# The Impact of the 1934-36 Corn-Belt Drought on the Adoption of Hybrid Corn

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ABSTRACT

This research report is background for my presentation. It is drawn from Sutch [2007] which makes the following claims:

1] There was *not* an unambiguous yield advantage of hybrid corn over the open-pollinated varieties before 1936.

2] The early adoption of hybrid corn 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 campaign echoed that of the commercial seed companies.

3] The early adopters of hybrid seed were followed by later adopters as a consequence of the droughts of 1934 and 1936. The eventual improvement of yields as newer varieties were introduced explains the continuation and acceleration of the process.

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Every economist knows the story of hybrid corn. Zvi Griliches (1930-1999) made the adoption of hybrid varieties in the United States the exemplar for his model of technological diffusion [Griliches 1957]. This classic article is taught in every graduate program and routinely receives over twenty Web of Science citations a year. As evidence of its iconic status, the article's citation counts have been rising steadily over the last half century [Diamond 2004: 380]. Reproducing data originally collected by the Department of Agriculture's Statistical Reporting Service on the percentage of corn acreage planted with hybrid seed, Griliches observed a lazy **s**-shaped cumulative logistic diffusion pattern. Figure 1 returns to the original data and extends the coverage to 1960 (the last date available). It illustrates the well-known shape.

Hybrid corn (technically "double-cross inbred-hybrid corn") was "invented" by Donald 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 1921. His hybrid won first place in 1924. Commercial adoption began in 1932 [Olmstead 2006: IV-9; May 1949: 513; Zuber and Robinson 1941: 589]. In 1933 about 0.1 percent of the nation's corn acreage was planted to the new 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]. Griliches considered the adoption pattern displayed in Figure 1 to have been remarkably rapid [Griliches 1957: 502].

Griliches's explanation for the rapidity and the completeness of the 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 and suggested that that superiority was established in 1935 and persisted thereafter.[1] The advantage of hybrids, according to Griliches, could be objectively

[1] 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

measured by the relative increase in yield over the open-pollinated corn [pp. 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 district was one of disequilibrium transition. 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 somewhat by the supply lags in developing and introducing hybrid varieties tailored to the specific soil type, weather conditions, and latitude of the peripheral regions.[2] But even this process was rapid. Using the rule of thumb suggested by Griliches to mark the start of an adoption process in a follower region as the date that five percent of acreage was planted to hybrid corn, Iowa in 1935 was followed by Illinois and Wisconsin in 1936, by Indiana, Minnesota, and Ohio in 1937, and Nebraska in 1938.[3] See Figure 2.

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 1944:101].[4] In a chart that is perhaps even

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development had passed the experimental stage and that superior hybrids were available to farmers in commercial quantities" [Griliches 1957: 507]. The region where this breakthrough occurred was the Sixth Iowa Crop Reporting District [1957: Table II, p. 508]. The sixth district comprised Bremer, Black Hawk, Benton, Buchanan, Linn, Delaware, Jones, Dubuque, Jackson, and Clinton Counties, all in Iowa.

[2] Paul David, in an insightful review, has criticized the Griliches approach "for lacking any real micro-level technology choice model" [David 2003:5]. 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.

[3] 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).

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

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 3 reproduces the chart that has been reproduced dozens of time in the scientific literature.[5] 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 1935.[6] Thereafter yields began to increase and they have continued to do so ever since. Yields per acre rose from an average of 25 bushels per acre before 1935 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 1935 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 increase 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 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. Even then high

[5] As an indication of how ubiquitously Figure 3 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].

[6] Alan Olmstead and Paul Rhode [forthcoming] have challenged the notion of a biological stasis before 1935. They view the stability of yields before 1935 as due to a balance of conflicting forces some of which would depress yields and counterbalancing ones that worked to raise yields. I thank them for allowing me an advanced look at their manuscript. I have collected supporting evidence on their finding, which I find to be plausible, but this is not the place to introduce that material.

density was possible only with the heavy application of fertilizer. Increased planting densities required the abandonment of the horse and the need for a 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.[7] Since hybrid seed, synthetic fertilizer, and gasoline tractors were a necessary triad, it is not really possible to partition responsibility for the yield increases between them.

The continuing improvement in the performance of hybrids after their initial introduction is an important part of the story. Figure 4 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 4 illustrates, yields advanced at an average rate of 1.16 bushels per acre per year throughout this 55-year period.

Despite the undeniable improvement in plant traits and the obvious appeal of the Griliches adoption story, this report makes the following claims:

1] There was *not* an unambiguous yield advantage of hybrid corn over the open-pollinated varieties in 1935.

2] The early adoption of hybrid corn 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 producers of hybrid seed. The early adopters of hybrid seed were followed by later adopters as a consequence of the droughts of 1934 and 1936. The eventual improvement of yields as newer varieties were

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[7] On several of these points see: Castleberry, Crum, and Krull [1984: 33].

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 harvest one's own seed, adoption tended to be irreversible.

3] The biological revolution in corn, commonly associated with the introduction of hybrid varieties, was not a unique phenomenon. Indeed, we find remarkably similar "hockey stick graphs" for the yields per acre in cotton, wheat, tobacco, oats, potatoes, and barley. The discovery of an economical process to synthesize ammonia and the resulting increase in the use of commercial fertilizers are the more likely sources of the increase in yields of so many other crops during this period.

**Hybrid Vigor 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 1957: 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 (consult Figure 2). The 1940 USDA report cited the claims of "plant breeders" [Griliches 1957:517].[8] 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

[8] 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."

99.5 percent hybrid planting was reported [Sprague 1946: Figure 1, p. 101].[9] 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 decade.

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.[10] Beginning with the Iowa Agricultural Experiment Station in the early-1920s, many of the Stations in corn-belt 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.

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[9] 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.

[10] Although not cited in his published *Econometrica* article [1957], Griliches's unpublished PhD 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*, 1957: 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 calculus decision toward adoption, and thus they would bias the argument against the claim I make in this paper that the hybrid advantage was not large enough to encourage early adoptions.

For the Iowa tests the State was partitioned into 12 districts, shown in the inset map in Figure 5. 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 5 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.

American corn, or more properly, "maize" (*Zea mays,* L.) is native to North America.[11] 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 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-polination is known to be very low. If this fertilization process is left to the wind, selective breeding

[11] 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].

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.[12] 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.[13] 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.

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

[12] 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: ].

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

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 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 5 were double-cross varieties. The trial results reveal that for the period 1926-1934 the average yield advantage of the hybrids was 9.8 percent (averaging across the 12 districts and 109 observations). It is clear that an advantage of 15 to 20 percent would be an exaggeration for this period. See Figure 6. Note, too, that 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 10 percentage advantage reported by the Iowa

Experiment Station. Also it is clear from the table in Figure 5 that the relative gain in the period 1935 to 1938 was considerably higher, 19.3 percent, suggesting that Griliches's 15-20 percent would be an accurate claim for the last half of the decade.[14]

Can we say that the higher 15-20 percent yield advantage after 1934 translated into an *economic* advantage? Before we can do so, we much factor in at least three additional considerations: (1) the high price of hybrid corn seed, (2) the lower nutritional content of hybrid corn, and (3) the fixed and variable costs of fertilizer and tractors.

According to the USDA's Agricultural Marketing Service, the average price of hybrid seed for 1935-1939 was $8.77 per bushel, while the average cost of open-pollinated seed was $2.35 per bushel [AMS 1957]. For farmers who saved and replanted their seed, the oportunity cost would be the farm-gate price of field corn which averaged only 65.6 cents per bushel in those years [Carter *et al* 2006: Series Da687]. The difference in seed costs were thus between $6.42 and $8.11, approximately the value of 10 to 12 bushels of field corn per bushel of hybrid seed. Whether the gain in yield would cover this cost depends upon the seeding rate, that is, the number of acres that would be covered by a bushel of seed. Seeding rates varied widely depending upon the local practice. Figure 7 presents several observations that may be relevant. Drilling corn, a practice used in the mid-nineteenth century, required more than a bushel of seed per acre. At that rate the gain in number of bushels achieved per acre that would warrant the extra cost of the seed would be approximately ten bushels. The current practice today, as reported by Donald Duvick [1992: 71], is a seeding rate of 2.9 acres per bushel, which would require a 3.4 bushel-per-acre gain. The table in Figure 7 displays three observations relevant to the corn-belt in the 1930s. They range from a seeding rate of 1.3 acres per bushel to 2.2 acres per bushel. Thus the required gain per acre would range

[14] This increase in the relative yield advantage of hybrid corn is consistent with the evidence displayed in Figure 4 obtained (largely) by extrapolating backward from the post 1940 progress. Figure 4 has only three observations for 1934-1938, they are: 1934, 14.9 percent; 1936, 32.9 percent (for hybrid number 307); and 1937, 17.7 percent [Duvick 1992: Table 3, p. 73].

from 4.5 to 7.7 bushels. The seeding rate deemed "typical of central Iowa" by Duvick would require an anticipated gain of five bushels.

Can such gains have been anticipated in the late 1930s? Figure 8 provides an answer in the form of a histogram displaying the Iowa Corn Test results for 1935-1938. With 43 observations the average expected gain in bushels per acre from using hybrid seed was 8.5 bushels. This definitely exceeds the five bushels per acre required to justify the high cost of hybrid seed.[15] But we may wish to take into account another consideration. The nutritional content of hybrid corn is only 93 percent that of open-pollinated corn [Morison 1940, Jennings 1958]. An adjustment for this factor would shift the yield distribution to the left as shown in Figure 9.

Whether farmers recognized that hybrid corn was less nutritional and thus more would be required for animal feed and thus (presumably) it would sell for less are open questions, so Figure 9 displays both the adjusted and unadjusted distributions. If we take the required gain to be 5 bushels it is clear that adoption would probably make probabilistic sense for risk takers even with the nutritional adjustment and for risk-neutral farmers if the nutritional content of the corn is neglected. This conclusion applies to the period after 1934, not to the early period when hybrid seed prices were certainly higher and the yield gains less certain. The large impact of seed costs on corn farmers in the 1930s and 1940s is suggested by the chart in Figure 10 that plots seed costs as a percentage of all production costs for all of agriculture for the entire country.

## Henry Agard Wallace and Hybrid Hype

The puzzle then is why some adventurous farmers were willing to adopt hybrid corn before 1934, before its economic superiority was demonstrated by controlled tests. My suggestion has two parts: (1) there was an aggressive marketing campaign launched by

[15] I am assuming that the average Iowa farmer could achieve the same bushel gain as the test farmers. Griliches would have argued that they would not. If he was right, then my test is biased toward recommending adoption.

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.[16] He was an early champion of scientific farming, a path-breaking plant scientist, a talented statistician and geneticist, American'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.[17] 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, according to historian Arthur Schlesinger Jr [2000], America's best Secretary of Agriculture.[18] 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

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[16] 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.

[17] 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].

[18] 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].

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.

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. 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 corns 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, of course, high profits helped cover the cost of on-going research intended to improve the varieties [pp. 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 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 [Culver and Hyde 2000: 91]. Typically, only one farmer on each lane was offered the deal with the hope that a demonstration effect 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. By 1934 only 2.1 percent of Iowa's corn was hybrid. The Depression had sent the market price of corn 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] 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 of about 9 percent revealed by the Iowa Corn Tests at this time were, as we have already pointed out, generally insufficient to justify the cost of seed.[19]

[19] During the Depression Hi-Bred seed was selling for $6.00 a bushel [Culver and Hyde 2000: 91] 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. Expecting no more than 32 cents per bushel for the crop when sold, the advantage of the hybrid seed would have had to have been great indeed. 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].

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 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. See Figure 11.

What the droughts starkly demonstrated was that the *relative* yield of hybrid corn was greatest when the *absolute* yields were generally depressed. Figure 12 reveals the relationship using, once again, the Iowa Corn Yield Test results to illustrate the relationship. 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 4). 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.[20] The research in both sectors was closely co-coordinated. According to Sprague [1945: 101] there was unrestricted 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].

[20] 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].

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. 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]. Consult Figure 4 again, where number 307 is labeled for easy identification.

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 1934 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. 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 introduced 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.

## Ammonia and Tractors

We might close on this note, but there is one point worth adding. This takes us back to Figure 2 and the idea that the yield advances after 1935 can be attributed exclusively to the adoption of hybrid corn and its continuing improvement. Certainly the "hockey-stick graph" displayed in Figure 2 is an almost irresistible piece of evidence. Yet an important curiosity, not reported in the academic literature on corn yields, is that the same hockey-stick profile with the same transition date is seen in most other crops. Wheat, cotton, potatoes, barley, tobacco, oats; they all display the same time series profile. See Figure 13.

Hybridization cannot explain similar spurts in yield per acre in these other crops. Plant breeders have yet to successfully develop commercial hybrids for any of them.[21] Indeed, very different stories have been told about each crop. For example, the advances in cotton yields between 1935 and 1965 have been attributed to increasing participation in the Smith-Doxey Cotton Grading Program [Olmstead and Rhode 2003]. The advances in tobacco yields are attributed to the acreage reductions under the AAA and "better cultural practices" [USDA, "Tobaccos of the United States," 1948: 30]. The story usually told for wheat involves the cross-breeding of short and semi-dwarf varieties from Asia [Dalrymple 1986 and 1988: Figure 2, p. 81]. The only common element that explains productivity advances in all of these crops, including corn, is the introduction of synthetic fertilizer.

[21] Hybridization is technically feasible for many field crops other than corn but is generally-speaking not economical [Fuglie, Ballenger, et al 1996: 34]. Sorghum and sugar beets are two exceptions. However, many of the flower and vegetable seeds sold to individual consumers are hybrids. For an account of the unsuccessful effort to develop hybrid wheat see Knudson and Ruttan [1988].

Vaclav Smil makes the case that "the single most important change affecting the world's population – its expansion from 1.6 billion people in 1900 to today's 6 billion – would not have been possible without the synthesis of ammonia" [Smil 2001: xiii]. The nitrogen in ammonia ($NH_3$) is the key. Plants need nitrogen but they cannot absorb it from the air. The nitrogen must be "fixed" as in ammonia or ammonium nitrate ($NH_4NO_3$). Decomposing plant material can return fixed nitrogen to the soil, nitrogen-fixing bacteria can manufacture ammonia, and lightening can oxidize nitrogen. Nonetheless, on heavily-cropped land, a shortage of fixed nitrogen can become the bottleneck that prevents crop yields from being sustained year after year. Thus the invention of a process to synthesize ammonia by Fritz Haber and the development of a commercially-viable ammonia manufacturing process by Carl Bosch shortly before World War I deserve much of the credit for the explosion of crop yields across so many crops after the mid-1930s.[22] For their work, Haber was awarded the Nobel Prize in 1918; Bosch received his in 1931.

As a consequence of these discoveries, commercial fertilizers became considerably cheaper and their use exploded at precisely the time when the yield per acre in crop after crop began to rise. Indeed, the graph of commercial fertilizer use displayed as Figure 14 displays its own hockey-stick profile.

There is widespread agreement that the adoption and increasing improvement of hybrid corn was accompanied by increasing application of nitrogen fertilizers [Shaw and Durost 1965: Table 21, p. 39; Johnson 1960]. It was also accompanied by the introduction of the tractor and increased planting densities.[23] But these were not

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[22] The timing of these discoveries was important since synthetic ammonia was used by the Germans in the production of explosives and thus probably prolongued the war. Haber also played a major role in the development and deployment of poison gas for the Germans during the war.

[23] In 1939 only 9 percent of the corn was planted using tractor planters in the Corn Belt states. In 1946 the percentage had jumped to 44 percent and 82 percent of the acreage was cultivated with tractors and 64 percent of the acreage was harvested with mechanical corn pickers [USDA, Bureau of Agricultural

independent influences.  Hybrid corn varieties were developed to take maximum advantage of fertilizer and the increased planting densities would not have been possible unless the hybrid varieties could thrive when planted so close together [see Figure 15]. Increased planting densities required the gasoline-powered tractor as well as the heavy application of fertilizer.  Where horse-drawn equipment was employed, reducing the space between corn rows was limited by the physical space required for the horse.

The appealing search for a mono-causal story for the yield advance in corn, I argue, is wrong headed.  The corn yield advance is certainly due to unique circumstances in the industry, but the introduction of hybrid corn being only one of them. Moreover, the story we would tell for corn cannot be generalized to other crops.  Each crop requires its own detailed study with commercial fertilizers, perhaps, the only common element.

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Economics, 1949: Tables 19-20, pp. 58-59].  Also see Alan Olmstead and Paul Rhode [2001] for a general discussion of the diffusion and impact of the tractor.

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