Volume Title: Economics of Research and Innovation in Agriculture

Volume Authors/Editors: Petra Moser, editor

Volume Publisher: University of Chicago Press

Volume ISBNs: 978-0-226-77905-8 (cloth),
978-0-226-77919-5 (electronic)

Volume URL:
https://www.nber.org/books-and-chapters/economics-research-and-innovation-agriculture

Conference Date: May 17, 2019

Publication Date: September 2021

Chapter Title: Yield Performance of Corn under Heat Stress: A Comparison of Hybrid and Open-Pollinated Seeds during a Period of Technological Transformation, 1933–55

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Chapter URL:
https://www.nber.org/books-and-chapters/economics-research-and-innovation-agriculture/yield-performance-corn-under-heat-stress-comparison-hybrid-and-open-pollinated-seeds-during-period

Chapter pages in book: p. 107 – 129

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Yield Performance of Corn under Heat Stress
A Comparison of Hybrid and Open-Pollinated Seeds during a Period of Technological Transformation, 1933–55

Keith Meyers and Paul W. Rhode

3.1 Introduction

The advent of commercially viable hybrid corn seeds in the 1930s preceded a rapid rise in US corn yields over the rest of the 20th century. This technology spread and quickly replaced the once predominant open-pollinated seed varieties grown in the United States. Zvi Griliches's (1957) pathbreaking work used the example of hybrid corn seeds to explain patterns in technological diffusion. Griliches hypothesized that hybrid seeds had a fixed productivity advantage over open-pollinated seeds and increased the potential yield ceiling of corns. Hybrid corn adoption started where (open-pollinated) yields were initially higher, and adoption patterns radiated out from these areas. Other observers including Culver and Hyde (2001) and Sutch (2008, 2011) claim that hybrid corn seeds performed better relative to open-pollinated seeds principally during conditions of drought. Academic research, however, has not determined to what extent hybrid seeds mitigated the effects of drought and heat stress (temperatures generally associated with reductions in corn yields and drought-like conditions).[1] Using uncovered

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For acknowledgments, sources of research support, and disclosure of the authors' material financial relationships, if any, please see https://www.nber.org/books-and-chapters/economics-research-and-innovation-agriculture/yield-performance-corn-under-heat-stress-comparison-hybrid-and-open-pollinated-seeds-during-period.

1. For corn, daily temperature averages in excess of 29°C are associated with reductions in corn yields (Schlenker and Roberts 2009; Schauberger et al. 2017). We also use drought measures as reported in the Palmer drought severity index (PDSI) as a measure of weather stress.

archival records, we study how prolonged periods of abnormal temperatures and dryness affected yields for the two types of corn seed. We use both variables denoting drought and deviations in agronomic measures of growing degree days (GDDs).

The work of economic historians entails the development and rediscovery of novel data sources. Such archival resources contain reams of informative records with granular details that are not available in official digitally curated publications. Through archival work, economic historians can answer otherwise unanswerable questions. In our efforts to understand the hybrid diffusion story, we have located, digitized, and organized a treasure trove of unpublished manuscripts reporting on hybrid corn diffusion and performance at a more granular geographic level than is available in US Department of Agriculture (USDA) publications. Using unpublished documents contained in Zvi Griliches's personal manuscripts and field trial data buried in obscure Iowa experimental station reports, we construct a panel of hybrid and open-pollinated corn yields. With these records, we can ascertain whether hybrid seeds exhibited drought tolerance or if Griliches's assumption that hybrid seeds increased the yield potential overall were correct.

Understanding the relative performance of hybrid versus open-pollinated corn seeds during periods of drought informs our understanding of the mechanisms driving the diffusion of the new technology. The Pioneer Hi-Bred Corn Company introduced the first successful commercial hybrid corn seeds in the early 1930s during a period of extreme farm distress, historically low commodity prices, and adverse weather conditions. While hybrid seeds cost two to three times more than their open-pollinated counterparts, they quickly replaced open-pollinated corns. If hybrid corns exhibited drought tolerance, then those traits could explain the rapid diffusion of hybrid seed technology in response to the distress caused by the Dust Bowl droughts of the 1930s (Dowell and Jesness 1939; Crabb 1947).

Past research studying hybrid corn adoption starts with the pathbreaking work of Zvi Griliches (1957, 1958, 1960, 1980). Griliches's analyses posited that the profitability of the new seed technology, as captured by expected yield improvements, drove adoption. Even though hybrid seeds diffused across the Corn Belt and Great Plains during a period of extreme drought, Griliches did not investigate the effect of weather on adoption. In his preferred specification, Griliches assumed that the new hybrids were superior to the existing open-pollinated varieties by a multiple that did not vary significantly over time, across regions, or over weather conditions.

More recent research contests Griliches's account and suggests that drought shocks in 1934 and 1936 accelerated hybrid adoption (Culver

The PDSI captures drought-like conditions over multiple months due to excess temperatures and water deficits. The PDSI is strongly correlated with measures of soil moisture (Dai and NCAR 2019).

and Hyde 2001; Sutch 2008, 2011). Richard Sutch notes that hybrid seeds remained relatively expensive during the 1930s—a period of historically low commodity prices—and that the geographic pattern of hybrid corn diffusion shows a dependence on local weather conditions. Narrative evidence adds further support. To cite one example, a *New York Times* headline read in 1940, "50% of Corn Crop in Hybrid Species . . . Agricultural Marketing Service Lays Its Popularity to Drought Resistance."[2] Indeed, Sutch (2008, 2011) highlights the USDA's role in promoting the adoption of hybrid seed technology and argues that hybrid corn's tolerance to drought conditions made the technology more salient for farmers. The economic stress of the Great Depression and extreme droughts of the 1930s eroded the wealth of farmers. One would expect slower hybrid adoption under such circumstances. Richard Hornbeck (2012) finds that many of the adaptive responses to the Dust Bowl were relatively slow. In comparison, from 1931 onward, US farmers rapidly adopted hybrid corn. This turn toward hybrids may have mitigated some of the adverse effects of the Dust Bowl. Switching to hybrids was costly. Nevertheless, the varieties produced by hybrid breeders promised beneficial qualities, including higher yields, shortened the time to maturity, stronger root systems, thicker stalks, disease resistance, and drought tolerance.

3.2 Factors Driving Hybrid Adoption and the (Potential) Yield Advantage of Hybrid Corn Seeds

The story of hybrid corn has been told many times (Crabb 1947; Fitzgerald 1990; Kloppenburg 1988; Olmstead and Rhode 2008). For economists, the starting point is Griliches (1957). In his seminal article, Griliches analyzed this "invention of a way to invent" and mapped estimated parameters of the diffusion process into economic variables of supply and demand. He viewed the diffusion process as primarily a shift between two equilibria over time rather than as a shift of equilibria. He fit logistic curves to annual diffusion data for states and crop reporting districts, reducing the differences across regions to differences in three parameters: origins, slopes, and ceilings.[3] The origin represented the year (relative to 1940) when diffusion in an area crossed the 10 percent adoption threshold. Griliches related the origin date to the "availability" of hybrid seed—and more specifically, to

2. "50% of Corn Crop in Hybrid Species . . . Agricultural Marketing Service Lays Its Popularity to Drought Resistance," *New York Times*, September 10, 1940. The text noted the hybrid's advantages of both drought resistance and higher yields.

3. The analysis covered 31 (out of 48) states and 132 (out of 249) crop reporting districts (CRDs) in the period up to 1956. The USDA's Agricultural Marketing Service (ASM) made available unpublished data for the CRDs. Griliches restricted his analysis to observations between 0.05 and 0.95 of his estimated ceiling level, K. The ceiling was estimated in an admittedly ad hoc way by picking the K that makes the resulting diffusion curves plotted on logistic graph paper look linear.

supply-side forces, including the profitability of seed producers, the cost of innovation, and the potential market density. He related the slope (or speed of diffusion) and the ceiling levels to demand-side forces, specifically to the profitability to farmers of using the new seed. Griliches found that the estimated speed of adoption was rather uniform but declined as one moved away from the center of the Corn Belt. The origin date and ceiling level also declined with distance from the center.

Griliches (1957) argued the diffusion process could be interpreted in a way that was consistent with rational, long-run, profit-seeking behavior by seed producers and farmers. He made no reference to adverse weather shocks or the drought-resistance qualities of hybrid varieties.[4] According to his preferred specification, hybrids promised a time- and region-invariant yield increase—in the range of 10–15 percent—over existing open-pollinated varieties. He further argued that including the changing advantages of the new seed, the prices of corn output, or the prices of hybrid seed would add "nothing of significance" to the explanation of the diffusion process.[5]

Griliches (1957) tabulated but did not use USDA data on the prices (per bushel) of hybrid and open-pollinated seed by state (box 59).[6] He argued that the hybrid seed prices did not vary significantly across space and could be ignored in his analysis of the rate of diffusion (which was modeled as a transition between two equilibria). His treatment of hybrid seed prices is problematic for several reasons. The leading seed companies, especially in the early periods, possessed some market power to set hybrid prices. The farmer's adoption decision relied not on the hybrid corn price alone but on the hybrid seed price relative to other prices—for example, the price of open-pollinated seed. In figure 3.1, the average price of hybrid seed at the state level is approximately 2 to 3 times greater than the average price of open-pollinated seed. Over the 1937–57 period, the coefficient of variation of the price of hybrid seed across states averaged approximately 10 percent. The coefficient of variations of the ratio of hybrid to open-pollinated seed was substantially higher, averaging 16 percent. Griliches also ignored changes over time. In the late 1930s, hybrid seed cost about 3.5 times as much as open-pollinated seed. By the mid-1950s, the ratio had fallen roughly in half, to about 1.8 times. Griliches tabulated but did not use state-level data on seeding rates (box 59).[7] Again, he argued the cross-state variation was negligible. The coefficient of variation of seeding rates in bushels per acre was around 18.7 percent.

4. Although weather conditions clearly affected the "availability" of seed on the supply side and the drought-resistance qualities of new seed impacted the farmer profitability and "acceptance" on the demand side, Griliches does not mention weather effects in the text of his work.

5. It should be noted that in the mid-1950s, Griliches did not have access to low-cost computing power to conduct his econometric analysis. His records show calculations made by hand. This helps explain why he sought such parsimonious specification.

6. Griliches relied on a USDA publication entitled "Seed Crops." These data are essentially the same as in USDA (1963).

7. These data were based on USDA (1945, 1949, 1950).

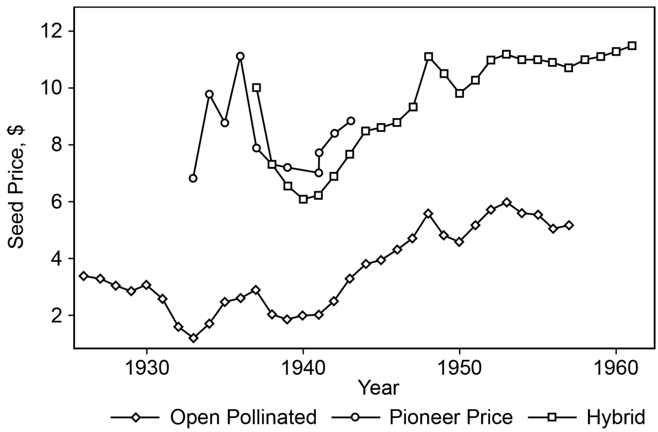

Fig. 3.1 Nominal prices ($) of open-pollinated (OP) and hybrid corn seeds

Sources: Pioneer Company Archives; USDA (1963). Prices paid by farmers for seed: spring season averages, 1926–61: September 15, 1949–61, prices by states and the United States. *Statistical Bulletin* No. 328 (Washington, DC: GPO).

Griliches's pathbreaking work inspired a vigorous scholarly response (see Skinner and Staiger 2007). Sutch (2008, 2011) revisited the early diffusion of hybrid corn, emphasizing the role of adverse weather shocks.[8] Sutch (2008) argued that marketing campaigns and drought stresses (and the 1936 drought in particular) caused farmers to make the costly switch from open-pollinated to hybrid corns. The use of commercial hybrid seed reduced the self-sufficiency of farmers at a time of severe market stress, plausibly increasing risk. Sutch asserted that the early hybrid varieties were not inherently superior to available open-pollinated seeds and that farmers were rightly slow to adopt the expensive seeds in the late 1920s and early 1930s. Sutch (2008, 11) wrote, "During the Depression hybrid seed was selling in Iowa for $6.00 a bushel. Since a bushel of seed would plant two acres, a farmer would have to expect a financial gain of $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 hybrid seed would have had to approach 9 bushels per acre, not the 4–6 seen in the Iowa field tests."[9]

Sutch (2008) argued the adverse weather shocks of the mid-1930s, in

8. Rural sociologists Bruce Ryan and N. C. Gross (1943, 1950) had conducted an earlier study of how Iowa farmers learned about hybrid technologies and how peer effects influenced their adoption decisions. They found that younger and more educated farmers adopted hybrids more readily than older or less educated farmers. They also highlighted the importance of drought conditions on early adoption.

9. Sutch (2008) noted that commodity prices were low and seed was expensive. His analysis did not mention that seed prices were endogenous, set according to market conditions. Nor did he address the subsidies hybrid seed producers gave farmers to adopt hybrids. One strategy seed sellers used to promote adoption was to initially offer farmers enough hybrid seed to plant half a field and take payment as the difference in yields at the end of the growing season.

combination with an intense USDA propaganda campaign, convinced midwestern farmers to adopt the new seed. He noted the conflict of interest that hybrid pioneer Henry A. Wallace faced serving as USDA secretary while retaining ownership of Pioneer Hybrid.[10] Other observers in the 1930s, including the *Chicago Tribune*, were even more critical, arguing the yield-enhancing seed increased crop output at the very time that federal farm programs, run by Wallace, sought to reduce output through acreage restrictions.

Narrative evidence suggests that farmers readily noticed that hybrid corn coped with the dry conditions better than open-pollinated corn planted nearby. As one farmer put it, in these very bad years, the hybrid corn was the last to die (Urban 1975). Singling out the 1936 Dust Bowl drought, Sutch (2011) performed an analysis of hybrid diffusion on state-level data in the Corn Belt in the 1930s and argued that the 1936 drought hastened the adoption of hybrids through learning effects. Sutch was hampered by the lack of comprehensive, geographically decentralized data. He was able to identify records on hybrid and open-pollinated seed productivity only from Iowa. With our new data (or more accurately, newly recovered old data), we seek to address these issues afresh and study hybrid performance from the late 1920s through the 1950s.[11] Combining our data sources allows us to construct a panel of hybrid corn yields, open-pollinated yields, yield differences, hybrid adoption rates, temperature exposure, and precipitation at the crop reporting district (CRD) and year levels for the regions where hybrid seeds first diffused.[12]

3.3 Building Our New Panel Data Set

3.3.1 Data on Hybrid Corn Adoption

The hybrid corn adoption data used in this research project come from unpublished USDA data and notes contained in Zvi Griliches's archival collection held at the Special Collections Library at Harvard University.[13] These data, on the percentage of maize acreage planted in hybrid seed, are available at the level of the CRD. These detailed records—drawn from a grid of roughly nine entries per state—are based on unpublished data from the USDA's Agricultural Marketing Service (AMS). We have recovered these

10. Pioneer was one of the leading commercial seed companies; other leadings hybrid producers at the time included DeKalb, Funk Farms, and Pfister.

11. We thank Richard Sutch for making us aware that the CRD-level diffusion data were available in the Griliches archives.

12. CRDs are relatively equivalent to contemporary agricultural statistics districts.

13. We thank Diane Griliches for allowing access to these materials. We have also sought data at the USDA and AAA collections at the National Archives and the National Agricultural Library.

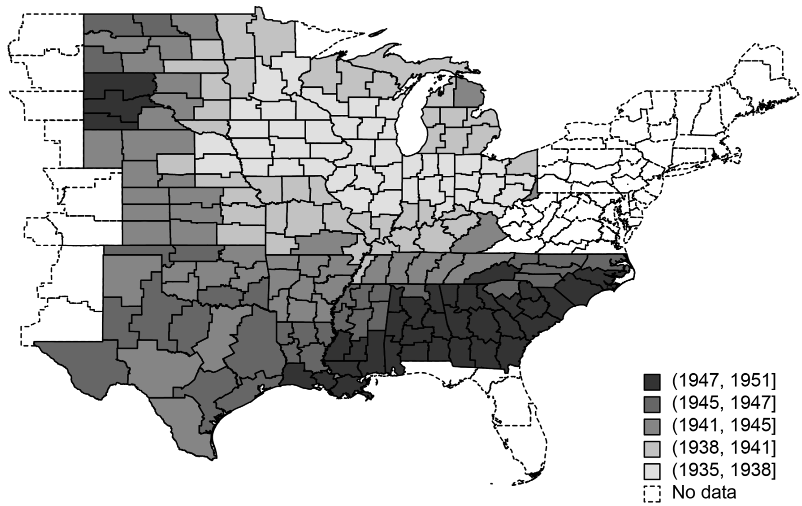

Fig. 3.2 Crop reporting district map, years when hybrid corns exceed 10 percent of planted corn

Source: Compiled from Zvi Griliches's Archival Records.

series for use for the first time since the 1950s. Many previous researchers had to rely on the USDA's state-level data from *Agricultural Statistics*.

The CRD diffusion data were compiled from (1) a set of handwritten spreadsheets for the 1944–55 period; (2) a spreadsheet for Ohio CRDs for the 1935–54 period; (3) very carefully marked diffusion graphs drawn by Griliches's own hand, all in box 58; and (4) typed sheets for all the CRDs in the United States in 1959 in box 60. The graphs indicate the annual rate of diffusion by CRD for each state on a 100-point (or finer) scale covering the period from the first diffusion to 1954/55. The numbers derived from the graphs match exactly those from available nongraphical sources.[14]

The adoption data allow us to define the region of interest for this study. Figure 3.2 visualizes how hybrid corn rapidly diffused across the Corn Belt and the United States in the years following its initial introduction.

3.3.2 Data on Yields of Hybrid and Open-Pollinated Corns

The yield data used in this empirical inquiry come from two primary sources. The first source is the data from experimental farm trials in Iowa

14. We have data for the northeastern states from 1945 on. However, these data do not cover the period of early hybrid adoption in northeastern states. We are seeking to supplement these data but have not been successful in our search for other archival sources. Griliches did collect maps of CRD data from the AAA for the 1938–41 period (box 57). The AAA data have more extensive geographic coverage than the AMS data that Griliches chiefly used. Where there is overlap, the differences are relatively minor.

from 1928 to 1942. These trials, which compared the relative performance of hybrid seeds to open-pollinated seeds, are reported in Zuber and Robinson (1941, 1942). These were the sources that Sutch investigated.[15]

The second source of information on yields is unpublished data held in the Griliches archives. Griliches collected voluminous data on the differential yields achieved by hybrid seed relative to open-pollinated seed. The data, including the results of state yield trials and Agricultural Adjustment Administration (AAA) surveys as well as some yield data, are at the substate level (boxes 57, 60).[16] The CRD data that Griliches actually used in his analysis were derived from AMS studies of "identicals," covering the period from 1939 on (box 59). For early adopting states such as Iowa and Illinois, the series is short because little open-pollinated seed was grown after the mid-1940s. Griliches used the AMS series chiefly in summary form. Note that these data do not allow a direct measurement of the effects of the weather shocks (e.g., droughts) of the mid-1930s. But the Iowa experimental trial yield data do.

Thus Griliches's archival records provide two measures for comparing hybrid and open-pollinated yield differences. For some CRDs, average hybrid and open-pollinated corn yields are available for selected years between 1937 and 1941. Figure 3.3 presents the regions these data cover and the differences between hybrid and open-pollinated yields by quartile.

An alternative measure for the difference between hybrid and open-pollinated yields comes from yield "identicals." These are average differences in hybrid and open-pollinated corn seeds grown on the same farm within a CRD. These "identicals" are more consistently documented in Griliches's archival records. The identical data are reported from 1939 to 1953, have broader geographic coverage than the alternative yield data, and are presented in figure 3.4. With both the seed type yield specific data and "identicals" data, there is a broad geographic coverage. The trade-off with these data is that they cover a time period almost a decade after hybrids had initially entered the market.

The rediscovery and rescue of the yield data, separating open-pollinated and hybrid yields by CRD, again demonstrate the value of archival research. Zvi Griliches was a preeminent researcher who collected and analyzed the pertinent evidence relevant to his study. He knew the importance of making direct comparisons of the yields of corn varieties under comparable settings, at the same time, and in the same place. He collected data from experiment

15. Sutch (2011) described ratios from Iowa corn yield tests as representing all varieties tested. But the data are in fact for *reporting* section varieties, the subset of varieties entered in tests in all three districts in a section. Records from Iowa reports average yield for all and section varieties for 1928–32 ratios for all and the section subset are reported. The average hybrid to openpollinated yield ratio was 1.1069 for all varieties entered but 1.095 for section varieties. A further issue with the test data is that the districts and trial locations change (marginally) over time. How these inconsistencies affect the comparison is unclear, a priori.

16. The substate regions covered do not always translate directly into CRDs.

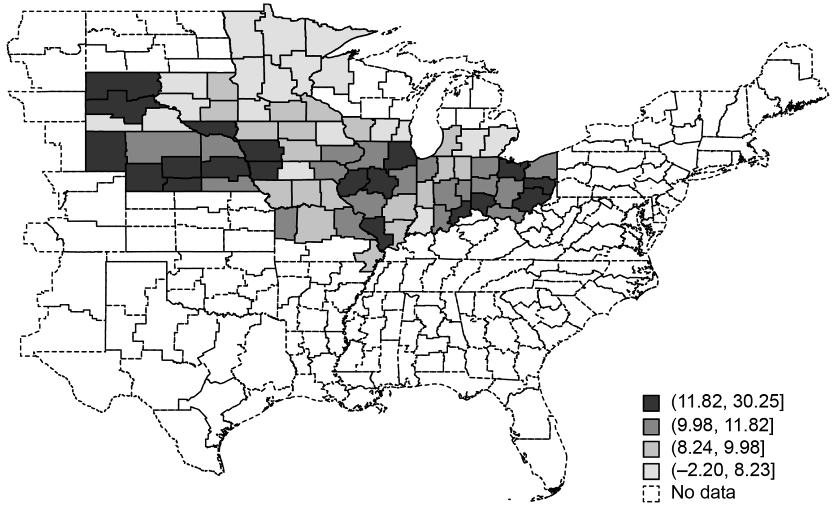

Fig. 3.3 Average hybrid minus average open-pollinated corn yield per acre, quartiles, 1937–41

Source: Griliches's Archival Records.

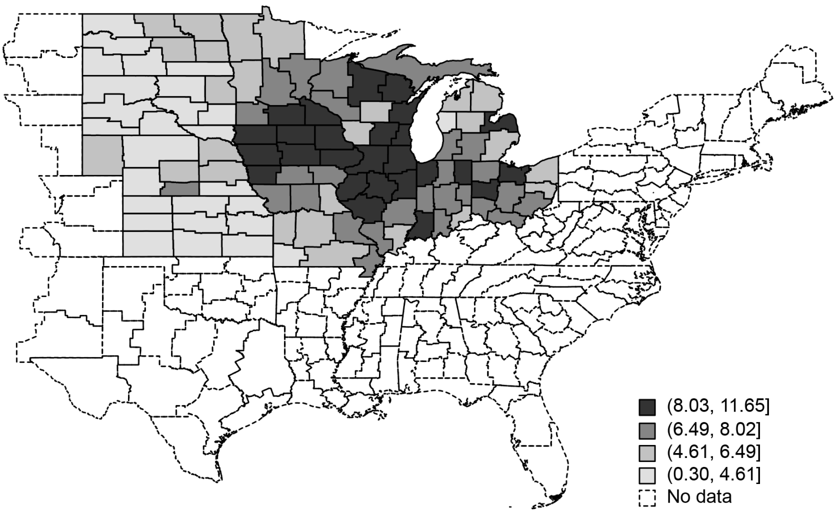

Fig. 3.4 "Yield identicals" per acre, quartiles, 1939–53

Source: Griliches's Archival Records.

station trials and real-world production of identical farms. In his model, the yield difference drove adoption, and hence Griliches sought independent measures of the gap.

3.3.3 Data on Weather

The weather data used in this study also come from two sources. The first is the Palmer drought severity index (PDSI) derived from the Global Historic Climatology Network (Menne et al. 2012). Drought conditions are generally associated with prolonged periods of above-average temperatures and moisture deficits. The PDSI utilized a hydrological accounting model to assess cumulative departure in surface water balance. The PDSI captures drought conditions over a multimonth period and is strongly correlated with observed soil moisture levels (Dai and NCAR 2019).[17]

Extreme deviations in temperature are also often correlated with drought. Therefore, we use temperature and precipitation from Schlenker and Roberts (2009) as our second measure of weather variation.[18] GDDs are aggregations of daily temperature conditions and a common measure utilized in the literature studying climate change and agriculture. Such measures account for deviations in aggregate temperature exposure over a period of time but do not necessarily discern differences between more mild, prolonged temperature spikes and shorter, more extreme temperature spikes. Schlenker and Roberts's information on GDDs is based on the PRISM weather data set.[19] The raw data consist of daily minimum and maximum temperatures as well as total precipitation on a 2.5-by-2.5-mile grid of the continental United States. For each CRD, we use this gridded data to calculate the average daily minimum and maximum temperatures along with total daily precipitation. We then construct GDDs in accordance with agronomically observed heat sensitivity in corn yields, heat in excess of 29°C (Schlenker and Roberts 2009; Schauberger et al. 2017). For each growing season, defined as lasting from April 1 to September 30, we calculate the total number of moderate GDDs and extreme GDDs.

$$(1) \qquad GDD = \begin{cases} \frac{T_{max} - T_{min}}{2} - T_{base} & \text{if } \frac{T_{max} - T_{min}}{2} > T_{base} \\ 0 & \text{if } \frac{T_{max} - T_{min}}{2} \leq T_{base} \end{cases}.$$

The equation above defines a GDD as the average daily temperature calculated between the daily maximum temperature, T_{max}, and daily minimum

17. The index is normalized around 0, with values greater than 0 associated with abnormally wet conditions for a specific region and values less 0 zero associated with abnormally dry conditions for a specific region. Values on the index between −1 and −2 denote mild drought conditions, values between −2 and −3 denote moderate drought conditions, and values less than −3 denote extreme drought conditions.

18. We thank Michael Roberts for recommending that we use this source.

19. See the website at http://prism.oregonstate.edu.

temperature, T_{min}, minus some base temperature, T_{base}. A GDD measures the amount of heat exposure crops receive during a specific day and takes a value of zero for days below T_{base}. Following the example of Schlenker and Roberts (2009), we differentiate between two measures of heat exposure for corn for each CRD for each year from 1920 to 1955 using GDD. We first sum up the number of GDD between 10°C and 29°C during the growing season as moderate GDDs. This calculation assumes a base temperature of 10°C. We sum days with average temperatures in excess of 29°C as extreme GDDs (and assume a base temperature of 29°C in this calculation). In addition to these heat measures, we also total the amount of precipitation during the growing season.

3.4 Empirical Analysis of Our Panel Data Set

3.4.1 Summary Statistics

Tables 3.1 and 3.2 describe the two unbalanced samples constructed for the analysis. In the hybrid and open-pollinated yields sample, most data are for the years 1939 to 1941 and do coincide with the end of the Dust Bowl drought waves. The yield-identical data span from 1939 to 1953 and

Table 3.1 Summary statistics of hybrid and open-pollinated yields sample

Variable	Observations	Mean	Std. dev.	Min	Max
Hybrid yield per acre	211	51.430	15.069	13	97.969
Open-pollinated yield per acre	211	40.669	15.854	3.8	90.092
Yield difference	211	10.761	4.8226	2	31.700
Moderate drought, PDSI	211	0.531	0.500	0	1
Extreme drought, PDSI	211	0.289	0.454	0	1
Moderate growing degree days	211	1,773.318	228.086	1,181.853	2,433.123
Extreme growing degree days	211	60.205	29.489	12.248	146.674
Precipitation	211	0.545	0.113	0.254	0.879
Precipitation squared	211	0.310	0.128	0.065	0.773
Year	211	1,939.787	1.103	1,937	1,941

Table 3.2 Summary statistics of yield identicals sample

Variable	Observations	Mean	Std. dev.	Min	Max
Yield identical	989	6.029	3.148	0.1	31
Moderate drought, PDSI	989	0.568	0.500	0	1
Extreme drought, PDSI	989	0.267	0.442	0	1
Moderate growing degree days	989	1,581.220	348.529	841.531	2433.123
Extreme growing degree days	989	47.621	38.649	0.721	214.064
Precipitation	989	0.547	0.160	0.197	1.233
Precipitation squared	989	0.325	0.199	0.039	1.519
Year	989	1,944.219	3.876	1,939	1,953

Table 3.3 **Summary statistics of Iowa experimental trials sample**

Variable	Observations	Mean	Std. dev.	Min	Max
Yield ratio, hybrid/open-pollinated	170	114.303	10.585	97.4	153.9
Moderate drought, PDSI	170	0.5	0.515	0	1
Extreme drought, PDSI	170	0.224	0.418	0	1
Moderate growing degree days	170	1,688.860	155.203	1,289.026	2,091.285
Extreme growing degree days	170	57.457	35.310	9.589	206.420
Precipitation	170	0.567	0.088	0.394	0.841
Precipitation squared	170	0.329	0.105	0.155	0.708
Year	170	1,933.565	4.740	1,926	1,941

have broader geographic coverage and more variability in their measures of heat exposure and precipitation. The difference between hybrid corn and open-pollinated yields is on average 10.8 bushels of corn per acre. The yield identical finds a smaller difference of 6 bushels per acre for corns grown on the same farm.

Table 3.3 summarizes the Iowa experimental trial data from 1928 to 1942. The ratio of hybrid corn yields to open-pollinated yields ranges from 97.4 to 153.4 and is on average 114.3. These data suggest that hybrid corn seeds outperformed open-pollinated corns by 14.3 percent between 1926 and 1941. This average is consistent with Griliches's claims.[20]

3.4.2 Empirical Method and Results

To assess the relationship between drought and yield performance of hybrid and open-pollinated corns, we run the following regression specification:

$$y_{it} = \theta_1 MD + \theta_2 ED_{it} + \alpha_i + \gamma_t + \varepsilon_{it}. \quad (2)$$

The variable y_{it} denotes the natural log of the corn yields, yield difference, or yield identical in CRD i in year t. In the Iowa trials data, y_{it}, denote the ratio of hybrid yields divided by open-pollinated yields. These outcomes are regressed on moderate and extreme drought indicator variables constructed from the PDSI, MD_{it}, and ED_{it}. We construct these drought indicators from the average PDSI over the growing season (April–September). Time-invariant effects specific to each CRD are controlled for by using CRD fixed effects, α_i, and a quadratic time trend, γ_t, controls for potential underlying trends, such as concurrent changes in technology, shared across CRDs. Heteroskedastic standard errors, ε_{it}, are clustered at the state (or CRD) level to account for potential correlation in the errors shared across CRDs from the same state.

20. As Sutch (2011) notes, Griliches did not fully credit the yield gaps reports in the Iowa corn yield test data because the farmers engaged in the test program were plausibly not representative of the farm population and achieved yields that were substantially higher than those commonly prevailing.

To assess the effects of heat exposure on the yield performance of hybrid and open-pollinated corns, we run the following linear regression specification:

$$(3) \quad y_{it} = \theta_1 \mathrm{MGDD}_{it} + \theta_2 \mathrm{EGDD}_{it} + \delta_1 \mathrm{Prec}_{it} + \delta_2 \mathrm{Prec}^2 + \alpha_i + \gamma_t + \varepsilon_{it}.$$

The specification using GDDs follows the predominant paradigm used in the agricultural economics literature. The outcomes of interest, corn yields, are regressed on the temperature measures of moderate and extreme GDDs, MGDD_{it} and EGDD_{it}. To address the relationship between corn yields and rainfall we control for growing season precipitation quadratically with PREC_{it} and PREC_{it}^2.

3.4.3 Iowa Experimental Farm Results, 1926–42

Much of the foundational work on developing commercial hybrid corn seeds occurred in Iowa. We use experimental farm data from Zuber and Robinson (1941, 1942) to study the relationship between heat stress and the performance of hybrid corns relative to open-pollinated corns. The data from the Iowa corn yield tests allow us to study hybrid performance when commercial hybrids are introduced and novel. They also let us study hybrid performance during early waves of the Dust Bowl droughts. Figure 3.5 suggests that hybrid yield performance in Iowa was much greater in 1936, a year of extreme Dust Bowl drought, relative to open-pollinated seed lines. It appears the pattern in hybrid to open-pollinated yield ratios starts to shift upward in 1936. Both the floor and average of the ratios also increase until 1942. The last year that yields for open-pollinated corns are reported in Iowa

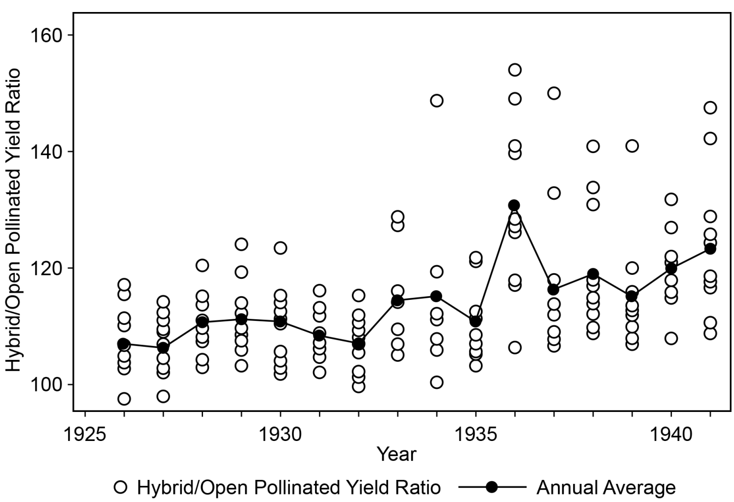

Fig. 3.5 Hybrid to open-pollinated corn yield ratios, Iowa trials data, 1926–41
Source: Authors' tabulation.

Table 3.4 Drought and Iowa hybrid and open-pollinated corn ratios, 1926–41

	Iowa yield ratio (1)	Iowa yield ratio (2)
Moderate drought, PDSI	1.22031	1.64091
	(1.32036)	(1.34115)
Extreme drought, PDSI	6.45368***	14.31629***
	(2.16306)	(3.39188)
CRD fixed effects	Yes	Yes
Quad. time trend	Yes	No
Year fixed effects	No	Yes
Sample	1926–41	1926–41
N	170	170
Adj. R^2	0.251	0.449

Robust standard errors are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 3.5 Extreme heat and Iowa hybrid and open-pollinated corn ratios, 1926–41

	Iowa yield ratio (1)	Iowa yield ratio (2)
Moderate GDD, 10°–29°C	−0.02343***	−0.02925
	(0.00867)	(0.03604)
Extreme GDD, > 29°C	0.21526***	0.41668***
	(0.04057)	(0.09231)
Precipitation, meters	−12.79066	24.73739
	(65.88781)	(80.88737)
Precipitation^2	14.94762	−17.50428
	(51.77032)	(65.28811)
CRD fixed effects	Yes	Yes
Quad. time trend	Yes	No
Year fixed effects	No	Yes
Sample	1926–41	1926–41
N	170	170
Adj. R^2	0.391	0.488

Robust standard errors are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

stations is 1942. This is because hybrid corn seed technology had come to dominate corn production in Iowa by that time.

In table 3.4, we regress the Iowa yield ratio against the moderate and extreme drought indicator variables. Moderate drought does not seem to have a differential effect on the relative performance of hybrid seed corn relative to open-pollinated corn. Both specifications (2) and (3) find that extreme drought increases the relative performance of hybrids to open-pollinated corns substantially and indicate that hybrids in the Iowa field trials exhibited some drought tolerance while the open-pollinated corns failed.

In table 3.5, we regress the Iowa yield ratio against the temperature and

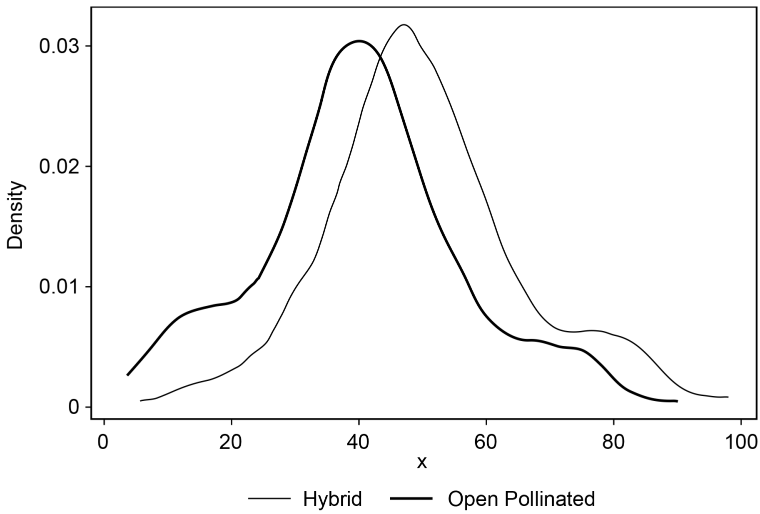

Fig. 3.6 Kernel density plots of hybrid and open-pollinated corn yields, various ranges between 1937 and 1941

Source: Authors' tabulation.

precipitation data. We find results that are consistent with Sutch's (2011) arguments about the role that drought played in diffusion. Specification (2) finds that moderate GDDs decrease the relative performance of hybrids, and the effect is statistically significant at the 1 percent level. A 100-unit increase in moderate GDDs decreases the ratio by 2.3. The statistical significance of the negative effect of moderate GDDs is sensitive to the choice of quadratic time trends or year fixed effects. The coefficients for extreme GDDs show that the relative performance of hybrids increased during periods of extreme heat. In specification (2), a 100-unit increase in extreme GDDs increases the ratio by 21.5 and by 41.7 in specification (3). In both specifications, the coefficients are statistically significant at the 1 percent level. These results support the narrative accounts that hybrid corns performed much better than open-pollinated corns during periods of drought.

3.4.4 Variety-Specific Yield and Yield-Identical Regressions

The yields of hybrid seed corn and open-pollinated seed corn appear to have a fixed gap on average. The kernel density plots of variety-specific yields in figure 3.6 suggest that hybrid seeds shifted the yield distribution to the right. Limiting the sample to CRDs experiencing a drought in a year provides a similar pattern.[21] Figure 3.7 presents kernel density plots of variety-specific yields, and the peaks of the distributions are in similar locations to

21. We define drought as moderate or worse on the PDSI (a value less than −2).

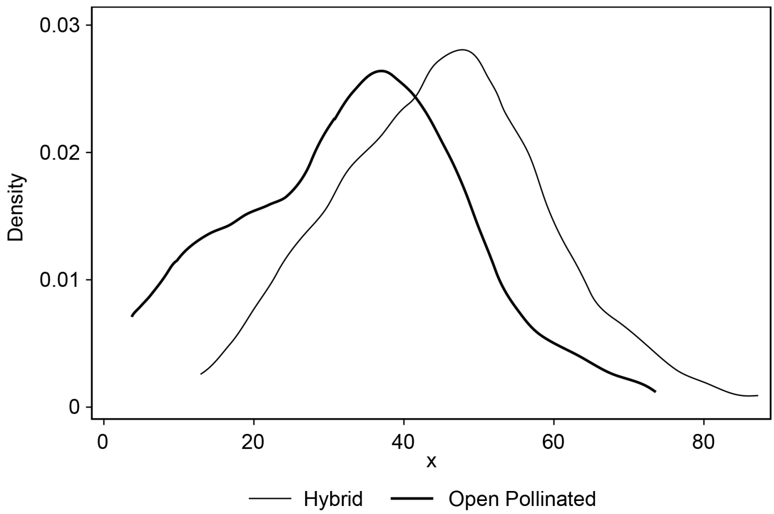

Fig. 3.7 Kernel density plots of hybrid and open-pollinated corn yields under drought conditions, various ranges between 1937 and 1941
Source: Authors' tabulation.

those in figure 3.6. The distribution of yields during droughts shifts probability mass toward the left, but there does not appear to be a stark contrast between the two figures suggesting drought-specific vigor in hybrid seeds relative to open-pollinated seeds. Our regression analysis using yield-specific data further suggests that hybrid seeds were not necessarily drought tolerant relative to open-pollinated seeds.

Columns (1), (2), and (3) in table 3.6 report the effects of moderate and extreme drought on hybrid and open-pollinated corn yields. These yields are averages per acre of specific seeds within each CRD. Column (4) reports the effects of temperature and precipitation on yield "identicals," which is the average difference in hybrid and open-pollinated yields for farms where both seed types were grown. The results from columns (1) and (2) suggest that moderate drought did not strongly reduce hybrid or open-pollinated yields. Extreme drought decreases both hybrid and open-pollinated yields, and the effects are significant at the 5 percent level and below. Nevertheless, the extreme drought indicator variable does not find a strong statistically significant change in either the yield gap or yield "identical" variables. Table 3.7 provides an alternative specification where quadratic time trends are replaced with year fixed effects.

Tables 3.8 and 3.9 report the relationship between GDDs and precipitation on the measures of hybrid versus open-pollinated performance. In table 3.7, the results from columns (1) and (2) suggest that corn yields increase for

Table 3.6 **Regression results, effect of palmer drought severity index drought measures on corn yields, quadratic time trends**

	ln(hybrid yield per acre) (1)	ln(open-pollinated yield per acre) (2)	ln(yield difference) (3)	ln(yield identical) (4)
Moderate drought, PDSI	−0.04312	−0.03525	−0.04267	−0.04166
	(0.03872)	(0.04083)	(0.06336)	(0.04742)
	[0.02462]*	[0.02867]	[0.05517]	[0.04121]
Extreme drought, PDSI	−0.12809	−0.15996	−0.05841	−0.07761
	(0.04796)**	(0.07718)*	(0.09487)	(0.03967)*
	[0.03173]***	[0.04594]***	[0.06713]	[0.05908]
CRD fixed effects	Yes	Yes	Yes	Yes
Quad. time trend	Yes	Yes	Yes	Yes
Sample	1937–41	1937–41	1937–41	1939–53
N	212	212	211	989
Adj. R^2	0.760	0.824	0.471	0.346

Standard errors in parentheses are clustered by state. Standard errors clustered by crop reporting district are in brackets. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 3.7 **Regression results, effect of PDSI index drought measures on corn yields, year fixed effects**

	ln(hybrid yield per acre) (1)	ln(open-pollinated yield per acre) (2)	ln(yield difference) (3)	ln(yield identical) (4)
Moderate drought, PDSI	−0.02516	−0.03045	0.01987	−0.03732
	(0.03830)	(0.04180)	(0.06250)	(0.04316)
Extreme drought, PDSI	[0.02267]	[0.02857]	[0.06014]	[0.04327]
	−0.09129	−0.14050	0.02762	−0.06327
	(0.07218)	(0.10992)	(0.07857)	(0.05739)
	[0.03849]**	[0.05543]**	[0.07215]	[0.07011]
CRD fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Sample	1937–41	1937–41	1937–41	1939–53
N	212	212	211	989
Adj. R^2	0.771	0.824	0.490	0.354

Standard errors in parentheses are clustered by state. Standard errors clustered by CRD are in brackets. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

both hybrid and open-pollinated corns under moderate GDDs. However, the regression coefficients are essentially the same and suggest that 100 additional moderate GDDs increase corn yields by approximately 6.7 percent (the coefficients are statistically significant at the 1 percent level). Column (3) presents some evidence that hybrid corns perform better relative to open-

Table 3.8 **Regression results, effect of heat stress on corn yields, quadratic time trends**

	ln(hybrid yield per acre) (1)	ln(open-pollinated yield per acre) (2)	ln(yield difference) (3)	ln(yield identical) (4)
Moderate GDD, 10°–29°C	0.00065	0.00066	0.00047	0.00041
	(0.00012)***	(0.00017)***	(0.00035)	(0.00023)*
	[0.00009]***	[0.00012]***	[0.00021]**	[0.00022]*
Extreme GDD, > 29°C	−0.00720	−0.01086	0.00055	−0.00362
	(0.00224)**	(0.00415)**	(0.00382)	(0.00157)**
	[0.00154]***	[0.00243]***	[0.00271]	[0.00136]***
Precipitation, meters	0.05134	1.28623	0.52408	2.16976
	(1.49331)	(1.51984)	(2.34221)	(0.78107)**
	[1.13843]	[1.34332]	[2.03963]	[0.62225]***
Precipitation^2	−0.249615	−1.311283	−0.750254	−1.577880
	(1.22555)	(1.19457)	(2.04302)	(0.49249)***
	[0.93803]	[1.10756]	[1.71669]	[0.42972]***
CRD fixed effects	Yes	Yes	Yes	Yes
Quad. time trend	Yes	Yes	Yes	Yes
Sample	1937–41	1937–41	1937–41	1939–53
N	212	212	211	989
Adj. R^2	0.812	0.876	0.487	0.364

Standard errors in parentheses are clustered by state. Standard errors clustered by CRD are in brackets. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table 3.9 **Alternative specification, regression results, effect of heat stress on corn yields, year fixed effects**

	ln(hybrid yield per acre) (1)	ln(open-pollinated yield per acre) (2)	ln(yield difference) (3)	ln(yield identical) (4)
Moderate GDD, 10°–29°C	0.00068	0.00083	−0.00133	−0.00031
	(0.00061)	(0.00080)	(0.00155)	(0.00022)
	[0.00051]	[0.000579]	[0.00111]	[0.00039]
Extreme GDD, 29°C	−0.00749	−0.01135	0.00308	−0.00250
	(0.00284)**	(0.00477)**	(0.00459)	(0.00151)
	[0.00175]***	[0.00274]***	[0.00338]	[0.00164]
Precipitation, meters	−0.44043	1.018168	−3.05435	1.441982
	(1.62519)	(1.67158)	(2.75151)	(0.86282)
	[1.57646]	[1.84648]	[2.93167]	[0.72885]*
Precipitation^2	0.261705	−0.98615	2.33118	−0.95899
	(1.29111)	(1.24845)	(2.12156)	(0.60857)
	[1.30403]	[1.54234]	[2.45383]	[0.49951]*
CRD fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Sample	1937–41	1937–41	1937–41	1939–53
N	212	212	211	989
Adj. R^2	0.810	0.874	0.498	0.366

Standard errors in parentheses are clustered by state. Standard errors clustered by CRD are in brackets. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

pollinated corns. The yield gap between the two hybrid and open-pollinated varieties increases with additional moderate GDDs, with a 100-unit increase in moderate GDDs increasing the yield gap by 0.48 percent (this result is statistically significant at the 5 percent level when standard errors are clustered at the CRD level). The outcomes for yield "identicals" in column (4) corroborate this result and suggest that a 100-unit increase in moderate GDDs raises the yield gap by 0.42 percent (this result is statistically significant at the 10 percent level under both state and CRD clustered errors).

Extreme GDDs negatively affect the performance of both hybrid and open-pollinated corns. According to columns (1) and (2) in table 3.8, a 100-unit increase in extreme GDDs reduces hybrid corn yields per acre by approximately 51.3 percent and reduces open-pollinated corn yields by 66.2 percent (both coefficients are statistically significant at the 5 percent level). However, there is no statistically significant difference in the gap between the two varieties observed in column (3). According to the yield "identicals" regression in column (4), additional extreme GDDs reduce the performance of hybrids relative to open-pollinated corns. An additional 100 extreme GDDs reduces the yield "identicals" by 30.4 percent (this effect is statistically significant at the 5 percent and 1 percent levels depending on clustering). Only in column (4) does total precipitation during the growing season appear to affect the observed difference in hybrid corn and open-pollinated corn yields. In columns (1) through (3), we find no statistically significant relationship between corn yields and changes in precipitation. This gap appears to be increasing in magnitude until total annual precipitation exceeds 68.7 centimeters, and rainfall decreases hybrid performance relative to open-pollinated corns once total rainfall exceeds 137.3 centimeters. In table 3.9, we present an alternative specification using year fixed effects in place of the quadratic time trends. For all specifications, this change removes all statistical significance associated with moderate GDDs. The statistical significance for the negative effect of extreme GDDs on the yield "identicals" also attenuates. For the hybrid and open-pollinated corn yields, this specification change does not appear to alter yield sensitivity to extreme GDDs. Using year fixed effects does not substantively change the coefficients or statistical significance of extreme GDDs in specifications (2) and (3).

3.5 Conclusion

Our work returning to the original source materials used by Griliches reveals that hybrid seeds increased productivity in corns over a wide range of weather conditions rather than principally during droughts. This finding is consistent with Griliches's assumption that hybrid seed technology increased overall yield potential. We find little evidence that hybrid corn seeds performed differentially better than open-pollinated seeds in periods of drought. If hybrid corns exhibited a unique tolerance toward drought, then we would expect that the difference between hybrid and open-pollinated corn yields to increase in periods of drought. The measures of yield difference suggest that drought conditions decreased the relative advantages of hybrid corns over open-pollinated corns. The evidence using GDDs also does not support the narrative that hybrid seeds outperformed open-pollinated seeds when exposed to extreme temperatures. If anything, the yield advantage of hybrids may have increased during periods of moderate temperatures. Our results indicate that the main benefit hybrid seeds provide in mitigating the adverse effects of drought and extreme temperature is their overall increase in the yield ceiling. This increase in yields cushions the adverse effects of drought.

The arguments made by rural sociologists and historians regarding drought-tolerant hybrids derive from the experiences of early hybrid adopters in Iowa and seem particular to that region during the Dust Bowl. For CRDs in Iowa from 1928 to 1942, extreme temperatures increased the yield performance of hybrid seeds relative to open-pollinated seeds. This evidence is consistent with the claims of Richard Sutch and the rural sociologists regarding the drought-tolerant nature of hybrids. In Iowa, hybrid corns outperformed their open-pollinated contemporaries. The patterns we uncover are consistent with a scenario where farmers' preferences for drought tolerance drove hybrid adoption. Nevertheless, seed producers were introducing a tremendous variety of hybrid seed lines and hybrid varieties marketed outside of Iowa after the period of the Dust Bowl. From the data, it appears these varieties did not exhibit the same drought-resistant characteristics observed in the Iowa experimental field trials.

Appendix

In figures 3.A1 and 3.A2, we plot fitted quadric lines to the data to highlight the relationship between moderate and extreme GDDs and corn yields. We construct estimated hybrid and open-pollinated corn yields using data on harvested corn acreage and output from the National Agricultural Statistics Service's Quick Stats 2.0 program, the yield "identical," and information on share of acreage planted as hybrid corn.[22] This descriptive evidence suggests that hybrid performance increases more under moderate GDDs than open-pollinated corns. It also suggests that the difference in yields is either fixed or decreasing in response to extreme GDDs.

22. The formulas used to construct the data are $\text{Yield}_{op} = \text{Yield}_{total} - \text{Share}_{hybrid} * \text{Identical}$ and $\text{Yield}_{hy} = \text{Yield}_{op} + \text{Identical}$, where Yield_{total} is the overall average yield in a CRD from Quick Stats and Share_{hybrid} is the fraction of acreage planted as hybrid seed.

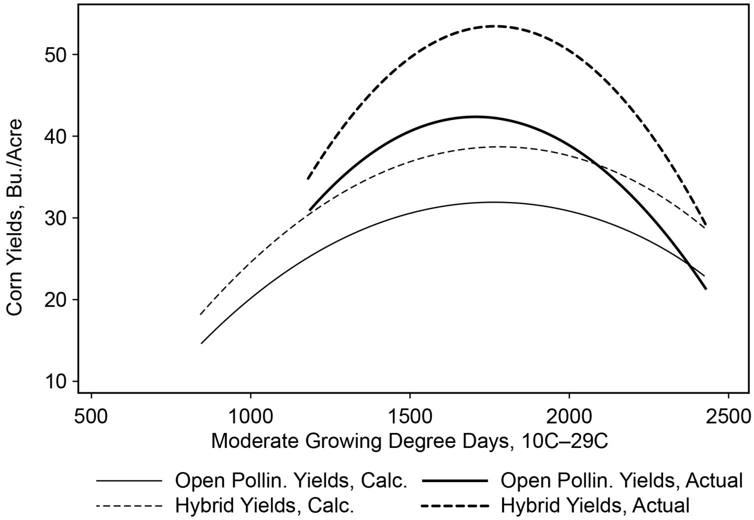

Fig. 3.A1 Moderate GDDs and fitted quadratic lines for constructed and actual hybrid and open-pollinated corn yields

Source: Authors' calculations.

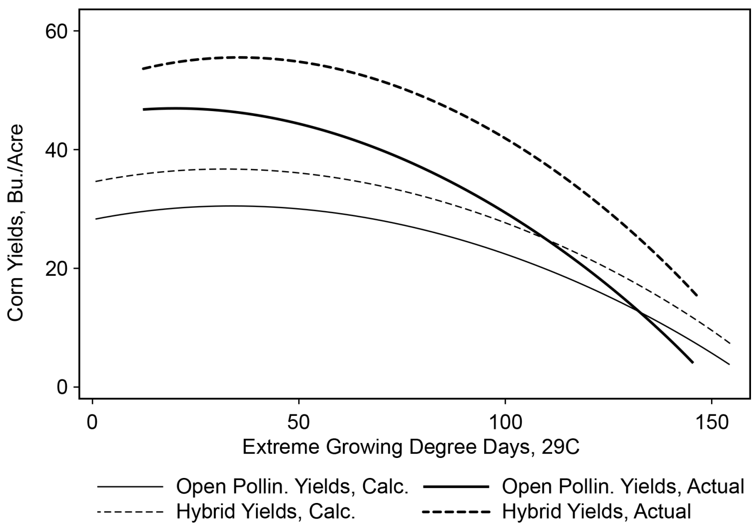

Fig. 3.A2 Extreme GDDs and fitted quadratic lines for constructed and actual hybrid and open-pollinated corn yields

Source: Authors' calculations.

References

Crabb, A. R. 1947. *The Hybrid-Corn Makers: Prophets of Plenty*. New Brunswick, NJ: Rutgers University Press.

Culver, J. C., and J. Hyde. 2001. *American Dreamer: The Life and Times of Henry A. Wallace*. New York: W. W. Norton.

Dai, Aiguo, and National Center for Atmospheric Research (NCAR), eds. 2019. "The Climate Data Guide: Palmer Drought Severity Index (PDSI)." Climate Data Guide, last modified December 12, 2019. https://climatedataguide.ucar.edu/climate-data/palmer-drought-severity-index-pdsi.

Dowell, A. A., and O. B. Jesness. 1939. "Economic Aspects of Hybrid Corn." *Journal of Farm Economics* 21 (2): 479–88.

Fitzgerald, D. 1990. *The Business of Breeding: Hybrid Corn in Illinois, 1890–1940*. Ithaca, NY: Cornell University Press.

Griliches, Z. Papers. Special Collections Library, Harvard University.

———. 1957. "Hybrid Corn: An Exploration in the Economics of Technological Change." *Econometrica* 25 (4): 501–22.

———. 1958. "Research Costs and Social Returns: Hybrid Corn and Related Innovations." *Journal of Political Economy* 66 (5): 419–31.

———. 1960. "Hybrid Corn and the Economics of Innovation." *Science* 132 (3422): 275–80.

———. 1980. "Hybrid Corn Revisited: A Reply." *Econometrica* 48 (6): 1463–65.

Hornbeck, R. 2012. "The Enduring Impact of the American Dust Bowl: Short- and Long-Run Adjustments to Environmental Catastrophe." *American Economic Review* 102 (4): 1477–1507.

Kloppenburg, J. 1988. *First the Seed: The Political Economy of Biotechnology, 1492–2000*. Cambridge: Cambridge University Press.

Menne, M. J., I. Durre, R. S. Vose, B. E. Gleason, and T. G. Houston. 2012. "An Overview of the Global Historical Climatology Network-Daily Database." *Journal of Atmospheric and Oceanic Technology* 29:897–910. doi:10.1175/JTECH-D-11–00103.1.

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

Pioneer Hi-Bred Company Papers. Special Collections, Iowa State University Library.

Ryan, B., and N. C. Gross. 1943. "The Diffusion of Hybrid Seed Corn in Two Iowa Communities." *Rural Sociology* 8 (1): 15.

———. 1950. "Acceptance and Diffusion of Hybrid Corn Seed in Two Iowa Communities." *Research Bulletin (Iowa Agriculture and Home Economics Experiment Station)* 29 (372). https://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=1386&context=researchbulletin.

Schauberger, Bernhard, Sotirios Archontoulis, Almut Arneth, Juraj Balkovic, Philippe Ciais, Delphine Deryng, Joshua Elliott et al. 2017. "Consistent Negative Response of US Crops to High Temperatures in Observations and Crop Models." *Nature Communications* 8 (1): 1–9.

Schlenker, W., and M. J. Roberts. 2009. "Nonlinear Temperature Effects Indicate Severe Damages to US Crop Yields under Climate Change." *Proceedings of the National Academy of Sciences* 106 (37): 15594–98.

Skinner, J., and D. Staiger. 2007. "Technological Diffusion from Hybrid Corn to Beta Blockers." In *Hard-to-Measure Goods and Services: Essays in Honor of Zvi*

Griliches, edited by Ernst R. Berndt and Charles R. Hulten, 545–70. Chicago: University of Chicago Press.

Sutch, R. 2008. "Henry Agard Wallace, the Iowa Corn Yield Tests, and the Adoption of Hybrid Corn." NBER Working Paper No. 14141. Cambridge, MA: National Bureau of Economic Research.

———. 2011. "The Impact of the 1936 Corn Belt Drought on American Farmers' Adoption of Hybrid Corn." In *The Economics of Climate Change: Adaptations Past and Present*, edited by Gary Libecap and Richard Steckel, 195–223. Chicago: University of Chicago Press.

Urban, N. 1975. "A History of Pioneer's First Ten Years." Unpublished memo, Pioneer Hi-Bred Company Papers. Special Collections, Iowa State University Library.

US Department of Agriculture (USDA). 1945. *Agricultural Statistics*. Washington, DC: Government Printing Office.

———. 1949. *Agricultural Statistics*. Washington, DC: Government Printing Office.

———. 1950. *Agricultural Statistics*. Washington, DC: Government Printing Office.

———. 1963. *Prices Paid by Farmers for Seed: Spring Season Averages, 1926–1961: September 15 Prices, 1949–1961, by States and United States*. Statistical Bulletin No. 328. Washington, DC: Government Printing Office.

Zuber, M. S., and J. L. Robinson. 1941. "The 1940 Iowa Corn Yield Test." *Bulletin P* 1 (19): 1.

———. 1942. "The 1941 Iowa Corn Yield Test." *Bulletin P* 2 (38): 1.

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3.C1 Introduction

Keith Meyers and Paul Rhode consider an iconic and transformational period of time in economic and agricultural history: the adoption and spread of hybrid corn. This topic may seem obscure to some in the discipline, and it would be even more obscure were it not for the famous work of Zvi Griliches (1957), who documented the *S* curve of technological adoption that is now almost universally emblematic of transformation and change. This particular technical change and all that was associated with it—the systematic commercial breeding of seed, massive growth in chemical fertilizer and pesticide applications, and increasing mechanization—mattered tremendously. It marked an acceleration of productivity growth that literally fed the world as its population soared from about 2.3 billion to over 7 billion. Today, we produce over five times as much corn per acre of land as we did before the adoption of hybrid corn (figure 3.C1). Other crops have seen similar advances. With most of the planet's arable land already

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For acknowledgments, sources of research support, and disclosure of the author's material financial relationships, if any, please see https://www.nber.org/books-and-chapters/economics-research-and-innovation-agriculture/comment-yield-performance-corn-under-heat-stress-comparison-hybrid-and-open-pollinated-seeds-during.