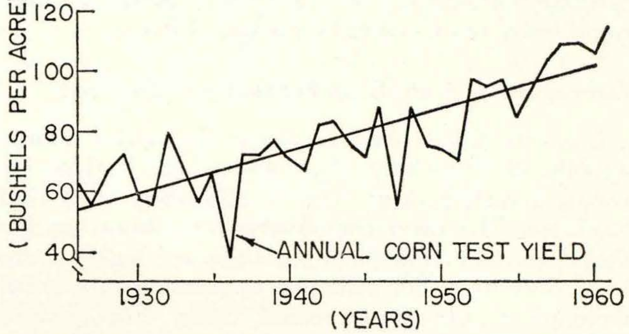

Fig. 10. **Corn test yields and trend yields, Iowa, 1926-1961.**

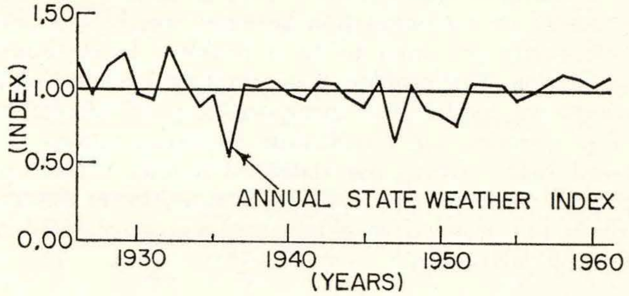

Fig. 11. **Estimated corn weather index, Iowa, 1926-1961.**

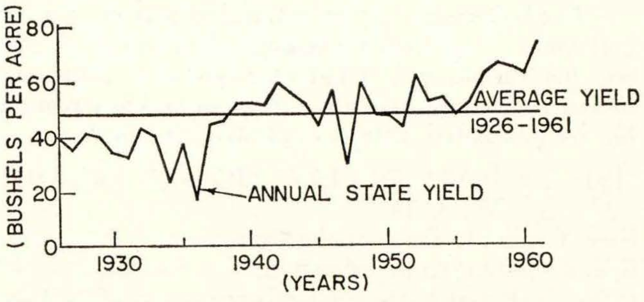

Fig. 12. **State corn yields, Iowa, 1926-1961.**

more recent years by (a) deducting the estimated trend acreage of 1939 from actual crop acreages of 1939 and preceding years and (b) extending the trend line back to earlier years by forcing the trend line through the 1939, or zero value, of origin. This estimating procedure for trend values of state crop acreages was designed to make all acreage trend lines used cover the same period, 1939 to 1960, but to allow the effects of acreage trends of earlier years when data were available. The state crop acreage index was computed by dividing annual state crop acreages by estimated trend-line values. In contrast to crop variety indexes, acreage indexes were not designed to measure yield effects directly, on the basis of *a-priori* knowledge, but were merely inserted as an independent crop-yield variable to subsequent analyses.

Other crop yield variables: Aside from the major forces discussed thus far, other improved practices relating to insecticides, herbicides, irrigation, drainage, tillage and timeliness of operations undoubtedly have influenced crop yields. None of these practices was considered individually, but an attempt was made to include their net effects by using a time-trend variable in the production function analysis. The time-trend variable's use will be explained later.

Estimation of State Crop Production Functions

Production functions represent the major method applied in this study. This method of analysis encounters certain difficulties in estimating crop yield increases. The main complexity stems from the fact that important crop yield variables are highly correlated over time. For example, application rates of all three plant nutrients increased, newer crop varieties replaced older ones, and use of other crop yield variables changed simultaneously during the analysis. Because of strong correlation between variables, multicollinearity promised to be a problem in statistical estimation. This problem was overcome by selecting a functional model that incorporated yield effects of crop varieties and fertilization from estimations derived before fitting the statistical function. This approach posed certain undesirable rigidities in the analysis, but promised to eliminate the primary problem of multicollinearity.

ALGEBRAIC FORM

A Cobb-Douglas or power function was chosen for analysis of crop yield technology. As mentioned earlier, the various crop yield variables were estimated so that they could be readily incorporated in equation 15, the postulated state crop-production function.

$$(15)\quad Y = b_0 V^{1.0} (N+1.0)^{n'} (P+1.0)^{p'} (K+1.0)^{k'} W^{w} A^{a} T^{t}$$

Here Y refers to the annual estimated state crop yield; b_0 is a constant to be estimated; V is the crop variety index; N, P and K are rates of application of N, P_2O_5 and K_2O; and n′, p′ and k′ are the corresponding exponents.[19] W, A and T denote weather index, acreage index and net time-trend variable (with origin in 1938), respectively, and w, a and t are the corresponding exponents. Annual state crop yield Y is a function of a set of crop-yield variables that assume values of unity under certain conditions. For example, the variety index V is 1.00 for the base period, 1947-49, and the terms (N+1.0), (P+1.0) and (K+1.0) are 1.00 if no fertilizer is applied; the weather index W is 1.00 if weather for a given crop year is normal, and acreage index A is 1.00 if actual acreage is the same as long-run trend acreage. If variety improvement is at the 1947-49 level, no fertilizer is applied, weather is normal and acreage coincides with its long-run trend value; estimating equation 15 reduces to equation 16, where the constant term b_0 is multiplied by the time-trend T_0 with origin in 1938 (e.g., 1939=1.0) raised to its appropriate power

$$(16)\quad Y_0 = b_0 T_0^{t}$$

which can be interpreted as the 1947-49 base yield of a particular crop and state. The concept of a base yield value is useful here in explaining the logic of production function 15. If, for example, the variety index V in any one year is not 1.00 but 1.10, the base yield is multiplied by 1.10 with the implication that, because of superior crop varieties, the state crop yield is 10 percent higher than the base yield. If fertilizer is applied, then the base yield is altered according to the adjusted nutrient response exponents n′, p′ and k′. As long as the sum of these nutrient response exponents is smaller than unity, a 1-percent change in (plant nutrients applied) is expected to cause a change of less than 1 percent in state yield; this is a reflection of diminishing marginal productivity of the plant nutrients. Similarly, the effects of weather (W), acreage (A) and other crop yield variables (T) depend on the magnitude of their exponents w, a and t. However, exponents w, a and t differ from the nutrient exponents n′, p′ and k′, in the sense that the former are estimated on the basis of actual state crop-yield data, whereas the latter, as well as the exponent 1.0 of the crop-variety index, are predetermined on the basis of extensive experimental data. This differential treatment is essential to avoid the problems of multicollinearity discussed next.

STATISTICAL ESTIMATION

The state crop-production functions were estimated by least-squares regression after modification of the state yield data. For estimation purposes, the proposed state crop-production function was rearranged according to equation 17. It is identical to equation 15

$$(17)\quad Y/V^{1.0} = (N+1.0)^{n'} (P+1.0)^{p'} (K+1.0)^{k'} = b_0 W^{w} A^{a} T^{t} e$$

---

[19] The nutrient response exponents n′, p′ and k′ are equivalent to exponents $n^2/(n+p+k)$, $p^2/(n+p+k)$ and $k^2/(n+p+k)$ in equation 8.

except for the error term e and that annual estimated state crop yields, denoted by Y, were deflated by the annual crop variety index and the crop-yield response to application of plant nutrients. Although this modification did not affect the algebraic form of production equation 15, it did alter the statistical regression estimates significantly.

Without this modification, instability of regression estimates would have caused undesirable distortions in the production-function analysis. The independent variables of technological change were highly correlated as illustrated by the frequency distribution of correlation coefficients for pairs of corn yield variables in 13 states (table 7). In 39 cases, the correlation coefficients tested significant at the 1-percent level of probability. In contrast, 91 other correlation coefficients were not significantly different from zero at the 1-percent level. Obviously, correlation between hybrid corn indexes, rates of fertilizer application and the time-trend variable was very strong. Adverse effects of this multicollinearity on regression estimates were avoided by using estimating equation 17, which incorporates estimates of yield effects of crop variety improvement and fertilizer application, before the function was fitted to the data. By separating the effects of these two sets of variables from trend effects, the time-trend variable could be used to measure the yield changes due to other unspecified crop yield variables. It thus is identified as the "net time-trend" variable.

Comparing the results of state crop production functions fitted in conventional (equation 15) and modified (equation 17) form favors the modified form. Two multiple-regression equations were fitted to Iowa corn yield data, the first according to the conventional estimating equation 18, where Y, V, F, W, A and T denote annual Iowa corn yield

$$(18) \quad Y = b_0 V^v F^f W^w A^a T^t e$$

hybrid corn index, rate of fertilizer nutrient application per acre, weather index, acreage index and time in years, respectively. The second equation, was fitted according to equation 17 described earlier. Both functions were estimated on the basis of 36 annual data sets covering the years 1926 to 1961. Their coefficients were statistically significant (table 8) but even though the multiple correlation coefficient of the conventional estimating equation, 18, was high, certain coefficients were not acceptable on the basis of *a-priori* knowledge. In equation 18, the coefficient of fertilizer application was negative, a contradiction of numerous experiments conducted at Iowa State University showing positive response and a contradiction of actual farm results. Also, the coefficient of the hybrid corn index was unrealistic, its value of 2.27 implying that state corn yield increased by 2.27 percent for every 1-percent change in the hybrid corn index.

More realistic coefficients were obtained by using the modified estimating equation 17. Fixed on the basis of other empirical evidence, with the coefficients of N, P and K being positive, the coefficient of the hybrid corn index was set at unity, suggesting that a 1-percent change in the index corresponded to a 1-percent change in corn yields. These modified coefficients were accepted as superior estimators, even though the original least-squares estimators provided a "better" fit in the sense of R^2. The multiple-correlation coefficient was reduced from 0.94 to 0.87 by using equation 17.

Table 8. Regression coefficients of estimating equations fitted to Iowa state corn yield data, 1926-1961.

Crop yield variables and multiple correlation coefficient	Regression coefficients	
	Equation 17 (modified)	Equation 18 (modified)
Hybrid corn index	1.00[b]	2.27
N-P-K application per acre of corn[a]	0.02[c]	-0.09**
Weather index	1.18**	1.25**
Acreage index	0.15	0.06
Time trend	0.20	0.07
Multiple correlation coefficient	0.87**	0.94**

[a] $P = P_2O_5$, $K = K_2O$.
[b] Predetermined coefficient of corn hybrid index.
[c] Predetermined coefficient of N-P-K response.
**Significantly different from zero at the 1-percent level.

Table 7. Frequency distribution of absolute values of simple correlation coefficients between corn yield variables of 13 states.

Variables	Intervals in values of correlation coefficients									
	0.00-0.09	0.10-0.19	0.20-0.29	0.30-0.39	0.40-0.49	0.50-0.59	0.60-0.69	0.70-0.79	0.80-0.89	0.90-0.99
Weather index, hybrid index	8	3	2							
Weather index, N-P-K application[a]	8	4	1							
Weather index, acreage index	5	5	1	2						
Weather index, time trend	9	4								
Acreage index, hybrid index	7	3	1	1	1					
Acreage index, N-P-K application[a]	2	5	4	1		1**				
Acreage index, time trend	5	1	1	1**						
Hybrid index, N-P-K application[a]									*	*
Hybrid index, time trend										13*
N-P-K application, time trend									1*	12*
Frequency	44	29	10	5	2	1	0	0	10	29

* Significantly different from 0 to the 1-percent level.
** Significantly different from 0 to the 5-percent level.
[a] P and K denote P_2O_5 and K_2O, respectively.

Estimation of the Impact of Crop Yield Technology

After estimating state crop production functions, it was possible to quantify changes in yield per acre attributable to the different variables or technologies. The contributions of crop-yield technology to estimated yield was measured on an annual, as well as a cumulative, basis over the past 2 decades.

YIELD TECHNOLOGY AND STATE CROP YIELDS

The direct goal of the predictions is to estimate expected yield for each crop and year although the overall analysis is directed at crop-yield variables (variety improvement, application rates of fertilizer and others) reflecting long-run effects of technology. Short-run variations in weather and crop acreages are not considered in this context of yield technology, but are examined separately later. Hence, predictions of expected yields in any year, which suppose normal weather and acreage, differ from actual yields. Annual indexes of weather and crop acreage are set equal to unity in the estimating equation. In equation 19, the symbols from left to right have these definitions:

$$(19)\quad Y_j = b_o V_j^{1.0} (N_j + 1.0)^{n'} (P_j + 1.0)^{p'} (K_j + 1.0)^{k'} \, 1.0^{w} \, 1.0^{a} \, T_j^{t}$$

Y_j is estimated state crop yield, b_o is the constant term, V_j is crop variety index, N_j is nitrogen, P_j is P_2O_5, K_j is K_20 and T_j is net time-trend as defined before. Equation 19 is the same as 15 except that subscripts j are added to denote annual values of crop yield variables, and indexes of annual weather (1.0^w) are set equal to unity. With weather and acreage indexes equated to 1.0 in equation 19, annual variations in both variables are ignored and crop yields estimated by this equation can be interpreted as those expected under normal weather and acreage.

Equation 19 was simplified further to express yield response to fertilizer. Terms involving variables N, P and K in equation 19 were replaced by a single term F_j as in equation 20, where F_j is defined by equation 21. Factor F_j is a ratio that measures response to fertilizer

$$(20)\quad Y_j = b_o V_j F_j T_j^{t}$$

$$(21)\quad F_j = (N + 1.0)^{n'} (P + 1.0)^{p'} (K + 1.0)^{k'}$$

in a manner similar to the crop variety index V_j. It changes from year to year with changes in nutrient mix of fertilizer.

After this simplification, annual changes in expected state crop yields were approximated by a first-term Taylor expansion of equation 20 (see equation 22), where the change in yield from year j to year j+1

$$(22)\quad Y_{j+1} - Y_j \sim (\partial Y/\partial V)_j (V_{j+1} - V_j) + (\partial Y/\partial F)_j (F_{j+1} - F_j) + (\partial Y/\partial T)_j (T_{j+1} - T_j)$$

was attributed, according to marginal productivities and increments of each variable, to annual changes in varieties, fertilizer application and other crop yield technologies. Application of the Taylor expansion required a function that had finite and continuous partial derivatives of all orders and a remainder term approaching 0 upon further expansion. These conditions are met in the Cobb-Douglas function if the exponents are greater than 0, but smaller than 1.0, and if the changes in the variables are smaller than the original levels. The exponents of V_j and F_j equaled 1.0, and the first order (partial) derivatives were not zero in equation 20. Although derivatives of higher order vanished, approximation was not seriously impaired because substitution of a slightly smaller exponent, say 0.999, made equation 20 differentiable to any desired order. A first-order expansion proved adequate. Annual changes of crop yield variables were smaller than the original input levels, and hence, the second condition also was met. To change approximation equation 22 into an equality, approximate values of individual terms were adjusted proportionally, an adjustment that usually amounted to less than 1 percent of the total change in crop yield or production. Cumulative changes in estimated state crop yields were computed by adding the estimated annual changes for each variable.

Ohio wheat yield data serve as an empirical example of estimation. In table 9, expected or estimated[20] annual Ohio wheat yields Y_j, annual variety indexes V_j and fertilizer response values F_j are shown in columns 1 to 3. Annual yield changes attributed to other (unspecified) crop yield variables, variety improvement and fertilizer use are presented in columns 4 to 6, and cumulative yields listed in columns 7 to 9. All data of table 9 were derived from equation 23 and its equivalent form, equation 24. According to table 9 (column 1), expected wheat yields increased from 20.38 bushels in

$$(23)\quad Y_j = 5.829\, V_j (N + 1.0)_j^{0.035} (P + 1.0)_j^{0.095} (K + 1.0)_j^{0.017} A_j^{0.040} W_j^{0.140} T_j^{\,0.253}$$

$$(24)\quad Y_j = 5.829\, V_j F_j T_j^{0.253}$$

in 1939 to 28.33 bushels in 1960. Over the same period, variety indexes advanced from 0.952 to 1.043 (column 2) and fertilizer response values from 1.452 to 1.655 (column 3). Annual crop variety indexes increased year after year, and consequently, annual yield changes attributed to variety improvement were positive for all years (column 5). Yield changes attributed to changes in fertilizer application were negative in 5 of 22 years (column 6). For example, a state yield change of minus 0.112 bushels of wheat was attributed to a change in fertilizer use between the years 1943 and 1944. This negative change resulted from a decline in estimated fertilizer response from 1.483 to 1.475 (column 3) and of a reduction of fertilizer use (N, P_20_5 and K_20 as denoted by N, P and K, respectively) from 38.0 to 35.6 pounds per acre.

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[20] Expected or estimated annual wheat yields refer to estimated wheat yields based on normal acreage and weather conditions as specified earlier. The expected or estimated yields are not those realized in the particular years, but are those computed on the basis of the production functions derived in this study. Actual yields may differ from the expected or estimated yields because of weather effects or other variables not included in the analysis.

had been identical in all states. Even if crop yields had differed among states, the question of regional specialization could have been ignored if state crop acres of any particular crop had remained constant over time. However, since crop yields did not advance at the same rate in all states and relative state crop acres changed over time, production location or regional specialization effects in the analysis of aggregate crop yield change were examined.

To estimate the yield effect of regional specialization, a variable for relative state acreage was used. Aggregate crop yield aY_j, in year j was defined by equation 25, as the sum of m state crop yields, Y_{ij}, weighted by relative state acreage R_{ij}. The relative state acreage R_{ij}

$$(25) \quad aY_j = \sum_{i}^{m} Y_{ij} R_{ij} = \sum_{i}^{m} b_i V_{ij} F_{ij} T_{ij}^{t} R_{ij}$$

$$\text{where } R_{ij} = A_{ij} / \sum_{i}^{m} A_{ij} \qquad \begin{array}{l} i = 1, 2, \ldots, m \\ j = 1, 2, \ldots, n \end{array}$$

of state i, in year j was defined as state crop acreage, A_{ij}, divided by aggregate crop acreage, the sum of all m state acreages. The right-hand side of equation 25 was equivalent to the sum of m state crop production functions. Applying a first-term Taylor expansion to equation 25 yielded, after simplifying, the notation of change as in equation 26. An approximation of change in aggregate yield, $\triangle aY_j$, is

$$(26) \quad \begin{aligned} \triangle aY_j &= aY_j - aY_{j-1} \\ \triangle V_{ij} &= V_{ij} - V_{i,j-1} \\ \triangle F_{ij} &= F_{ij} - F_{i,j-1} \\ \triangle T_{ij} &= T_{ij} - T_{i,j-1} \\ \triangle R_{ij} &= R_{ij} - R_{i,j-1} \end{aligned}$$

indicated by equation 27. Individual summation terms in equation 27 were composed of the product

$$(27) \quad \triangle aY_j \sim \sum_{i}^{m} [(\partial aY/\partial V_i)_j \quad \triangle V_{ij} + (\partial aY/\partial F_i)_j \quad \triangle F_{ij} + (\partial aY/\partial T_i)_j \quad \triangle T_{ij} + (\partial aY/\partial R_i)_j \quad \triangle R_{ij}]$$

of partial derivatives of aggregate crop yield with respect to crop yield variables of state i, year j and annual changes of these variables between year j and year j-1. Partial derivatives of *aggregate* crop yield change—e.g., $(\partial aY/\partial V_i)_j$—were equal to partial derivatives of state crop yield change multiplied by R_{ij}—e.g., $(\partial Y_i/\partial V_i)_j (R_{ij})$—because aggregate crop yields were composed of state crop yields weighted by relative crop acreage as shown in equation 25. The last term in equation 28 quantifies change in aggregate crop yield attributable to yield effects of acreage distribution among states. In this way, the

$$(28) \quad \triangle aY_j \sim \sum_{i}^{m} \left(\frac{\partial Y_i}{\partial V_i} \right)_j \triangle V_{ij} R_{ij} + \sum_{i}^{m} \left(\frac{\partial Y_i}{\partial F_i} \right)_j \triangle F_{ij} R_{ij} + \sum_{i}^{m} \left(\frac{\partial Y_i}{\partial T_i} \right)_j \triangle T_{ij} R_{ij} + \sum_{i}^{m} \left(\frac{\partial Y_i}{\partial R_i} \right)_j \triangle R_{ij}$$

impact of crop yield could be measured annually. For each year, approximate values of individual terms in equation 28 were adjusted proportionately to make equation 27 an equality. Again the required adjustments were small, except when year-to-year changes in state crop acres were large or changes in aggregate yields were exceptionally small. Estimated annual yield changes attributed to various technologies and regional specialization were then summed over years and thus furnished estimates of aggregate changes in yield and production for the period under consideration.

Using the Corn Belt as an empirical example, we illustrate the estimation of the effect of crop-yield technology and regional specialization. Over the 2 decades, nearly 30 million acres of corn were grown annually in five Corn Belt states: Ohio, Indiana, Illinois, Iowa and Missouri. Estimated yields[21] in 1939 averaged 39.6 bushels for Corn Belt states and ranged from a low of 26.5 bushels in Missouri to a high of 43.4 bushels in Iowa (table 10). In 1961, 2 decades later, estimated Corn Belt yields averaged 64.1 bushels, a 50-percent increase over the 1939 yield and ranged from 48.4 bushels in Missouri to 71.4 bushels in Illinois. Missouri estimated yields were still lowest, but Illinois yields advanced at a rate of 1.40 bushels per year and surpassed Iowa yields in later years. Since

Table 10. Estimated corn yields and acreage trend values of 5 Corn Belt states, 1939-1961.

Item	Corn Belt states					Corn Belt
	Ohio	Indiana	Illinois	Iowa	Missouri	
Estimated corn yields						
1939 (bu. per acre)	40.8	42.2	40.5	43.4	26.5	39.6
1961 (bu. per acre)	64.0	61.4	71.4	63.9	48.4	64.1
Change in corn yields						
Total (bu. per acre)	23.2	19.2	30.9	20.5	21.9	24.5
Annual (bu. per acre)	1.05	0.87	1.40	0.93	1.00	1.11
Acreage trend values						
1939 (1000 acres)	3391	4058	7929	9705	4284	29367
1961 (1000 acres)	3212	4999	9544	11429	3891	33076
Change in acreage						
Total (1000 acres)	-178	9411	1615	1724	-393	3709
Annual (1000 acres)	-8.5	+44.8	+76.9	+82.1	-18.7	+193.6

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[21] Estimated or expected yields were derived on the basis of normal acreage and weather conditions as described earlier.

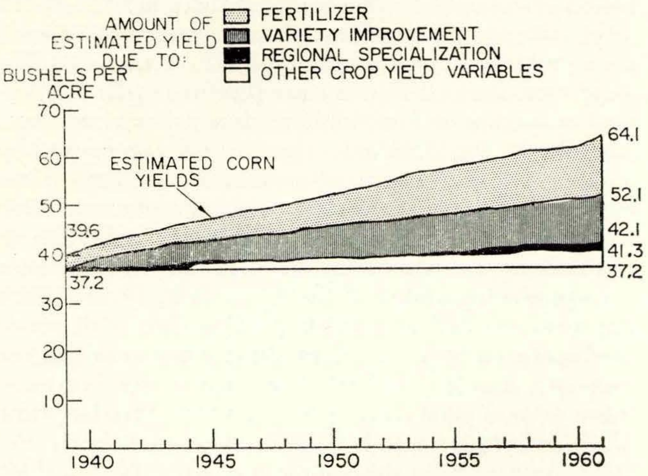

Fig. 14. Estimated corn yields and cumulative change in yields due to changes in fertilizer use, variety improvement and other crop yield variables, Corn Belt, 1939-1961, (weather and acreage constant).

1939, corn acreage in the Corn Belt has increased by 3,709,000 acres. During this period relative shifts (i.e., a reduction in lower-yielding Missouri corn acreage and an increase in the higher yielding Illinois acreage) occurred.

The effect of major crop-yielding technologies and regional specialization on estimated Corn Belt corn yields is illustrated in fig. 14. Estimated Corn Belt yields advanced from 39.6 bushels in 1939 to 64.1 in 1961 as shown by the uppermost line in the graph. This line represents the annual corn yields that could be "expected" under normal conditions. The other lines show the amount by which crop yield technologies and regional specialization contributed to the rise of corn yields in the Corn Belt. As evidenced by the shaded areas, a yield increase of 9.6 bushels per acre[22] was attributed to higher rates of fertilizer application and an increase of 10.0 bushels (52.1 bushels –42.1 bushels) was attributed to adoption of improved corn hybrids. In addition, an estimated 4.1 bushels per acre (41.3 bushels–37.2 bushels), or about one-sixth of the total yield change, were added by other crop yield variables not quantified individually. Regional specialization raised corn yields by less than 1 bushel per acre over 2 decades and reached a maximum of 0.8 bushel in 1961. This small change is because the Corn Belt has long been the center of United States corn production. Corn acreage shifts and yield differentials among Corn Belt states are less than those between regions. Hence, although regional specialization has had a significant impact on national corn yields, it was less effective within the Corn Belt.

Specific relationships between aggregate Corn Belt yields and state production functions of corn are considered next. Corn production functions are presented by equations 29 through 33, respectively, for Ohio, Indiana, Illinois, Iowa and Missouri. The exponents of the variety indexes and rates of N-P-K fertilizer application were predetermined on the basis of experimental data. For estimating aggregate crop yields, the acreage and weather indexes were set equal

$$\begin{aligned}(29)\quad Y_{\text{Ohio},j} = {} & 26.286\ V_{1,j}^{1.0}\ (N+1.0)_{1,j}^{0.037} \\ & (P+1.0)_{1,j}^{0.085}\ (K+1.0)_{1,j}^{0.007} \\ & A_{1,j}^{0.167}\ W_{1,j}^{0.569}\ T_{1,j}^{0.089}\end{aligned}$$

$$\begin{aligned}(30)\quad Y_{\text{Ind.},j} = {} & 57.127\ V_{2,j}^{1.0}\ (N+1.0)_{2,j}^{0.016} \\ & (P+1.0)_{1,j}^{0.080}\ (K+1.0)_{2,j}^{0.015} \\ & A_{2,j}^{-0.346}\ W_{2,j}^{0.486}\ T_{2,j}^{-0.101}\end{aligned}$$

$$\begin{aligned}(31)\quad Y_{\text{Ill.},j} = {} & 9.658\ V_{3,j}^{1.0}\ (N+1.0)_{3,j}^{0.042} \\ & (P+1.0)_{3,j}^{0.014}\ (K+1.0)_{3,j}^{0.013} \\ & A_{3,j}^{0.260}\ W_{3,j}^{0.870}\ T_{3,j}^{0.413}\end{aligned}$$

$$\begin{aligned}(32)\quad Y_{\text{Ia.},j} = {} & 23.626\ V_{4,j}^{1.0}\ (N+1.0)_{4,j}^{0.013} \\ & (P+1.0)_{3,j}^{0.007}\ (K+1.0)_{4,j}^{0.003} \\ & A_{4,j}^{0.150}\ W_{4,j}^{0.185}\ T_{4,j}^{0.199}\end{aligned}$$

$$\begin{aligned}(33)\quad Y_{\text{Mo.},j} = {} & 44.553\ V_{5,j}^{1.0}\ (N+1.0)_{5,j}^{0.070} \\ & (P+1.0)_{5,j}^{0.027}\ (K+1.0)_{5,j}^{0.004} \\ & A_{5,j}^{-0.124}\ W_{5,j}^{0.203}\ T_{5,j}^{-0.089}\end{aligned}$$

to unity, and the three variables of plant nutrient response were combined into a single variable, as explained earlier. Aggregate Corn Belt yield was then computed by weighting state yields according to relative state corn acreage and summing them over states as shown in equation 34, where aY_j is aggregated Corn Belt yield of year j, V is the corn hybrid index, F is fertilizer

$$\begin{aligned}(34)\quad \sum_{1}^{5} aY_j = {} & 26.286\,V_{1,j}F_{1,j}T_{1,j}^{0.089}\,R_{1,j} \\ & +57.127\,V_{2,j}F_{2,j}T_{2,j}^{0.101}\,R_{2,j} \\ & +\ \ 9.658\,V_{3,j}F_{3,j}T_{3,j}^{0.413}\,R_{3,j} \\ & +23.626\,V_{4,j}F_{4,j}T_{4,j}^{0.199}\,R_{4,j} \\ & +44.553\,V_{5,j}F_{5,j}T_{5,j}^{-0.089}R_{5,j}\end{aligned}$$

response, T is the net time-trend variable and R is the ratio of state corn acreage relative to Corn Belt corn acreage. In all cases, the first subscript stands for the state, and the second subscript denotes the year. The impact of individual crop-yield technologies and regional specialization can now be computed as shown in equation 35, where $\triangle aY_j$ refers to aggregate annual yield change between year j and year j-1 of the annual corn crop grown in the Corn Belt. Only parts of the total sum are shown. The first five terms of this sum represent the change in annual Corn Belt yield of corn attributed to hybrid corn improvement; the last five terms represent the change attributed to regional specialization. The first set of summations is comparable

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[22] Computed from the yield differences, (64.1 bushels—52.1 bushels) —(39.6 bushels—37.2 bushels) = 9.6 bushels, as illustrated in fig. 14.

to the first summation in equation 28, and the last set to the fourth summation in equation 28. The second and third summations follow the same general pattern and specify how much of the aggregate yield change was attributed to changes in rates of fertilizer application and changes in other crop yield technologies. To estimate cumulative

$$
\begin{aligned}
\triangle aY_j \sim\ & 26.286\, F_{1,j}\, T_{1,j}^{\ 0.089}\, R_{1,j}\, \triangle V_{1,j} \\
& + 57.127\, F_{2,j}\, T_{2,j}^{-0.101}\, R_{2,j}\, \triangle V_{2,j} \\
& + \ \ 9.658\, F_{3,j}\, T_{3,j}^{\ 0.413}\, R_{3,j}\, \triangle V_{3,j} \\
& + 23.626\, F_{4,j}\, T_{4,j}^{\ 0.199}\, R_{4,j}\, \triangle V_{4,j} \\
& + 44.553\, F_{5,j}\, T_{5,j}^{-0.089}\, R_{5,j}\, \triangle V_{5,j} \\
& \qquad \vdots \qquad\qquad \vdots \\
& + 26.286\, V_{1,j}\, F_{1,j}\, T_{1,j}^{\ 0.089}\, \triangle R_{1,j} \\
& + 57.127\, V_{2,j}\, F_{2,j}\, T_{2,j}^{-0.101}\, \triangle R_{2,j} \\
& + \ \ 9.658\, V_{3,j}\, F_{3,j}\, T_{3,j}^{\ 0.413}\, \triangle R_{3,j} \\
& + 23.626\, V_{4,j}\, F_{4,j}\, T_{4,j}^{\ 0.199}\, \triangle R_{4,j} \\
& + 44.553\, V_{5,j}\, F_{5,j}\, T_{5,j}^{-0.089}\, \triangle R_{5,j}
\end{aligned}
\qquad (35)
$$

yield changes over time, these annual sets were computed and summed over time. Finally, for estimating the impact of crop yield technology on aggregate production, yield change was multiplied by aggregate acreage; and thus, an estimate of the physical impact on aggregate production was obtained. This quantity was converted into constant dollar value by multiplying it by the aggregate (i.e., national) market price of the crop in question.[23]

Numerical estimates of changes in corn yields of the Corn Belt are presented in table 11. All data of this table were based on the five corn yield functions 29 to 33, estimated for the Corn Belt states. Estimated annual Corn Belt yields were computed according to equation 34 and are listed in column 1. Annual yield changes attributed to different technologies and regional specialization are listed in columns 2 to 5, and the corresponding cumulative yields in columns 6 to 9. Adoption of higher-yielding corn hybrids raised estimated Corn Belt yields by 1.218 bushels per acres in 1940, by 1.192 bushels in 1941 and 0.780 in 1942. Each of these annual yield changes was computed by substituting annual values of crop yield variables into the first equation of the equation set 35 and computing the yield changes attributable to hybrid corn improvement. Over the 3-year period 1940-42, the cumulative yield change amounted to $1.218 + 1.192 + 0.780 =$ 3,190 bushels. Annual yield changes and cumlative yields due to other crop yield variables were derived in the same way. Corresponding estimates were made for each crop at regional and national levels.

The magnitude of annual yield changes generally differed between crop yield variables and between years. The causes of annual variations could be readily identified. For example, between the crop years 1944 and 1945, regional specialization in the Corn Belt raised corn yields by an estimated 0.312 bushel, but in 1946, the same variable reduced expected regional corn yield by 0.151 bushel (table 11, column 3). The yield increase in 1945 was caused primarily by a 7-percent reduction of low-yielding Missouri corn acreage. Conversely, the yield reduction in 1946 was caused by a 6-percent increase in Missouri corn acreage. Similarly, the negative yield effect of fertilizer use in 1960 (column 5) was caused by a significant reduction in fertilizer application in Indiana and Illinois, two major corn-producing states of the Corn Belt. Hybrid corn improvement had a strong impact on Corn Belt yields during the early period of adoption when annual yield increase exceeded 1.0 bushel per year. Later, however, when annual yield increments came from replacement of older hybrid corns by more advanced hybrids, the yield increase from this source was only about a third of a bushel per year. Other crop yield technologies measured by the net time-trend variable, increased corn yields across the Corn Belt by approximately a fifth of a bushel per year.

Estimation of Acreage and Weather Effects

In addition to the long-run yield effects of crop-yield technologies, short-run statewide effects of acreage and weather were also estimated nationally. In previous computations of estimated crop yields, both variables were held constant because normal acreage and weather conditions were assumed. To the extent that farmers did not try to change yields per acre by contracting or expanding acreage or could not control weather factors, these simplifying assumptions appear justified. However, whether acreage contraction on a statewide basis had significant impact on state crop yields and whether unusual weather conditions changed state crop yields over prolonged periods still had to be analyzed. The latter consideration is particularly significant to the buildup of food and feed grain stocks in the early 1960's.

ACREAGE EFFECTS

According to classical theory, acreage expansion of any particular crop is restricted by the "extensive margin."[24] Beyond this margin, production of the crop in question becomes uneconomical because revenue from cultivating the extra acreage falls below costs or returns of other crops. If price change favors one crop over others, the extensive margin of the crop becomes less restrictive and expansion to less-favored land becomes profitable. Conversely, as a crop loses its price advantage, its area is contracted from regions in which its advantage is least.

The classical concept of the extensive margin was incorporated into the analysis. A "normal" acreage is assumed as best suited for producing each crop. This normal acreage is assumed the long-run acreage as

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[23] No attempt was made to measure the impact of crop yield technology on national crop prices.

[24] R. Barlowe. Land resource economics. Prentice Hall, Inc., Englewood Cliffs, N.J. 1961.

defined earlier. The crop-acreage index was constructed as the ratio of actual annual acreage over the long-run trend acreage. If actual acreage of a crop was the same as its estimated long-run acreage for a particular year, then the estimated yield for that crop year was not affected by the acreage variable. But if actual acreage differed from trend acreage, the estimated state yield was changed according to acreage index A and its estimated exponent a in equation 36.[25] A negative value of the exponent a implies that crop yields

$$(36)\quad Y = b_o V^{1.0} (N+1.0)^{n'} (P+1.0)^{p'} (K+1.0)^{k'} W^{w} A^{a} T^{t}$$

decrease with acreage expansion, but increase with acreage contraction. This hypothesis is tested empirically during later stages of the analysis.

WEATHER EFFECTS

The second variable held constant at "normal" values for estimating equation 36 in the previous section was the weather index W. Based on yield data of experiment station plots, its positive exponent w implied that state crop yields and experiment station yields were directly related and that w would be smaller than unity. This follows from the observation that yield variations tend to diminish as the relevant land area, over which crop yields are averaged, increases.[26] Year-to-year fluctuations in experiment station yields may reflect local weather conditions quite accurately, but are probably less closely related to yield variations of larger regions surrounding experiment stations. An exponent w equal to or larger than unity implies that regional yield fluctuations are equal to or greater than local yield variations. If the value is smaller than unity, yield variation is expected to decline with expansion of the area; a proposition subjected to empirical tests in subsequent analysis.

Table 11. Impact of corn hybrid improvement, fertilizer use, other crop yield technology and regional specialization on estimated regional corn yield in the Corn Belt, 1939 to 1961[a].

		Estimated annual yield change due to:				Estimated cumulative yield change after adding effect of:[b]			
Year	Estimated Corn Belt corn yield (bu.)	Other Crop technology (bu.)	Regional specialization (bu.)	Corn hybrid improvement (bu.)	Fertilizer use (bu.)	Other Crop technology (bu.)	Regional specialization (bu.)	Corn hybrid improvement (bu.)	Fertilizer use (bu.)
(5)	(6)	(7)	(8)	(9)		(1)	(2)	(3)	(4)
0.000	37.20	37.20	37.20	39.63	1939	39.63	0.000	0.000	0.000
0.396	37.38	37.39	38.61	41.44	1940	41.44	0.175	0.019	1.218
0.149	37.56	37.67	40.08	43.05	1941	43.05	0.180	0.091	1.192
0.304	37.74	37.80	40.99	44.27	1942	44.27	0.181	−0.043	0.780
0.282	37.92	37.99	41.70	45.27	1943	45.27	0.181	0.007	0.521
0.097	38.10	38.16	42.31	45.97	1944	45.97	0.182	−0.014	0.441
0.526	38.28	38.65	43.23	47.42	1945	47.42	0.181	0.312	0.427
0.522	38.47	38.69	43.63	48.33	1946	48.33	0.185	−0.151	0.358
0.704	38.65	38.95	44.23	49.64	1947	49.64	0.184	0.076	0.346
0.315	38.84	39.15	44.75	50.47	1948	50.47	0.188	0.010	0.318
0.343	39.02	39.44	45.38	51.45	1949	51.45	0.187	0.108	0.335
0.291	39.22	39.45	45.71	52.07	1950	52.07	0.192	−0.181	0.327
1.001	39.40	39.77	46.35	53.72	1951	53.72	0.183	0.140	0.316
0.795	39.59	39.90	46.81	54.97	1952	54.97	0.189	−0.063	0.333
0.889	39.78	40.18	47.43	56.48	1953	56.48	0.190	0.091	0.336
0.531	39.97	40.31	47.90	57.48	1954	57.48	0.194	−0.066	0.344
0.125	40.16	40.55	48.47	58.17	1955	58.17	0.191	0.048	0.331
0.096	40.35	40.70	48.97	58.77	1956	58.77	0.189	−0.040	0.348
0.605	40.54	41.02	49.60	60.01	1957	60.01	0.186	0.142	0.309
0.425	40.73	41.73	50.30	61.13	1958	61.13	0.194	0.148	0.353
0.332	40.93	41.38	50.67	61.83	1959	61.83	0.196	−0.179	0.351
−0.036	41.12	41.63	51.26	62.39	1960	62.39	0.193	0.051	0.354
0.918	41.32	42.10	52.09	64.13	1961	64.13	0.196	0.276	0.349

[a] Estimation procedures are described in the text.
[b] Total estimated yield after adding effect of variables in order of columns.

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[25] Notations used in this equation were described previously in equation 15.

[26] W. Darcovich. Yield variance and size of farm in one-crop production. Canadian Jour. of Agr. Econ. 7:26-35. 1959.

Relative Economic Optima

For empirical analysis of economic incentives, criteria of efficient resource allocation defind by classical marginal analysis are used. These criteria are the same for all production functions irrespective of algebraic form. For illustrative purposes, the production represented by equation 36 is further simplified in equation 37 by eliminating the acreage variable A. The variables for variety improvement, V_j, and other yield technology, T_j, are fixed at their annual levels

$$(37) \quad Y_j = b_o V_j T_j^t (N_j+1.0)^n (P_j+1.0)^p (K_j+1.0)^k$$

so that economic optimum yields are solely a function of fertilizer variables N, P and K. Optimum yields are determined by differentiating yield equation 37 with respect to variables N, P and K and by equating the derivatives to their respective fertilizer crop price ratios as in equations 38, 39 and 40. From these we obtain the optimum input

$$(38) \quad \frac{\partial Y}{\partial N} = \frac{n Y}{N+1.0} = \frac{P_n}{P_y}, \text{ or } N_{opt} = nY \frac{P_y}{P_n} - 1.0$$

$$(39) \quad \frac{\partial Y}{\partial P} = \frac{p Y}{P+1.0} = \frac{P_p}{P_y}, \text{ or } P_{opt} = pY \frac{P_y}{P_p} - 1.0$$

$$(40) \quad \frac{\partial Y}{\partial K} = \frac{k Y}{K+1.0} = \frac{P_k}{P_y} \text{ or } K_{opt} = kY \frac{P_y}{P_k} - 1.0$$

quantities N_{opt}, P_{opt} and K_{opt} and, after inserting them in yield equation 37, obtain the crop yield supply equation 41 in which the subscript j refers to year. Optimum output $(Y_{opt})_j$ is computed on the basis of variety index V_j; (net) time-trend variable T_j; crop price P_j;

$$(41) \quad (Y_{opt})_j = b V_j T_j^t (b_o V_j P_{yj})^{n+p+k} \left(\frac{n}{P_{nj}}\right)^n \left(\frac{p}{P_{pj}}\right)^p \left(\frac{k}{P_{kj}}\right)^k \frac{1}{1-n-p-k}$$

and prices, P_{nj}, P_{pj} and P_{kj} for the fertilizer variables N, P and K. No prices are attached to variety indexes because price differences between the seed of older and newer varieties are relatively small. Prices of other (unspecified) crop yield variables are not considered.

The economic incentive ratios used in the analysis are $Y_j/(Y_{opt})_j$, or equation 37 divided by equation 41. They represent crop yields expected under current practices divided by optimum yields attainable with optimum fertilizer use, under given crop and fertilizer prices at specified levels of crop yield technology. Prices of plant nutrients were computed on a weighted basis relating to nutrient sources.

The economic incentive ratios of "expected yields divided by economic optimum yields," the relative economic optima, were computed by crops, years and states. They were also computed as aggregates for the nation. Only the aggregate ratios will be presented.

EMPIRICAL RESULTS

This study involved estimating variables defined earlier by specified methods. The only specific data of the several sets underlying the estimated production functions reported are the fertilizer response coefficients. Following presentation of these underlying data, we turn immediately to the results of the estimated production functions.

Fertilizer Response

Fertilizer response coefficients estimated from a nationwide summary of fertilizer response data with procedures described earlier, are tabulated in table 12. The estimated regression coefficients, denoted by n, p and k are equivalent to the b coefficient of equation 4. To indicate goodness of fit, coefficients of determination (r^2 values) are listed. They can be expected to range from 0 to 1.0, where zero implies a minimum and 1.0 implies a maximum correlation between the original (hand drawn) response curves and the regression estimates. Most r^2 values of this study range from 0.80 to 0.99.

Fertilizer response varied among regions and among crops as evidenced by variations in the n, p and k coefficients of table 12. Response generally was stronger in the eastern Lake States and Corn Belt than in the western states and the Northern Plains. For example, for wheat, the Ohio response coefficients are 0.116, 0.192, 0.081 compared with 0.090, 0.036 and 0.000 of Iowa. There is a similar east-west decline from the Delta States to the Southern Plains. The response of cotton in Mississippi was estimated at 0.098, 0.025 and 0.016 compared with 0.027, 0.017 and 0.023 for Texas in the Southern Plains.

This regional response pattern, very similar to the regional distribution of application rates, is related to regional variations in climate. Average annual precipitation in the eastern parts of the Lake States, Corn Belt and the Delta regions exceeds 40 inches, but declines to less than 20 inches in the Northern and Southern Plains.

Table 12. Characteristics of estimated response functions for variables N, P and K response functions by crops and states.

Crop	State	N functions		P functions		K functions	
		n	r^2	p	r^2	k	r^2
Wheat	Mich.	0.077	0.89	0.180	0.98	0.049	0.96
	Wis.	0.054	0.92	0.182	0.98	0.049	0.96
	Minn.	0.035	0.85	0.037	0.89	0.012	0.92
	Ohio	0.116	0.94	0.192	0.98	0.081	0.99
	Ind.	0.149	0.97	0.247	0.99	0.056	0.98
	Ill.	0.083	0.85	0.058	0.78	0.034	0.75
	Iowa	0.090	0.94	0.036	0.96	0.000	..
	Mo.	0.074	0.88	0.199	0.99	0.019	0.88
	N. D.	0.000	..	0.056	0.96	0.000	..
	S. D.	0.136	0.94	0.066	0.89	0.000	..
	Neb.	0.080	0.99	0.045	0.98	0.000	..
	Kan.	0.069	0.95	0.037	0.93	0.031	0.98
	Tex.	0.100	0.97	0.042	0.99	0.000	..
	Okla.	0.203	0.99	0.157	0.86	0.000	..
Oats	Mich.	0.076	0.94	0.054	0.91	0.041	0.96
	Wis.	0.084	0.87	0.100	0.87	0.061	0.89
	Minn.	0.075	0.98	0.043	0.88	0.006	0.96
	Ohio	0.083	0.83	0.102	0.95	0.058	0.97
	Ind.	0.073	0.88	0.048	0.99	0.006	0.88
	Ill.	0.156	0.95	0.094	0.79	0.016	0.82
	Iowa	0.043	0.86	0.029	0.91	0.002	0.46
	Mo.	0.185	0.88	0.078	0.92	0.011	0.74

Table 12. (cont'd).

		N functions		P functions		K functions	
Crop	State	n	r^2	p	r^2	k	r^2
	N. D.	0.075[a]	..	0.043[a]	..	0.006[a]	..
	S. D.	0.084	0.93	0.000	..	0.000	..
	Neb.	0.072[b]	..	0.019[b]	..	0.000	..
	Kan.	0.061	0.89	0.038	0.81	0.000	..
	Tex.	0.086	0.93	0.033	0.99	0.033	0.97
	Okla.	0.199	0.99	0.132	0.84	0.002	0.63
Soybeans	Mich.	0.049	0.95	0.042	0.93	0.048	0.93
	Wis.	0.000	..	0.043	0.85	0.048	0.92
	Minn.	0.000[c]	..	0.033[c]	..	0.035[c]	..
	Ohio	0.000	..	0.043	0.88	0.055	0.96
	Ind.	0.009	0.90	0.021	0.96	0.026	0.82
	Ill.	0.031	0.94	0.077	0.96	0.080	0.92
	Iowa	0.000	..	0.023	0.95	0.010	0.96
	Mo.	0.026	0.90	0.021	0.90	0.000	..
	Ark.	0.000	..	0.052	0.87	0.027	0.85
	Miss.	0.000	..	0.013	0.97	0.012	0.95
	La.	0.000	..	0.026	0.87	0.016	0.98
Barley	Minn.	0.044	0.96	0.033	0.96	0.006	0.78
	N. D.	0.000	..	0.045	0.93	0.000	..
	S. D.	0.141	0.91	0.053	0.93	0.000	..
	Neb.	0.100[b]	..	0.056[b]	..	0.000[b]	..
	Kan.	0.059	0.91	0.060	0.95	0.000	..
Flax	Minn.	0.084	0.95	0.097	0.84	0.049	0.94
	N. D.	0.136[d]	..	0.120[d]	..	0.025[d]	..
	S. D.	0.188	0.97	0.143	0.95	0.000	..
Cotton	Tex.	0.027	0.79	0.017	0.84	0.023	0.98
	Okla.	0.061	0.92	0.035	0.84	0.045	0.99
	Ark.	0.089	0.95	0.009	0.79	0.073	0.98
	Miss.	0.098	0.98	0.025	0.96	0.016	0.94
	La.	0.128	0.98	0.067	0.92	0.043	0.81
Gr. Sorg.	Neb.	0.085[e]	..	0.026[e]	..	0.000[e]	..
	Kan.	0.085	0.95	0.026	0.96	0.000	..
	Tex.	0.840	0.96	0.025	0.96	0.026	0.96
	Okla.	0.084[f]	..	0.025[f]	..	0.026[f]	..
Corn	Mich.	0.039	0.84	0.031	0.95	0.037	0.96
	Wis.	0.099	0.85	0.110	0.90	0.132	0.92
	Minn.	0.056	0.92	0.036	0.81	0.019	0.87
	Ohio	0.109	0 89	0.165	0.98	0.046	0.85
	Ind.	0.068	0.92	0.150	0.99	0.064	0.97
	Ill.	0.090	0.83	0.052	0.90	0.049	0.88
	Iowa	0.029	0.91	0.021	0.94	0.013	0.82
	Mo.	0.129	0.79	0.080	0.84	0.029	0.81
	N. D.	0.072	0.78	0.029	0.89	0.000	..
	S. D.	0.082	0.86	0.055	0.98	0.000	..
	Neb.	0.065	0.92	0.000	..	0.000	..
	Kan.	0.142	0.97	0.000	..	0.028	0.91
	Tex.	0.880	0.84	0.045	0.78	0.009	0.92
	Okla.	0.037	0.67	0.031	0.74	0.012	0.98
	Ark.	0.184	0.93	0.050	0.93	0.133	0.96
	Miss.	0.176	0.94	0.030	0.85	0.015	0.89
	La.	0.141	0.89	0.030	0.85	0.025	0.77
Tame Hay	Mich.	0.000	..	0.140	0.95	0.098	0.95
	Wis.	0.155	0.92	0.088	0.91	0.131	0.93
	Minn.	0.000	..	0.078	0.77	0.027	0.96
	Ohio	0.000	..	0.105	0.77	0.142	0.92
	Ind.	0.045	0.95	0.108	0.83	0.157	0.87
	Ill.	0.141	0.86	0.206	0.99	0.132	0.80
	Iowa	0.038	0.87	0.065	0.87	0.004	0.47
	Mo.	0.138	0.90	0.238	0.92	0.101	0.91
	N. D.	0.000	..	0.060	0.81	0.000	..
	S. D.	0.044	0.86	0.065	0.87	0.000	..
	Neb.	0.000	..	0.033	0.80	0.000	..
	Kan.	0.145	0.87	0.042	0.97	0.061	0.89
	Tex.	0.095	0.91	0.092	0.98	0.000	..
	Okla.	0.000	..	0.141	0.99	0.000	..
	Ark.	0.087	0.81	0.119	0.94	0.082	0.88
	Miss.	0.000	..	0.065	0.94	0.000	..
	La.	0.096	0.94	0.111	0.95	0.166	0.96

[a] Minn. coefficient.
[b] Average of S. D. and Kan. coefficients.
[c] Average of Iowa and Wis. coefficients.
[d] Average of Minn. and S. D. coefficients.
[e] Kan. coefficient.
[f] Tex. coefficient.

State Crop Production Functions

GENERAL CHARACTERISTICS

Table 13 includes regression coefficients, R^2 values and constants for the 86 state crop production functions estimated by equation 17. The correlation indexes (R^2 values) measure the fit between actual and estimated state crop yields. The frequency distribution of these R^2 values, stratified by intervals and crops in table 14, shows that 4 of 86 are in the 0.90 to 0.99 range, 27 are in the 0.80 to 0.89 range and 55 are below 0.80. There were significant differences between crops, with lowest R^2 values for flax, barley and oats; an intermediate range for soybeans, wheat, cotton and tame hay; and highest for corn and grain sorghum.

The R^2 values in table 13 depend to some extent on the statistical significance of the weather indexes. Only 6 of 14 weather index coefficients for oats tested statistically significant at the 1-percent level. For corn, all 16 weather coefficients were significant at this level. As hypothesized earlier, all weather index coefficients are positive and, with few exceptions, are smaller than 1.0. This condition implies that state yield variations are usually less pronounced than yield variations at experiment stations.

Statistical significance of weather indexes did not assure high R^2 values. For example, three of four weather indexes for barley and grain sorghum tested significant at the 1-percent level, but the R^2 values of the barley functions ranged from 0.24 to 0.66, and all grain sorghum functions exceeded 0.85.

ACREAGE COEFFICIENTS

Acreage index coefficients varied, depending on the crop and geographic location. Regression coefficients of acreage indexes are shown in table 15. They are from the acreage index column in table 13, but are stratified according to crops for states (for ease of presentation, some wheat coefficients are excluded). It was hypothesized earlier that acreage expansion leads to yield reductions at the "extensive margin," and, therefore, that a negative acreage-index coefficient could be expected. Only 24 of the acreage coefficients shown in table 13 tested statistically significant at the 1- to 10-percent levels, and approximately half of the coefficients were negative. Eight of 10 coefficients for soybeans were negative. The negative coefficients imply a yield reduction with acreage expansion, confirming the sensitivity of soybeans to production location. The acreage coefficients of tame hay and crops grown in the northern part of the Lake States region and the Dakotas are mostly negative. Again, these results imply that short-run expansion results in yield reduction. Under these consistencies, the acreage indexes were not rejected as irrelevant variables, even though most of them were not statistically significant.

TIME-TREND COEFFICIENTS

Coefficients of time-trend variables measured yield effects of unspecified technical improvements related to soil conservation, timeliness of farm operations, irri-

Table 13. Characeristics of estimated state crop production functions by crops and states.

Crop State	Constant[a]	Regression Coefficients N+1.0	P+1.0	K+1.0	Acreage index	Weather index	Net time trend	R²	Years
Wheat									
Mich.	17.6	0.019	0.106	0.008	0.192+	0.267*	0.057	0.80	39-60
Wis.	18.1	0.010	0.117	0.008	−0.173	0.171+	0.400	0.60	42-60
Minn.	17.0	0.015	0.016	0.002	0.005	0.543**	−0.121	0.89	29-60
Ohio	15.5	0.035	0.095	0.017	0.040	0.104	0.253	0.42	39-60
Ind.	12.8	0.049	0.135	0.007	−0.107	0.563**	0.254	0.82	39-60
Ill.	19.6	0.039	0.019	0.007	0.032	0.475**	0.291**	0.81	29-60
Iowa	19.8	0.064	0.011	0.000	0.013	0.594**	0.096	0.68	27-60
N. D. (S)[b]	13.2	0.000	0.056	0.000	−0.248	0.599**	0.467**	0.82	29-60
S. D. (S)	11.0	0.092	0.022	0.000	0.052	0.546**	0.209	0.57	31.60
S. D. (W)[c]	15.8	0.092	0.022	0.000	0.440*	0.225*	1.237**	0.69	31-60
Neb. (S)	12.1	0.051	0.016	0.000	−0.113	0.441**	0.131	0.53	29-60
Neb. (W)	19.5	0.051	0.016	0.000	0.073	0.251**	0.517**	0.75	31-60
Kan. (W)	17.2	0.035	0.010	0.007	−0.154	0.337**	0.478**	0.66	51-60
Tex.	12.1	0.070	0.012	0.000	0.312*	0.159	0.314	0.53	31-60
Okla.	13.5	0.115	0.068	0.000	0.325+	0.573**	−0.350+	0.58	31-60
Oats									
Mich.	32.0	0.034	0.017	0.010	0.272	0.505**	−0.068	0.54	42-60
Wis.	38.5	0.029	0.041	0.015	−0.182	0.118	−0.472	0.35	42-60
Minn.	37.6	0.045	0.015	0.000	−0.372	0.189+	−0.589*	0.45	42-60
Ohio	30.4	0.028	0.043	0.014	0.624+	0.323	0.784*	0.56	42-60
Ind.	33.1	0.042	0.018	0.000	0.101	0.201	0.467	0.48	42-60
Ill.	36.7	0.091	0.033	0.001	0.007	0.349**	−0.106	0.54	42-60
Iowa	35.9	0.025	0.011	0.000	0.244	0.763**	−0.515	0.59	42-60
Mo.	21.2	0.125	0.022	0.000	0.388+	0.248+	−0.106	0.64	42-60
N. D.	28.4	0.045	0.015	0.000	0.086	0.420*	−0.283	0.55	42-60
S. D.	33.7	0.084	0.000	0.000	−0.654+	0.729**	−1.682	0.61	44-60
Neb.	26.3	0.057	0.004	0.000	−0.289	0.616**	−1.105+	0.56	42-60
Kan.	21.9	0.038	0.014	0.000	0.220	0.136	0.391	0.44	42-60
Tex.	21.0	0.049	0.007	0.006	0.223*	0.252*	0.157	0.49	42-60
Okla.	18.4	0.119	0.052	0.000	0.190**	0.416**	−1.379**	0.73	40-60
Soybeans									
Mich.	16.7	0.017	0.013	0.017	−0.056	0.141	0.392*	0.73	42-60
Wis.	12.7	0.000	0.018	0.035	−0.008	0.207	−0.378+	0.54	42-60
Minn.	15.9	0.000	0.016	0.018	−0.144	0.177	0.288	0.65	42-60
Ohio	19.3	0.000	0.019	0.031	−0.026	0.208*	−0.027	0.66	41-60
Ind.	19.8	0.002	0.008	0.012	−0.022	0.221	0.375*	0.82	41-60
Ill.	22.0	0.005	0.032	0.034	−0.153	0.318*	−0.272	0.55	41-60
Iowa	21.3	0.000	0.016	0.003	−0.078	0.402**	0.303	0.69	41-60
Mo.	17.9	0.014	0.010	0.000	0.134	0.374**	0.550+	0.71	41-60
Ark.	15.1	0.000	0.035	0.009	−0.108	0.196	0.402	0.36	43-60
Miss.	15.7	0.000	0.007	0.005	0.091	0.310	0.505	0.56	43-60
Barley									
Minn.	24.1	0.024	0.013	0.000	−0.153	0.414**	0.907	0.66	43-60
N. D.	21.1	0.000	0.045	0.000	0.332*	0.213	−0.426	0.24	43-61
S. D.	19.0	0.102	0.015	0.000	0.323+	0.415**	0.125	0.59	43-60
Neb.	19.6	0.064	0.021	0.000	−0.064	0.414**	−0.134	0.47	40-61
Flax									
Minn.	8.9	0.031	0.041	0.010	−0.052	0.856**	0.357	0.45	44-61
N. D.	7.8	0.066	0.051	0.002	−0.010	0.301	−0.143	0.26	44-61
S. D.	8.9	0.107	0.062	0.000	−1.196	0.573*	−0.450	0.34	39-60
Cotton									
Tex.	201.3	0.011	0.004	0.008	0.017	0.270*	1.471**	0.78	40-60
Okla.	176.7	0.026	0.009	0.015	−0.104	0.036**	1.716**	0.70	39-60
Ark.	307.6	0.046	0.000	0.031	−0.394*	0.503**	−0.248	0.74	41-60
Miss.	276.4	0.069	0.004	0.002	0.072	0.658*	0.546+	0.55	39-60
Grain sorghum									
Neb.	20.9	0.065	0.006	0.000	0.137+	0.460**	1.317**	0.90	39-61
Kan.	18.1	0.065	0.006	0.000	0.232*	0.363**	0.145	0.89	39-60
Tex.	19.5	0.053	0.005	0.005	0.197+	0.153*	1.222**	0.88	39-60
Okla.	14.2	0.053	0.005	0.005	0.316*	0.447**	0.684+	0.93	44-60

Table 13. (cont'd).

Crop State	Constant[a]	Regression Coefficients N+1.0	P+1.0	K+1.0	Acreage index	Weather index	Net time trend	R^2	Years
Corn									
Mich.	38.8	0.014	0.009	0.013	−0.245	0.749**	0.253	0.73	38-61
Wis.	37.4	0.029	0.035	0.051	−0.365	0.340**	−0.075	0.88	37-61
Minn.	43.3	0.028	0.012	0.003	−0.622**	0.484**	−0.013	0.87	37-61
Ohio	37.0	0.037	0.085	0.007	0.167	0.569**	0.089	0.72	39-61
Ind.	38.6	0.016	0.080	0.015	−0.346	0.486**	−0.101	0.80	37-61
Ill.	47.7	0.042	0.014	0.013	0.260	0.870**	0.413**	0.86	34-61
Iowa	51.1	0.013	0.007	0.003	0.150	1.185**	0.199**	0.87	26-61
Mo.	31.5	0.070	0.027	0.004	−0.124	1.203**	−0.089	0.85	37-61
N. D.	21.4	0.051	0.009	0.000	−0.833*	0.895**	−0.680	0.70	44-61
S. D.	24.4	0.049	0.022	0.000	−0.907*	0.695**	0.419+	0.75	37-61
Neb.	26.8	0.065	0.000	0.000	0.185	0.849**	0.972**	0.89	37-61
Kan.	23.4	0.118	0.000	0.005	0.501*	0.661**	0.303	0.84	39-61
Tex.	16.3	0.055	0.014	0.001	0.288+	0.482**	−0.145	0.85	41-61
Okla.	18.1	0.017	0.012	0.002	0.123	0.350**	−0.037	0.81	43-61
Ark.	14.7	0.092	0.007	0.048	0.317	0.505**	−0.091	0.82	42-61
Miss.	12.1	0.140	0.004	0.001	0.133	0.482**	0.583**	0.86	39-61
Tame hay									
Mich.	1.28	0.000	0.053	0.047	−0.123	0.707**	0.044	0.82	27-60
Wis.	1.69	0.064	0.021	0.046	0.182	0.760**	0.254**	0.84	27-60
Minn.	1.61	0.000	0.058	0.007	0.620**	0.775**	0.212**	0.88	27-60
Ohio	1.27	0.000	0.044	0.082	−0.268	0.793**	0.128+	0.85	27-60
Ind.	1.23	0.007	0.037	0.080	−0.044	0.695**	0.180**	0.90	27-60
Ill.	1.46	0.042	0.088	0.037	−0.053	0.592**	0.338**	0.94	27-60
Iowa	1.65	0.013	0.039	0.000	0.206	0.580**	0.401**	0.83	27-60
Mo.	1.03	0.040	0.119	0.021	−0.250*	0.595**	0.304**	0.78	27-60
N. D.	1.12	0.000	0.060	0.000	0.062	0.703**	0.022	0.70	27-60
S. D.	1.18	0.018	0.039	0.000	−0.045	0.516**	0.259	0.71	27-60
Neb.	1.66	0.000	0.034	0.000	−0.270	0.683**	0.244**	0.86	27-60
Kan.	1.65	0.085	0.607	0.015	0.025	1.008**	−0.655	0.07	27-60
Tex.	0.95	0.048	0.046	0.000	−0.159	0.519**	−0.042	0.38	27-60
Okla.	1.10	0.000	0.141	0.000	−0.373*	0.542**	−0.445**	0.61	27-60
Ark.	1.04	0.026	0.049	0.024	−0.108	0.670**	−0.075	0.73	27-60
Miss.	1.06	0.000	0.065	0.000	−0.100	0.616**	−0.205**	0.46	27-60
La.	1.07	0.025	0.033	0.074	−0.220	0.558**	−0.205**	0.54	27-60

[a] Constant is coded by letting weather indexes equal 1.0, N-P-K application rates equal zero and using 1948 as base year, where P = P_2O_5 and K = K_2O.

[b] (S) denotes spring wheat.

[c] (W) denotes winter wheat.

** Significant at the 1-percent level.

* Significant at the 5-percent level.

\+ Significant at the 10-percent level.

Table 14. Frequency distribution of R^2 values for state crop production functions.

Crop	Intervals for R^2 in state crop yield regression equations. 0.00-0.09	0.10-0.19	0.20-0.29	0.30-0.39	0.40-0.49	0.50-0.59	0.60-0.69	0.70-0.79	0.80-0.89	0.90-0.99	Number of functions
Wheat					1	3	4	1	5		14
Oats				1	4	6	2	1			14
Soybeans				1		3	3	2	1		10
Barley			1		1	1	1				4
Flax			1	1	1						3
Cotton							1	3			4
Grain Sorghum									2	2	4
Corn								3	13		16
Tame Hay	1			1	1	1	1	4	6	2	17
All crops	1		2	4	8	14	12	14	27	4	86

gation, herbicides and insecticides, etc. Had coefficients of the trend variable been consistently negative, yield increases attributed to crop variety improvement and higher rates would have been generally overestimated. However, in most cases, they were positive. The net time-trend coefficients of table 13 are stratified in table 16 by crops and states to identify crop and location effects. The coefficients for oats are negative in 10 of 14 state production functions and account for nearly one-third of all negative coefficients. These coefficients are not rejected because the index values for oats variety and fertilizer response were small compared with other crops. Other factors, arising as oats became a crop of declining acreage importance, may be responsible for these negative time trends. Negative time-trend coefficients of the remaining state crop production functions did not seem directly related to crop or regional effects. Hence, we conclude that the combined yield increase attributed to variety improvement and increased fertilizer application generally is not overestimated.

COEFFICIENTS OF FERTILIZER RESPONSE AND VARIETY IMPROVEMENT

Regression coefficients of fertilizer and variety improvement were estimated before the functions were fitted. Coefficients for variety indexes equal to 1.0 for all functions as shown in equation 15 are not listed in table 13. Nutrient response coefficients listed under the headings N+1.0, P+1.0 and K+1.0 are the empirical estimates of the "adjusted" n′, p′ and k′ values of equation 15.

The Impact of Crop-Yield Technology on Regional Yields

Assuming normal "expected" conditions of weather and acreage, the impact of crop technology is mea-

Table 15. Regression coefficients of ratios or actual acreages divided by long-run trend acreages by crops and states.

State	Wheat	Oats	Soybeans	Barley	Flax	Cotton	Grain sorghum	Corn	Tame hay
Ohio	0.040	0.624+	−0.026					0.167	−0.268
Ind.	−0.107	0.101	−0.022					−0.346	−0.044
Ill.	0.032	0.007	−0.153					0.260	−0.053
Iowa	0.013	0.244	−0.078					0.150	0.206
Mo.	..	0.388+	0.134					−0.124	−0.250*
Mich.	0.192+	0.272	−0.056					−0.245	−0.123
Wis.	−0.173	−0.182	−0.008					−0.365	0.182
Minn.	0.005	−0.372	−0.144	−0.153	−0.052			−0.622**	0.620**
N. D. (S)[a]	−0.248	0.086		0.332*	−0.110			−0.833*	0.062
S. D. (S)	0.052	−0.654+		0.323+	−1.196			−0.907*	−0.045
Neb. (W)[a]	0.073	−0.289		−0.064			0.137+	0.185	−0.270
Kan. (W)	−0.154	0.220					0.232*	0.501*	0.025
Okla.	0.325+	0.190**				−0.104	0.316*	0.123	−0.373*
Tex.	0.312*	0.223*				0.017	0.197+	0.288+	−0.159
Miss.			0.091			0.072		0.133	−0.100
Ark.			−0.108			−0.394*		0.317	−0.108
La.									−0.220

[a] (S) = spring wheat; (W) = winter wheat.
** Significant at the 1-percent level.
* Significant at the 5-percent level.
+ Significant at the 10-percent level.

Table 16. Regression coefficients of net time-trend by crops and states.

State	Wheat	Oats	Soybeans	Barley	Flax	Cotton	Grain sorghum	Corn	Tame hay
Ohio	0.253	0.784*	−0.027					0.089	0.128+
Ind.	0.254	0.467	0.375*					−0.101	0.180**
Ill.	0.291**	−0.106	−0.272					0.413**	0.338**
Iowa	0.096	−0.515	0.303					0.199**	0.401**
Mo.	..	−0.106	0.550+					−0.089	0.304**
Mich.	0.057	−0.068	0.392*					0.253	0.044
Wis.	0.400	−0.472	−0.378+					−0.075	0.254**
Minn.	−0.121	−0.589*	0.288	0.907	0.357			−0.013	0.212**
N. D. (S)[a]	0.467**	−0.283		−0.426	−0.143			−0.680	0.022
S. D. (S)	0.209	−1.682		0.125	−0.450			0.419+	0.259
Neb. (W)[a]	0.517**	−1.105+		−0.134			1.317**	0.922**	0.244**
Kan. (W)	0.478**	0.391					0.145	0.303	−0.655
Okla.	−0.350+	−1.379**				1.716**	0.684+	−0.037	−0.445**
Tex.	0.314	0.157				1.471**	1.222**	−0.145	−0.042
Miss.			0.505			0.546+		0.583**	−0.205**
Ark.			0.402			−0.248		−0.091	−0.075
La.									−0.205**

[a] (S) = spring wheat; (W) = winter wheat.
** Significant at the 1-percent level.
* Significant at the 5-percent level.
+ Significant at the 10-percent level.

sured in terms of estimated yield changes attributed to each major variable of crop yield technology.

REGIONAL ESTIMATES

Estimated crop yields (weather and acreage held constant) in table 17 are tabulated for the first and last years of selected periods in terms of total and average changes. Annual estimates of the contribution of fertilization, variety improvement and other yield variables are illustrated in figs. 15 to 21 by crops and regions. Again, the estimated or expected yield increases discussed assume weather and acreage constant at normal levels.

Wheat: Estimated wheat yields of the Lake States (table 17) increased 67.7 percent from 1939 to 1960, the greatest gain among major producing regions. Yields advanced from 16.1 to 27.0 bushels, an annual rate of 0.52 bushel per acre. The estimated increase in the Southern Plains was 39.2 percent, an annual rate of 0.22 bushels per acre. As shown in fig. 15, this yield advance was due to fertilizer use, improvement in varieties and positive yield effects of other, but unspecified, variables. Gains in Michigan are attributed to a change in fertilizer application rates, from 19.8 pounds in 1939 to 109.8 pounds in 1961, and the introduction of Genessee, a superior variety. In Minnesota, fertilizer application rates, which increased from less than 1 pound in 1939 to over 30 pounds in 1960, and the adoption of two varieties, Lee and Selkirk, contributed markedly to the yield change. Because of the relatively small state wheat acreage, yield changes in Wisconsin were less important than in other Lake States.

In the Corn Belt, yields increased by 51.6 percent or by 0.46 bushels per year. Most of this increase came from higher rates of fertilizer applications. Estimated annual yield changes in the spring and winter wheat regions of the Northern Plains amounted to 0.31 and 0.35 bushels, respectively. A considerable portion of this increase was due to yield effects of unspecified variables.

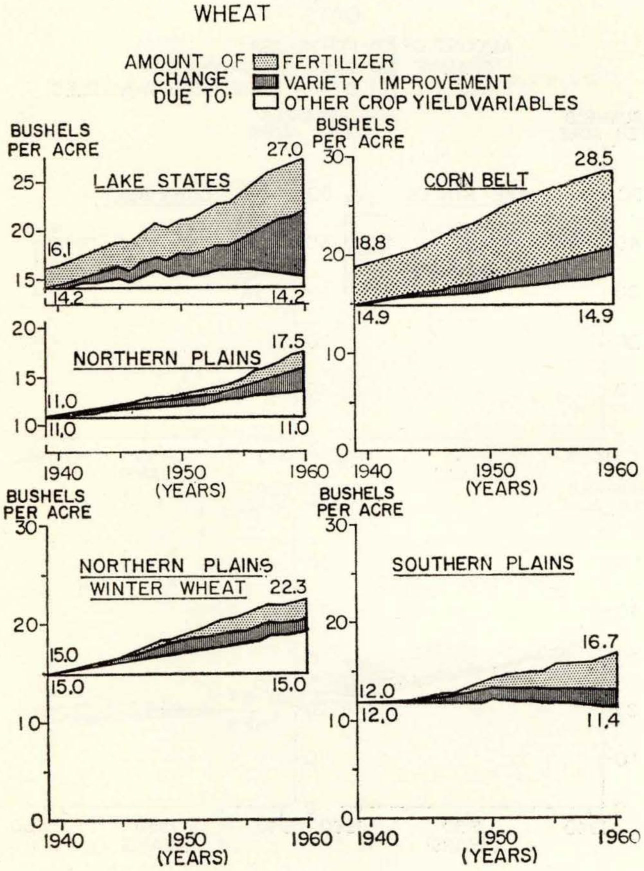

Fig. 15. Changes in estimated regional wheat yields due to technology, 1939-1960, (weather and acreage constant).

Table 17. Estimated crop yields[a] and yield changes over selected time periods by crops, regions and states.

Crop Time period	Region & state	Estimated Crop Yields First year bu.	Estimated Crop Yields Last year bu.	Total Yield Change Relative percentage	Total Yield Change Cumulative bu.	Average annual change bu.
Wheat 1939-60	Lake States	16.1	27.0	67.7	10.9	0.52
	Mich.	22.4	33.4	49.1	11.0	0.52
	Wis.	16.0	28.6	78.8	12.6	0.60
	Minn.	15.6	23.3	49.4	7.7	0.37
	Corn Belt[b]	18.8	28.5	51.6	9.7	0.46
	Ohio	20.4	28.3	38.7	7.9	0.38
	Ind.	18.2	29.4	61.5	11.2	0.53
	Ill.	17.9	28.2	57.5	10.3	0.49
	Iowa	18.4	23.6	28.3	5.2	0.25
	N. Plains[c]	11.0	17.5	59.1	6.5	0.31
	N. D.	11.4	18.6	63.2	7.2	0.34
	S. D.	10.0	13.6	36.0	3.6	0.17
	Neb.	10.6	14.8	39.6	4.2	0.20
	N. Plains[d]	15.0	22.3	48.7	7.3	0.35
	S. D.	11.6	22.8	96.6	11.2	0.53
	Neb.	16.4	25.1	53.0	8.7	0.41
	Kan.	14.6	21.4	46.6	6.8	0.32
	S. Plains	12.0	16.7	39.2	4.7	0.22
	Tex.	10.8	15.6	44.4	4.8	0.23
	Okla.	12.8	17.6	37.5	4.8	0.23
Oats 1942-60	Lake States	38.3	45.3	18.3	7.0	0.39
	Mich.	34.1	45.7	34.0	11.6	0.64
	Wis.	40.7	50.0	22.8	9.3	0.52
	Minn.	38.4	42.5	10.7	4.1	0.23
	Corn Belt	34.5	40.0	15.9	5.5	0.31
	Ohio	32.0	50.3	57.2	18.3	1.02
	Ind.	31.8	45.3	42.5	13.5	0.75
	Ill.	39.9	42.4	6.3	2.5	0.14
	Iowa	37.2	36.3	-2.4	-0.9	-0.05
	Mo.	22.8	32.1	40.8	9.3	0.52
	N. Plains	30.6	26.8	-12.4	-3.8	-0.21
	N. D.	28.5	30.2	6.0	1.7	0.09
	S. D.	41.3	25.3	-38.7	-16.0	-0.89
	Neb.	29.4	23.8	-19.0	-5.6	-0.31
	Kan.	21.0	28.2	34.3	7.2	0.40
	S. Plains	19.8	23.9	20.7	4.1	0.23
	Tex.	20.2	24.6	21.8	4.4	0.24
	Okla.	19.6	22.6	15.3	3.0	0.17
Soybeans 1943-60	Lake States	15.0	21.3	42.0	6.3	0.37
	Mich.	16.1	23.6	46.6	7.5	0.44
	Wis.	13.2	15.9	20.5	2.7	0.16
	Minn.	15.0	21.3	42.0	6.3	0.37
	Corn Belt	19.7	24.6	24.9	4.9	0.29
	Ohio	19.6	24.1	23.0	4.5	0.26
	Ind.	18.6	25.9	39.2	7.3	0.43
	Ill.	21.1	25.4	20.4	4.3	0.25
	Iowa	19.4	24.3	25.3	4.9	0.29
	Mo.	15.4	22.0	42.9	6.6	0.39
	Delta States[e]	12.6	19.7	56.3	7.1	0.42
	Ark.	13.1	20.1	53.4	7.0	0.41
	Miss.	11.7	18.7	59.8	7.0	0.41
Barley 1943-60	Lake States Minn.	22.0	32.5	47.7	10.5	0.62
	N. Plains[f]	20.4	23.6	15.7	3.2	0.19
	N. D.	22.1	23.8	7.7	1.7	0.10
	S. D.	18.6	22.2	19.4	3.6	0.21
	Neb.	19.9	22.9	15.1	3.0	0.18

Table 17. (cont'd).

Crop Time period	Region & state	Estimated Crop Yields First year bu.	Estimated Crop Yields Last year bu.	Total Yield Change Relative percentage	Total Yield Change Cumulative bu.	Average annual change bu.
Flax 1944-60	Lake States					
	Minn.	8.8	9.7	10.2	0.9	0.06
	N. Plains[g] .	8.1	7.2	-11.1	-0.9	-0.06
	N. D.	7.9	7.1	-10.1	-0.8	-0.05
	S. D.	8.7	7.8	10.3	-0.9	-0.06
Cotton[h] 1939-60	S. Plains ..	137.1	316.5	130.9	179.4	8.54
	Tex.	138.9	319.9	130.3	181.0	8.62
	Okla.	128.5	282.1	119.5	153.6	7.31
	Delta States[e]	314.6	447.0	42.1	132.6	6.31
	Ark.	345.0	437.6	26.8	92.6	4.41
	Miss.	289.0	455.6	57.6	166.6	7.93
Grain Sorghum 1939-60	N. Plains[i] .	17.9	32.5	81.6	14.5	0.70
	Neb.	16.7	38.8	132.3	22.1	1.05
	Kan.	18.4	29.7	61.4	11.3	0.54
	S. Plains ..	13.6	34.1	150.7	20.5	0.98
	Tex.	13.9	35.3	154.0	21.4	1.02
	Okla.	12.4	23.5	89.5	11.1	0.53
Corn 1939-61	Lake States	35.3	55.9	58.4	20.6	0.94
	Mich.	30.6	53.0	73.2	22.4	1.02
	Wis.	35.3	61.8	75.1	26.5	1.20
	Minn.	37.0	54.1	46.2	17.1	0.78
	Corn Belt .	39.6	64.1	61.9	24.5	1.11
	Ohio	40.8	64.8	56.9	23.2	1.05
	Ind.	42.2	61.4	45.5	19.2	0.87
	Ill.	40.5	71.4	76.3	30.9	1.40
	Iowa	43.4	63.9	47.2	20.5	0.93
	Mo.	26.5	48.4	82.6	21.9	1.00
	N. Plains ..	19.1	40.9	114.1	21.8	0.99
	N. D.	24.4	21.2	-13.1	-3.2	-0.15
	S. D.	20.1	34.2	70.1	14.1	0.64
	Neb.	18.0	48.8	171.1	30.8	1.40
	Kan.	18.9	39.3	107.9	20.4	0.93
	S. Plains ..	14.8	23.3	57.4	8.5	0.39
	Tex.	14.7	23.0	56.5	8.3	0.38
	Okla.	15.2	25.1	65.1	9.9	0.45
	Delta States[e]	14.0	29.9	113.6	15.9	0.72
	Ark.	14.0	27.3	95.0	13.3	0.60
	Miss.	14.0	30.6	118.6	16.6	0.75
		tons	tons		tons	tons
Tame Hay 1939-60	Lake States.	1.513	1.876	24.0	0.363	0.0173
	Mich.	1.318	1.500	13.8	0.182	0.0087
	Wis.	1.615	2.027	25.5	0.412	0.0196
	Minn.	1.553	1.911	23.1	0.358	0.0170
	Corn Belt ..	1.315	1.662	26.4	0.347	0.0165
	Ohio	1.303	1.661	27.5	0.358	0.0170
	Ind.	1.281	1.598	24.7	0.317	0.0151
	Ill.	1.362	1.752	28.6	0.390	0.0186
	Iowa	1.517	1.875	23.6	0.358	0.0170
	Mo.	1.052	1.336	27.0	0.284	0.0135
	N. Plains[j] .	1.262	1.406	11.4	0.144	0.0069
	N D.	1.119	1.177	5.2	0.058	0.0028
	S. D.	1.121	1.263	12.7	0.142	0.0068
	Neb.	1.590	1.786	12.3	0.196	0.0093
	S. Plains ..	1.058	1.100	4.0	0.042	0.0020
	Tex.	0.962	1.012	5.2	0.050	0.0024
	Okla.	1.208	1.238	2.5	0.030	0.0014
	Delta States[e]	1.108	1.198	8.1	0.090	0.0043
	Ark.	1.056	1.120	6.1	0.064	0.0030
	Miss.	1.153	1.196	3.7	0.043	0.0020
	La.	1.176	1.325	12.7	0.149	0.0071

[a] Estimates are derived from state crop production functions with weather and short-run acreage effects excluded.
[b] Excluding Missouri.
[c] Spring wheat area, excluding Kansas.
[d] Winter wheat area, excluding North Dakota.
[e] Excluding Louisiana.
[f] Excluding Kansas.
[g] Excluding Nebraska and Kansas.
[h] Crop yields and crop yield changes measured in pounds.
[i] Excluding North Dakota and South Dakota.
[j] Excluding Kansas.

Summer fallow acreage has been expanded greatly over the last 2 decades. Hence, it is likely that much of this "unexplainable" yield increase was due to a shift from wheat-wheat to wheat-fallow rotations. In North Dakota, for example, the percentage of spring wheat acreage (excluding Durum) planted after summer fallow increased from 37.4 percent in 1949 to 61.9 percent in 1960.[27] In the Southern Plains, wheat yields were lower than in other areas. Fertilizer and variety effects caused a yield increase over time. Otherwise, yields would have declined from 12.0 bushels in 1939 to 11.4 bushels in 1960 on a basis of the time-trend variable.

Oats: Oat yields increased less than wheat yields in most regions. The highest average annual yield increase was 0.39 bushels in the Lake States (table 17). Corresponding yield changes in the Corn Belt, Northern Plains and Southern Plains were 0.31, -0.21 and 0.23 bushels, respectively. Effects of fertilization, variety improvement and other crop yield variables are illustrated in fig. 16. After accounting for yield advances due to fertilizer application and variety improvement, net yields would have declined in all regions. Negative trend effects were strongest in South Dakota and Nebraska. Positive trends in North Dakota and Kansas did not compensate for this decline, and an over-all regional decline in the Northern Plains resulted. Yields in other regions moved upwards, but the increase was not large. Perhaps unfavorable changes

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[27] R. A. Young and S. W. Voelker. Spring wheat acreage and production after fallow and after crop, North Dakota state totals, 1949 to 1960. (Mimeo.) Agronomy Department, North Dakota State University. April 1962.

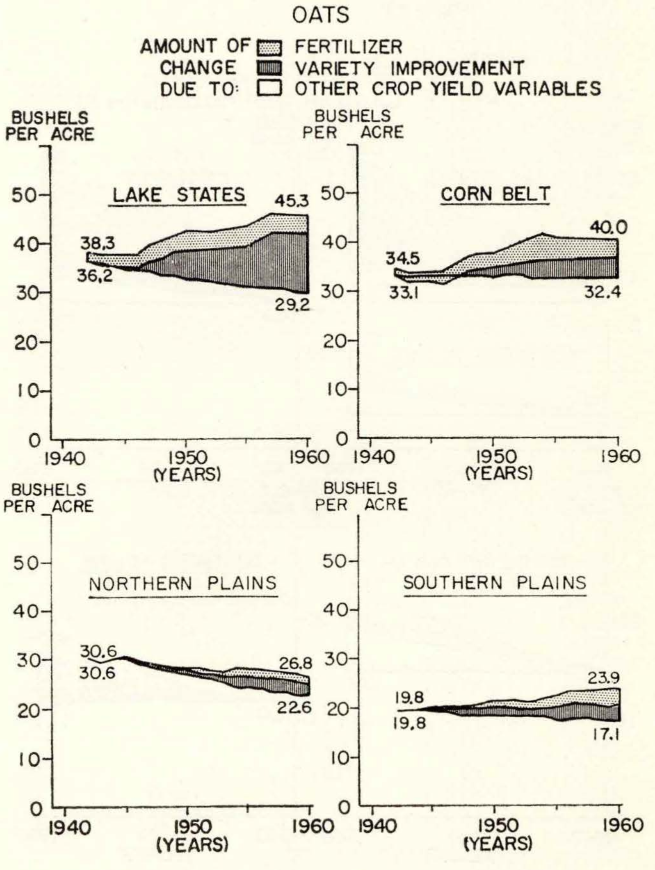

Fig. 16. Changes in estimated regional oat yields due to technology, 1942-1960, (weather and acreage constant).

in rotation or the use of inferior crop land had adverse effects on oat yields.

Soybeans: Estimated yields advanced in all regions. The greatest percentage increase, 56.3, was for the Delta States, followed by the Lake States with 42.0 and the Corn Belt with 24.9 (table 17). Absolute yield changes were 7.1 bushels in the Delta States, 6.3 bushels in the Lake States and 4.9 bushels in the Corn Belt. As shown in fig. 17, variety improvement was the primary cause of higher yields in all regions, and fertilizer raised yields only slightly. Other yield effects were positive in all regions and were highest for the Delta States. Coefficients for variables other than variety were positive and are particularly significant for changes in aggregate soybean yields. Compared with oats, advances in soybean yields were quite uniform among states and regions. Note, however, that in the Lake States region, yields advanced more rapidly during the 1950's than in the 1940's (fig. 17). This differential advance was caused by the late development and use of early-maturing varieties in northern regions.

Barley, flax, cotton and grain sorghum: For Minnesota, estimated barley yields increased from an estimated 22.0 bushels in 1943 to 32.5 bushels in 1960 (table 17). Yields advanced quite uniformly over the Northern Plains states, but the rate of 0.19 bushels per year was much lower than that of Minnesota. Annual yield curves in fig. 19 illustrate the more rapid change in the Northern Plains in recent years as a result of the widespread adoption of Traill, a superior barley variety.

Flax yields advanced from 8.8 to 9.7 bushels in Minnesota, but declined by almost 1 bushel in North and South Dakota from 1944 to 1960. Very little yield increase is attributed to fertilization or variety improvement (fig. 18). The North Dakota decline in the flax variety index also decreased the Northern Plains average.

By contrast, estimated cotton yields advanced at a remarkable pace, especially in Texas and Oklahoma where yields more than doubled over 21 years (table 17). Most of the estimated cotton yield increase in the Southern Plains cannot be explained by higher rates of fertilizer application or variety improvement, but must be attributed to other crop yield variables (fig. 19): The large expansion in irrigated acreage contributed greatly to higher cotton yields in Texas. In the Texas high plains, a highly specialized cotton area, yields nearly tripled from 1944 to 1954 in response to irrigation.[28] On the other hand, most of the yield in-

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[28] M. M. Tharp and E. L. Langsford. Where our cotton comes from. pp. 129-135. In: Land, the Yearbook of Agriculture, 1958. U.S. Govt. Print. Off., Washington, D.C. 1958.

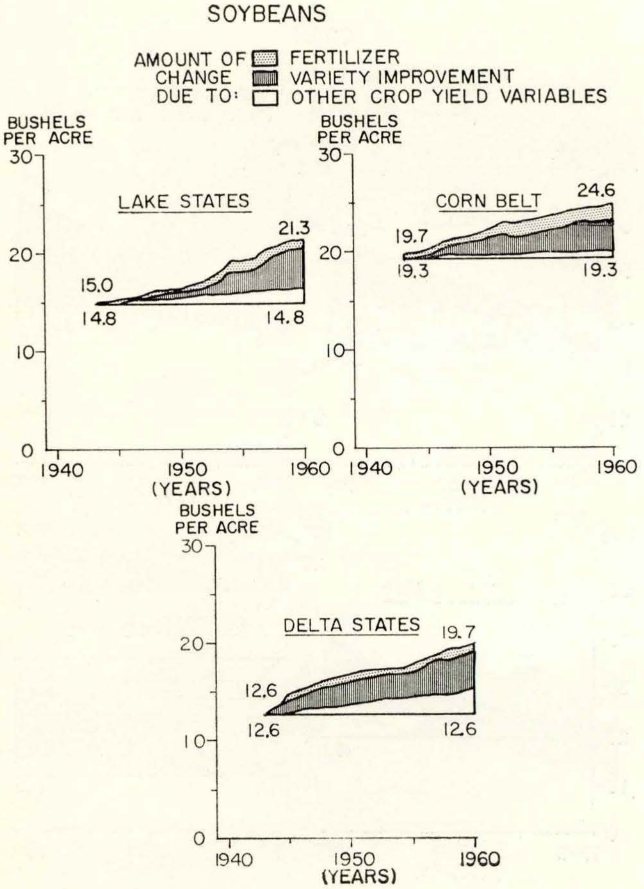

Fig. 17. Changes in estimated regional soybean yields due to technology, 1943-1960, (weather and acreage constant).

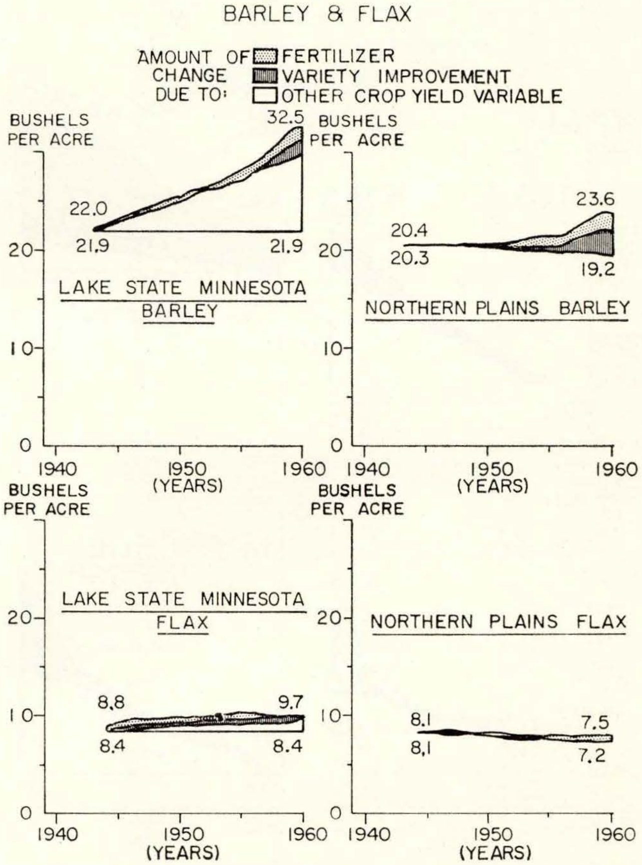

Fig. 18. Changes in estimated regional barley and flax yields due to technology, 1943-1960, (weather and acreage constant).

crease in the Delta States was attributed to increased fertilizer use. Variety improvement and other variables contributed about equally to yield improvement, but their total effect was less than for fertilizer.

Percentage gains in estimated grain sorghum yields were large. Yields increased by about 61.4 percent in Kansas, 89.5 percent in Oklahoma, 154.0 percent in Texas and 132.3 percent in Nebraska after 1939 (table 17). Most of the change in the Northern Plains was attributed to variety improvement and fertilization; only a third of the change was attributable to other crop yield variables (fig. 19). In the Southern Plains, the greatest part of the increase during the earlier years was due to unspecified crop yield variables. In later years, variety improvement and fertilizer use contributed nearly one-half of the cumulative change. The expansion of irrigated acreage contributed some change, but less than the very rapid adoption of sorghum hybrids.

Corn: Estimated corn yields advanced in all regions. The greatest percentage increases occurred in the Delta States and Northern Plains. Fertilization and continued improvement of corn hybrids accounted for most of the yield change (fig. 20). Estimated yield advance was primarily due to higher rates of fertilization in the Corn Belt and Delta States; adoption of higher-yielding hybrids in the Lake States and Southern Plains; and almost equally fertilization, hybrid improvement and other yield variables in the Northern Plains.

Other crop yield variables had negative effects in the Southern Plains. After allowance for fertilization and hybrid improvement, these effects reduced net yield by 1.1 bushels over the 22-year period. In all other regions, yield effects of unspecified variables were positive, and they were especially strong in the Northern Plains where irrigated corn acreages expanded. Regional differentials were maintained over time; yields remaining highest in the Corn Belt and lowest in the Southern Plains and Delta States.

Tame Hay: Estimated yields of tame hay increased in all regions, but progress was irregular in most regions and quite unusual in the Southern Plains (fig. 21). Since no variety index was computed for tame hay, all yield changes were attributed to only two variables, fertilizer application and other (unspecified) variables. From 1939 to 1960, yields advanced by 0.363 tons in the Lake States, 0.347 tons in the Corn Belt, 0.144 tons in the Northern Plains, and by less than 0.100 tons in the Southern Plains and Delta States (table 17). In the Lake States, yields increased at a fairly uniform rate. However, in the Corn Belt, the Northern and Southern Plains and the Delta States, peaks occurred between the years 1948 and 1954.

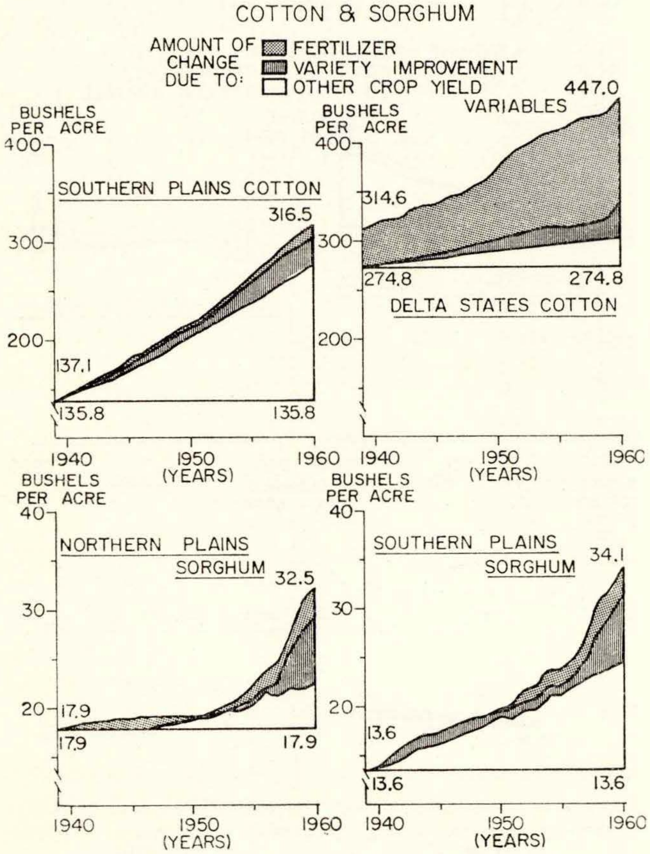

Fig. 19. **Changes in estimated regional cotton and grain sorghum yields due to technology, 1939-1960, (weather and acreage constant).**

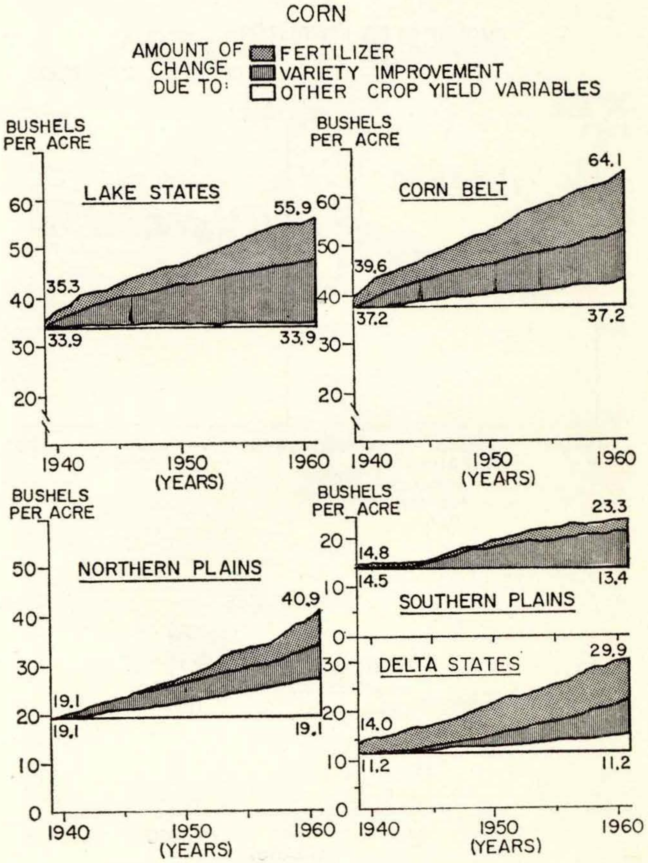

Fig. 20. **Changes in estimated regional corn yields due to technology, 1939-1960, (weather and acreage constant).**

These irregularities are attributed to abrupt changes in estimates of fertilizer application. For example, total nutrient application for tame hay in Illinois was estimated at 2.8 pounds in 1951, 11.4 pounds in 1954 and 5.0 pounds in 1959. Since fertilizer response coefficients were determined before regressing adjusted yields on other variables, unusual patterns of yield curves could be expected in abnormal estimates of application rates.[29]

AGGREGATE ESTIMATES

Aggregate estimated yield changes follow essentially the same technique as estimation of regional changes. However, in the aggregate analysis, yield effects of production location are taken into account. These effects, although evaluated in regional analysis, were omitted because location effects within regions generally were not significant. The effects of shifts in production location or regional specialization were quantified by inserting one additional variable, the relative state crop acreage, in the state crop-production functions.

Crop acreage trends: Relative crop acreage changed between states and regions in both the short run and the long run. Yields, differing between states and regions at the outset, advanced at different rates over time. Without permanent long-run trends in relative state acreages, effects of regional specialization on aggregate yields would have been temporary. Indications of the long-run trends are evident in table 18, where regression coefficients of linear time-trend lines of state crop acreages are tabulated.[30] The a values in column 1 represent the estimated 1939 acreage (in 1,000 acres), the b values in column 2 are the estimated annual changes in acreage (in 1,000 acres), and the r^2 values in column 3 measure the correlation between acreage and time-trends. All estimates from 1939 to 1960 are comparable. Only for grain sorghum were regressions fitted for the years 1950 to 1960 and connected to the average acreage of the years 1939 to 1949 (because sorghum acreages remained almost constant during the earlier period but advanced rapidly in later years). All regional acreage trend coefficients were computed by adding state trend coefficients, a permissible procedure since all state regressions were fitted over the identical time period.

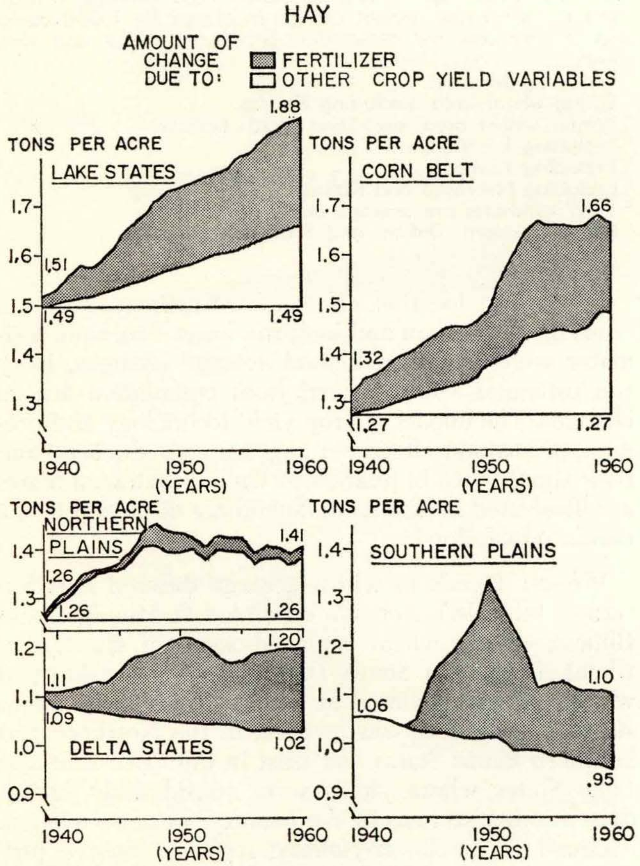

Fig. 21. Changes in estimated regional tame hay yields due to technology, 1939-1960, (weather and acreage constant).

Table 18. Estimated harvested crop acreage (000) trends by states and regions, 1939 to 1960.

Crop	Region and state	Estimated coefficients a[a]	b	r^2
Wheat	Lake States . . .	3,259.2	−15.8	
1939-60	Mich.	836.8	19.4*	0.28
	Wis.	93.4	−1.5*	0.23
	Minn.	1,429.0	−33.7**	0.65
	Corn Belt[b]	5,226.5	−20.9	
	Ohio	2,081.7	−22.3+	0.18
	Ind.	1,452.0	−5.9	0.03
	Ill.	1,440.3	13.4	0.09
	Iowa	252.5	−6.1*	0.21
	N. Plains[c]	12,695.8	−145.8	
	N. D.	9,419.3	−91.3	0.15
	S. D.	3,161.7	49.3	0.19
	Neb.	114.8	−5.2**	0.74
	N. Plains[d]	15,223.8	−46.7	
	S. D.	119.0	17.7**	0.78
	Neb.	3,157.6	20.4	0.05
	Kan.	11,947.2	−84.8	0.06
	S. Plains	9,420.4	−86.0	0.09
	Tex.	4,382.2	−69.5	0.01
	Okla.	5,038.2	−16.5	0.01
Oats	Lake States . . .	8,638.4	−20.26	
1942-60	Mich.	1,390.8	−19.47**	0.35
	Wis.	2,604.4	8.86	0.05
	Minn.	4,643.2	−9.65	0.01
	Corn Belt	13,361.6	−142.72	
	Ohio	1,105.2	0.47+	0.01
	Ind.	1,314.7	−14.08*	0.26
	Ill.	3,571.4	−50.80**	0.40
	Iowa	5,477.8	−13.33	0.02
	Mo.	1,892.5	−64.98**	0.77
	N. Plains	8,308.4	−39.38	
	N. D.	2,104.3	−14.24	0.09
	S. D.	2,608.2	41.85+	0.17

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[29] No corrections were made for these abnormalities because they were adopted from original data sources. Since application rates for over 80 state crops were considered in this study, it is obvious that irregularities such as these were exceptional.

[30] These regression estimates were required for estimation of acreage indexes that measured short-run deviations from acreage trends, but they were not used for estimation of production-location effects.

Table 18. (cont'd).

Crop	Region and state	Estimated coefficients a[a]	b	r^2
	Neb.	2,099.7	−19.11	0.07
	Kan.	1,496.2	−47.88**	0.60
	S. Plains	2,587.2	−62.91	
	Tex.	1,348.6	−14.42	0.06
	Okla.	1,238.6	−48.49**	0.60
Soybeans 1943-60	Lake States	410.6	148.43	
	Mich.	83.4	7.56**	0.57
	Wis.	31.1	3.67**	0.60
	Minn.	296.1	137.20**	0.89
	Corn Belt	6,394.0	421.19	
	Ohio	851.8	33.28**	0.62
	Ind.	1,161.4	71.79**	0.93
	Ill.	2,899.8	126.48**	0.86
	Iowa	1,011.5	79.18**	0.65
	Mo.	469.5	110.46**	0.96
	Delta States[e]	169.8	148.76	
	Ark.	95.5	104.36**	0.83
	Miss.	74.3	44.40**	0.86
Barley 1943-60	Minn.	1,362.4	−32.38*	0.28
	N. Plains[f]	4,746.3	−66.70	
	N. D.	2,040.6	85.44**	0.59
	S. D.	1,630.7	−81.69**	0.79
	Neb.	1,075.0	−70.45	0.61
Flax 1944-60	Minn.	1,341.2	−42.2**	0.53
	N. Plains[g]	1,666.9	130.6	
	N. D.	1,252.0	106.3**	0.58
	S. D.	414.9	24.3**	0.56
Cotton 1939-60	S. Plains	9,578.1	−129.3	
	Tex.	8,127.6	−70.2	0.07
	Okla.	1,450.5	−59.1**	0.80
	Delta States[e]	4,408.5	94.4	
	Ark.	1,981.5	−38.7**	0.40
	Miss.	2,427.0	−55.7**	0.62
Grain sorghum[h] 1939-60	N. Plains[i]	1,444	436.1	
	Neb.	166	134.8**	0.86
	Kan.	1,278	301.3**	0.80
	S. Plains	4,315	348.2	
	Tex.	3,637	334.1**	0.76
	Okla.	678	14.1	0.15
Corn 1939-61	Lake States	8,520.1	121.24	
	Mich.	1,530.4	20.19**	0.62
	Wis.	2,346.0	21.64**	0.61
	Minn.	4,644.5	79.41**	0.61
	Corn Belt	29,376.8	193.61	
	Ohio	3,391.4	8.52	0.10
	Ind.	4,058.0	44.82**	0.64
	Ill.	7,929.3	76.88**	0.47
	Iowa	9,704.9	82.09**	0.32
	Mo.	4,284.2	−18.70+	0.14
	N. Plains	15,113.5	−76.99	
	N. D.	1,080.4	12.52**	0.60
	S. D.	3,166.3	53.16**	0.54
	Neb.	7,692.2	−62.62*	0.24
	Kan.	3,174.6	−70.05**	0.61
	S. Plains	6,663.2	−267.98	
	Tex.	4,710.5	−175.88**	0.90
	Okla.	1,952.7	−92.10**	0.96
	Delta States	5,164.6	−182.17	
	Ark.	2,125.6	−90.05**	0.97
	Miss.	3,039.0	−92.12**	0.98
Tame hay 1939-60	Lake States	9,839.9	−46.63	
	Mich.	2,856.9	−43.36	0.86
	Wis.	3,982.5	5.60+	0.10
	Minn.	3,000.5	2.33+	
	Corn Belt	14,879.5	−117.11	
	Ohio	2,676.5	−24.23**	0.53
	Ind.	2,054.0	−27.11**	0.72
	Ill.	3,059.8	−36.45	0.58
	Iowa	3,465.6	10.23	0.04
	Mo.	3,623.6	−39.55**	0.34
	N. Plains	1,573.1	265.91	
	N. D.	632.2	61.56**	0.71
	S. D.	138.2	120.57**	0.81
	Neb.	802.7	83.78**	0.82
	S. Plains	2,175.9	22.70	
	Texas	1,320.2	10.29+	0.16
	Okla.	855.7	12.41*	0.27
	Delta States	2,563.2	−44.17	
	Ark.	1,338.1	−35.41**	0.92
	Miss.	931.7	−14.04**	0.83
	La.	293.4	5.28**	0.54

** Significant at the 1-percent level.
* Significant at the 5-percent level.
+ Significant at the 10-percent level.

[a] a is a constant representing estimated 1939 acreage. b measures the estimated annual change in acrage (in 1,000 acres) and r^2 measures the correlation between acreage and time trends.

[b] Excluding Missouri.

[c] Spring wheat area, excluding Kansas.

[d] Winter wheat area, excluding North Dakota.

[e] Excluding Louisiana.

[f] Excluding Kansas.

[g] Excluding Nebraska and Kansas.

[h] 1939 estimates are average acres 1939-1949.

[i] Excluding North Dakota and South Dakota.

Production location effects were estimated for all crops on a short-run and long-run basis. Short-run estimates were based on annual acreage changes, long-run estimates were derived from cumulative annual changes. The impact of crop yield technology and production location effects on aggregate production, and their significance in relation to United States estimates are illustrated in figs. 22 to 30 and are discussed in the paragraphs following.

Wheat: Trends in wheat acreage differed between states (table 18). Acreage expanded in Michigan and Illinois; winter wheat replaced some of the spring wheat acreage in South Dakota and Nebraska, and wheat acreage declined at varying rates in all other states. The decline was greatest in the Northern and Southern Plains States and least in the Corn Belt and Lake States where yields were considerably higher than in other sections of the country. Because acreage declined in the lower-yielding regions, positive production location effects could be expected. Fig. 22 (upper part), illustrating changes in aggregate wheat yield for all 13 states, shows the greatest part of yield change can be attributed to increased fertilization. The 1960 expected wheat yield of 21.0 bushels was nearly 50 percent greater than the 1939 expected yield of 14.1 bushels. Wheat variety improvement and other crop yield variables contributed an estimated 2.1 bushels each. Production location effects added only 0.1 bushel. Production location effects were negative during earlier years because of expansion of wheat into lower-yielding regions. These negative effects do not contradict the positive effects of the long-run trends in production location.

Actual yields and production function estimates of yields can be compared in fig. 22 (lower left). Estimates differed greatly from actual yields in 1942, 1958 and 1960 since the estimated yields assumed normal weather.

Oats: Effects of crop yield technology on oat yields are shown in fig. 23. The largest part of the oat yield change, from an estimated 33.6 bushels per acre in 1942 to 37.0 bushels in 1960, was attributed to variety improvement. Fertilizer application was next in importance, and a small positive effect of 0.9 bushel was due to production location. As shown in table 18, the positive acreage resulted because there was only a small reduction in high-yield states such as Minnesota, Indiana and Iowa, and a large reduction in lower-yielding states such as Missouri. Negative effects of other oats yield variables reduced the 9.0 bushel gain[31] because other variables had a net gain of 3.4 bushels over the period studied. The states included in the oats analysis covered about 85 percent of United States production.

Soybeans: Expected soybean yields increased from 19.2 to 23.3 bushels, an increase of 21 percent over the 17 years included (fig. 24). Corresponding estimates for regional changes (table 17) were larger, ranging from 25 to 56 percent. Figure 24 shows that soybean yields are sensitive to acreage expansion, negative location effects reduced yields by 1.4 bushels per acre. Cumulative yields would have exceeded 25 bushels at the end of the period without acreage expansion into lower-yielding regions. Yield gains from fertilizer were small and did not offset yield reductions caused by shifts to less advantageous regions.

Annual production of the 10 states included in the analysis amounted to 95 percent of total United States production during earlier years. However, this percentage declined by nearly 15 percent as soybean production expanded into regions not included in the study. Estimated soybean yields conformed fairly close to actual yields, even though the soybean production functions explained only two-thirds of annual crop yield variations.

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[31] The 9.0-bushel gain is defined as follows (37.0—26.9)—(33.6—32.5).

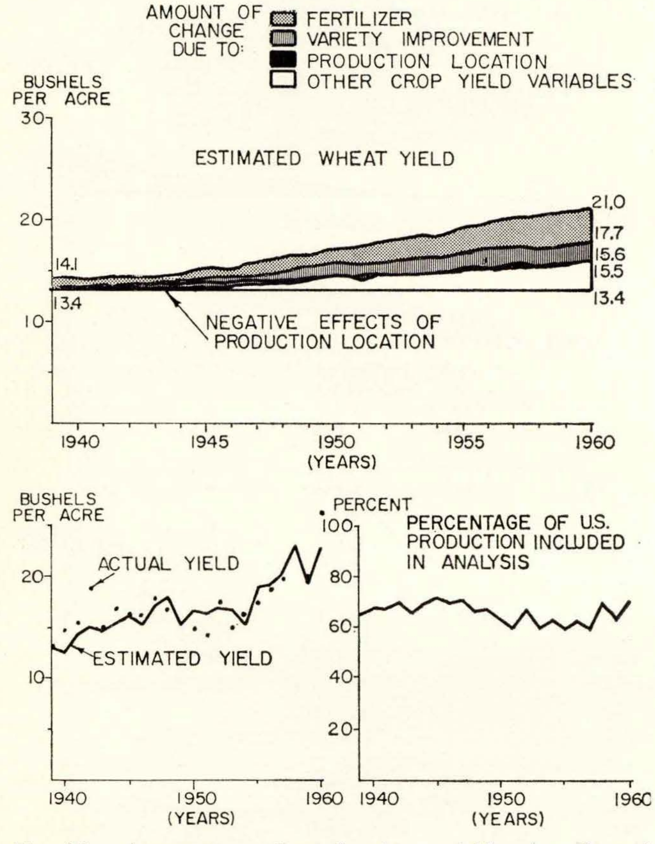

Fig. 22. **Aggregate estimated wheat yields, actual and estimated yields, and percentage of United States production for all 13 states included in analysis, 1939-1960.**

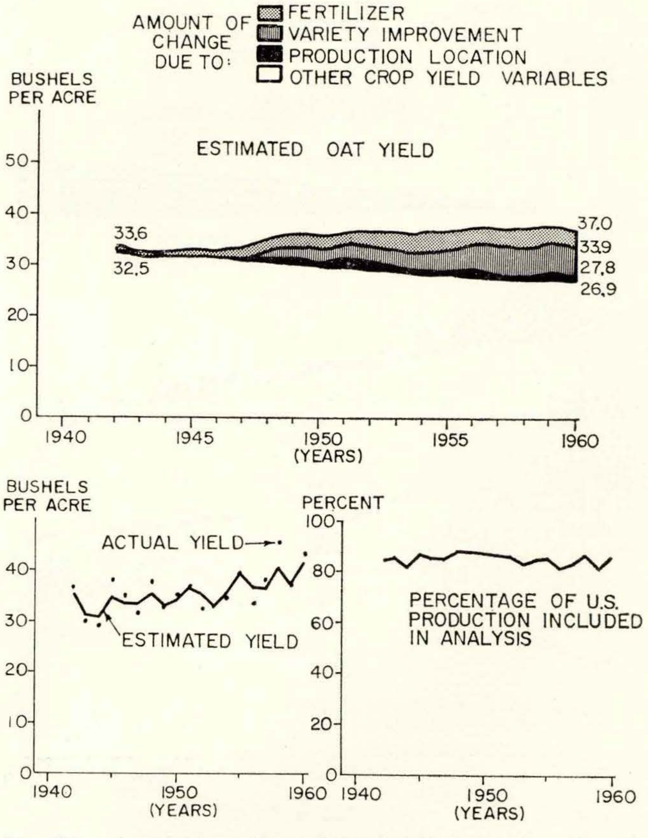

Fig. 23. **Aggregate estimated oat yields, actual and estimated yields, and percentage of United States production represented in analysis for the 14 states, 1942-1960.**

Barley, flax, cotton and grain sorghum: Aggregate changes in barley yields are illustrated in fig. 25. States included in the analysis covered about 40 percent of United States production during 1943-48, but only 30 percent at the end of the period. Because of this limited coverage, the estimates relate more to production in the Northern Plains and Lake States than to the nation. Expected yields increased from 20.6 bushels in 1943 to 25.1 bushels in 1960. Fertilizer use is the source of 1.4 bushels, and superior varieties account for 2.4 bushels. The remaining increase is due mainly to changes in production location. Barley acreage shifted toward higher-yielding states such as Minnesota, in the late 1940's and early 1950's, but shifted back toward the lower-yielding Northern Plains area in later years. As a result, production-location effects, which were large in the middle period, declined in the last 10 years of the period. The aggregate effects of other crop yield variables were small causing a yield increase of only 0.6 bushel. (Actually, some strong positive yield effects in Minnesota were cancelled by slightly negative effects of other variables of the larger Northern Plains area.)

Actual and estimated barley yields differ markedly in the years 1949, 1958 and 1959 and are consistently higher from 1950 to 1954. This 4-year deviation may have been caused partly by random errors in annual weather indexes, plus the assumption of normal weather.

Estimated flax production related to three states that have produced from 80 to 90 percent of the total United States production, Minnesota, North Dakota and South Dakota (fig. 26). The initial rise in estimated yields was largely due to a relative increase in the Minnesota flax acreage. Later, this gain was offset by a decline in variety index values and especially by a reversal in acreage shifts. Actual flax yields ranging from 10.6 bushels in 1948 to 5.0 bushels in 1957, fluctuated widely among years.

Of variables quantified in cotton yields, fertilizer and variety improvement had fairly large positive effects. However, most of the estimated increase was due to variables not measured in this study; i.e., the distance at the end of the period between 179.1 and 280.0 (top half of fig. 27). Irrigated acreage in Texas and the Southwest expanded significantly over the years. Hence, much of the unquantifiied yield increase is probably due to irrigation. Location effects were positive early in the period, but negative from 1951. The negative effect was caused by a shift in acreage to the lower-yielding Southern Plains where cotton acreage expanded by 5.8 million acres between 1950 and

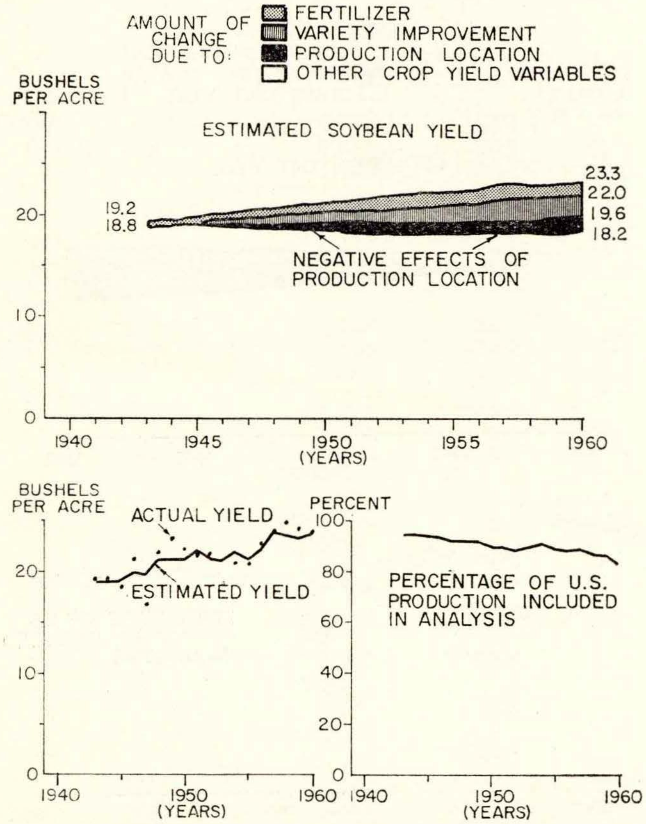

Fig. 24. Aggregate estimated soybean yields, actual and estimated yields, and percentage of United States production included in analysis for the 10 states, 1943-1960.

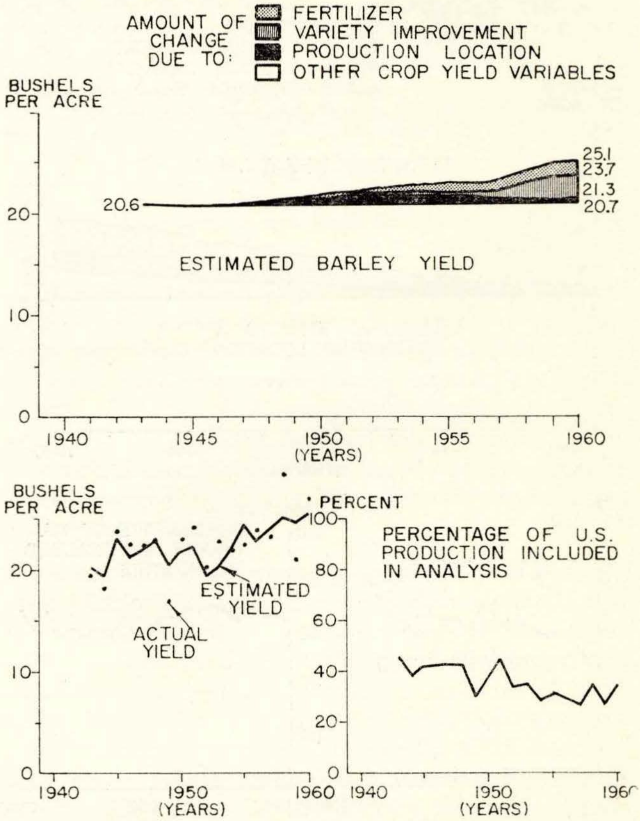

Fig. 25. Aggregate estimated barley yields, actual and estimated yields, and percentage of United States production for 4 states included in analysis, 1943-1960.

1951, and reversed acreage shifts in later years were not strong enough to compensate for the earlier effects. Since the analysis includes only about half of the national production, part of the United States yield increase caused by shifts from the lower-yielding Southeast (short staple cotton varieties) to the higher-yielding irrigated areas of the Southwest (Arizona, New Mexico and California—long staple cotton varieties) is not considered.

Estimated yields for grain sorghums increased from 14.9 bushels in 1939 to 33.3 bushels in 1960, an increase of 18.4 bushels (fig. 28), with most of the change occurring during the late 1950's. Estimated contributions of individual variables to total yield increases are: 6.7 bushels to sorghum hybrids, 3.1 bushels fertilizer application and 1.0 bushel product location. Although a significant portion of the yield increase is attributed to unquantified crop yield variables, expansion of irrigated acreage without doubt was the most important of these.

Estimated and actual grain sorghum yields were rather highly correlated. Sorghum production of the

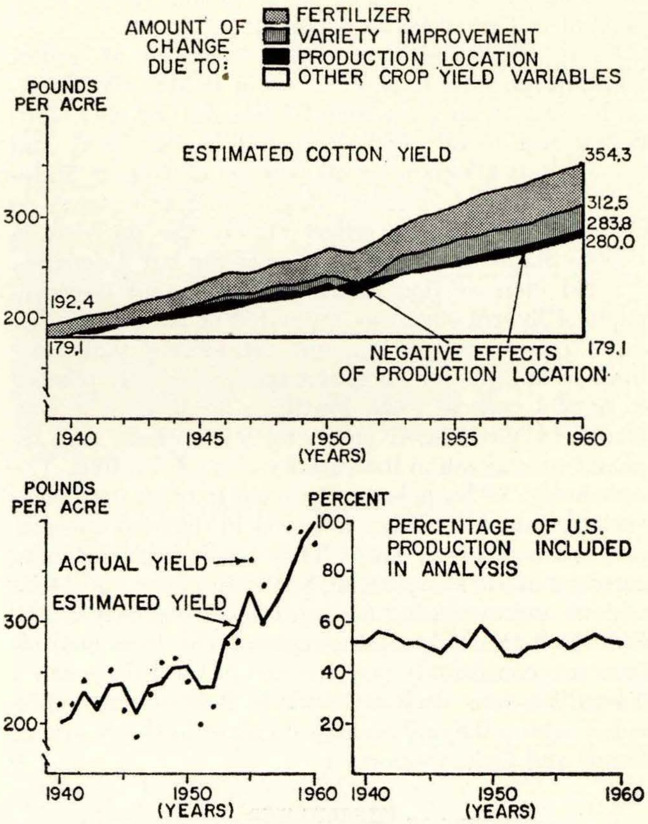

Fig. 27. (top right) Aggregate estimated cotton yields, actual and estimated yields, and percentage of United States production included in the 4 states of the analysis, 1939-1960.

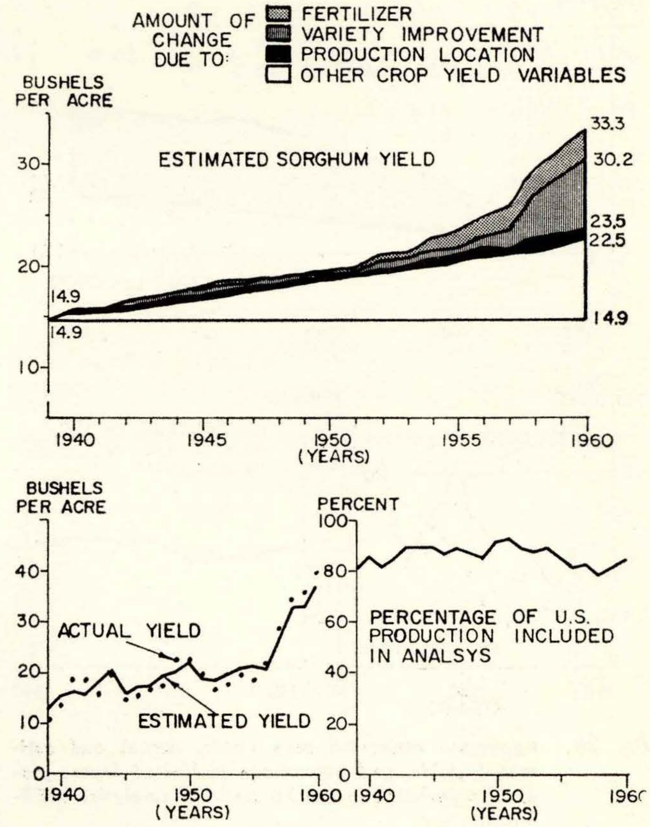

Fig. 28. (lower right) Aggregate estimated grain sorghum yields, actual and estimated yields, and percentage of United States production included in a 4 states of analysis, 1939-1960.

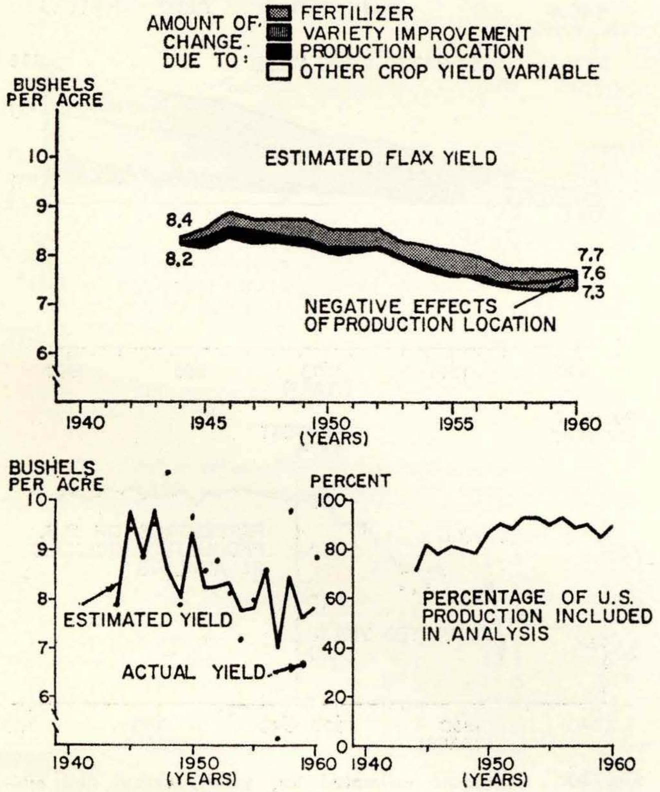

Fig. 26. Aggregate estimated flax yields, actual and estimated yields, and percentage of United States production included in 3 states of analysis, 1944-1960.

states included in the analysis accounted for 80 to 90 percent of United States production.

Corn: Estimated corn yields advanced at almost constant rates, from 30.0 bushels in 1939 to 55.8 bushels in 1961, or by more than 85 percent (fig. 29). Estimated and actual yields were highly correlated, and the analysis covers over 80 percent of United States corn production. Hence, yield changes imputed to different technologies reflect closely the progress in United States corn production over the last 2 decades.

Yield increase due to increased use and improvement of hybrid corn was estimated at 9.2 bushels per acre. This is a large amount considering that more than half of the Corn Belt acreage was already planted to hybrid corn in 1939. Fertilizer application is estimated to have raised yields by 9.7 bushels, and regional specialization increased yields 4.6 bushels. The remainder, 3.9 bushels, is attributed to other corn yield variables. Yield changes imputed to regional specialization are relatively large. They result from declining acreages in the low-yielding Southern Plains and Delta regions and increasing acreages in the higher-yielding Corn Belt and Lake States regions. The locational effects are consistently positive except for 1959 when a 3.4-million-acre decline in Corn Belt acreage coincided with a 0.8-million-acre increase in the Southern Plains and Delta regions.

Tame Hay: States included in this study account for 40 to 50 percent of the total United States hay production. Most of the yield increase for tame hay in these states is attributed to higher rates of fertilization (fig. 30). Production location effects are negative and fairly strong from 1950 to 1960 when tame hay acreage expanded in the lower-yielding Northern Plains and contracted in the Corn Belt and Lake States regions. Estimated yields follow the general pattern of actual yields, but the two are not highly correlated (perhaps because of estimating errors in fertilizer application rates as discussed for fig. 21 in connection with regional estimates.)

Added Value for United States Production

Previously the impacts of crop yield technology have been described in terms of annual yield changes for specific crops. Estimates are summarized now in terms of the "annual dollar value added" to gross crop return for the United States. Where sufficient information is available, estimates for United States agriculture are derived. The *dollar value* is used as a simple aggregative measure of regional or national effects. It is recognized, of course, that price elasticities of demand are typically less than 1.0 and that increased output should reduce sale values of crops. Another aggregative mea-

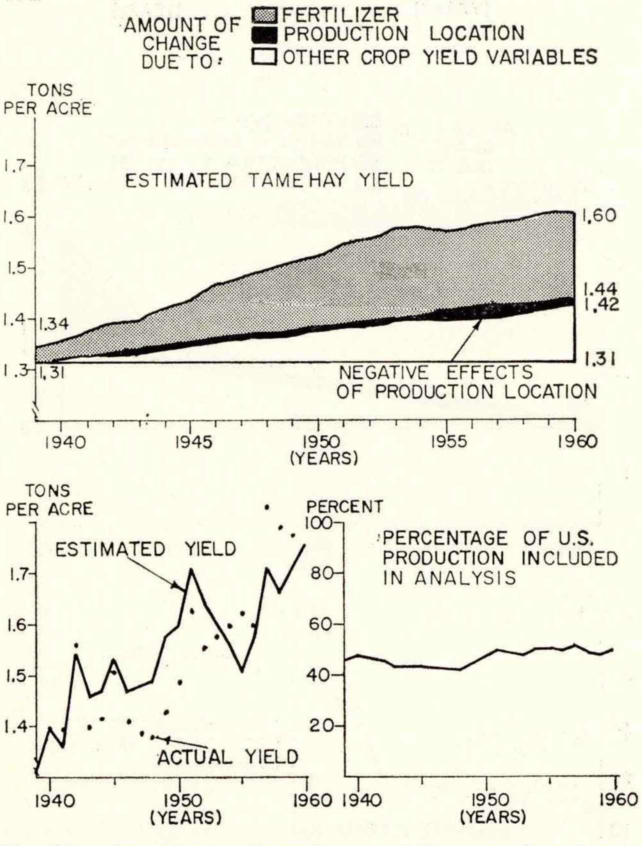

Fig. 29. Aggregate estimated corn yields, actual and estimated yields, and percentage of United States production included in the 16 states of analysis, 1939-1961.

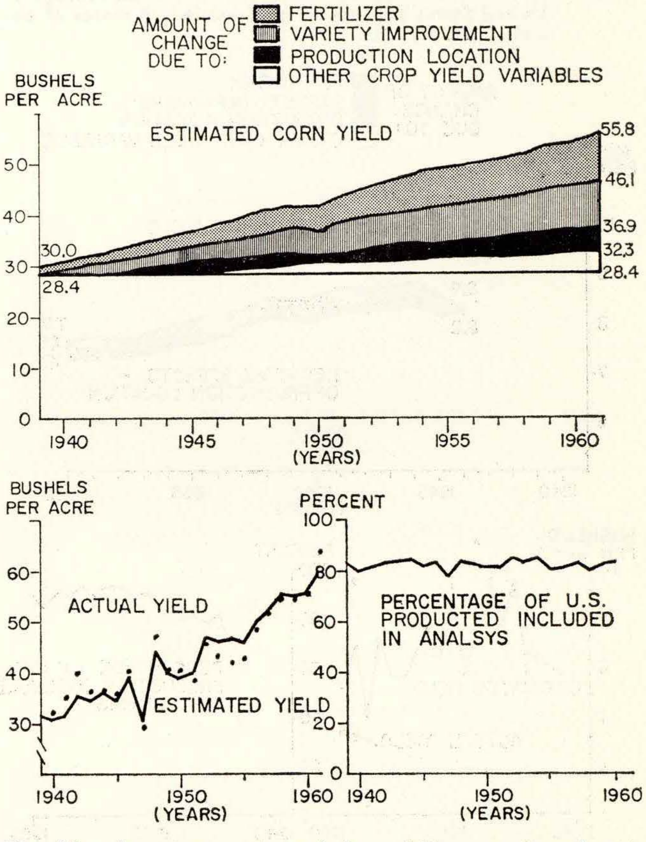

Fig. 30. Aggregate estimated hay yields, actual and estimated yields, and percentage of United States production included in the 16 states of analysis, 1939-1960.

sure might have been tonnage of crops produced. However, the monetary aggregate was used since it was easier to compute and included some weighting relative to the market. The prices used for all crops in all years are for 1960, rather than those for individual years. Largely, the value measure is used, rather than a physical measure in bushels or tons, to allow an easier grasp of the relative importance, among crops and technologies, of yield improvement practices at a 1960 point in time (using 1960 prices as applied to yield increases from the base year).

AGGREGATIVE REGIONAL CHANGES PER ACRE

A summary of the estimated annual increases per acre aggregated over all regions studied is presented in table 19. This summary includes all crops considered previously and refers to the per-acre increases of 1960 over the base year yields (i.e., base years of 1939 for wheat, cotton, grain sorghum, corn and tame hay; 1942 for oats, and 1943 for soybeans and barley, as shown in figs. 22 to 29). The figures given in table 19 are total per-acre effects for the regions discussed earlier and included in the study. They refer to the acreages of these regions and not to United States acreages.

The aggregate yield changes of 1960 over the base year due to fertilization, variety improvement, production location and other crop yield variables for wheat, for example, are estimated to be 3.3, 2.1, 0.1 and 2.1 bushels, respectively. A total change of 7.6 bushels, from 13.4 to 21.0 bushels per acre is shown. To obtain dollar values per acre of these yield changes, bushel changes were multiplied by 1960 United States prices. The dollar value added to gross return per acre, as an aggregate over all regions studied, due to fertilization was computed as $5.78 ($1.75 × 3.3 = $5.78). The corresponding total dollar value, as an aggregate over all regions, added by all variables was computed as $13.32 per acre.

TOTAL VALUE ADDED TO PRODUCTION

Table 20 includes estimates of the aggregative value or amount added to total production for each crop over the regions studied and for part of the crops, for the entire nation. The figures in the top half of the table,

Table 19. Aggregative change in crop yields and dollar value added per acre by crop yield technology and crops for regions studied, 1960 as compared with base year.

	Wheat	Oats	Soy-beans	Barley	Flax	Cotton	Grain sorghum	Corn	Tame hay
Base Year[a]	1939	1942	1943	1943	1944	1939	1939	1939	1939
Bushel yield change per acre[b] due to:									
Fertilization	3.3	3.1	1.3	1.4	0.4	41.8[c]	3.1	9.7	0.18[d]
Variety improvement	2.1	6.1	3.8	2.4	−0.3	32.5[a]	6.7	9.2	..
Production location	0.1	0.9	−1.4	0.6	−0.5	−3.8[c]	1.0	4.6	−0.02[d]
Other crop yield variables	2.1	−5.6	0.8	0.1	−0.1	104.7[c]	7.6	3.9	0.13[d]
Total	7.6	4.5	4.5	4.5	−0.5	175.2[c]	18.4	27.4	0.29[d]
1960 U.S. price in dollars per bushel[e]	1.75	0.60	2.21	0.83	2.66	0.30	1.49	1.00	21.70
Dollar value added to gross return per acre due to:									
Fertilization	5.78	1.86	2.87	1.17	1.06	12.54	4.62	9.68	3.91
Variety improvement	3.68	3.66	8.40	2.01	−0.80	9.75	9.98	9.18	..
Production location	0.18	0.54	−3.09	0.50	−1.33	−1.14	1.4	4.59	−0.43
Other crop yield variables	3.68	−3.36	1.77	0.08	−0.27	31.41	11.32	3.89	2.82
Total	13.32	2.70	9.95	3.76	−1.34	52.56	27.41	27.34	6.30

[a] Year from which measurement to 1960 was initiated.

[b] Refers to aggregate estimated yield change of states included in analysis and measured in bushels except for cotton and tame hay measured in pounds and tons, respectively.

[c] Pounds.

[d] Ton.

[e] Refers to 1960 prices per bushel except for cotton and hay, where prices relate to pounds and tons, respectively.

Table 20. Dollar value added to aggregate returns of regions studied and to United States agriculture by crop yield technology, 1960 yields as compared with base year yields.

	Wheat	Oats	Soy-beans	Barley	Flax	Cotton	Grain sorghum	Corn	Tame hay
Base Year	1939	1942	1943	1943	1944	1939	1939	1939	1939
Dollar value added to aggregate gross return (in million dollars) for regions studied due to:									
Fertilization	212.8	42.4	56.1	5.9	3.3	122.8	63.2	630.5	119.6
Variety improvement	135.5	83.4	164.3	10.2	−2.5	95.5	136.5	597.9	..
Production location	6.6	12.3	−60.4	2.5	−4.2	−11.2	20.4	298.9	−13.2
Other crop yield variables	135.5	−76.6	34.6	0.4	−0.8	307.7	154.8	253.4	86.2
Total	490.4	61.5	194.6	19.0	−4.2	514.8	374.9	1,730.7	192.6
Percentage of U.S. production	70.4	86.0	83.3	32.1	89.3	51.4	84.8	83.6	48.3
Dollar value added to gross return to U.S. agriculture (in million dollars) due to:									
Fertilization		49.3	67.3		3.7		74.5	754.2	
Variety improvement		−97.0	197.2		−2.8		161.0	715.2	
Production location		−14.3	−72.5		−4.7		24.1	357.5	
Other crop yield variables		−89.1	41.5		−0.9		182.5	303.1	
Total		71.5	233.5		−4.7		442.1	2,130.0	

for the regions studied, are obtained by multiplying the total 1960 harvested acreages in the regions by the added value per acre shown in table 19. The figures for the United States in the bottom of table 20 were computed by making adjustments for the acreage not included in the study regions. Estimates for the United States were made only when the study regions included more than 80 percent of the United States harvested acreage for the particular crop. Among the different yield technologies, fertilization and variety improvement added most to gross value of production for both the regional aggregates and the nation. For corn, an estimated 357.5 million dollars was added by production location.

Further Incentive to Improvement

The increases in yields and production to 1960 were remarkable. However, the question remains: Were the yield and production levels attained by 1960 at the economic optimum level, or could they have been increased profitably to even higher levels? We now make some simple comparisons of (a) the yields estimated and (b) those that were computed as optimum in terms of the prices existing in each year for the inputs represented by the crop yield technologies and the estimated production functions. These comparisons are made for each year. The method used is aggregative and simple. We just use the production functions of regions and the prices of each year to compute profit-maximizing yields of the same year. The profit-maximizing yields do not consider captial restraints of individual farmers or the effect of uncertainty, tenure and other obstacles on resource use. These over-simplifications should be kept in mind as comparisons are made between yield levels estimated for 1960 and those computed as profit-maximizing quantities. The optimum yields are functions of the predicted production functions and crop and fertilizer prices as indicated in equation 41.

We also compute *relative economic yields*, by dividing the estimated yield for each year by the economic optimum yield and expressing the quantity as a percentage. These relative economic yields are illustrated in figs. 31 and 32. If less than 100, these figures indicate that under the conditions outlined, yields could still have been increased profitably under the technology and prices existing in each year. (Yields can be further increased profitably in the future as new technologies are developed, as prices change, or both. The relative economic yields are weighted (by acreage) averages for all regions included in the study.

Wheat

In 1939, expected yields were below optimum yields in all 13 states included in the analysis, a condition maintained through 1960. Percentage ratios of most states reached minimum values shortly after 1945, when wheat prices were extremely high. Thereafter they progressed slowly toward the economic optimum levels. The decline in the relative economic wheat yield in the early years is a reflection of both rising crop prices and limited fertilizer supplies during the war years. In later years, states with lower relative eco-

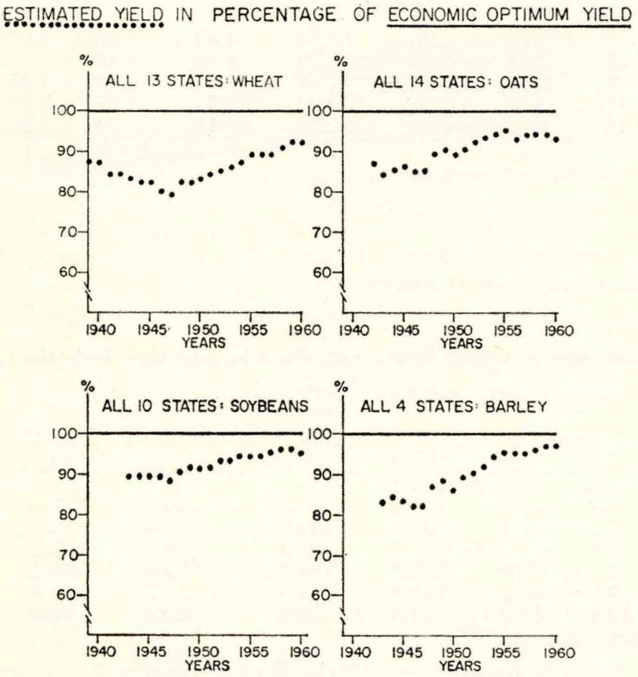

Fig. 31. Estimated yields of wheat, oats, soybeans and barley in percentage of economic optimum yields, 1939-1961.

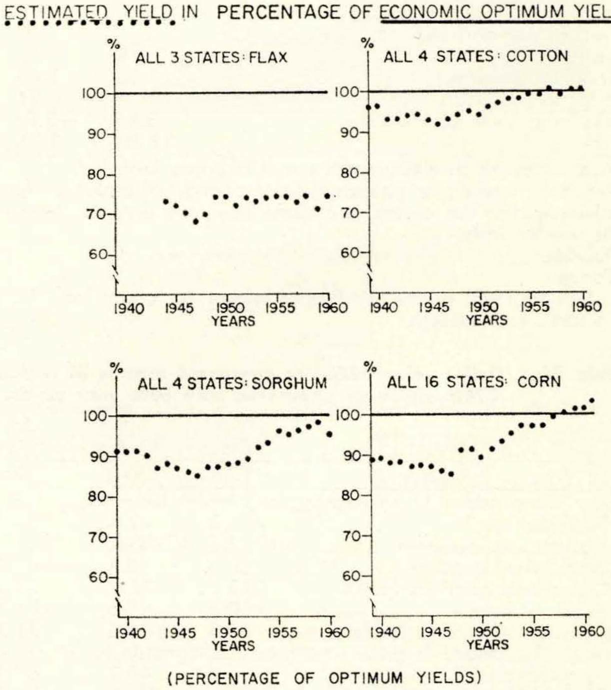

Fig. 32. Estimated yields of flax, cotton, grain sorghum and corn in percentage of economic optimum yields, 1939-1961.

nomic optima advanced yields more rapidly, as a percentage of earlier years, than those with higher relative ratios. Toward the end of the period, the gap between estimated and optimum yield for all regions narrowed to about 10 percent of optimum economic yields.

Oats

The pattern of individual states was not as uniform for oats as it was for wheat. However, the pattern for the aggregate of regions was the same for wheat and oats. As fig. 31 shows, estimated yields moved up to about 90 percent of optimum yields by 1960.

Soybeans

Soybean yields compared to those of other crops close to optimum yields throughout the period. Exceptions existed mainly in Wisconsin, Illinois, Ohio and Arkansas.

Barley, Flax, Cotton and Grain Sorghum

Estimated barley yields (fig. 31) were 83 percent of optimum yields in 1943 and 95 percent in 1960. Estimated flax yields (fig. 32) averaged only about 75 percent of optimum yields over the period, and there was no trend toward improvement. Estimated cotton yields were high relative to optimum yields at the beginning of the period (fig. 32) and appeared to coincide with them by the end of the period. Cotton is highly responsive to fertilizer, and application rates increased from 6.8 pounds in 1939 to 57.1 pounds in 1960 in the four-state area (Oklahoma, Texas, Arkansas and Mississippi). Similarly, estimated grain sorghum yields approached optimum yields in later years.

Corn

Comparison of estimated and optimum yields of corn revealed great uniformity among the 16 states included in the analysis. The relative economic optimum declined at the outset, reached a low in 1947, and then advanced toward 100 percent in all states. It declined during the period of rapidly advancing feed-grain prices, which rose in terms of index numbers from 85 in 1940 to 258 in 1948. Feed grain prices then declined to 151 in 1960. However, the trend of the relative economic optimum toward 100 must be attributed to higher rates of fertilizer application over all states studied. The rate increased from 3.1 pounds of plant nutrients per acre in 1939 to 71.8 pounds in 1961.

Estimated corn yields exceeded optimum yields in 11 of 16 states by 1960. Also, as an average for all states included in the analysis (fig. 32), estimated yield for the last few years exceeded optimum yield. However, in evaluating these results, the following must be remembered: The estimated yields were computed for average weather in each year. During the early 1960's, weather was more favorable than "average." To the extent that above-average weather conditions shifted corn production functions upward, farmers were justified in applying greater than optimum rates under normal weather conditions.

The pattern expressed for corn in fig. 32 could also result from the estimational and other procedures used in this analysis. However, it does appear that estimated corn yields more nearly approached optimum yields than did any other crops included in the study.

Limitations

Results of this study are subject to errors of estimation and analysis. Crop variety improvement was measured by variety indexes based on test yield comparisons and aggregated over areas within states and sometimes over several states. These aggregation procedures may have been inadequate because of variety-location interactions. Estimates of fertilizer use were derived from results of nationwide surveys. Survey results were not comparable, and adjustment procedures may not have adequately compensated for differences. Indexes computed for estimation of weather effects often were based on a very limited number of tests, and inevitably, they were confounded with station-location and variety-disease interactions. Acreage indexes, designed to measure relative deviations from trend acres, may have underestimated acreage effects because of unidentified, compensatory changes in fertilizer application rates. Effects of other crop-yield variables were estimated by a time trend variable. Although this variable was adequate for measuring constant rates of change, it was inappropriate for irregular and abrupt changes in unspecified yield variables.

The production-function model was oversimplified. To avoid serious errors caused by multicollinearity, coefficients of variety indexes and fertilizer response were estimated independently. This procedure appeared to yield satisfactory results, but probably did not account sufficiently for interaction effects between variables. Also, it imposed certain inflexibilities inherent in the type of functions used.

We hope, however, that this research has provided better insight into the source of recent increases in crop yields and production. In any case, it has provided some initial estimates that can serve as a basis for further refinements in predictions and imputations.