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HYBRID CORN: AN EXPLORATION IN THE ECONOMICS OF TECHNOLOGICAL CHANGE [1]

BY ZVI GRILICHES

This is a study of factors responsible for the wide cross-sectional differences in the past and current rates of use of hybrid seed corn in the United States.

Logistic growth functions are fitted to the data by states and crop reporting districts, reducing differences among areas to differences in estimates of the three parameters of the logistic: *origins*, *slopes*, and *ceilings*.

The lag in the development of adaptable hybrids for particular areas and the lag in the entry of seed producers into these areas (differences in *origins*) are explained on the basis of varying profitability of entry, "profitability" being a function of market density, and innovation and marketing cost.

Differences in the long-run equilibrium use of hybrid corn (*ceilings*) and in the rates of approach to that equilibrium (*slopes*) are explained, at least in part, by differences in the profitability of the shift from open pollinated to hybrid varieties in different parts of the country.

The results are summarized and the conclusion is drawn that the process of innovation, the process of adapting and distributing a particular invention to different markets and the rate at which it is accepted by entrepreneurs are amenable to economic analysis.

1. INTRODUCTION

THE WORK presented in this paper is an attempt to understand a body of data: the percentage of all corn acreage planted with hybrid seed, by states and by years. By concentrating on a single, major, well defined, and reasonably well recorded development—hybrid corn—we may hope to learn something about the ways in which technological change is generated and propagated in U. S. agriculture.

The idea of hybrid corn dates back to the beginning of this century and its first application on a substantial commercial scale to the early thirties. Since

[1] This research was begun during my tenure as a Research Training Fellow of the Social Science Research Council. It has been supported by the Office of Agricultural Economics Research at the University of Chicago and is being supported by a generous grant from the National Science Foundation. I am indebted to Professor T. W. Schultz for arousing my interest in this problem and for encouraging me in my work, to Professors H. G. Lewis and A. C. Harberger for their valuable advice and guidance, and to the members of the Public Finance Workshop and other members of the Department of Economics at the University of Chicago, both faculty and students, for their suggestions and criticisms. I owe to the generosity of the Field Crop Statistics Branch of the Agricultural Marketing Service a large part of the unpublished data used in this paper. I also want to acknowledge and thank the people directly connected with hybrid corn, both in the Agricultural Experiment Stations and in the private seed companies, for their complete cooperation. This article is based on my unpublished Ph.D. dissertation, "Hybrid Corn: An Exploration in Economics of Technological Change," on file at the University of Chicago Library.

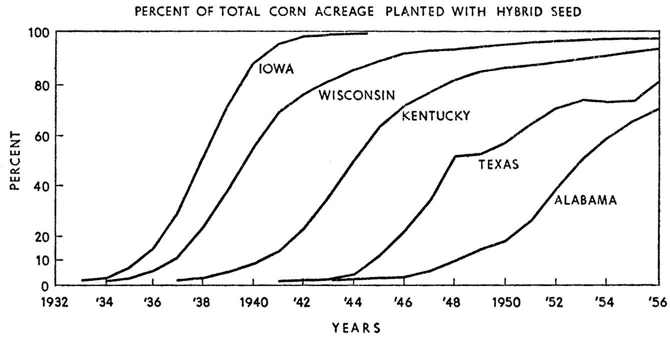

FIGURE 1.—Percentage of Total Corn Acreage Planted with Hybrid Seed. Source: U.S.D.A., *Agricultural Statistics*, various years.

then it has spread rapidly throughout the Corn Belt and the rest of the nation.[2] There have been, however, marked geographic differences in this development (see Figure 1). Hybrid corn was the invention of a method of inventing, a method of breeding superior corn for specific localities.[3] It was not a single invention immediately adaptable everywhere. The actual breeding of adaptable hybrids had to be done separately for each area. Hence, besides the differences in the rate of adoption of hybrids by farmers—the "acceptance" problem—we have also to explain the lag in the development of adaptable hybrids for specific areas—the "availability" problem.

In the following sections I shall first outline a method used to summarize the data. Essentially it will consist of fitting trend functions (the logistic) to the data, reducing thereby the differences among areas to differences in the values

[2] A popular history of hybrid corn can be found in A. R. Crabb, *The Hybrid Corn Makers: Prophets of Plenty*, Rutgers University Press, 1948. See also F. D. Richey, "The Lay of the Corn Huckster," *Journal of Heredity*, 39(1), 1946, 10–17; P. C. Mangelsdorf, "The History of Hybrid Corn," *loc. cit.*, 39, 1948, 177–180; G. F. Sprague, "The Experimental Basis for Hybrid Maize," *Biological Reviews*, 21, 1946, 101–120; M. T. Jenkins, "Corn Improvement," *U. S. Department of Agriculture Yearbook*, 1936, 455–522; and H. A. Wallace and W. L. Brown, *Corn and Its Early Fathers*, Michigan State University Press, 1956.

[3] "Hybrid corn is the product of a controlled, systematic crossing of specially selected parental strains called 'inbred lines.' These inbred lines are developed by inbreeding, or self-pollinating, for a period of four or more years. Accompanying inbreeding is a rigid selection for the elimination of those inbreds carrying poor heredity, and which, for one reason or another, fail to meet the established standards." "[The inbred lines] are of little value in themselves for they are inferior to open-pollinated varieties in vigor and yield. When two unrelated inbred lines are crossed, however, the vigor is restored. *Some* of these hybrids prove to be markedly superior to the original varieties. The development of hybrid corn, therefore, is a complicated process of continued self-pollination accompanied by selection of the most vigorous and otherwise desirable plants. These superior lines are then used in making hybrids." First quote is from N. P. Neal and A. M. Strommen, "Wisconsin Corn Hybrids," Wisconsin Agricultural Experiment Station, Bulletin 476, February, 1948, p. 4; and the second quote is from R. W. Jugenheimer, "Hybrid Corn in Kansas," Kansas Agricultural Experiment Station, Circular 196, February, 1939, pp. 3–4. See also the references in the previous footnotes.

of a few parameters. Then I will present a model rationalizing these differences and illustrate it with computational results. Finally, I shall draw some conclusions on the basis of these results and other accumulated information.

2. THE METHOD AND THE MODEL

A graphical survey of the data by states and crop reporting districts along the lines of Figure 1 led to the conclusion that nothing would be gained by trying to explain each observation separately, as if it had no antecedent.[4] It became obvious that the observations are not points of equilibrium which may or may not change over time, but points on an adjustment path, moving more or less consistently towards a new equilibrium position. Hence we should phrase our questions in terms of the beginning of the movement, its rate, and its destination. This led to the decision to fit some simple trend functions to the data and concentrate on the explanation of the cross-sectional differences in the estimates of their parameters.

The choice of a particular algebraic form for the trend function is somewhat arbitrary. As the data are markedly S-shaped, several simple S-shaped functions were considered. The cumulative normal and the logistic are used most widely for such purposes. As there is almost no difference between the two over the usual range of data,[5] the logistic was chosen because it is simpler to fit and in our context easier to interpret. While there are some good reasons why an adjustment process should follow a path which is akin to the logistic, I do not want to argue the relative merits of the various S-curves.[6] In this work the growth curves serve as a summary device, perhaps somewhat more sophisticated than a simple average, but which should be treated in the same spirit.

[4] This conclusion was also supported by the results of an attempt to fit a model in which the year-to-year changes in the percentage planted to hybrid seed were to be explained by year-to-year changes in the price of corn, price of hybrid seed, the superiority of hybrids in the previous year or two, etc. The trend in the data was so strong that, within the framework of this particular model, it left nothing of significance for the "economic" variables to explain.

[5] For a comparison, see C. P. Winsor, "A Comparison of Certain Symmetrical Growth Curves," *Journal of the Washington Academy of Sciences*, 22, 1932, 73–84, and J. Aitchison and J. A. C. Brown, *The Lognormal Distribution*, Cambridge University Press, 1957, pp. 72–75.

[6] It may be worthwhile to indicate why it is reasonable that the development should have followed an S-shaped growth curve. The dependent variable can vary only between 0 and 100 per cent. If we consider the development to be an adjustment process, the simplest reasonable time-path between 0 and 100 per cent is an ogive. While the supply of seed can increase exponentially, the market for seed is limited by the total amount of corn planted, and that will act as a damping factor. Also, if we interpret the behavior of farmers in the face of this new, uncertain development as if they were engaged in sequential decision making, the ASN curve will be bell-shaped, and the cumulative will again be S-shaped. See also H. Hotelling, "Edgeworth's Taxation Paradox and the Nature of Demand and Supply Curves," *Journal of Political Economy*, 40, October, 1932. The argument for the logistic is given by R. Pearl, *Studies in Human Biology*, Baltimore, 1924, 558–583, and S. Kuznets, *Secular Movements in Production and Prices*, Houghton Mifflin, Boston, 1930, 59–69.

The logistic growth curve is defined by $P = K/1 + e^{-(a+bt)}$, where P is the percentage planted with hybrid seed, K the ceiling or equilibrium value, t the time variable, b the rate of growth coefficient, and a the constant of integration which positions the curve on the time scale. Several features of this curve are of interest: It is asymptotic to 0 and K, symmetric around the inflection point, and the first derivative with respect to time is given by $dP/dt = -b/(P/K)(K - P)$.[7] The rate of growth is proportional to the growth already achieved and to the distance from the ceiling. It is this last property that makes the logistic useful in so many diverse fields.[8]

There are several methods of estimating the parameters of the logistic.[9] The method chosen involves the transformation of the logistic into an equation linear in a and b. By dividing both sides of the logistic by $K-P$ and taking the logarithm, we get its linear transform, $\log_e [P/(K-P)] = a + bt$, allowing us to estimate the parameters directly by least squares.[10] The value of K, the ceiling, was estimated crudely by plotting the percentage planted to hybrid seed on logistic graph paper and varying K until the resulting graph approximated a straight line. After adjusting for differences in K, the logistic was fitted to the data covering approximately the transition from 5 to 95 per cent of the ceiling. The observations below 5 and above 95 per cent of the ceiling value were discarded because they are liable to very large percentage errors and would have had very little weight anyway in any reasonable weighting scheme. The period included in the analysis, however, accounts for the bulk of the changes in the data.

The procedure outlined above was used to calculate the parameters of the

[7] For a more detailed description of the logistic and its properties, see Pearl, *op. cit.*

[8] Perhaps the simplest interpretation of the logistic is given by A. Lotka, *Elements of Physical Biology*, Williams and Wilkins, Baltimore, 1925, p. 65. We are interested in the general adjustment function, $dP/dt = F(P)$. Using a Taylor Series approximation and disregarding all the higher terms beyond the quadratic we get a function whose integral is the logistic. The logistic is the integral of the quadratic approximation to the adjustment function.

[9] See Pearl, *op. cit.*; H. T. Davis, *The Theory of Econometrics*, Principia Press, 1941, Chapter II; and G. Tintner, *Econometrics*, John Wiley & Sons, 1952, 208–211, and the literature cited there.

[10] This is a simplification of a method proposed by Joseph Berkson. Berkson's method is equivalent to weighted least squares regression of the same transform with $P(K - P)$ as weights. J. Berkson, "A Statistically Precise and Relatively Simple Method of Estimating the Bioassay with Quantal Response, Based on the Logistic Function," *Journal of the American Statistical Association*, 48 (1953), 565–599, and "Maximum Likelihood and Minimum Chi-square Estimates of the Logistic Function," *loc. cit.*, 50 (1955), 130–162. Berkson proposed this procedure in the context of bio-assay. It is not clear, however, whether the bio-assay model is applicable in our context, nor is it obvious, even in bio-assay, what system of weights is optional. See also J. Berkson, "Estimation by Least Squares and by Maximum Likelihood," *Proceedings of the Third Berkeley Symposium on Mathematical Statistics*, Vol. I, University of California Press, 1–11. Hence no weights were used. In view of the excellent fits obtained, it is doubtful whether alternative weighting systems would have made much difference.

logistic for 31 states and for 132 crop reporting districts within these states.[11] The states used account for almost all of the corn grown in the U.S. (all states except the West and New England). Out of a total of 249 crop reporting districts only those were used for which other data by crop reporting districts were readily available. Districts with negligible amounts of corn and unreliable estimates of hybrid corn acreage were also left out.[12]

The results of these calculations are presented in Tables I and II. Table I summarizes the state results, Table II the results by crop reporting districts. Time is measured from 1940, and $(-2.2-a)/b$ indicates the date at which the function passed through the 10 per cent value. This date will be identified below with the date of *origin* of the development. Several things are noteworthy about these figures: the high r^2's indicate the excellent fits obtained.[13] The b's, representing the slope of the transform or the rate of adjustment, are rather uniform, becoming lower as we move towards the fringes of the Corn Belt. The values of $(-2.2-a)/b$, the dates of *origin,* indicate that the development started in the heart of the Corn Belt and spread, rather regularly, towards its fringes.[14] The ceiling—K—also declines as we move away from the Corn Belt.

In this section we have succeeded in reducing a large mass of data to three sets of variables—*origins, slopes,* and *ceilings.* "Thus on the basis of three numbers we are prepared, in principle, to answer all the questions the original data sheet can answer provided that the questions do not get down to the level of a single cell . . . . . This is saying a great deal."[15]

The economic interpretation of the differences in the estimated coefficients will be developed in the following sections. The values of the different parameters are not necessarily independent of each other, but for simplicity will be considered separately. Variations in the date of origin will be identified with supply factors, variations in slopes with factors affecting the rate of acceptance

[11] Each state is usually divided into nine crop reporting districts numbered in the following fashion:

		N		
	1	2	3	
W	4	5	6	E
	7	8	9	
		S		

[12] It should be noted that the sum of logistics is not usually a logistic. However, the logistic is also valid for an aggregate, as long as the components are similar in their development. See L. J. Reed and R. Pearl, "On the Summation of Logistic Curves," *Journal of the Royal Statistical Society,* 90 (New Series), 1927, 729–746. How good the approximation is in fact is indicated by the results below.

[13] These r^2's should be taken with a grain of salt. They are the r^2's of the transform rather than of the original function and give less weight to the deviations in the center. Also, they do not take into account the excluded extreme values. Nevertheless, an examination of the original data indicates that they are not a figment of the fitting procedure.

[14] *Origin* is measured from 1940. Hence, the *origin* in Iowa is placed approximately in 1936, and in Georgia in 1948.

[15] R. R. Bush and F. Mosteller, *Stochastic Models for Learning,* John Wiley and Sons, New York, 1955, p. 335.

TABLE I

HYBRID CORN LOGISTIC TREND FUNCTIONS BY STATES

States	*Origin* $\frac{-2.2-a}{b}$	*Rate of acceptance* b	*Ceiling* K	r^2
N.Y.	−.89	.36	.95	.99
N.J.	−1.48	.54	.98	.90
Pa.	−1.29	.48	.95	.98
Ohio	−3.35	.69	1.00	.97
Ind.	−3.13	.91	1.00	.99
Ill.	−4.46	.79	1.00	.99
Mich.	−1.44	.68	.90	.98
Wisc.	−3.52	.69	.91	.99
Minn.	−3.06	.79	.94	.99
Iowa	−4.34	1.02	1.00	.99
Mo.	−3.32	.57	.98	.98
N.D.	−.65	.43	.65	.96
S.D.	−.40	.42	.85	.95
Neb.	−.60	.62	.97	.99
Kan.	.42	.45	.94	.97
Del.	.21	.47	.99	.98
Md.	−.73	.55	.98	.97
Va.	1.60	.50	.92	.97
W. Va.	−.23	.39	.85	.98
N.C.	5.14	.35	.80	.89
S.C.	5.72	.43	.60	.96
Ga.	7.92	.50	.80	.99
Fla.	2.89	.38	.90	.93
Ky.	.08	.59	.90	.99
Tenn.	2.65	.34	.80	.97
Ala.	7.84	.51	.80	.99
Miss.	4.75	.36	.60	.98
Ark.	1.46	.41	.78	.99
La.	4.89	.45	.53	.99
Okla.	3.57	.56	.80	.98
Tex.	3.64	.55	.78	.98

Notes: $P = \frac{K}{1+e^{-(a+bt)}}$; $\log_e\left(\frac{P}{K-P}\right) = a + bt$; $t_{1940} = 0$; $N = -6$ to 16; Max $S_b = .06$; *Origin* = Date of 10 per cent $= \frac{-2.2-a}{b}$, measured from 1940, e.g., $-4.0 = 1936$, $+7.0 = 1947$; *Rate of acceptance* = Slope = b; and *Ceiling* = K

by farmers, and variations in ceilings with demand factors affecting the long-run equilibrium position. In each case we shall consider briefly the implicit identification problem.

3. THE SUPPLY OF A NEW TECHNIQUE

There is no unique way of defining the data of *origin* or of "availability." Hybrid corn was not a single development. Various experimental hybrids were tried until superior hybrids emerged. After a while, these were again superseded by newer hybrids. Nor is there a unique way of defining *origin* with respect to growth curve. The logistic is asymptotic to zero; it does not have a "beginning." Nevertheless, it is most important to distinguish between the lag in "availability" and the lag in "acceptance." It does not make sense to blame the Southern farmers for being slow in acceptance, unless one has taken into account the fact that no satisfactory hybrids were available to them before the middle nineteen-forties.

I shall use the date at which an area began to plant 10 per cent of its ceiling acreage with hybrid seed as the date of *origin*.[16] The 10 per cent date was chosen as an indicator that the development had passed the experimental stage and that superior hybrids were available to farmers in commercial quantities. The reasonableness of this definition has been borne out by a survey of yield tests in various states and it has been supported by conversations with various people associated with developments in hybrid corn in the experiment stations and private seed companies.[17]

"Availability" is the result of the behavior of agricultural experiment stations and private seed companies. If we include the growers of station hybrids in the general term "commercial seed producers," then availability is the direct result of the actions of seed producers with the experiment stations affecting it through the provision of free research results and foundation stocks. The activities of the experiment stations serve to reduce the cost of innovation facing the seed producers but the entry decisions are still their own. The date at which adaptable hybrids became available in an area is viewed as the result of seed producers ranking different areas according to the expected profitability of entry and deciding their actions on this basis.[18] The relative profitability of entry into an area will depend on the size of the eventual market in that area, marketing cost, the cost of innovating for that area, and (given a positive rate of interest) the expected rate of acceptance.[19]

It is extremely difficult to define "market size" operationally. The definition

[16] The date at which the fitted logistic passes through 10 per cent is given by $Y = (-2.2 - a)/b$. As the variation of b is small relative to that of a, small changes in the definition of Y will be in the nature of an additive constant and will rarely change the ranking of the data of *origin* in different areas.

[17] This is essentially a definition of "commercial" availability. An attempt was made to measure the date of "technical" availability by going through yield tests and other official publications and noting the first year in which hybrids clearly outyielded the open pollinated varieties. The rank correlation between this technical definition and the "10 per cent" definition was .93. The average lag between the technical and the commercial availability was approximately 2 years. Also, preliminary explorations with 1 and 5 per cent definitions, and with the rank of an area rather than the absolute date, indicated that the results are not very sensitive to changes in definition.

[18] Implicitly, we have assumed here that the lag between the entry decision and actual availability is approximately constant or at least independent of other variables under analysis.

[19] Throughout the paper it is assumed that the price of hybrid seed is given and approximately uniform in different areas. This is a very close approximation to reality and a result of a very elastic long-run supply curve of seed.

TABLE II

HYBRID CORN LOGISTIC TREND FUNCTIONS BY CROP REPORTING DISTRICTS*

State and C. R. District		Origin	Rate of Accept-ance	Ceiling	r^2	State and C. R. District		Origin	Rate of Accept-ance	Ceiling	r^2
Pa.	1	.15	.41	.85	.99	Wisc.	5	−2.54	.61	.90	.98
	2	1.16	.49	.90	.99		6	−3.03	.87	.78	.99
	3	.76	.46	.91	.98		7	−4.16	.89	.98	.99
	4	.44	.47	.92	.99		8	−3.55	.88	.95	.99
	5	.11	.62	.95	.98		9	−3.21	.72	.95	.98
	6	−1.02	.55	.95	.99						
	7	−.63	.40	.90	.98	Minn.	7	−3.08	1.36	1.00	.99
	8	−1.04	.54	.96	.99		8	−3.66	1.14	1.00	.99
	9	−2.35	.60	.98	.97		9	−3.04	1.01	1.00	.99
Ohio	1	−3.22	1.25	1.00	.99	Iowa	1	−4.39	1.01	1.00	.99
	2	−2.73	.99	1.00	.98		2	−4.78	1.05	1.00	.99
	3	−1.77	.75	.95	.98		3	−4.46	1.00	1.00	.99
	4	−3.00	.90	1.00	.98		4	−3.71	1.12	1.00	.99
	5	−3.19	.77	1.00	.98		5	−4.70	1.13	1.00	.99
	6	−3.14	.69	.95	.94		6	−5.15	1.09	1.00	.99
	7	−2.69	.88	1.00	.98		7	−2.74	1.25	1.00	.99
	8	−1.78	.60	.95	.99		8	−3.61	1.07	1.00	.99
	9	−1.80	.73	.95	.97		9	−4.15	1.10	1.00	.99
Ind.	1	−3.82	1.15	1.00	.99	Mo.	1	−1.37	1.19	1.00	.97
	2	−3.60	1.10	1.00	.99		2	−1.33	1.15	1.00	.95
	3	−3.12	1.15	1.00	.99		3	−1.27	1.15	1.00	.96
	4	−3.24	.95	1.00	.99		4	−1.51	.66	.95	.98
	5	−2.85	1.07	1.00	.99		5	−.64	.78	.93	.99
	6	−2.63	1.12	1.00	.99		6	−1.11	.72	.97	.97
	7	−1.67	.87	1.00	.96		7	.16	.46	.90	.99
	8	−1.57	.82	1.00	.98		8	.63	.63	.87	.99
	9	−1.88	.76	1.00	.98		9	−.94	.64	.97	.99
Ill.	1	−4.81	1.13	1.00	.99	N.D.	9	.40	.74	.85	.96
	3	−4.59	.98	1.00	.99						
	4	−4.16	1.08	1.00	.99	S.D.	3	−.53	.57	.90	.99
	4a	−2.65	1.09	1.00	.99		6	−.71	.85	.93	.99
	5	−4.68	1.17	1.00	.99		9	−1.72	.75	.95	.99
	6	−4.25	1.18	1.00	.99						
	6a	−2.46	.91	1.00	.99	Neb.	3	−2.48	.90	1.00	.99
	7	−.81	.64	1.00	.97		5	.36	.82	.93	.99
	9	−.58	.78	1.00	.97		6	−2.18	.85	1.00	.99
							7	2.33	.90	.95	.99
Mich.	7	−1.12	.77	.92	.97		8	1.60	.94	.95	.99
	8	−1.04	.89	.92	.98		9	−.77	.91	1.00	.97
	9	−1.70	.78	.92	.98						
						Kan.	1	2.68	.41	.95	.95
Wisc.	1	−2.17	.81	.85	.99		2	1.52	.66	1.00	.98
	2	−2.22	.97	.70	.99		3	−.88	.72	1.00	.99
	3	−2.42	.93	.60	.99		6	−.88	.68	.92	.99
	4	−3.24	.67	.95	.96		9	.73	.41	.95	.99

TABLE II—*Continued*

State and C. R. District	Origin	Rate of Acceptance	Ceiling	r^2	State and C. R. District	Origin	Rate of Acceptance	Ceiling	r^2
Md. 1	2.92	.37	.97	.94	Ala. 1	7.73	.56	.60	.98
2	−1.12	.64	1.00	.97	2	6.33	.57	.99	.99
8	.88	.48	.98	.98	2a	8.80	.45	.90	.97
9	.40	.60	1.00	.93	3	7.68	.54	.95	.98
					4	7.45	.42	.50	.95
Va. 2	.87	.68	1.00	.99	5	8.08	.49	.70	.95
4	1.51	.61	.98	.93	6	8.15	.39	.60	.95
5	2.37	.68	.95	.99	7	7.84	.58	.85	.97
6	2.06	.63	.97	.96	8	8.24	.45	.70	.97
7	1.21	.29	.80	.85	9	8.53	.55	.90	.99
8	2.18	.40	.85	.90					
9	1.04	.50	.95	.96	Ark. 1	.41	.37	.75	.97
					2	1.98	.40	.82	.98
Ky. 1	.67	.89	.95	.97	3	.68	.50	.85	.99
2	−.42	.72	.98	.99	4	2.24	.42	.77	.94
3	.49	.61	.90	.97	5	1.89	.35	.85	.95
4	−.36	.83	.92	.99	6	1.54	.35	.80	.99
5	−.77	.78	.90	.99	7	1.66	.32	.55	.93
6	1.94	.62	.60	.98	8	2.41	.37	.70	.92
					9	1.88	.33	.85	.99
Tenn. 1	.76	.29	.85	.97					
2	1.88	.33	.55	.99	Okla. 3	2.61	.49	.80	.97
3	2.64	.39	.70	.97	5	3.62	.55	.90	.97
4	2.53	.43	.75	.96	6	3.17	.52	.88	.93
5	3.43	.35	.80	.91	7	4.05	.39	.80	.97
6	2.94	.33	.70	.95	8	4.85	.67	.90	.98
					9	4.08	.52	.75	.95

* I am indebted to the Field Crop Statistics Branch of the Agricultural Marketing Service for the unpublished data by crop reporting districts.

is not independent of marketing cost or of the particular characteristics of the innovation (the area of adaptability of a particular hybrid) and is complicated by the arbitrariness of the political subdivisions used as the geographic units of analysis. The problem of the "right" geographic unit of analysis, however, will be postponed to the end of this section. As an approximation to the size of the market I used the average corn acreage in the area at about the time of the date of entry, adjusted for differences in ceilings. That is, the average corn acreage was multiplied by .9 if that was the estimate of the fraction of the corn acreage which would be ultimately planted with hybrid seed. Because the political subdivisions are of various and sundry sizes, to make them more comparable the adjusted corn acreage was divided by total land in farms. The resulting variable —X_1 = (Average corn acreage) $\times$ $K \div$ Total land in farms—is a measure of "market density" rather than of "market size."[20] If the areas are not too different

[20] Differences in seeding rates have been disregarded here. There is, however, some evidence that the results would have been somewhat better if X_1 were adjusted for these differences.

in size and in the range of adaptability of their hybrids, market density will closely approximate a relevant measure of market size. Also, in its own right, it is important as a measure of marketing cost, the relative cost of selling a given supply of seed in different areas. Under the name of "market potential," such a variable was, in fact, used by at least one major seed company in its decision making process. The importance of a variable of this sort was strongly emphasized, in private conversations, by executives of the major seed companies.

The importance of marketing cost is underscored by the striking differences in marketing methods of hybrid seed in different parts of the country. While almost 90 per cent of all the seed in the Corn Belt is sold by individual salesmen who call on each farmer, almost all of the seed in the South is sold through stores where the farmer must come and get it. The small size of the corn acreage per farm, the relative isolation of the small farm, and the large proportion of corn on noncommercial farms make the type of marketing used in the Corn Belt prohibitively expensive in the South. The cost of selling a given amount of seed is quite different in various parts of the country, as many more farmers have to be reached in one area than in another. As a measure of "average size of sale," I used average corn acres per farm reporting corn, X_3.

The estimated slope coefficient, b, was used as a measure of the expected rate of acceptance in different areas. This assumes that producers were able to predict reasonably well the actual rate of acceptance.

There is no good way of estimating the relative costs of innovation. It is probably true that there are no substantial differences in the cost of developing a hybrid from scratch for any corn growing area of the country and, if there were some, they would be swamped by the large differences in returns. A difficulty arises, however, from the fact that a hybrid may be adaptable in more than one

TABLE III

CORRELATION COEFFICIENTS ON THE STATE LEVEL—N = 31

	X_1	X_3	b	X_4	X_{10}
Y	−.44	−.35	−.62	−.89	.82
X_1		.52	.77	.55	−.39
X_3			.46	.28	−.36
b				.68	−.51
X_4					−.79

Note:

Y = Date of *origin*. The date an area reached 10 per cent, computed. See Tables I and II.

X_1 = Market density. For states: average corn acreage 1937–46 times K, divided by land in farms in 1945. Similar for crop reporting districts but averaged over different periods, depending on the availability of data. Source: *Agricultural Statistics, Census of Agriculture*, and published and unpublished materials from state agricultural statisticians.

X_3 = For states, average corn acres per farm, 1939. Source: *Census of Agriculture*. By crop reporting districts: the same average corn acreage as in X_1, divided by the 1939 or 1945 census number of farms reporting corn, depending on availability of data.

b = The slope of the logistic transform, computed.

X_4 = "Corn Beltliness." The proportion of all inbred lines accounted by "Corn Belt" lines in the pedigrees of recommended hybrids by areas. Source: C. B. Henderson, "Inbred Lines of Corn Released to Private Growers from State and Federal Agencies and Double Crosses Recommended by States," 2nd revision, Illinois Seed Producers Association, Champaign, April 15, 1956; and unpublished data from the Funk Bros. Seed Co., Bloomington, Ill.

X_{10} = Earliest date of origin in the immediate neighborhood.

area, allowing the cost of innovation to be spread over several areas, and because the experiment stations have borne a substantial part of the innovation cost by developing and releasing inbred lines and whole hybrids. That is, the actual cost of innovating for an area will depend on whether or not hybrids which have already been developed for other areas prove adaptable in this area, and on whether or not the experiment stations have produced and released inbred lines or hybrids adaptable to this area.

Since most of the early research was done for the area known as the "Corn Belt," other areas benefitted from the availability of these research results to a varying degree, depending on the adaptability of Corn Belt inbred lines to those areas. A measure of the degree to which other areas are different from the Corn Belt with respect to the adaptability of Corn Belt lines can be approximated by taking the published pedigrees of the recommended hybrids in different areas in 1956 and computing the percentage of all inbred lines represented by "Corn Belt" lines. An index of "Corn Beltliness," X_4, was defined as the number of Corn Belt inbred lines in the pedigrees of the recommended hybrids for that area, divided by the total number of lines.[21]

To take other aspects of the "complementarity" problem into account, another variable, X_{10}, was defined as the earliest date of entry (*origin*) in the immediate (contiguous) neighborhood of the area under consideration.[22] X_{10} was introduced on the assumption that it may be cheaper, both from the point of view of the additional research needed and from the point of view of setting up a marketing organization, to enter an area contiguous to an area already entered even though the "market potential" there may be lower than in some other area farther away.

Using either the number of released inbred lines or hybrids or the reported research expenditures, several unsuccessful attempts were made to measure the relative contribution of the various experiment stations. To some extent, however, the impact of this variable is already accounted for by our measures of the "market." The contribution of the various experiment stations is strongly related to the importance of corn in the area. In the "good" corn areas the stations did a lot of work on hybrids and in the marginal areas, less.[23]

The simple correlation coefficients between these variables, on the state level and on the crop reporting district level, are presented in Tables III and IV respectively. All of the correlation coefficients with Y have the expected sign and

[21] On the state level, a published list of recommended hybrids and their pedigrees was used, with Iowa, Illinois, Indiana, Ohio, and Wisconsin lines defined as "Corn Belt" lines. See C. B. Henderson, "Inbred Lines of Corn Released to Private Growers from State and Federal Agencies and Double Crosses Recommended by States," Second Revision, Illinois Seed Producers Association, Champaign, April 15, 1956. On the crop reporting district level, I used unpublished data from the Funk Bros. Seed Co., listing their hybrids by "maturity groups" and giving coded pedigrees.

[22] This is analogous to the introduction of a lagged value of the dependent variable into the regression in time series analysis. Except that the "lag" here is spatial rather than a time lag.

[23] There are a few exceptions to this statement. In the North, Connecticut, Wisconsin, and Minnesota contributed more than their "share," and so did Texas and Louisiana in the South.

TABLE IV

CORRELATION COEFFICIENTS ON THE CROP REPORTING DISTRICT LEVEL—N = 132

	X_1	X_3	b	X_4	X_{10}
Y	−.56	−.35	−.70	−.73	.95
X_1		.69	.73	.57	−.57
X_3			.54	.40	−.36
b				.67	−.73
X_4					−.76

See *Note* at bottom of Table III.

most of them are also significantly different from zero. The inter-correlation among the independent variables, however, prevents us from successfully estimating their separate contributions from these data. Almost all sets and subsets of independent variables in these tables were tried without yielding more than one significant coefficient in each multiple regression.[24] These results are disappointing, particularly because the highest correlations are with the rather artificial variables X_4 ("Corn Beltliness") and X_{10} (the "spatial trend").[25] Hence, another approach to the problem was sought.

The trouble with the above approach is that it does nothing about the problem of the "right" geographic unit of analysis. Considering only the "market density" variable, it is obvious that it does not always measure what we want. Markets are continuous. While some areas are poor by themselves they may be a part of a larger market. Also an area may be entered because it is a springboard to other areas rather than on its own grounds. One way of taking these considerations into account is to define the "market potential" of an area as a weighted average of the "market densities" in *all* areas, densities in other areas weighted inversely to the distance from the area under consideration.[26] Given more than a few areas, however, the calculation of such a variable becomes impracticable.[27]

[24] Similar results were obtained when the logarithms rather than the actual values of the independent variables were used.

[25] The good performance of X_{10} is not surprising. The smaller the geographic unit of analysis, the better will be the relationship between Y and X_{10}. This can be seen by comparing the correlation coefficients on the state and crop reporting district levels. There is, however, another way of rationalizing the performance of X_{10}. See footnote 27.

[26] See W. Warnz, "Measuring Spatial Association with Special Consideration of the Case of Market Orientation of Production," *Journal of the American Statistical Association*, 51, December 1956, 597–604.

[27] It does suggest, though, a reason for the good performance of X_{10}. Consider a simple model in which the date of origin is a function of the "true" market measure, the "true" measure being a weighted average of the densities in all areas, weights declining with distance. This "true" measure can be approximated by the actual density in the area and the "true" measure in the immediate neighborhood. But the date of origin in the immediate neighborhood is a function of the "true" density there and can serve as its measure. This implies that X_{10} is another measure of the "market!" For a similar approach in a different context, see M. Nerlove, "Estimates of the Elasticities of Supply of Selected Agricultural Commodities," *Journal of Farm Economics*, 38, May 1956, 500–503.

The trouble with our geographic units arises because states are too large while crop reporting districts are too small and neither corresponds either to technical regions of adaptation of particular hybrids nor to the decision units of the private seed companies. It is possible, however, to ask a more modest question: What were the characteristics of the areas entered in a particular year as compared with the characteristics of areas entered in another year? It is possible to aggregate areas according to the year of entry and test the "market potential" hypothesis on these aggregates. I shall define areas according to the year of entry, i.e., all districts with the *origin* in 1939 will make up one such area, and aggregate the data by crop reporting districts into such areas. Given our "10 per cent" definition of *origin*, we have 16 such areas, 1935 to 1950. Alternatively, we would like to define areas according to the adaptability of particular hybrids. However, most hybrids overlap geographically and there are almost no data on the geographical distribution of particular hybrids, but there are breakdowns of the country into "maturity regions." A major seed company breaks down the U.S. and its line of hybrids into 11 "maturity groups," locating the areas of adaptation of these groups on a map. It is possible to aggregate the crop reporting districts into these "technical" regions and ask whether high market areas were entered earlier than others.

The results of these calculations are presented in Table V-A. In the aggregation by year of origin, to simplify the calculations, the actual "10 per cent or more" year rather than the calculated date from the logistic was used. For the technical regions the computed origins by districts were used, weighted by the average corn acreage in the district and adjusted for differences in ceilings. That is, aggregate $Y = \Sigma Y\,A\,K/\Sigma\,A\,K$, where A stands for average corn acres. Aggregate X_1 was defined as $\Sigma\,A\,K/\Sigma\,L$, where L stands for total land in farms. Because

TABLE V-A

Correlation Coefficients between the Aggregates of Y, X_1, X_4 and X_{10}

Aggregation by	X_1	X_4	X_{10}
"Date of Origin": All areas $N = 16$			
Y	−.82	−.98	.95
X_1		.82	−.64
X_4			−.93
"Date of Origin": All areas except the Southeast $N = 13$			
Y	−.94	−.97	.96
X_1		.90	−.86
X_4			−.97
"Technical Regions": $N = 12$			
Y	−.69	−.82	.95
X_1		.90	−.59
X_4			−.78

of the simplicity of the computations involved in this particular approach, 90 more crop reporting districts were added at this point to the analysis, raising the number of included districts to 222. Where separate logistic curves were not computed, Y was estimated by linear interpolation. As the technical regions overlap, each of the aggregates includes a few districts also included in the neighboring aggregates.[28]

To make the results comparable with those presented in Table IV, similar calculations were also performed on X_4 and X_{10}. For the aggregation procedure by "date of origin," X_{10} was defined as the earliest date of origin in the immediate neighborhood of the area defined by the procedure, and X_4 as a simple unweighted average for the districts included in the aggregate. For the aggregation by "technical regions," X_{10} was defined as the lowest weighted average date of origin among the neighboring "technical regions." No aggregation had to be performed on X_4, as it had been originally defined and computed for these regions.

The results presented in Table V-A indicate a strong association between the date of *origin* and average market density in the area, and suggesting that the market density variable is much more important than is indicated by the results in Tables III and IV. The association is higher if we exclude the Southeast from the aggregation procedure. This is explained by the relative lateness of the research contributions of the southeastern experiment stations and by the various obstacles put in the way of private seed companies there. Also, after we come down to a certain low level, it does not really pay to discriminate between areas on the basis of X_1 because the differences are too small, and other factors predominate. This is brought out when we ask the same question about the association of Y with X_1 within each technical region separately. When regressions of Y on log X_1 were computed for each of the technical regions separately, 9 had the expected sign and were significantly different from zero, while the other 3 were not significantly different from zero. This result is significant on a sign test alone. But more interestingly, the r^2's were .66 rank correlated with the mean value of X_1, indicating that the explanatory power of this variable declined for areas with low average X_1 values.

The aggregation procedure, besides indicating that X_1 is a better variable than is implied by Tables III and IV, also helps us with the collinearity problem. Before aggregation, the partial correlation coefficient of Y with X_1, holding X_{10} constant, was $-.24$ on the state level and only $-.08$ on the crop reporting district level. Now it becomes $-.90$ for the aggregates by date of origin, $-.84$ when we leave out the Southeast, and $-.64$ for the data by technical regions. The regressions of Y on X_1 and X_{10} are presented in Table V-B. The coefficient of X_1 has the expected sign and is significantly different from zero for the aggregates by "date of origin" and is almost twice the size of its standard error for the aggregates by technical region. This indicates that it is possible to separate the contributions of X_1 and X_{10} if we define our area units correctly.

[28] Because one of the "maturity" areas is much larger than the others, it was divided into two on a north-south basis. Hence, we have 12 technical regions in our analysis.

TABLE V-B
REGRESSIONS OF Y ON X_1 AND X_{10}

Aggregation by	Coefficients of		R^2
	X_1	X_{10}	
"Date of Origin": All areas	−17.8 (2.5)	1.02 (.07)	.982
"Date of Origin": All areas except the Southeast	−16.5 (3.4)	1.03 (.07)	.077
"Technical Region":	−10.5 (5.6)	.88 (.12)	.925

Note: Figures in parentheses are the calculated standard errors.

While these results may not be too conclusive, together with information gathered in conversations with executives in the industry and a graphical survey of the data, they leave little doubt in my mind that the development of hybrid corn was largely guided by expected pay-off, "better" areas being entered first, even though it may be difficult to measure very well the variables entering into these calculations.

4. THE RATE OF ACCEPTANCE

Differences in the *slope* or adjustment coefficient b will be interpreted as differences in the rate of adjustment of demand to the new equilibrium, and will be explained by variables operating on the demand side rather than by variables operating on the supply side.[29] Actually, the path traced out is an intersection of short-run supply and demand curves. It is assumed, however, that while shifts on the supply side determine the origin of the development, the rate of development is largely a demand, or "acceptance," variable.[30] The usefulness of this assumption is due to a very elastic long-run supply of seed and is supported by

[29] The dimension of b, the adjustment coefficient, may be of some interest. b indicates by how much the value of the logistic transform will change per time unit. A value of $b = 1.0$ implies that the development will go from, e.g., 12 to 27 to 50 to 73 to 88 per cent from year to year; i.e., the distance from 12 to 88 per cent will be covered in 4 years. A value of $b = 0.5$ would imply a path: 12, 18, 27, 38, 50, 62, 73, 82, 88, etc., i.e., it would take twice the time 8 years, to transverse the same distance. If one thinks in terms of the cumulative normal distribution positioned on a time scale, which is very similar to the logistic, then b is approximately proportional to $1/\sigma$. A low standard deviation implies that it will take a short time to go from, e.g., 10 to 90 per cent, while a higher standard deviation implies a longer period of adjustment.

[30] Implicitly, we have the following model: the potential adjustment path of supply is an exponential function, which after a few years rises quickly above the potential adjustment function of demand. The demand adjustment function has the form of the logistic. The actual path followed is the lower of the two, which, after the first few years, is the demand path.

the fact that only local and transitory seed shortages were observed. On the whole, the supply of seed was not the limiting factor.[31]

Differences in the rate of acceptance of hybrid corn, the differences in b, are due at least in part to differences in the profitability of the changeover from open pollinated to hybrid seed. This hypothesis is based on the general idea that the larger the stimulus the faster is the rate of adjustment to it.[32] Also, in a world of imperfect knowledge, it takes time to realize that things have in fact changed. The larger the shift the faster will entrepreneurs become aware of it, "find it out," and hence they will react more quickly to larger shifts.[33]

My hypothesis is that the rate of acceptance is a function of the profitability of the shift, both per acre and total. Per acre profitability may be defined as the increase in yield due to the use of hybrid seed, times the price of corn, and minus the difference in the cost of seed. As there is very little relevant cross-sectional variation in the price of corn, the seeding rate, or the price of seed, these will be disregarded and only differences in the superiority of hybrids over open-pollinated varieties taken into account.[34]

I shall use two measures of the superiority of hybrids over open pollinated varieties: (1) the average increase in yield in bushels per acre, based on unpublished mail questionnaire data collected by the Agricultural Marketing Service, X_7, and (2) the long-run average pre-hybrid yield of corn, X_8. The latter measure was used on the basis of the widespread belief that the superiority of hybrids can be adequately summarized as a percentage increase.[35] A variation in pre-hybrid yields, given a percentage increase, will also imply a variation in the absolute superiority of hybrids over open pollinated varieties. Twenty per

[31] "Clearly it would have been physically impossible for a large percentage of operators to have planted hybrids in the early thirties. There simply was not enough seed. It seems likely, however, that this operated more as a potential than an actual limitation upon the will of the operator, and that rapidity of adoption approximated the rate at which farmers decided favorably upon the new technique." B. Ryan, "A Study in Technological Diffusion," *Rural Sociology*, 13, 1948, p. 273. Similar views were expressed to the author by various people closely associated with the developments in hybrid corn.

[32] E. g., "The greater the efficiency of the new technology in producing returns, . . . the greater its rate of acceptance."—"How Farm People Accept New Ideas," Special Report No. 15, Agricultural Extension Service, Iowa State College, Ames, November, 1955, p. 6.

[33] This is analogous to the situation in Sequential Analysis. The ASN (average sample number) is an inverse function of, among other things, the difference between the population means. That is, the larger the difference between the two things which we are testing, the sooner we will accumulate enough evidence to convince us that there is a difference. See A. Wald, *Sequential Analysis*, John Wiley & Sons, New York, 1947.

[34] The apparent cross-sectional variation in the average price of hybrid seed is largely due to differences in the mix of "public" versus "private" hybrids bought by farmers. The "public" hybrids sell for about $2.00 less per bushel. The rank correlation between the price of hybrid seed and the estimated share of "private" hybrids in 1956 was .73.

[35] The data from experiment station yield tests indicate that this is not too bad an assumption. See Sprague, *op. cit.*, and the literature cited there. It is unfortunate that these data are not comparable between states and, hence, cannot be used directly in this study.

cent is the figure quoted most often for this superiority.[36] Average corn acres per farm, X_3, were used to add the impact of total profits per farm.

As the value of b depends strongly on the ceiling K, to make them comparable between areas, the b's had to be adjusted for differences in K. Instead of b, $b' = bK$ was used as the dependent variable, translating the b's back into actual percentage units from percentage of ceiling units. Alternatively, one should have adjusted the independent variables to correspond only to that fraction of the acres which will eventually shift to hybrids. But there are no data for making such an adjustment; hence b was adjusted to imply the same actual percentage changes in different areas.[37]

Linear and log regressions were calculated for the data from 31 states and 132 crop reporting districts. The results are presented in Table VI.[38] The figures speak largely for themselves, indicating the suprisingly good and uniform results obtained. The log form and X_8 rather than X_7 did somewhat better but not significantly so. The similarity of the coefficients in comparable regression is striking. For example, compare the coefficients of X_8 and X_7 in the log regressions and all the coefficients in the similar regressions on the state and crop reporting district levels. These results were also similar to those obtained in preliminary analyses using b rather than b' as the dependent variable [39] (see Table VII).

An attempt was made to incorporate several additional variables into the analysis. Rural sociologists have suggested that socioeconomic status or level-of-living is an important determinant of the rate of acceptance of a new technique.[40] The United States Department of Agriculture level-of-living index for 1939,

[36] "If an average percentage increase in yield to be expected by planting hybrids as compared to open pollinated varieties were to be computed at the present it would probab y be near 20 per cent. . . ." —J. T. Swartz, "A Study of Hybrid Corn Yields as Compared to Open Pollinated Varieties," Insurance Section, FCIC, Washington, April and May, 1942, unpublished manuscript.

"Experience in other corn-growing regions of the United States shows that increases of approximately 20 per cent over the open pollinated varieties may be expected from the use of adapted hybrids. Results so far in Texas are in general agreement with this figure," J. S. Rogers and J. W. Collier, "Corn Production in Texas," Texas Agricultural Experiment Station, Bulletin 746, February 1952, p. 7.

"Plant breeders conservatively estimate increase in yields of 15 to 20 per cent from using hybrid seed under field conditions. They expect about the same relative increases in both ow—and high—yielding areas," USDA, *Technology of the Farm*, Washington, 1940, p. 2.2

[37] This adjustment affects our results very little. See Table VII, below.

[38] X_7 was not used on the state level because it was felt that the aggregation error would be too large. We want an average of differences while I could only get a difference between averages. For some states this difference exceeded the individual differences in all the crop reporting districts within the state.

[39] These were calculated for subsamples of 65 and 32 crop reporting districts.

[40] See "How Farm People Accept New Ideas," *op. cit.*, and E. A. Wilkening, "The Acceptance of Certain Agricultural Programs and Practices in a Piedmont Community of North Carolina," unpublished Ph.D. thesis, University of Chicago, 1949, and "Acceptance of Improved Farm Practices in Three Coastal Plain Counties," Tech. Bull. No. 98, North Carolina Agricultural Experiment Station, May 1952.

TABLE VI
REGRESSIONS OF *SLOPES* ON "PROFITABILITY" VARIABLES

Regression	Coefficients of			
	X_3	X_7	X_8	R^2
By states—N = 31:				
$b' = c_0 + c_3X_3 + c_8X_8$	.006		.017	.66
	(.002)		(.005)	
$\log b' = c_0 + c_3 \log X_3$	.30		.66	.67
$+ c_8 \log X_8$	(.08)		(.11)	
By crop reporting districts—N = 132:				
$b' = c_0 + c_3X_3 + c_7X_7$	.0073	.079		.57
	(.0008)	(.009)		
$b' = c_0 + c_3X_3 + c_8X_8$	.0076		.016	.61
	(.0007)		(.002)	
$\log b' = c_0 + c_3 \log X_3$	.44	.70		.61
$+ c_7 \log X_7$	(.04)	(.09)		
$\log b' = c_0 + c_3 \log X_3$	.44		.57	.69
$+ c_8 \log X_8$	(.03)		(.05)	

Notes:
Figures in parentheses are the calculated standard errors.
X_3—Average corn acres per farm reporting corn.
X_7—The average difference between hybrid and open pollinated yields by districts tabulated only from reports showing both and averaged over 4 to 10 years, depending on the overlap of the available data with the adjustment period (10 to 90 per cent). Based on unpublished AMS "Identicals" data.
X_8—Pre-hybrid average yield. Usually an average for the 10 years before an area reached 10 per cent in hybrids. Sometimes fewer years were used, depending on the available data. Source: for states, *Agricultural Statistics*; for crop reporting districts, various published and unpublished data from the AMS and from state agricultural statisticians.

TABLE VII
REGRESSIONS OF UNADJUSTED *SLOPES* ON "PROFITABILITY" VARIABLES

Regression	Coefficients of			
	X_3	X_7	X_8	R^2
$b = c_0 + c_3X_3 + c_7X_7$	.005	.06		.40
$(N = 65)$	(.001)	(.01)		
$b = c_0 + c_3X_3 + c_8X_8$	.005		.022	.75
$(N = 32)$	(.001)		(.002)	

when added to the regressions by states, had a negative coefficient in the linear form and a positive coefficient in the logarithmic form. In neither case was the coefficient significantly different from zero.

A measure of the "importance" of corn—the value of corn as a percentage of the value of all crops—was added in the belief that the rate of acceptance may be affected by the relative importance of corn within the farmer's enterprise. However, its coefficient was not significantly different from zero. Nor was the coefficient of total capital per farm significantly different from zero. The latter variable was introduced in an attempt to measure the impact of "capital rationing." [41]

The rate of acceptance may be also affected by the "advertising" activities of the extension agencies and private seed companies. There are no data, however, which would enable us to take this into account. There is also some evidence that the estimated rate of acceptance will be affected by the degree of aggregation and the heterogeneity of the aggregate. Heterogeneous areas imply different component growth curves and hence a lower aggregate slope coefficient. This is exhibited by the lower state values for b as compared to the values for the individual crop reporting districts within these states. No way has been found, however, to introduce this factor into the analysis.

Nevertheless, our results do suggest that a substantial proportion of the variation in the rate of acceptance of hybrid corn is explainable by differences in the profitability of the shift to hybrids in different parts of the country.

5. THE EQUILIBRIUM LEVEL OF USE

I am interpreting the *ceilings* as the long-run equilibrium percentages of the corn acreage which will be planted to hybrid seed. Differences in the percentage at which the use of hybrid seed will stabilize are the result of long-run demand factors. It is assumed that in the long run the supply conditions of seed are the same to all areas, the same percentage increase in yield over open pollinated varieties at the same relative price. However, this same technical superiority may mean different things in different parts of the country.

The ceiling is a function of some of the same variables which determine b, the rate of acceptance. It is a function of average profitability and of the distribution of this profitability. With the average above a certain value no farmer will be faced with zero or negative profitability of the shift to hybrids. With the average profitability below this level some farmers will be facing negative returns and hence will not switch to hybrids. In marginal corn areas, however, "average profitability" may become a very poor measure. Its components lose their connection with the concepts they purport to represent. Yield variability may overshadow the average increase from hybrids. The relevance of the published price of corn diminishes. In many marginal corn areas there is almost no market for corn off the farm. The only outlet for increased production is as an input in another production or consumption process on the farm. But on farms on which corn is a marginal enterprise, with little or no commercial livestock production, the use of corn is limited to human consumption, feed for draft animals, a cow and a few chickens. The farmer is interested in producing a certain amount of corn to fill his needs, having no use for additional corn. It will pay him to switch to hybrid corn only if he has alternative uses for the released land and other resources which would return him more than the extra cost of seed. But in many

[41] The failure of the last two variables is due largely to their strong intercorrelation with the included variables. "Importance" is highly correlated with average yield and capital with corn acres per farm. When used separately, these two variables did as well on the state level as yield and corn acres per farm.

of these areas corn is already on the poorest land and uses resources left over from other operations on the farm. Also, there may already be substantial amounts of idle land in the area. All these factors may tend to make hybrids unprofitable although they are "technically" superior. Similarly, in areas where capital rationing is important the recorded market rate of interest will be a poor measure of the opportunity costs of capital. While the returns to hybrid corn may be substantial, if corn is not a major crop, the returns to additional investments in other branches of the enterprise may be even higher.

Ceilings are not necessarily constant over time. Even without any apparent change in the profitability of the shift from open pollinated to hybrid corn, a change in the relative profitability of corn growing, an improvement in the functioning of the market for corn, or an increase in storage facilities may change them. Also, in areas where there are large year-to-year changes in the corn acreage, the percentage planted to hybrid seed may fluctuate as a result of the differential exit and entry in and out of corn of farmers using hybrid or open pollinated seed. These changes may occur without any "real" changes in the relative profitability of hybrids or in farmers' attitudes towards them. It is very difficult to deal statistically with a development composed of a series of adjustments to shifting equilibrium values.[42] As a first approximation I shall ignore this problem. Only in the marginal corn areas is this a problem of some importance. For most of the Corn Belt the assumption of an immediate ceiling of 100 per cent is tenable. In the fringe areas ceiling values somewhat lower than 100 per cent fit very well. There are some indications that in the South ceilings may have shifted over time, but I doubt that this is important enough to bias seriously our results.

In spite of all these reservations and the crudeness with which the ceilings were estimated in the first place, it is possible to explain a respectable proportion of their variation with the same "profitability" variables that were used in the analysis of *slopes*. Because there is a ceiling of 1.00 to the possible variation in K, the logistic function was used again, giving us logit $K = \log_e [K/(1 - K)]$ as our dependent variable. As there were a substantial number of areas with $K = 1.0$, a value not defined for the transform, two approximations were used. On the state level all values of $K = 1.0$ were set equal to .99, while on the crop reporting level, where there was no problem of degrees of freedom, these values were left out of the analysis. X_3, average corn acres per farm, and X_8, pre-hybrid yield, were used as "profitability" measures, and X_{11}, capital per farm, was added to take "capital rationing" into account. The results of these calculations are presented in Table VIII. They indicate that differences in measures of average profitability, differences in average corn acres and pre-hybrid yields, can explain a substantial proportion of the variation in *ceilings*, the long-run equilibrium level of hybrid seed use. The proportion of the variation explained on the state

[42] I am aware of only one attempt in the literature to deal with this kind of problem. See C. F. Roos and V. von Szelisky, "Factors Governing Changes in Domestic Automobile Demand," particularly the section on "The Concept of a Variable Maximum Ownership Level," pp. 36–38, in General Motors Corporation, *Dynamics of Automobile Demand*, New York, 1939.

TABLE VIII

REGRESSIONS OF LOGIT K ON "PROFITABILITY" VARIABLES

Regression	Coefficients of X_3	X_8	X_{11}	R^2
By states—N = 31:				
$c_0 + c_3X_3 + c_8X_8$	.03	.11		.71
	(.01)	(.02)		
$c_0 + c_3 \log X_3 + c_8 \log X_8$	1.94	5.88		.71
	(.56)	(.80)		
$+ c_{11} \log X_{11}$	1.55	5.25	.71	.72
	(.84)	(1.30)	(1.14)	
By crop reporting districts— N = 86:				
$c_0 + c_3 \log X_3 + c_8 \log X_8$	1.09	2.22	1.35	.39
$+ c_{11} \log X_{11}$	(.48)	(.61)	(.64)	

Notes:

Figures in parentheses are the calculated standard errors.

X_3—Average corn acres per farm.

X_8—Pre-hybrid yield.

X_{11}—On the state level, value of land and buildings per farm, 1940. Source: *Statistical Abstract of the United States, 1948*, p. 600. On the crop reporting district level, total capital investment per farm, 1949. Computed from Table 11, E. G. Strand and E. O. Heady, "Productivity of Resources Used on Commercial Farms," USDA, Technical Bulletin No. 1128, Washington, November 1955, p. 45.

level is substantially higher, indicating that additional variables which may be at work at the crop reporting district level may cancel out at the state level. For example, the coefficient of capital investment per farm, a measure of "capital rationing," is significant at the crop reporting district level but not at the state level. Undoubtedly this analysis could be improved by the addition of other variables but I would not expect it to change the major conclusion appreciably.

6. LIMITATIONS, SUMMARY, AND CONCLUSIONS

The above analysis does not purport to present a complete model of the process of technological change. Rather the approach has been to break down the problem into manageable units and to analyze them more or less separately. I have concentrated on the longer-run aspects of technological change, interpreting differences in the pattern of development of hybrid corn on the basis of the long-run characteristics of various areas, and ignoring the impact of short-run fluctuations in prices and incomes. This limitation is not very important in the cases of hybrid corn because the returns from the changeover were large enough to swamp any short-run fluctuations in prices and other variables.[43] It might, however, become serious were we to consider other technical changes requiring substantial investments, and not as superior to their predecessors as was hybrid corn. Nor can we transfer the particular numerical results to the consideration of other developments. Nevertheless, a cursory survey of trends in the number of cornpickers and tractors on farms, and of trends in the use of fertilizer, does

[43] Estimates made for Kansas data indicate returns from 300 to 1000 per cent on the extra cost of seed.

indicate that it might also be possible to apply a version of our approach to their analysis.

I hope that this work does indicate that at least the process of innovation, the process of adapting and distributing a particular invention to different markets and its acceptance by entrepreneurs, is amenable to economic analysis. It is possible to account for a large share of the spatial and chronological differences in the use of hybrid corn with the help of "economic" variables. The lag in the development of adaptable hybrids for particular areas and the lag in the entry of seed producers into these areas can be explained on the basis of varying profitability of entry. Also, differences in both the long-run equilibrium use of hybrids and in the rate of approach to that equilibrium level are explainable, at least in part, by differences in the profitability of the shift from open pollinated to hybrid varieties.

Looking at the hybrid seed industry as a part of the specialized sector which provides us with technological change, it can be said that both private and public funds were allocated efficiently within that sector.[44] Given a limited set of resources, the hybrid seed industry expanded according to a pattern which made sense, allocating its resources first to the areas of highest returns.

The American farmer appears also to have adjusted rationally to these new developments. Where the profits from the innovation were large and clear cut, the changeover was very rapid. It took Iowa farmers only four years to go from 10 to 90 per cent of their corn acreage in hybrid corn. In areas where the profitability was lower, the adjustment was also slower. On the whole, taking account of uncertainty and the fact that the spread of knowledge is not instantaneous, farmers have behaved in a fashion consistent with the idea of profit maximization. Where the evidence appears to indicate the contrary, I would predict that a closer examination of the relevant economic variables will show that the change was not as profitable as it appeared to be.[45]

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[44] Some minor quibbles could be raised about the allocation of public funds, but the returns to these funds have been so high that the impact of the existing inefficiencies is almost imperceptible.

[45] In this context one may say a few words about the impact of "sociological" variables. It is my belief that in the long run, and cross-sectionally, these variables tend to cancel themselves out, leaving the economic variables as the major determinants of the pattern of technological change. This does not imply that the "sociological" variables are not important if one wants to know which *individual* will be first or last to adopt a particular technique, only that these factors do not vary widely cross-sectionally. Partly this is a question of semantics. With a little ingenuity, I am sure that I can redefine 90 per cent of the "sociological" variables as economic variables. Also, some of the variables I used, e.g., yield of corn and corn acres per farm, will be very highly related cross-sectionally to education, socio-economic status, level-of-living, income, and other "sociological" variables. That is, it is very difficult to discriminate between the assertion that hybrids were accepted slowly because it was a "poor corn area" and the assertion that the slow acceptance was due to "poor people." Poor people and poor corn are very closely correlated in the U.S. Nevertheless, one may find a few areas where this is not so. Obviously, the slow acceptance of hybrids on the western fringes of the Corn Belt, in western Kansas, Nebraska, South Dakota, and North Dakota was not due to poor people, but the result of "economic" factors, poor corn area.