The Impact of the 1936 Corn-Belt Drought on American Farmers' Adoption of Hybrid Corn

Richard Sutch

University of California, Riverside
and the
National Bureau of Economic Research

Draft of January 6, 2010

ABSTRACT

The severe drought in 1936 revealed an advantage of hybrid corn not previously recognized – its drought tolerance. This revealed ecological resilience motivated some farmers to adopt hybrids despite their commercial unattractiveness in normal years. That response to climate change had a tipping effect. The increase in sales of hybrid seed in 1937 and 1938 financed research at private seed companies that led to new varieties with significantly improved yields in normal years. This development provided the economic incentive for late adopters to follow suit. Because post-1936 hybrid varieties conferred advantages beyond improved drought resistance, the negative ecological impact of the devastating 1936 drought had the surprising, but beneficial, consequence of moving more farmers to superior corn seed selection.

Thanks to Vilma Helena Sielawa Ferreira, Connie Chow, and Hiroko Inoue for research assistance, to Susan B. Carter for critical advice, and to Norman Ellstrand for assistance with the plant biology. Comments by Paul David, Bronwyn Hall, Gary Libecap, Michael Roberts, Paul Rhode, Hugh Rockoff, Richard Steckel, and Gavin Wright on earlier drafts are gratefully acknowledged. Parts of this chapter were previously released as a National Bureau of Economic Research *Working Paper* Number 14141 [Sutch 2008]. Financial support was provided by a National Science Foundation Grant: "Biocomplexity in the Environment, Dynamics of Coupled Natural and Human Systems." Administrative support was provided by the Biotechnology Impacts Center and the Center for Economic and Social Policy at the University of California, Riverside.

A severe and sustained drought struck central North America during the 1930s. Centered on eastern Kansas, it extended north into the Canadian prairies, east to the Illinois-Indiana boarder, south to the Gulf of Mexico, and west into Montana and Idaho. See Figure 1. The seven-year period of low rainfall and high temperatures, 1932-1938, was unprecedented in the memory of the Euro-Americans who inhabited the region in its extent, severity, and duration. It has been described by climate scientists as "one of the most severe environmental catastrophes in U.S. history" [Schubert et al, 2004: 1855]. The period is best remembered for the "Dust Bowl" conditions created on the panhandles of Texas and Oklahoma, and adjacent parts of New Mexico, Colorado, and Kansas.[1]

My interest in this paper is – not with the Dust Bowl – but with the Corn Belt that lies to the northeast of the Dust Bowl. Figure 1 also displays the outline of the Corn Belt on the drought map. As can be seen, the eastern portion of the Corn Belt (western Ohio, and Indiana) was largely outside the region struck by the severe drought. By contrast the western Corn Belt (southwest Minnesota, western Iowa, southeast South Dakota, and eastern Nebraska) was hard hit. This geographical contrast will allow me to explore the adaptations made by corn farmers to sudden climate change. The lens through which I will look is the adoption of hybrid corn in the 1930s.

The suggestion that I make in this chapter is that the severe drought of 1936 revealed an advantage of hybrid corn not previously recognized – its drought tolerance. This ecological resilience motivated some farmers to adopt hybrids despite their commercial unattractiveness in normal years. But that response to climate change had a tipping effect. The increase in sales of hybrid seed in 1937 and 1938 financed research at

[1] The Dust Bowl is not synonymous with the drought area. The Dust Bowl had a naturally semi-arid climate and was settled during an untypical period of favorable climatic conditions. The first farmers imposed a "system of agriculture to which the Plains are not adapted to bring into a semi arid region methods which, on the whole, are suitable only for a humid region." Arid conditions returned with the North American precipitation anomaly of the 1930s. For more detail see the *Report* of the President's Great Plains Drought Area Committee [August 27, 1936], Libecap and Hansen [2004], and Hornbeck [2009].

private seed companies that led to new varieties with significantly improved yields in *normal* years. This development provided the economic incentive for late adopters to follow suit. Because post-1936 hybrid varieties conferred advantages beyond improved drought resistance, the negative ecological impact of the devastating 1936 drought had the surprising, but beneficial, consequence of moving more farmers to superior corn seed selection sooner than they might otherwise.

There is no doubt that the drought decimated corn crops in 1934 and 1936. One index of the impact is the fraction harvested of each year's acreage planted to corn. When the damage to the crop is extensive, it is not worthwhile to attempt a harvest. If the damage is total, there is no crop to harvest. Figure 2 presents the percentage of the corn acreage planted that was harvested in the state of Iowa for the years 1926 to 1950. The two years 1934 and 1936 stand out as quite depressed. Figure 3 displays the data for Illinois (top panel), a state that was less affected by the participation shortfall, and Kansas (bottom panel), a hard hit state at the epicenter of the drought.

Another index of drought is the yield (in bushels of corn per harvested acre). Figures 2 and 3 also display the yield statistics.[2] As Figure 3 suggests, the yield data is somewhat less satisfactory as an index. All we have for most counties and crop districts is the yield per harvested, not planted, acres. In a state like Kansas only a very small fraction of the acreage was harvested, presumably located in areas that escaped the worst of the drought. On those privileged farms relative yields were depressed but not to the extent in percentage terms as in Iowa. In a state like Illinois the drought effect is more evident in the harvest-to-planting ratio than in the yield per harvested acre.

The Adoption of Hybrid Corn

Hybrid corn (technically "double-cross inbred-hybrid corn") was "invented" by Donald

[2] Unpublished state and county level data on acreage planted and harvested was made available by Michael Haines. I am most grateful.

F. Jones in 1917-1918 and was developed and introduced on a trial basis in 1924 by Henry Agard Wallace. In the 1920s the Iowa Experiment Station began scientific field trials. Wallace's hybrid was first entered in the Iowa tests in 1921. It won first place in 1924. It was first sold commercially in 1925. Competitors began sales in 1928. Widespread commercial adoption began in 1932 [Olmstead 2006: IV-9; Zuber and Robinson 1941: 589]. The US Department of Agriculture began tracking the adoption of the new varieties in the following year, 1933. At that time only about 0.1 percent of the nation's corn acreage was planted to the new seed. In 1936 the USDA proclaimed significant increases in yield per acre could be achieved by adopting hybrid corn [Jenkins 1936: 481]. Yet it took another decade before 70 percent of the corn acreage had been planted with hybrid seed. By 1960, 96.3 percent of acreage was planted to hybrid varieties [USDA, *Agricultural Statistics 1962*, Table 46: 41; USDA, *Track Records*, April 2004: 19]. Figure 4 reproduces the annual data for the country as a whole and reveals a lazy **S**-shaped cumulative diffusion pattern.[3]

Zvi Griliches made the adoption of hybrid varieties in the United States the exemplar for a statistical model of technological diffusion and fitted the cumulative adoption patterns reported by the USDA to a logistic curve [Griliches 1957b]. Despite the nearly three decades between initial adoption and full acceptance, Griliches considered the adoption pattern displayed in Figure 4 to have been remarkably rapid [p. 502]. By examining the pattern of adoption, first, state by state, and then, crop district by district, he argued that *at the local level* adoption proceeded rapidly. But, he continued, the initial introduction into a local farming community proceeded slowly as commercial seed

[3] National and state level data on the percentage of corn acres planted to hybrids are available in various annual issues of *Agricultural Statistics*. I have relied on the volumes for 1945 (Table 46, p. 42), 1948 (Table 50, p. 48), 1950 (Table 49, p. 47), 1952 (Table 43, p. 40), 1954 (Table 38, p. 30), 1957 (Table 40, p. 39), 1959 (Table 43, p. 33), and 1961 (Table 43, p.33). The year 1960 is the last date this data is available.

producers developed and marketed acceptable hybrids in different locales. Thus the rate of diffusion across the US proceeded slowly [p. 507].

Griliches's explanation for the rapid and complete abandonment of open-pollinated corn in favor of the new hybrid varieties was based on a simple set of "stylized facts." He considered hybrid corn superior to the traditional open-pollinated varieties from the beginning and suggested that that superiority was established in 1935 and persisted thereafter.[4] The advantage of hybrids, according to Griliches, could be objectively measured by the relative increase in yield over the open-pollinated corn [Griliches 1957b: 516-517]. He assumed that the new varieties required no significant increase in capital investment or annual inputs. According to this analysis the adoption process in a given crop district was one of disequilibrium transition [p. 503]. Griliches attributed the lags in the process to "imperfect knowledge." It "takes time to realize that things have in fact changed" [p. 516]. The spread of hybrid corn geographically was slowed by the supply lags in developing and introducing hybrid varieties tailored to the specific soil type, weather conditions, and latitude of the peripheral regions.[5] But even this process was rapid. Using the rule of thumb suggested by Griliches to mark the start of an adoption process as the date that ten percent of acreage was planted to hybrid corn, Iowa in 1936 was followed by Illinois, Indiana, and Wisconsin in 1937, by Minnesota in 1938, and by Ohio, Nebraska, and Missouri in 1939.

[4] The date 1935 is the year that acreage planted to hybrid corn exceeded ten percent of the total in the district at the heart of the hybrid revolution. Griliches chose ten percent "as an indicator that the development had passed the experimental stage and that superior hybrids were available to farmers in commercial quantities." The region where this breakthrough occurred was the Sixth Iowa Crop Reporting District [Griliches 1957b: 507 and Table II, p. 508]. The sixth district comprised Bremer, Black Hawk, Benton, Buchanan, Linn, Delaware, Jones, Dubuque, Jackson, and Clinton Counties, all in Iowa.

[5] Paul David, in an insightful review, has criticized the Griliches approach "for lacking any real micro-level technology choice model" [David 2006:4]. Edwin Mansfield [1961] can be credited with supplying such a model to explain the logistic shape (although as David points out, Mansfield's model is simply one of many formulations consistent with the data). Mansfield suggested that the probability that a non-user would switch to a new technology would be a function of the number of those in the immediate neighborhood who had already accepted the technology. This "contagion" model, borrowed from epidemiology, leads to the logistic diffusion curve. Bronwyn Hall [2004] provides a review of the theoretical literature on diffusion from both sociology and economics.

The development of hybrid corn and its rapid adoption were, nearly from the beginning, hailed as a triumph of twentieth-century biotechnology and one that carried with it enormous welfare benefits [Sprague 1946:101].[6] In a chart that is perhaps even more famous, at least among plant scientists, than Griliches's logistic, the rise in corn yields per acre is employed to suggest that hybrid corn was responsible for a biotechnological revolution that abruptly ended a sustained period of "biological stasis." Figure 5 displays the "hockey stick" graph reproduced dozens of time in the scientific literature.[7] The chart plots USDA statistics on corn yields per acre dating back to 1866. There was a remarkable stability in yields with no discernable trend before 1936.[8] Thereafter yields began to increase and they have continued upward ever since. Yields per acre rose from an average of 25 bushels per acre before 1936 to 135 bushels per acre in the years 2000-2002 [Carter *et al* 2006: Series Da693-694], more than a five-fold increase. Perhaps too casually, this increase has been attributed (1) to the continuing adoption of the hybrid varieties between 1936 and 1960 and (2) to the continuing improvement of hybrid traits as new varieties were introduced between 1936 and 1989 [Duvick 1992].

I say "perhaps too casually," because the introduction of hybrids was also accompanied by the increased use of synthetic nitrogen fertilizers, increased planting densities, and the adoption and improvements in planting and harvesting machinery. However, these developments were intimately interrelated. One of the hybrid traits introduced improved the plant's ability to absorb nitrogen fertilizers and indeed the use of

---

[6] Griliches estimated the rate of return on hybrid corn research to have been at least 700 percent annually as of 1955 [Griliches 1958: 419].

[7] As an indication of how ubiquitously Figure 5 appears, I note that a standard textbook on corn for plant scientists [Smith, Betrán, and Runge 2004] reproduces a version of this chart four times in four separate chapters [Troyer 2004: Chapter 1.4, Figure 32, p. 218; Betrán, Bänziger, and Menz 2004: Chapter 2.3, Figure 6, p. 351; Wisner and Baldwin 2004: Chapter 3.8, Figure 2, p. 759; and Halauer 2004: Chapter 4.4, Figure 1, p. 901].

[8] Alan Olmstead and Paul Rhode have challenged the notion of a biological stasis before 1936. They view the stability of yields before 1936 as due to a balance of conflicting forces some of which would depress yields and counterbalancing ones that worked to raise yields [Olmstead and Rhode 2008: 64-97].

fertilizer was required to reach the potential of the hybrids. Similarly, the increased planting densities were possible only because of traits that reduced the plant's requirements for full sunlight and that increased its resistance to lodging – the tendency of the plant to lie down or fall over when beaten down by the wind. Even then high density was possible only with the heavy application of fertilizer. Increased planting densities also required the abandonment of the horse and the horse-wide path between the rows of corn. Thus the adoption of machinery was a necessary component for achieving the full potential of hybrid corn.[9] Since hybrid seed, synthetic fertilizer, and gasoline tractors were a necessary triad, it is not really possible to partition responsibility for the yield increases among them.[10]

The continuing improvement in the performance of hybrids after their initial introduction is an important part of the story. Figure 6 reproduces the results of field experiments conducted in 1989 and 1990 in central Iowa. Forty-one varieties introduced between 1934 through 1989 by Pioneer Hi-Bred (a leading seed producer and a key player in the story to follow), "all popular in their time," together with the most famous open-pollinated variety, Reid's Yellow Dent, were planted in adjacent fields in a demonstration designed to illustrate the advance of yields due to genetic improvement [Duvick 1992: 70]. As Figure 6 illustrates, yields advanced at an average rate of 1.16 bushels per acre per year throughout this 55-year period.[11]

[9] On these points see: Castleberry, Crum, and Krull [1984: 33]; Shaw and Durst [1965, Table 21, p. 39]; Johnson [1960], and Sutch [2008].

[10] The biological revolution in corn, commonly associated with the introduction of hybrid varieties, was not a unique phenomenon. Indeed, I find remarkably similar "hockey stick graphs" for the yields per acre in cotton, wheat, tobacco, oats, potatoes, and barley [Sutch 2008: 19-26] . The simultaneous increase in the yields of so many different crops during this period is more properly attributed to the discovery of an economical process for synthesizing ammonia and the consequent increase in the use of synthetic fertilizers [Smil 2001].

[11] Also see Cardwell [198**2],** Russell [1983] and Castleberry, Crum, and Krull [1984].

Despite the undeniable improvement in plant traits and the obvious appeal of the Griliches adoption story, I make the following claims:

1] There was *not* an unambiguous economic advantage of hybrid corn over the open-pollinated varieties at the time of planting in 1936.

2] The early adoption of hybrid corn before 1937 can be better explained by a sustained propaganda campaign conducted by the U.S. Department of Agriculture at the direction of the Secretary of Agriculture, Henry Agard Wallace. The Department's message echoed that of the commercial seed companies. Wallace was the founder of the Pioneer Hi-Bred Seed Company, the first and largest producer of hybrid seed.

3] Later adopters of hybrid seed were motivated by the drought resistance of one experimental hybrid variety vividly demonstrated during the drought of 1936. The eventual improvement of yields as newer varieties were introduced and the imitative force of "collective logic" explain the continuation and acceleration of the process. Given the required capital investments in fertilizer tanks and tractors and the inability to save and plant one's own seed, adoption tended to be irreversible.

The Iowa Corn Yield Tests and Hybrid Superiority

Griliches assumed that hybrid corn had an economically significant and unambiguous superiority over open-pollinated corn from the time it was first introduced. He reported that this superiority could be gauged by a 15- to 20-percent higher yield achieved with hybrid corn over the traditional open-pollinated varieties. Griliches also suggested that this relative advantage applied to both high- and low-yielding soils, good years and bad [Griliches 1957b: 516-517; 1958: 421]. His citations to support this estimate of the yield advantage were from an unpublished Federal Commodity Insurance Corporation source dated 1942, and published sources dated 1940 [USDA], 1946 [Sprague], and 1952 [Rogers and Collier]. None of these sources referred to the 1932-1936 period of early adoption. The 1940 USDA report cited the claims of "plant breeders" [Griliches

1957b:517].[12] G.F. Sprague, an agronomist at Iowa State College, based his 20-percent estimate on the increase in per acre yields observed in Iowa between 1933, when only 0.7 percent of the corn acreage was hybrid, and 1943, when 99.5 percent hybrid planting was reported and he attributed the entire advance to the use of hybrid seed [Sprague 1946: Figure 1, p. 101].[13] John Rogers, a professor of agronomy at College Station, Texas, and Jesse Collier, at the Texas Blackman Experiment Station, simply reported without citation "experience in other corn-growing regions" [1952: 7]. None of these reports seems a very reliable source and none explicitly examine the relative superiority of hybrid corn in the first half of the 1930s.

The best and most appropriate data on the relative yields of different corn varieties are the reports of field trials conducted by the agricultural experiment stations. These remain unexploited by quantitative historians.[14] Beginning with the Iowa Agricultural Experiment Station in the early-1920s, many of the stations in corn-belt

---

[12] There was a survey of "scientists engaged in crop breeding" taken (probably) in 1938 that reported estimates of the hybrid yield advantage that ranged from 5 to 25 percent, the authors concluded that the probable range was 10 to 15 percent [Dowell and Jesness 1939: Table 1 and pp. 480-481]. This may have been the source for the USDA's 1940 report of the opinions of "plant breeders."

[13] The actual increase in yields between those two years was 38 percent [USDA, *Track Records*, 2004], but 1945 was a very poor year for Iowa corn, so perhaps Sprague, writing in 1945, tempered his estimate.

[14] Although not cited in his published *Econometrica* article [1957b], Griliches's unpublished Ph.D. thesis for the University of Chicago contains a comment in an Appendix that rejects the Agricultural Experiment Station data:

> The data raise several difficult problems. They represent results on one or several fields in the whole state, conducted under varying and better than average conditions. The relation between the experiment station results and what the farmer may expect on his own farm is not clear. In particular, this relation may not remain constant between different states. For example, while the average yield in Iowa tests was around 80 bushels per acre at a time when the average yield for the state was around 40 bushels, the North Carolina tests averaged more than 100 bushels, but at the same time the average state yield was only around 30 bushels [Griliches, *Thesis*, 1957a: 56-57].

These considerations may make the Iowa test results an exaggerated estimate of the absolute advantage, but all that is needed for Griliches's disequilibrium model is an estimate of the *relative* advantage. Elsewhere Griliches argued that the relative advantage was independent of the level of yield per acre. Moreover, to the extent that the test results exaggerated the absolute gain, they bias the farmer's decision calculus toward adoption, and thus they would bias the argument against the claim I make that the hybrid advantage was not large enough to encourage early adoptions.

states conducted controlled plantings of open-pollinated, experimental hybrid, and commercially-available hybrid seeds and published the results in the Stations' *Bulletins*. This paper relies on the data available from the Iowa Corn Yield Tests. These are the most complete. They begin at the earliest date. And, they are the most relevant. Iowa was both the heart of the Corn Belt and the first state to widely and most quickly adopt hybrid corn.

For the Iowa tests the state was partitioned into 12 districts, shown in the inset map in Figure 7. A volunteer farmer from each district, who was also a member of the Iowa Crop Improvement Association, planted several varieties in adjacent fields and employed a uniform cultivation practice to raise them to maturity. At harvest, the yields were measured separately for each variety and reported back to the Experiment Station. The Table displayed in Figure 7 summarizes the results for the years 1926 through 1940. For each district and each year the average yield for all hybrid varieties tested is expressed relative to the average for all open-pollinated varieties. It is immediately clear why the introduction of hybrid corn caused such excitement. Of the 166 observations in the table, only two recorded a relative below 101 (district 3 in 1926 and district 8 in 1927). These data provide strong support for the concept of hybrid vigor, or "heterosis" to use the scientific term. As we will see, however, hybrid vigor is not the same as economic superiority.

Hybrid Vigor

American corn, or more properly, "maize" (*Zea mays*, L.) is native to North America.[15] It originated in Mexico where farmers cultivated it for millennia, gradually improving the plant by the selection for genetically-based traits. Before the development of hybrid corn

[15] The sources for this and the next several paragraphs are many, but the science is well-known so a detailed list of sources will be omitted. References to the names and historical dates can be found in Duvick [2001]. For a history of corn varieties (germplasm), see Troyer [2004]. Much of the science is elaborated in Smith, Betrán, and Runge [2004]. A useful discussion of the relevant agricultural history is provided by Bogue [1983].

the seed used for farm-planted corn was the result of natural cross-pollination. Under these conditions, corn is said to be "open-pollinated." Pollen, produced by the corn plant's tassels, is released and carried on the air. Some of the pollen typically reaches the cornsilks (the "ear shoots," which are the stigmas of the female flower) of one or more nearby plants. The geminating pollen tube grows down the silk and fertilizes the egg cell, thereby starting the growth of a seed. In principle each seed on an ear of corn could have a different male parent. The fraction of corn seeds set by self-pollination is known to be very low. If this fertilization process is left to the wind, selective breeding consists of choosing individual ears of corn on the basis of desirable plant or grain properties and saving those seeds for the following year's crop. A great deal of natural hybridization between separate corn populations and varieties took place in this way.[16] As a consequence of repeated selection under open-pollination, corn lines evolved that were adapted to new climates and soil conditions such that corn cultivation spread across the North American continent in the nineteenth century.

The next step, deliberate control of parentage, produced "varietal hybrids" in experiments conducted by farmers and agronomists in the late nineteenth and early twentieth centuries. Ever since Charles Darwin's experiments with inbred and cross-pollinated corn, reported in 1876, it was known that the progeny of inbred plants were inferior to those of the cross-bred hybrids.[17] In Darwin's terms, hybrid plants had "innate constitutional vigour." The lack of this vigor in the inbreds is known as "inbreeding depression." Not surprisingly, Darwin's results stimulated experimentation with deliberate cross-variety hybrids.

[16] For a brief review of the history of maize cross pollination see Olmstead and Rhode [2008: 71-76]. The most popular open-pollinated variety at the time that the first hybrids were introduced was Reid's Yellow Dent. This was an accidental hybrid between a reddish semi-gourd and a yellow flint. The story is told by Russell Lord [1947: 147] and Troyer [2004].

[17] Darwin married his first cousin and their first child was retarded. He had a life-long interest in inbreeding.

Neither natural hybrids nor the deliberate varietal hybrids are the hybrid corn of the hybrid revolution under discussion. Hybrid corn as it is known today is more accurately described as a hybrid of inbred lines. Due to their inferior quality, the inbreds were generally avoided by plant breeders. So it took a leap of imagination when George Shull and Edward East, working independently, crossed two pure inbred lines of corn (homozygous strains) and produced plants superior to the run-of-field open-pollinated varieties. The results were published in 1908. The Shull-East "single-cross" hybrid of inbred lines in principle could revolutionize corn farming. Seeds could be produced on a field-wide basis by removing the tassels from one inbred line and allowing it to be fertilized by the pollen from a second inbred line planted in the neighboring row. It seemed evident, however, that this approach was impractical. Producing the inbred lines that were to be crossed involved laborious hand pollination and these parent lines were so depressed by inbreeding that their seed yields were extremely low, making the input costs to large-scale seed production prohibitive.

The problem of producing hybrid seed that the farmer could afford was further compounded by the need to plant freshly-made hybrid seed each year. If the seeds of an inbred hybrid were planted, the yields achieved the following season would drop significantly because seed from a hybrid field would suffer from inbreeding depression [Jugenheimer 1939: 18-19].

The practical problem was solved in 1918 by Donald F. Jones. He found that a "double-cross" hybrid could be made by crossing two single-cross varieties. The progeny, while generally not as productive as their single-cross parents, nevertheless out performed the open-pollinated varieties. Since single crosses were prolific parents (unlike the pure inbred lines) production costs for the double-crosses were reduced to an economical level.

All of the hybrids in the Iowa Corn Tests recorded in the table in Figure 7 were double-cross varieties. The trial results for the period 1926-1933 (before the drought of

1934) are plotted both as a histogram and as a density estimate in Figure 8. The average yield advantage of the hybrids was 9.3 percent (averaging across the 12 districts and 95 observations). The median yield advantage was 9 percent. An advantage of 15 to 20 percent would be an exaggeration for this period. The average advantage in District 6, where the adoption of hybrid corn first took place, was only 7 percent.

Although the 15-20 percent advantage cited by Griliches is an exaggeration for the period of first adoption, perhaps the story of a disequilibrium transition would be just as valid with the more modest 7 to 9 percentage advantage reported by the Iowa Experiment Station. The typical yield with open-pollinated corn reported by the farmers conducting the Iowa corn yield tests, 1926 through 1933, was 61.3 bushels per acre [Shaw and Durost 1965, Table 12: 28]. Presumably, this represents the yield achieved with best-practice farming by experienced farmers. The state-wide average for that period, however, was only 38.2 bushels per acre. Thus the typical farmer could anticipate a yield gain of less than four bushels per acre and an experienced best-practice farmer could anticipate perhaps as much as a six-bushel gain.

Before we can conclude that an advantage in physical yield translated into an economic advantage, we must factor in the depressed value of the corn crop and the high price of hybrid corn seed. With the advent of the Great Depression in the 1930s, the market price of corn came down from a high of 80 to 85 cents a bushel in the late 1920s to 32 cents in 1931 and 1932 [Carter *et al*, Series Da697]. During the Depression hybrid seed was selling in Iowa for $6.00 a bushel [Culver and Hyde 2000: 91].[18] Since a bushel of seed would plant two acres [Duvick 1992: 71], a farmer would have to expect a financial gain approaching $3.00 an acre to be tempted to pay full price.[19] Expecting no

---

[18] Elsewhere Culver and Hyde report "at the depths of the Depression, corn sold in Iowa for ten cents a bushel" and that Pioneer's price was $5.50 a bushel [p. 147].

[19] Corn seeding rates varied widely depending upon the local practice and climate. States with abundant rainfall, such as Ohio, supported heavier seeding rates [Fernandez-Cornejo 2004: 8].

more than 32 cents per bushel for the crop when sold, the advantage of the hybrid seed would have had to approach nine bushels per acre, not the four to six bushels that could be anticipated on the basis of the Iowa Corn Tests.

Henry Agard Wallace and Hybrid Hype

The puzzle then is why some adventurous farmers were willing to adopt hybrid corn before its economic superiority was demonstrated by controlled tests. My suggestion has two parts: (1) there was an aggressive marketing campaign launched by the commercial seed companies directed at potential adopters, and (2) the Secretary of Agriculture, Henry Agard Wallace, a commercial promoter of hybrid seed and former President of the major seed company, Pioneer Hi-Bred International, put the full weight of the Federal government behind an advocacy of hybrid corn.

Henry Agard Wallace, Franklin Roosevelt's first Secretary of Agriculture, was a multifaceted, complex, prolific, and eccentric man.[20] He was an early champion of scientific farming, a path-breaking plant scientist, a talented statistician and geneticist, America's first econometrician, author of a dozen books, a journalist, and the influential editor of *Wallaces' Farmer*, from 1921 to 1933, the most prominent agricultural magazine of its time.[21] Later he became the editor of *The New Republic*, 1946-1948. Wallace was a successful entrepreneur who made a personal fortune as the leading founder of the Hi-Bred Seed Company (later Pioneer Hi-Bred International, Inc.). Today, Pioneer is a wholly-owned subsidiary of E.I. du Pont de Nemours and Company and is the largest seed company in the world with a market share in 1997 of 42 percent [Fernandez-Cornejo 2004: Table 12, p. 26; Beck 2004: 568]. Henry Agard Wallace was,

[20] As one index of his eccentricity, I note that Wallace was a mystic and an ambidextrous, vegetarian, teetotaler before any of these affectations was considered legitimate. Republican teetotalers holding high office in Roosevelt's New Deal administration were rare indeed. The best biography of Wallace is by John C. Culver and John Hyde [2000] from which I draw the details in this paragraph.

[21] It was the USDA's statistician Louis Bean that named Henry A. Wallace the first American econometrician based on Wallace's book, *Agricultural Prices* [1920]. See Culver and Hyde [2000: 51].

according to historian Arthur Schlesinger Jr [2000], America's best Secretary of Agriculture.[22] He was Vice President of the United States during World War II – the most influential and powerful Vice President before Dick Cheney. Wallace served as Secretary of Commerce during the economic transition to peace time (1945-1946). He ran for President on the Progressive Party ticket in 1948. The *Des Moines Register* identified Henry A. Wallace the "Most Influential Iowan of the 20th Century" on December 31, 1999. His biographers identified him as the "state's greatest son" [Culver and Hyde 2000: ix]. When he died of Lou Gehrig's disease in 1965, the then-reigning Secretary of Agriculture, Orville Freeman, could declare, without hyperbole that: "No individual has contributed more to the abundance we enjoy today than Henry Wallace" [p. 531].

A unifying theme – an obsession, really – for Wallace throughout this prolific and many-sided career was hybrid corn. In 1910, two years after Shull and East reported on their single-cross inbred hybrid experiments, Wallace was debating the findings with Iowa State College agronomists in Ames. In 1912 he conducted his own experiments to produce single-cross hybrids. At the time, he concluded that the difficulty of hand pollination "was too laborious" [Wallace quoted by Culver and Hyde 2000: 67]. Over the next several years Wallace experimented with varietal hybrids without achieving consistent success. But when Edward East visited Wallace in 1919 and introduced him to Donald Jones' results with double-cross hybrids, Wallace immediately saw the commercial potential and began his own experiments with the new technique. He also used the pages of *Wallaces' Farmer* to proclaim the coming revolution [Culver and Hyde 2000: 68]. In 1920 the circulation of *Wallaces' Farmer* was 65,200 [Galambos 1968: 344]. The journal was read by a high proportion of corn and hog farmers.

[22] Precision requires that I use Wallace's middle name since his father, Henry Cantwell Wallace, was also Secretary of Agriculture (1921-1924), appointed by Warren Harding. Another Henry Wallace in the family was Henry A. Wallace's grandfather and the founder of *Wallaces' Farmer*. This Wallace had no middle name [Lord 1947].

In 1920 Wallace convinced the Iowa State Agronomist, H.D. Hughes, to establish the Iowa Corn Yield Tests. The idea was to challenge the current practice of judging corn by the physical appearance of the ear and instead focus on yields per acre. Wallace did not have enough seed to offer an entry of his own that first year, and his entry for 1921 failed to outperform the best of the open-pollinated varieties. He entered a new hybrid, named Copper Cross, in the 1922 tests and again in 1923, but it too failed to out-yield the best open-pollinated entries. However, Copper Cross was successful enough that Wallace was able to draw up a contract for its commercial release with the Iowa Seed Company. When Copper Cross won the gold medal at the 1924 test, the commercialization of hybrid corn was launched.[23] Wallace himself wrote the first advertising copy. "An Astonishing Product—Produces Astonishing Results … If you try it this year you will be among the first to experiment with this new departure, which will eventually increase corn production of the U.S. by millions of bushels" [quoted by Culver and Hyde 2000: 71].

In 1926 Wallace founded the Hi-Bred Seed Company [Culver and Hyde 2000: 82-83]. He continued to use the pages of *Wallaces' Farmer* to proclaim the virtues of hybrid corn and, of course, to advertise his company's seed. In that same year and the following year hybrid maize did reasonably well in the Iowa Corn Yield Tests recording about a 7 percent greater yield than their open-pollinated rivals. But that was an insufficient advantage to create much demand.

There were several obstacles, not the least of which was the astonishing price that Wallace was asking for his "astonishing" seed – it was $52 bushel in 1924 [May 1949: 514, Culver and Hyde 2000: 71]. Two founding principles of the Hi-Bred Seed Company were first, total honesty in advertising and, second, high prices. "High prices, Wallace believed, were necessary to convince farmers they were buying something special" and,

[23] The Funk Brothers Seed Company introduced its first double-cross hybrid in 1928 [Fitzgerald 1990: 218].

of course, high profits helped cover the cost of on-going research intended to improve the varieties [Culver and Hyde 2000: 91 and 148].

Another obstacle that had to be overcome was the reluctance of many farmers to abandon their reliance on their own home-grown seed and instead entertain a visit by, and the commercial pitch of, the traveling seed salesman. The role of the salesman was not so much to educate the farmer – the genetics of inbred-hybrid crosses and the "magic" of heterosis exceeded the common-sense knowledge of most farmers and indeed of most seed salesman. The claims of superiority had to be accepted, if they were, on faith. It was a particularly sore point with many farmers that seeds saved from a hybrid crop could not themselves be planted the next season with any hope of success. So, old habits were challenged. A commitment to hybrid seed was tantamount to an agreement to deal with the seed salesman every subsequent year as well as the current year. And that commitment meant that the farmer's skill in selecting seed corn from his own crop, a skill which many took great pride in, would be no longer needed or esteemed [Fitzgerald 1993].

Pioneer Hi-Bred designed a sophisticated marketing plan to address these problems. Seed salesmen working for Wallace offered to provide the reluctant farmer enough seed free of charge to plant half of his acreage. The farmer would plant the remaining land with the open-pollinated seed he preferred. In exchange the Hi-Bred company would reclaim one-half of the increased crop produced by its seed judged against the farmer's regular crop [Lee 1984: 43, Culver and Hyde 2000: 91]. Typically, only one farmer on each lane was offered the deal with the hope that a demonstration would spread interest to the neighborhood. Other farmers were given yield guarantees [May 1949: 514]. According to Culver and Hyde, it often took several years to persuade a farmer that the higher yields achieved with the Hi-Bred seed were not a fluke [p. 91].

With the advent of the Great Depression in the 1930s, marketing the new seed became even more difficult. As I have noted, the Depression had sent the market price of corn tumbling from a high of 85 cents a bushel in the late 1920s to 32 cents in 1932 and Iowa farmers, many who faced ruin, were hardly in the mood for experimentation and risk taking. Safety first was the general rule. Moreover the average yield gains from switching to hybrids were, as I have already pointed out, generally insufficient to justify the cost of seed.

Henry Agard Wallace became President Roosevelt's Secretary of Agriculture in 1933. The public position did not damp his enthusiasm for hybrid corn. For many years the Agriculture Department had published an annual volume, The *Yearbook of Agriculture*, devoted to reporting on the activities of the Department, of advances in many fields, and offering both general and specific advice to farmers. The *Yearbooks* had large press runs and were widely distributed by members of Congress to their farming constituency. For the 1936 edition Wallace made an unusual decision. As he explained:

> The 1936 Yearbook of Agriculture differs … from those published in recent years. … This year it is devoted to a single subject – the creative development of new forms of life through plant and animal breeding [Wallace 1936: foreword].

The article on "Corn Improvement" for this *Yearbook* was written by Merle T. Jenkins, the USDA's Principal Agronomist. A headline exaggeratedly claimed "Yield Advances up to 35 Percent over Open-Pollinated Varieties" [Jenkins 1936: 481]. The report was based on the Iowa Corn Yield Test despite the exaggeration of the headline.

In retrospect, and perhaps even at the time, the focus of the 1936 *Yearbook* was in jarring contrast to other efforts of the Roosevelt Administration to deal with the Great Depression. For the first several years of his administration, Wallace presided over the acreage reduction and crop destruction policies of the Agricultural Adjustment Administration. He was the one who ordered the plowing up of ten million acres of cotton in 1933 and the slaughter of six million baby pigs and sows in September [Culver and Hyde 2000: 123-125]. Yet Wallace looked into the future beyond the current crisis to foresee a time when the yield increases to be made possible by the spread of hybrid corn would be welcome.

By today's standards, the glaring conflict of interest between Wallace's financial interest in the Pioneer Hi-Bred Company and the use of the government agency he controlled to advertise and advocate his product would be outrageous. But even this propaganda barrage combined with the innovative marketing strategy of his company might not have been successful in tipping the balance in favor of hybrid corn. It took two other factors to put the company on the road to success.

Drought and Research

The eventual success of hybrid corn was due, first, to a tipping event and then to the self-reinforcing momentum of biotechnology. The factor which acted to tip the balance in favor of hybrid adoption was paradoxically another disaster to bedevil corn farmers in the 1930s. As if the Depression, with its devastating impact on agricultural prices were not enough, there were catastrophic droughts in 1934 and 1936. An index of the severity of these droughts, as we have suggested, is the fraction of the crop planted which was harvested. In Iowa and in the country overall, thirty to forty percent of the acreage planted was so devastated by drought that it was not worth harvesting. In Nebraska and Kansas the losses were nearly total. Consult Figures 2 and 3.

What the droughts starkly demonstrated was that the *relative* yield of hybrid corn was greatest when the *absolute* yields were generally depressed. Figure 9 reveals the relationship using, once again, the Iowa Corn Yield Test results to illustrate the correlation. In the extreme drought conditions of the mid 1930s, the yield differences between the new and traditional varieties were stark. Edward May, President of the May Seed Company, recalled:

> Yield differences became plainly evident in 1936, which was also a severe drouth year in Iowa. At this time nearly all farmers who were testing hybrid seed corn planted only a limited acreage. Yields of hybrids under these conditions in many areas of the state were approximately double the yields of other corn grown on the farm. The results were so convincing that it marked the end of the vast efforts of initial adoption [May 1949: 514].

"Almost overnight, demand for hybrid seed exploded" [Culver and Hyde 2000: 149]. Big percentage point gains in adoption came in 1937: 22.3 percentage points accounted for by new adoptions in Illinois, 21.2 percentage points Iowa, 18.3 points in Ohio, 17.4 in Indiana, 12.9 in Wisconsin [see footnote 3 for sources].

Once the move to hybrid corn was launched -- and only because the switch was made – the technological diffusion process became self-sustaining and irreversible. The steady improvement of the yield advantage of hybrid corn began in 1937. See Figure 6, but also Figure 10 which illustrates the shift in the relative hybrid advantage after 1936. Farmers might have switched to hybrid corn out of fear of continued drought, but soon the genetic advance in hybrid corn made open-pollinated corn obsolete even though the price of hybrid seed was high and a farmer using it would need to purchase fresh seed each season. This genetic improvement was achieved thanks to continuing research funded by the seed companies using retained earnings generated by soaring sales and high prices.

Wallace believed that his hybrid revolution would have collapsed without a continuing, well-financed, research effort [Culver and Hyde 2000: 148]. Research by the federal government also played a supporting role.[24] The research in both sectors was closely co-coordinated. According to Sprague [1946: 101] there was unrestricted

[24] In 1922 when Henry Agard Wallace's father, Henry C. Wallace, was Secretary of Agriculture a well-funded hybrid corn research program was established by the Department in cooperation with the Experiment Stations in several corn-belt states. This federal program was vital during the 1920s. Donald Duvick suggests that "the commercial maize breeders probably could not have succeeded in the early years [without the contributions from the public sector], for individually they simply did not have enough inbred lines …" [Duvick 2001: 71].

interchange of ideas and seed stock between government researchers and the private companies. Most observers agree that the for-profit research was the driving partner of the private-federal joint effort after 1937 [Griliches 1958: 420-421 and Table 1, p. 424; Duvick 2001: 71; Fuglie, Ballenger, et al 1996: 45, Fernandez-Cornejo 2004: 41-50]. Wallace claimed that his company spent more money on corn research than the USDA and the state experiment stations combined [Culver and Hyde 2000: 148].

Ironically, the drought of 1934 was, in part, responsible for the remarkable improvement in hybrid development seen thereafter. One of the farmers that Hi-Bred recruited as part of its experimental research on new hybrid strains suffered greatly in the drought of 1934. Most of his experimental plants were lost. But he continued to work with the few plants that had managed to survive. The result was the unexpected discovery of a hardy new hybrid, number 307, with a remarkable ability to withstand drought. Consult Figure 6 again, where number 307 is labeled for easy identification. The experimenter remarked that this plant "proved very valuable when we found ourselves in another serious drought condition in the summer of 1936" [Culver and Hyde 2000: 149].

What we have, then, is a story of the diffusion of hybrid corn that is more complex and more interesting than the one usually told by Griliches-inspired plant scientists [Griliches, *Science*, 1960]. Rather than disequilibrium transition slowed by information imperfections that were gradually overcome by commercial advertising and agricultural extension education, the history reveals that neither the innovation of 1918, nor the commercial product of 1924, nor the highly-touted seeds of 1936 were economically and culturally attractive. The advertising and marketing campaigns of the seed companies were effective in the late 1920s or early 1930s not because they educated farmers, but because they offered inducements designed to lower the costs and risks of adoption, shifting those costs and risks to the seed companies. The tipping point came in 1936 when farmers choose what seeds to plant in 1937. How much credit should be given to the *Yearbook of Agriculture* that year and how much to the drought would be difficult to say given their simultaneity. But what is clear is that the genetic advance in hybrid corn varieties beginning with hybrid 307 (which was introduced commercially in 1936) is what locked in the transitional adopters and made the hybrid revolution seem inevitable in retrospect. Had Wallace not used the bully pulpit of the USDA to promote his own commercial and financial interests, had the USDA not supported the research effort in the late 1920s and early 1930s, had the droughts of 1934 and 1936 not occurred, had Hi-Bred not continued a major research effort following 1936, the Wallace crusade might have succumbed as just another fatality of the Great Depression.

The Impact of the Drought on Adoption: An Illustration

The relationship between the drought and the adoption of hybrid corn can be illustrated using crop district data for the years 1926-1960. For the purposes of reporting the data on the percentage of acreage planted to hybrid varieties and the statistics of acreage and output, the USDA partitioned each of the corn states into nine (or fewer) districts that aggregated contiguous counties. Unfortunately the county-level data on acreage planted is not complete and the data on yields is available only for Ohio, Indiana, Illinois, Wisconsin, Iowa, Missouri, eastern South Dakota, and eastern Nebraska. Michigan and Kansas are not yet available. Because the data on acreage planted is not available at the county or district level for most of these states, I use the yield per harvested acre as my measure of the severity of the drought in 1936. Specifically severity is measured as the percentage yield shortfall in 1936 when compared to the average yield for 1926-1935 excluding 1934.

The more severe the 1936 drought, the greater its depressing impact within a crop district, the faster we expect the adoption of the new drought-resistant hybrids would have been. Zvi Griliches collected annual data on the percentage of acreage planted in each crop district that was devoted to hybrid varieties. District-by-district he fit a simple three-parameter logistic curve to estimate the timing and speed of adoption. We used the parameters that he published [Griliches 1957, Table 2] to calculate three measures:[25] (1) the year that the district achieved a 40-percent adoption rate, (2) the number of years that elapsed between the time a 10-percent adoption rate was achieved and a 70-percent adoption rate was recorded, and (3) the percentage of new acreage adopting hybrid corn in 1937 compared with 1936. I name these three variables: "penetration," "cautiousness," and "jump."

We also conjecture that the eagerness to adopt the new varieties would be correlated with the productivity of corn farming within the district. The higher the yield per acre in normal years, the larger will be the pecuniary advantage of the higher yields the new varieties seemed to offer.

Penetration: A 40-percent rate of adoption would indicate that hybrid corn had made significant inroads in the region. Penetration is the date (in years) this threshold was achieved. The average over the 44 crop districts was 1939. The smaller this number, the earlier substantial penetration was achieved. I performed a simple statistical calculation to predict the year that 40-percent penetration was achieved for a cross section of the 44 crop reporting districts in the cotton belt. See the map inset in Figure 11. The average yield reported for the 1926-1933 and 1935 period and our measure of the yield shortfall in 1936 were used as linear regressors. The larger the shortfall in yield, the greater severity of the drought, and thus the earlier penetration should have been achieved. The regression confirms this relationship. The higher the normal yield per acre the earlier 40-percent penetration was achieved. Both coefficients are statistically significant at the 96 percent level. The regression statistics are presented in Figure 11.

[25] A purest might prefer to use the original data rather than the fitted curves. I have been unable to locate the original data. However, the fit of each curve as reported by Griliches is very high. Moreover, there is certain logic in using the fitted values since they create a continuous variable, smooth the data, and correct for noise in the original crop reporters' estimates.

Cautiousness: I expect that a severe drought would reduce caution and accelerate the speed of adoption. The results, also in Figure 11, confirm this conjecture. The larger the shortfall in the 1936 crop the faster the diffusion process proceeded.

Jump: The size of the jump in adoption rates, measured between 1936 and 1937, would be expected to be positively related to yield and to the shortfall. These results are also presented in Table 11. Both coefficients have the predicted sign. Large yields and large losses in 1936 are associated with a bigger jump between 1936 and 1937.

We conclude that the drought of 1936 sped the process of adoption after it revealed the drought resistance of hybrid corn. The commercial seed producers were quick to spread the word. An advertisement for DeKalb seed published in the *Prairie Farmer* of October 24, 1936 prominently featured hybrid corn's drought resistance and claimed it had been proven in eight corn belt states from Nebraska to Ohio [reproduced in Fitzgerald 1990: 176]. After 1937 a new dynamic was set in motion. The explosion of demand for hybrid corn generated large profits for the major hybrid seed companies: Pioneer, Funk, and DeKalb. As a result prices of hybrid seed fell and the companies invested heavily in research with new hybrid strains. They not only perfected the drought resistance of the plant, but found ways to permit increased planning density, increase the resistance to lodging, and increase responsiveness to artificial fertilizer. The result was a steady improvement in the yields per acre that hybrid corn could achieve. Once these post-1937 improvements were recognized adoption of hybrid corn became economically advantageous; before 1937 it had not been so.

We can trace the diffusion of hybrid corn from district to district. The insert map in Figure 11 illustrates when the various districts achieved 40-percent penetration. The crop district in the center of the Corn Belt (Iowa District 6) was the epicenter for the spread of the innovation. It had reached 40 percent in 1936. Eleven districts, all located in a concentric ring around the origin districts achieved that threshold in 1937 in the rush to achieve some protection in case another dry year were to follow. In 1938 the concentric ring expanded to the north and west. In 1938 there were also four districts in northern Indiana and northwest Ohio that reached the penetration threshold. These districts were less affected by the drought of 1936. It is possible that a geographical contagion coupled with new and superior varieties introduced for the 1938 crop year explain this move into northern and central Indiana and Ohio. Central Indiana and Ohio filled in the map in 1939. The southern tier of those states did not reach 40 percent until 1940 or after.

The sociologists Bryce Ryan and Neal Gross, writing in 1950, studied the diffusion of hybrid corn in two communities located in Greene County, Iowa [Ryan and Gross 1950]. In their view late adopters were farmers bound by tradition. They were irrational, backward, and "rural." The early adopters by contrast were flexible, calculating, receptive, and "urbanized." "Certainly," they summarized, "farmers refusing to accept hybrid corn even for trial until after 1937 or 1938 were conservative beyond all demands of reasonable business methods" [p. 672]. They drew a policy implication. "The interest of a technically progressive agriculture may not be well served by social policies designed to preserve or revivify the traditional rural-folk community" [p. 708]. In part this view was based on Ryan and Gross' (incorrect) belief that hybrid corn was profitable in the early 1930s [p. 668]. I have suggested that this was not the case. The map in Figure 11 should also give pause to the view that rural laggards delayed the adoption of hybrid corn. It would be hard to argue that the farmers in Iowa Crop Reporting District 6 were predominantly forward-thinking leaders, attentive, and flexible, while those in Indiana and Ohio were predominately backward rustics trapped by inflexible folk tradition.

I think an implication of this study is that farmers (even those of rural America in the 1930s) are remarkably resilient and adaptive. Sudden and dramatic climate change induced a prompt and prudent response. An unexpected consequence was that an otherwise more gradual process of technological development and adoption was given a kick start by the drought and the farmers' response. That pushed the technology beyond a tipping point and propelled the major Corn Belt states to the universal adoption of hybrid corn by 1943. The country as a whole reached universal adoption by 1960.

While this process was driven by individual farmers and privately-owned seed companies, there was also a role played by the government. The USDA not only campaigned vigorously for hybrid corn from 1936 onward, but engaged in the years before 1936 in its own research, and subsidized the dissemination of knowledge and seed samples. That this engagement was to some extent promoted by the Secretary of Agriculture, Henry Agard Wallace, a hybrid researcher and the founder of the major commercial producer of hybrid seed, should not blind us from recognizing the importance of the government subsidizes in preparing the new technology for the leap forward.

References

Beck, David L. 2004. "Hybrid Corn Seed Production." In C. Wayne Smith, Javier Betrán and E. C. A. Runge, *Corn: Origin, History, Technology, and Production,* Wiley, 2004: Chapter 3.4: 565-630.

Betrán, Javier; Marianne Bänziger; and Mónica Menz. 2004. "Corn Breeding." In C. Wayne Smith, Javier Betrán and E. C. A. Runge, editors, *Corn: Origin, History, Technology, and Production,* Wiley, 2004: Chapter 2.3.

Bogue, Allan G. 1983. "Changes in Mechanical and Plant Technology: The Corn Belt, 1910-1940," *Journal of Economic History* 43(1) March 1983: 1-25.

Cardwell, V.B. 1982. "Fifty Years of Minnesota Corn Production: Sources of Yield Increase," *Agronomy Journal* 74(6) December 1982: 984-990.

Carter, Susan B.; Scott Sigmund Gartner; Michael Haines; Alan Olmstead; Richard Sutch; and Gavin Wright, editors. 2006, *Historical Statistics of the United States*, Millennial Edition, Cambridge University Press, 2006.

Castlebery, R.M.; C.W. Crum; and C.F. Krull. 1984. "Genetic Yield Improvements of U.S. Maize Cultivars under Varying Fertility and Climatic Environments," *Crop Science* 24(1) January-February 1984: 33-36.

Culver, John C., and John Hyde. 2000. *American Dreamer: The Life and Times of Henry A. Wallace,* Norton, 2000.

David, Paul A. 2006. "Zvi Griliches on Diffusion, Lags and Productivity Growth ... Connecting the Dots," Conference on R&D, Education and Productivity held in Memory of Zvi Griliches (1930-1999), Carré des Science, Ministère de la Recherche, Paris France, Held 25-27 August 2003, Revised January 2006.

Dowell, A.A., and O.B. Jesness. 1939. "Economic Aspects of Hybrid Corn," *Journal of Farm Economics* 21(2) May 1939: 479-488.

Duvick, Donald N. 1992. "Genetic Contributions to Advances in Yield of U.S. Maize," *Maydica* (37) 1992: 69-79.

Duvick, Donald N. 2001. "Biotechnology in the 1930s: The Development of Hybrid Maize," *Nature Reviews: Genetics* (2) January 2001: 69-74.

Fernandez-Cornejo, Jorge. 2004. *The Seed Industry in U.S. Agriculture: An Exploration of Data and Information on Crop Seed Markets, Regulation, Industry Structure, and Research and Development,* Agriculture Information Bulletin Number 786, February 2004.

Fitzgerald, Deborah. 1990. *The Business of Breeding: Hybrid Corn in Illinois, 1890-1940.* Cornell University Press, 1990.

Fitzgerald, Deborah. 1993. "Farmers Deskilled: Hybrid Corn and Farmers' Work," *Technology and Culture* 34(2) April 1993: 324-343.

Fuglie, Keith; Nicole Ballenger; Kelly Day; Cassandra Klotz; Michael Ollinger; John Reilly; Utpal Vasavada; and Jet Yee. 1996. *Agricultural Research and Development: Public and Private Investments under Alternative Markets and Institutions*. U.S. Department of Agriculture Agricultural Research Service Agricultural Economics Report Number 735, May 1996.

Galambos, Louis. 1960. "The Agrarian Image of the Large Corporation, 1879-1920: A Study in Social Accommodation," *Journal of Economic History* 28(3) September 1968: 341-362.

Griliches, Zvi. 1957a. "Hybrid Corn: An Exploration in Economics of Technological Change," Thesis, Economics, University of Chicago, August 1957.

Griliches, Zvi. 1957b. "Hybrid Corn: An Exploration in the Economics of Technological Change," *Econometrica* 25(4) October 1957: 501-522.

Griliches, Zvi. 1958. "Research Costs and Social Returns: Hybrid Corn and Related Innovations," *Journal of Political Economy* 66(5) October 1958: 419-431.

Griliches, Zvi. 1960. "Hybrid Corn and the Economics of Innovation," *Science* (132) July 29 1960:

Hall, Bronwyn. 2004. "Innovation and Diffusion." In Jan Fagerberg, David C. Mowery and Richard R. Nelson, *Handbook on Innovation,* Oxford University Press, 2004.

Hallauer, Arnel R. 2004. "Specialty Corns." In C. Wayne Smith, Javier Betrán and E. C. A. Runge, editors, *Corn: Origin, History, Technology, and Production,* Wiley, 2004: Chapter 4.4.

Hornbeck, Richard. 2009. “The Enduring Impact of the American Dust Bowl: Short- and Long-Run Adjustments to Environmental Catastrophe,” *National Bureau of Economic Research Working Paper*, Number 15605, December 2009.

Jenkins, Merle T. [Principal Agronomist]. 1936. "Corn Improvement." In Henry A. Wallace [Secretary of Agriculture], *Yearbook of Agriculture 1936*, Government Printing Office, 1936.

Jennings, Ralph D. 1958. "Consumption of Feed by Livestock, 1909-56: Relation between Feed, Livestock, and Food at the National Level," *USDA Production Research Report* Number 21, 1958.

Johnson, Paul R. 1960. "Land Substitutes and Changes in Corn Yields," *Journal of Farm Economics* 42(2) May 1960: 294-306.

Jugenheimer, Robert W. 1939. "Hybrid Corn in Kansas," *[Kansas] Agricultural Experment Station Circular* 196, February 1939: 1-19.

Lee, Harold. 1984. *Roswell Garst: A Biography*, Iowa State University Press, 1984.

Libecap, Gary D., and Zeynep K. Hansen. 2004, “Small Farms, Externalities, and the Dust Bowl of the 1930s,” *Journal of Political Economy* 112(3) June 2004: 665-694.

Lord, Russell. 1947. *The Wallaces of Iowa*, Houghton Mifflin, 1947.

Mansfield, Edwin. 1961. "Technical Change and the Rate of Imitation," *Econometrica* 29(4) October 1961: 741-766.

May, Edward. 1949. "The Development of Hybrid Corn in Iowa," *[Iowa] Agricultural Experiment Station Research Bulletin* 371(1) December 1949: 512-516.

Olmstead, Alan L. 2006. "Agriculture: Introduction." In Susan B. Carter, Scott Sigmund Gartner, Michael Haines, Alan Olmstead, Richard Sutch, and Gavin Wright, editors. *Historical Statistics of the United States*, Volume IV, Cambridge University Press, 2006: 7-10.

Olmstead, Alan L., and Paul W. Rhode. 2008. *Creating Abundance: Biological Innovation and American Agricultural Development*, Cambridge University Press, 2008.

President's Great Plains Drought Area Committee, *Report*. August 27, 1936. http://newdeal.feri.org/Hopkins/hop27.htm.

Rogers, John S., and Jesse W. Collier. 1952. "Corn Production in Texas," *Texas Agricultural Experiment Station Bulletin* (746) February 1952.

Russell, W. A. 1984. "Agronomic Performance of Maize Cultivators Representing Different Eras of Breeding," *Maydica* (29) 1984: 375-390.

Ryan, Bryce, and Neal Gross. 1950. "Acceptance and Diffusion of Hybrid Corn Seed in Two Iowa Communities," *[Iowa] Agricultural Experiment Station Research Bulletin* (372) January 1950.

Schlesinger Jr., Arthur. 2000. "Who Was Henry A. Wallace? The Story of a Perplexing and Indomitably Naive Public Servant," *Los Angles Times* 12 March 2000.

Schubert, Siegfried D.; Max J. Suarez,, Philip J. Pegion; Randal D. Koster; and Julio T. Bacmeister. 2004. "On the Cause of the 1930s Dust Bowl," *Science* 303 (19 March 2004): 1855-1859.

Shaw, Lawrence H., and Donald D. Durost. 1965. *The Effect of Weather and Technology on Corn Yields in the Corn Belt, 1929-62*. U.S. Department of Agriculture, Economic Research Service, Agricultural Economic Report Number 80, 1965.

Smil, Vaclav. 2001. *Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production,* MIT Press, 2001.

Smith, C. Wayne; Javier Betrán; and E. C. A. Runge, editors. 2004. *Corn: Origin, History, Technology, and Production*, Wiley, 2004.

Sprague, G. F. 1946. "The Experimental Basis for Hybrid Maize," *Biological Reviews of the Cambridge Philosophical Society* 21(3) July 1946: 101-120.

Sutch, Richard. 2008. "Henry Agard Wallace, The Iowa Corn Yield Tests, and the Adoption of Hybrid Corn," *National Bureau of Economic Research Working Paper,* Number 14141, June 2008.

Troyer, Forest. 2004. "Persistent and Popular Germplasm in Seventy Centuries of Corn Evolution." In C. Wayne Smith, Javier Betrán and E.C.A. Runge, editors, *Corn: Origin, History, Technology, and Production*, Wiley, 2004: Chapter 1.4.

U.S. Department of Agriculture. 1940. *Technology of the Farm,* Government Printing Office, 1940.

U. S. Department of Agriculture, Bureau of Agricultural Economics. 1948. *Tobaccos of the United States,* Government Printing Office, July, 1948.

U.S. Department of Agriculture, National Agricultural Statistics Service. 2004. *Historical Track Records*. [Internet publication], April 2004.

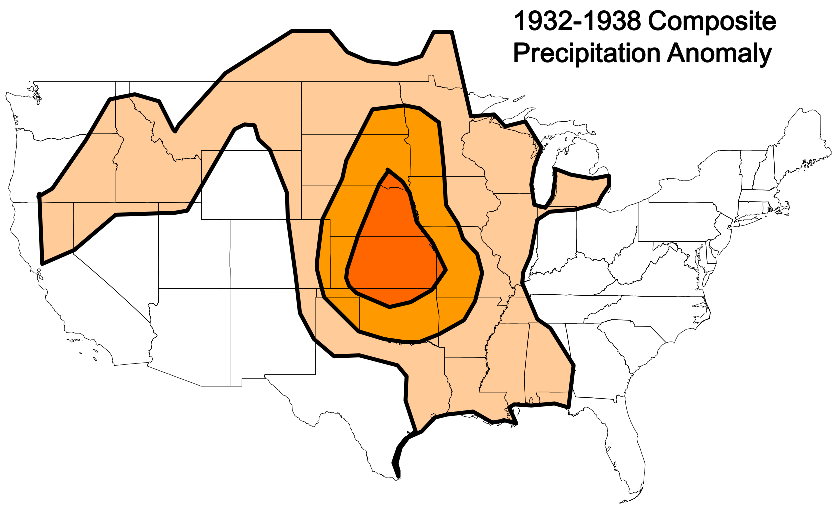
U.S. Department of Agriculture. 1945-1962. *Agricultural Statistics,* Government Printing Office, annual editions.

Wallace, Henry Agard [Secretary of Agriculture]. 1936. *Yearbook of Agriculture, 1936,* Government Printing Office, 1936.

Wallace, Henry Agard. 1920. *Agricultural Prices*, Wallace Publishing Company, 1920.

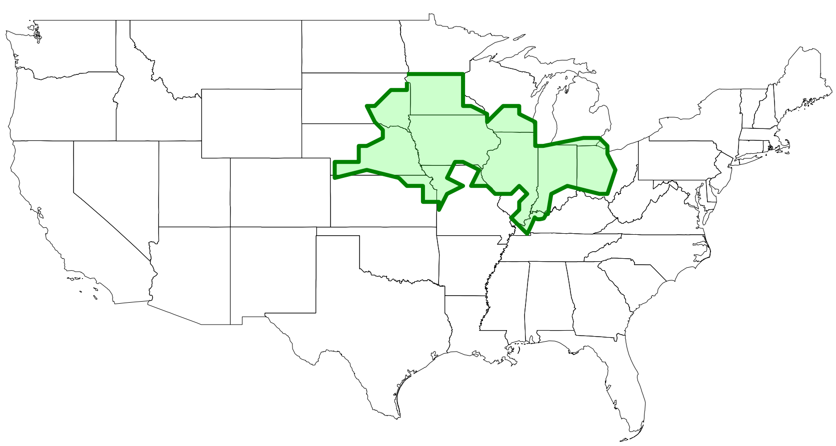
Wisner, Robert N., and E. Dean Baldwin. 2004. "Corn Marketing." In C. Wayne Smith, Javier Betrán and E. C. A. Runge, editors, *Corn: Origin, History, Technology, and Production,* Wiley, 2004: Chapter 3.8.

Zuber, Marcus S., and Joe L. Robinson. 1941. "The 1940 Iowa Corn Yield Test," *[Iowa] Agricultural Experiment Station Bulletin* P19(NS) February 1941: 519-593.



Based on Schubert, Suarez, et al [2004] Figure 1, p. 1855.

The American Corn Belt



Based on the 1950 Census of Agriculture. Counties with 25 percent or more of acreage planted to corn.

Figure 1

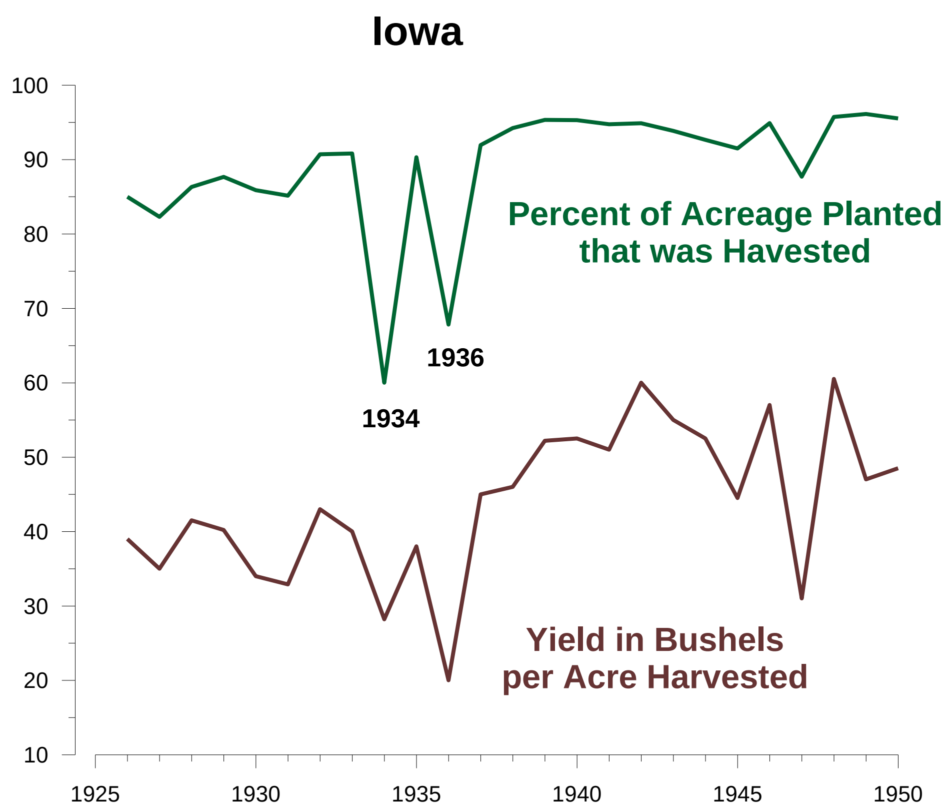

Iowa
Percent of Acreage Planted
that was Havested
1936
1934
Yield in Bushels
per Acre Harvested
100
90
80
70
60
50
40
30
20
10
1925
1930
1935
1940
1945
1950

Figure 2

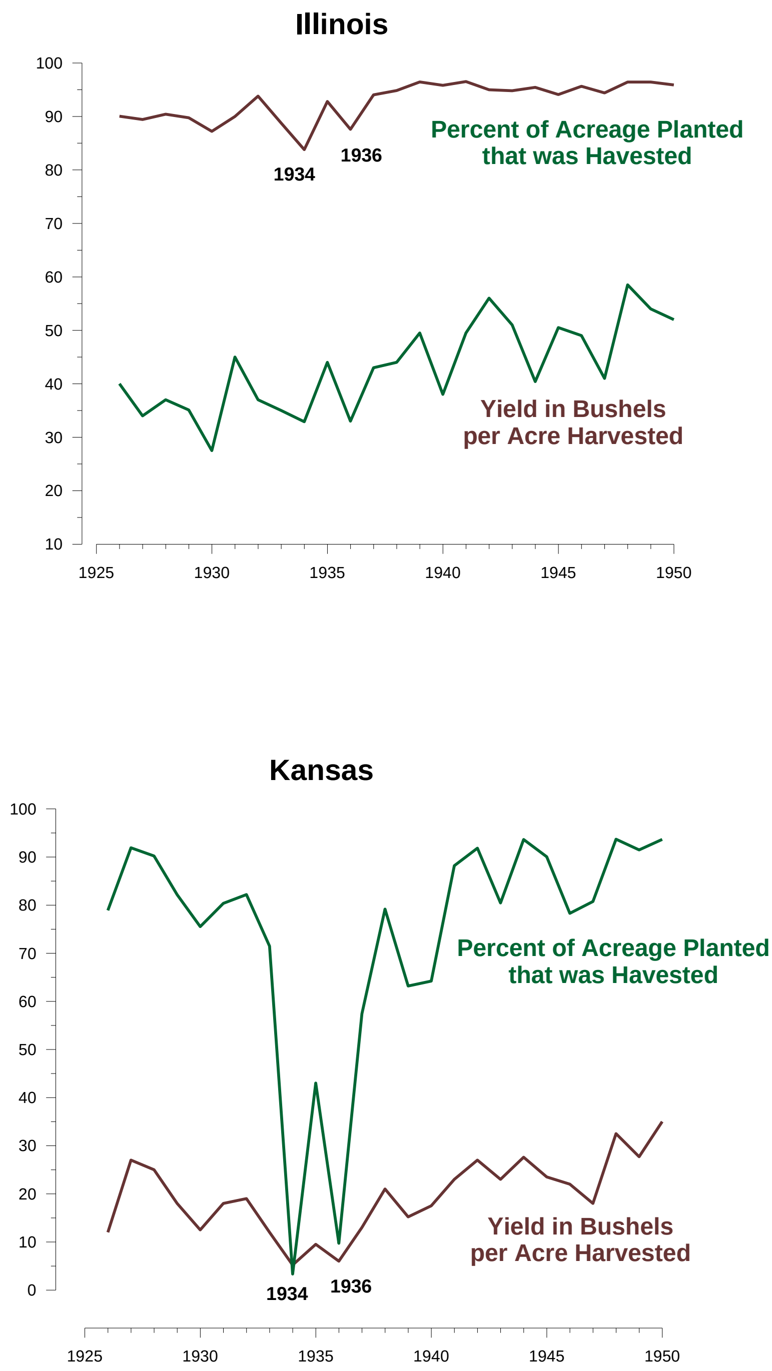
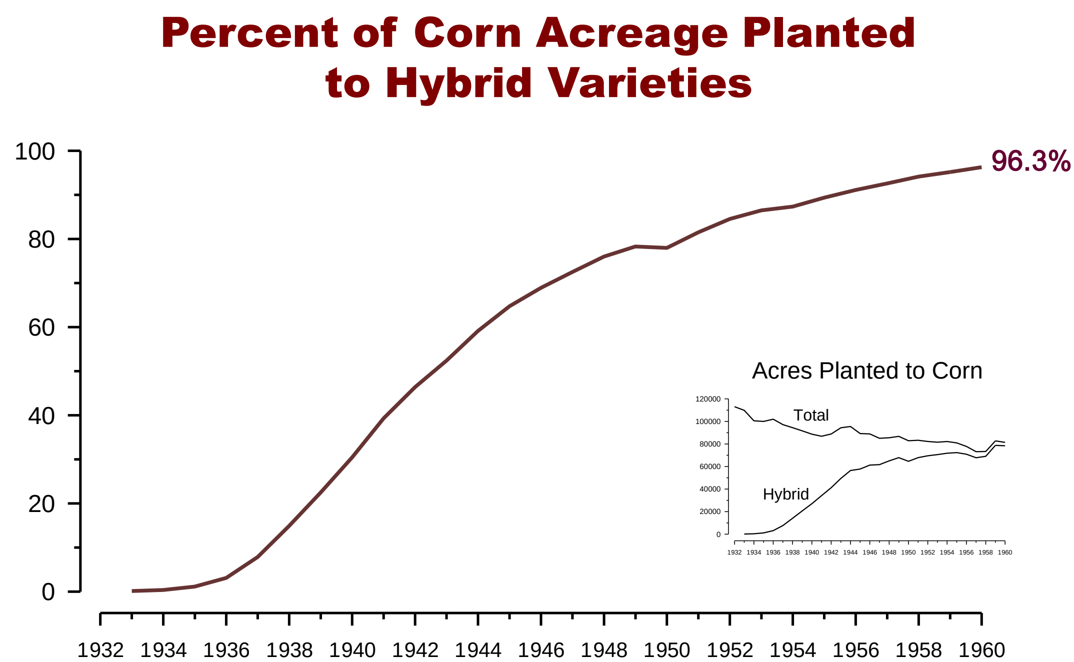
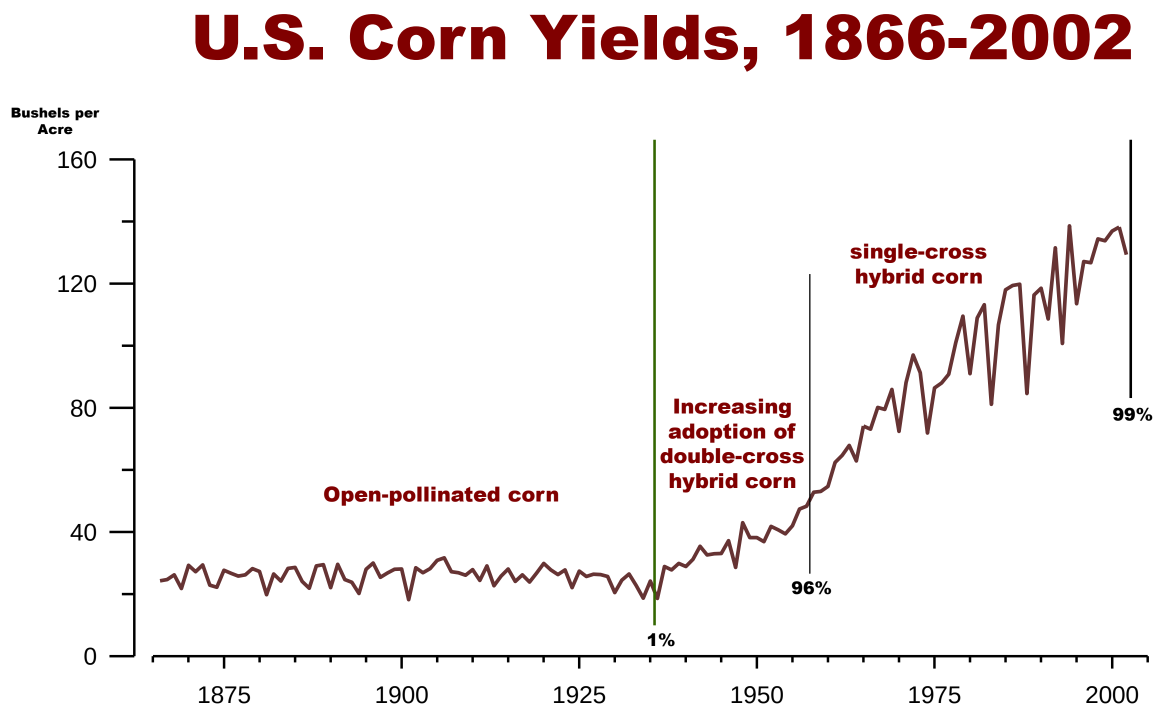

Illinois
100
90
80
70
60
50
40
30
20
10
1925
1930
1935
1940
1945
1950
1934
1936
Percent of Acreage Planted
that was Havested
Yield in Bushels
per Acre Harvested
Kansas
100
90
80
70
60
50
40
30
20
10
0
1925
1930
1935
1940
1945
1950
1934
1936
Percent of Acreage Planted
that was Havested
Yield in Bushels
per Acre Harvested

Figure 3



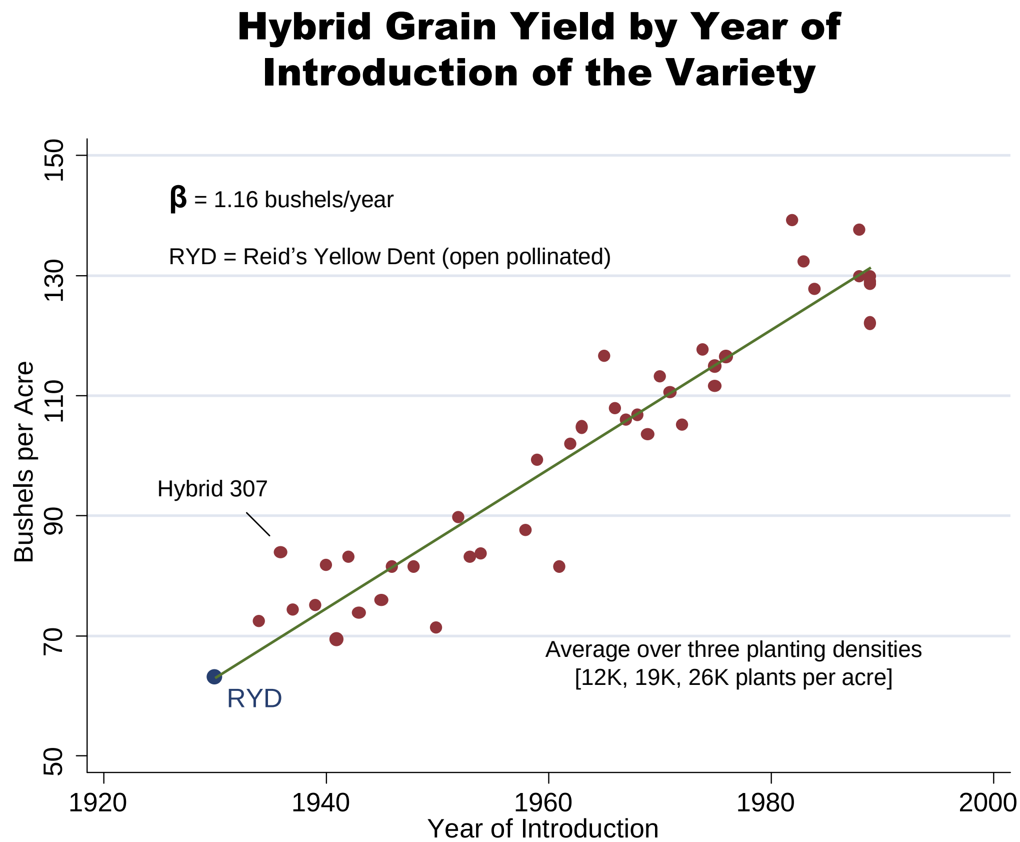
Source: Acreage planted to hybrid seed corn from USDA, *Agricultural Statistics*, 1962, Table 46, p. 41, divided by acreage planted to corn from USDA, National Agricultural Statistics Service, *Historical Track Records*, April 2004, p.19.

Figure 4



Source: Carter, et al. 2006: Series Da693-694. USDA, National Agricultural Statistics Service, 2004: 7 & 9.

Figure 5



Source: Dan N. Duvick, "Genetic Contributions to Advances in Yield of U.S. Maize," *Maydica* (37) 1992: 69-79; Table 3, p. 73.

Figure 6

Iowa Corn Yield Tests, 1926-1940

Relative Average Yield for all Hybrid Varieties
All Open-Pollinated Varieties = 100

District	1926	1927	1928	1929	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940
1	117	109	110	109	114	116	115	114	112	111	107	107	115	110	108
2	105	117	120	124	113	*	102	110	101	109	118	109	109	115	122
3	97	103	109	114	111	106	102	107	119	106	126	112	118	114	+
4	116	105	110	110	116	112	107	129	111	121	*	108	114	113	121
5	107	111	108	108	114	113	108	128	108	107	129	114	112	107	127
6	105	110	103	103	105	109	106	116	106	103	117	108	117	116	115
7	105	103	114	109	113	107	112	109	*	122	*	150	131	120	121
10	111	102	111	108	102	105	102				140	133	120	141	132
8	104	98	115	109	124	108	110	114	149	113	127	109	112	112	116
11	103	114	108	112	111	106	111				154	114	134	115	#
9	105	102	114	114	106	107	106	105	115	105	149	114	106	110	122
12	110	107	104	106	103	102	100				141	118	115	108	118

*** Crop lost -- drought**
+ Poor crop -- "not calculated"
 # Crop abandoned -- wire worms

Note: For 1933-1935 districts 10, 11, and 12 were combined with districts 7, 8, and 9 respectively.

Source: Marcus S. Zuber and Joe L. Robinson, "The 1940 Iowa Corn Yield Test,
[Iowa] Agricultural Experiment Station Bulletin P19 NS, February 1941:589.

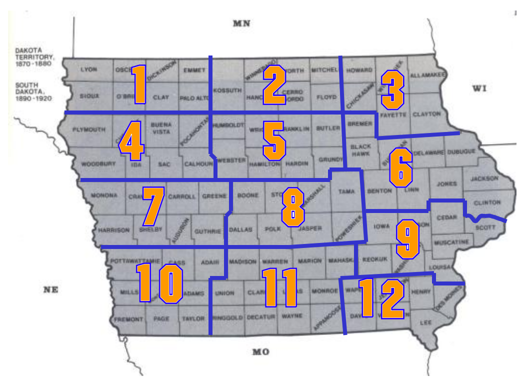


Figure 7

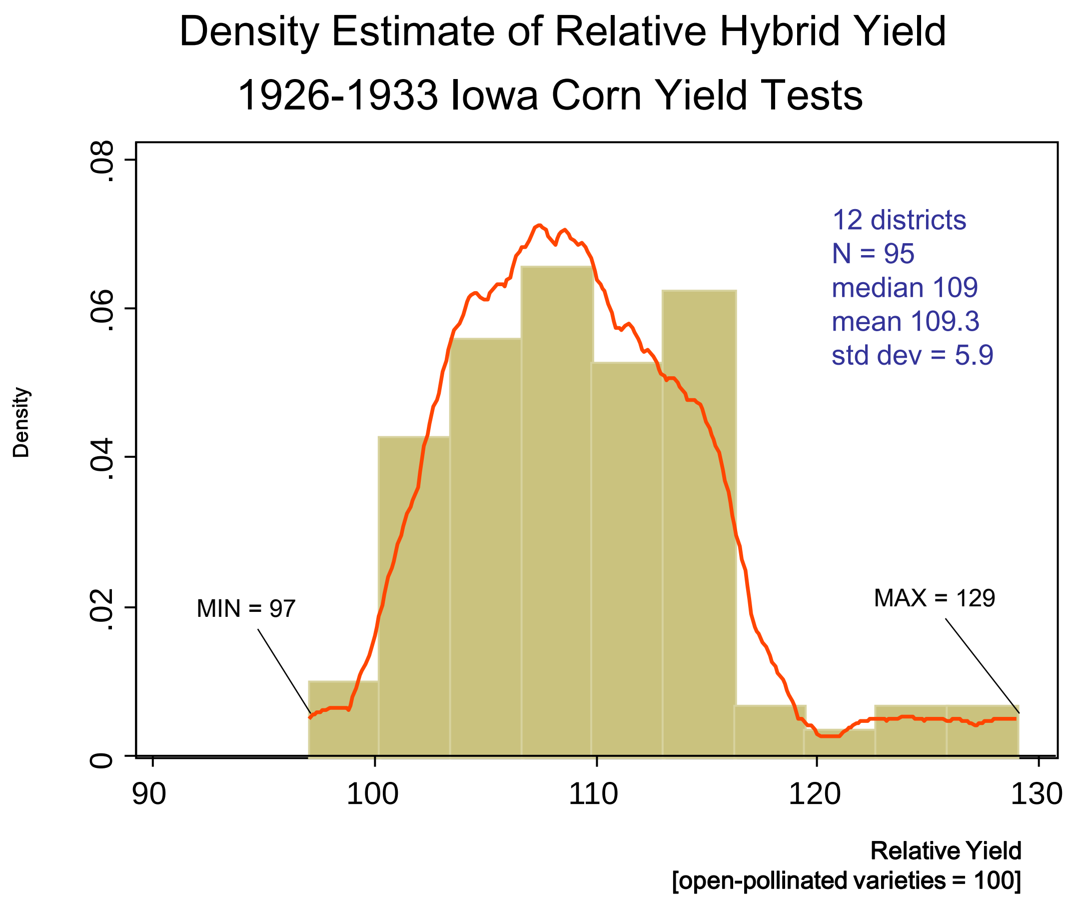

Density Estimate of Relative Hybrid Yield
1926-1933 Iowa Corn Yield Tests
Density
0
.02
.04
.06
.08
90
100
110
120
130
12 districts
N = 95
median 109
mean 109.3
std dev = 5.9
MIN = 97
MAX = 129
Relative Yield
[open-pollinated varieties = 100]

Figure 8

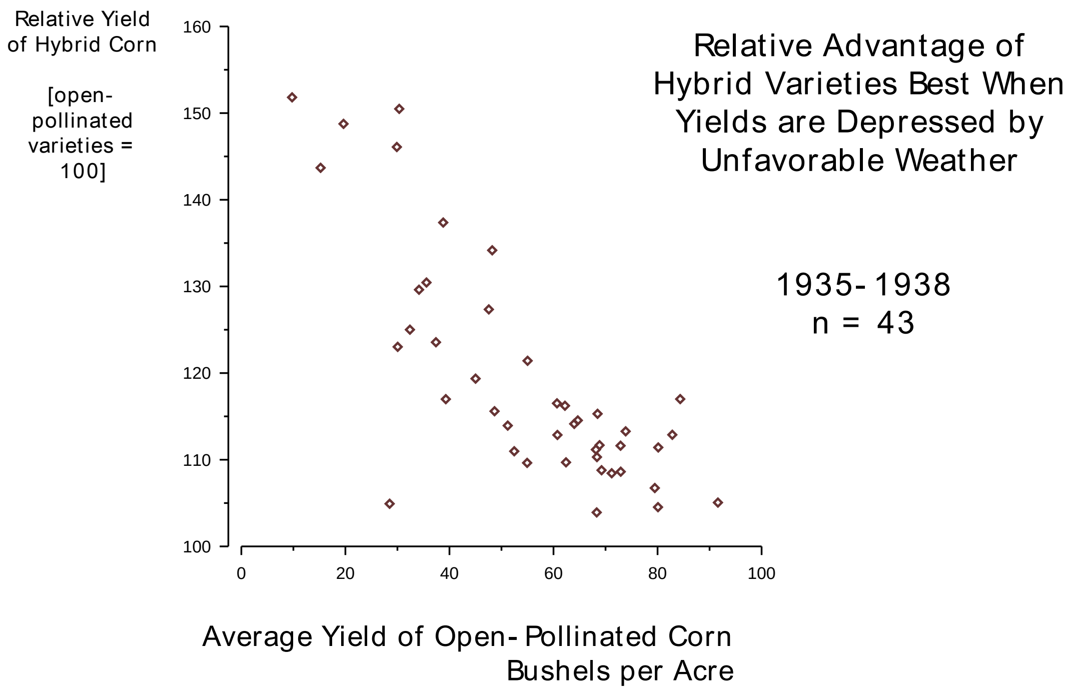

Relative Yield
of Hybrid Corn
[open-
pollinated
varieties =
100]
160
150
140
130
120
110
100
0
20
40
60
80
100
Relative Advantage of
Hybrid Varieties Best When
Yields are Depressed by
Unfavorable Weather
1935-1938
n = 43
Average Yield of Open-Pollinated Corn
Bushels per Acre

Figure 9

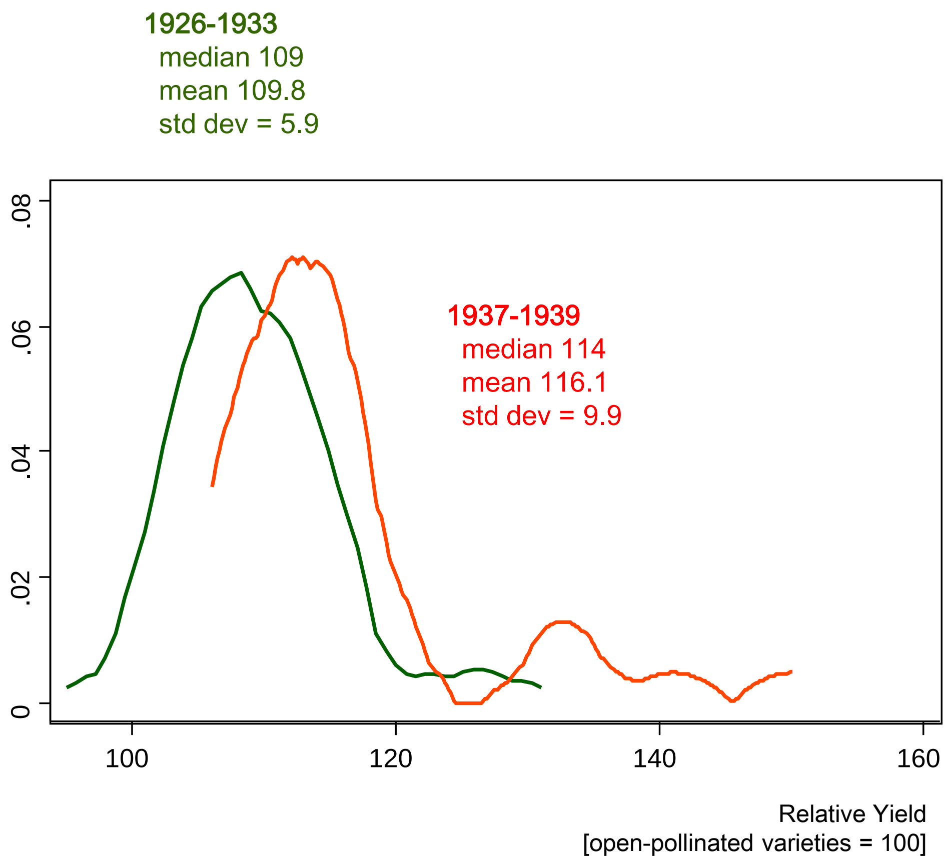

1926-1933
median 109
mean 109.8
std dev = 5.9
1937-1939
median 114
mean 116.1
std dev = 9.9
0
.02
.04
.06
.08
100
120
140
160
Relative Yield
[open-pollinated varieties = 100]

Figure 10

Regression Estimates of the Reaction to the Severity of the 1936 Drought
44 Crop Districts in the Corn Belt

	Dependent Variable		
	Penetration	Cautiousness	Jump
Independent Variables:			
Yield	-0.257	-0.068	1.067
Shortfall	-0.015	-0.011	0.074
Constant	1948.2	6.02	-30.17
R-squared	0.668	0.125	0.464
Mean of Dependent Variable	1938.89	3.272	9.145
Standard Error of Dependent Variable	0.23	0.138	1.143

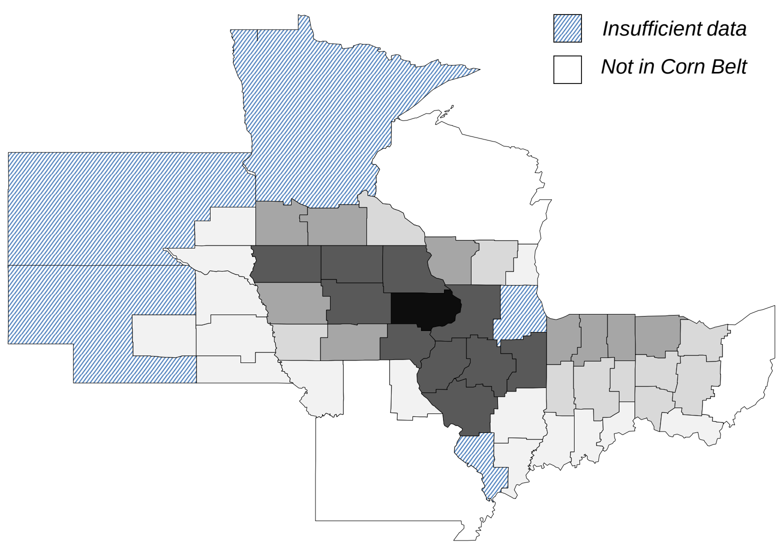


Figure 11