Title: Yield Performance of Corn under Heat Stress: A Comparison of Hybrid and Open-Pollinated Seeds during a Period of Technological Transformation, 1933-1955

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Abstract: Starting in the 1930s, commercial hybrid corn seeds rapidly replaced the once predominate open-pollinated varieties planted by farmers. By the mid-1950s almost all corn grown in the United States was of hybrid varieties. Observers have argued that the drought tolerant qualities of these hybrids were a major factor driving farmers' decisions regarding hybrid adoption, but there is little statistical evidence to substantiate this assertion. Hybrid seeds exhibited other attractive qualities, such as improved performance during prime weather conditions, resistance to wind damage, and increased suitability toward mechanized harvesting. Using historical evidence from Zvi Griliches's archival records, we reconstruct data on hybrid corn adoption and yields at a more disaggregated geographic level than previously available. We match these data with historical weather records to measure the extent to which hybrid seeds mediated the adverse effects of extreme heat. Our findings suggest that hybrid corns grown in Iowa from 1928 to 1942 did exhibit heat tolerance relative to open-pollinated varieties. This result is unique to Iowa as this reduced temperature sensitivity does not appear when comparing hybrid and open-pollinated yields grown in other states.

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Introduction

The Pioneer Hi-bred company introduced the first successful commercial hybrid corn seeds in early 1930s during a period of extreme farm distress, historically low commodity prices, and adverse weather condition. While hybrid seeds cost two to three times more than their open-pollinated counterparts, these new hybrid seeds rapidly replaced open-pollinated corns. Observers have argued that the drought resistant characteristics of hybrid seed technology and farmers' experiences with the Dust Bowl in the 1930s accelerated hybrid adoption (Dowell and Jesness 1939; Crabb, 1947; Sutch 2008;2011). Academic research, however, has not determined to what extent hybrid seeds mitigated the effects of drought and temperature stress. We construct a panel of hybrid and open-pollinated corn yields from unpublished U.S. Department of Agriculture (USDA) documents contained in Zvi Griliches' manuscripts and from Iowa experimental station report. We combine these records with historical measures of temperature stress for the period of hybrid adoption, and then explore whether hybrid corn seed technology mediated the effects of increased heat stress on corn yields.

Much of the research studying hybrid corn adoption follows the path-breaking work of Zvi Griliches, (1957; 1958; 1960; 1980). Griliches' analyses posited that profitability of the new seed technology (as captured by expected yield improvements) drove adoption. Even though hybrid seeds diffused across the Cornbelt and Great Plains during a period of historically extreme drought, Griliches does 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 by weather conditions. More recent research contests Griliches' account and suggests that drought shocks in 1934 and 1936 accelerated hybrid adoption (Culver and Hyde, 2001; Sutch, 2008, 2011). Narrative evidence also suggests that corn producers adopted hybrids in response to droughts and that farmers learned about the potential benefits of hybrids by observing neighbors' crops (Dowell and Jesness, 1939; Crabb, 1947). As a *New York Times* headline read in 1940: "50% of Corn Crop in Hybrid Species.....Agricultural Marketing Service Lays its Popularity to Drought Resistance."[3]

Hybrid corn seed technology rapidly spread during a period of low commodity prices and extreme drought. Explanations for this explosive growth vary. Griliches' asserts that profitability of the technology spurred adoption and that the relatively yield advantage of hybrids over open pollinated corn seeds was relatively fixed between 10% and 15%. Richard Sutch and others find this explanation insufficient considering the relatively expensive nature of hybrids at their time of introduction. Sutch (2008, 2011) highlights the role the U.S. Department of Agriculture played in promoting adoption of hybrid seed technology and argues that hybrid corn seed's resistance to drought 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's (2012) study of the Dust Bowl finds that many of the adaptive responses to the Dust Bowl were relatively slow. In comparison, from 1931 onward U.S. farmers rapidly adopted hybrid corn and these varieties eventually completely replaced the once dominant open-pollinated varieties. This switch towards hybrids may have mitigated some the adverse effects of the Dust Bowl. Switching to hybrids was costly-- hybrid seed was far more expensive than open-pollinated seeds (Olmstead and Rhode, 2008). Furthermore, hybrids required farmers to make a structural change in their agricultural practices and purchase seed from a seed company on an annual basis. Unlike the predominant open-pollinated varieties, seeds derived from hybrid corns are biologically unsuitable for sustained replanting. Nevertheless, hybrids promised beneficial qualities, included higher yields, shortened the time to maturity, stronger root systems, thicker stalks, disease resistance, and drought tolerance.

[3] *New York Times*, 10 Sept. 1940. The article's text noted the hybrid's advantages of both drought resistance and higher yields.

Past Economic Research on 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 (1957) analyzed this "invention of a way to invent" and maps estimated parameters of diffusion process into economic variables of supply and demand. He views 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-- the origins, slopes, and ceilings.[4] 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 "availability" of hybrid seed, and more specifically to supply-side forces included the profitability of seed producers, the cost of innovation, and potential market density. He related the slope (or speed of diffusion) and ceiling levels to demand-side forces, specifically to the profitability to farmers of using the new seed. Griliches found the estimated speed of adoption was rather uniform but declined as one moves away from the center of the Cornbelt. 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 consistent with rational, long-run profit-seeking behavior by seed producers and farmers. He made no reference to adverse weather shocks or to the drought-resistance qualities of hybrid varieties.[5] According to Griliches' preferred specification, hybrids promised a time- and region-invariant yield increase -- in

[4] The analysis covered 31 (out of 48) states, and 132 (out of 249) crop reporting districts in the period up to 1956. The USDA's Agricultural Marketing Service made available unpublished data for the crop reporting districts. Griliches restricted 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.

[5] 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.

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.[6]

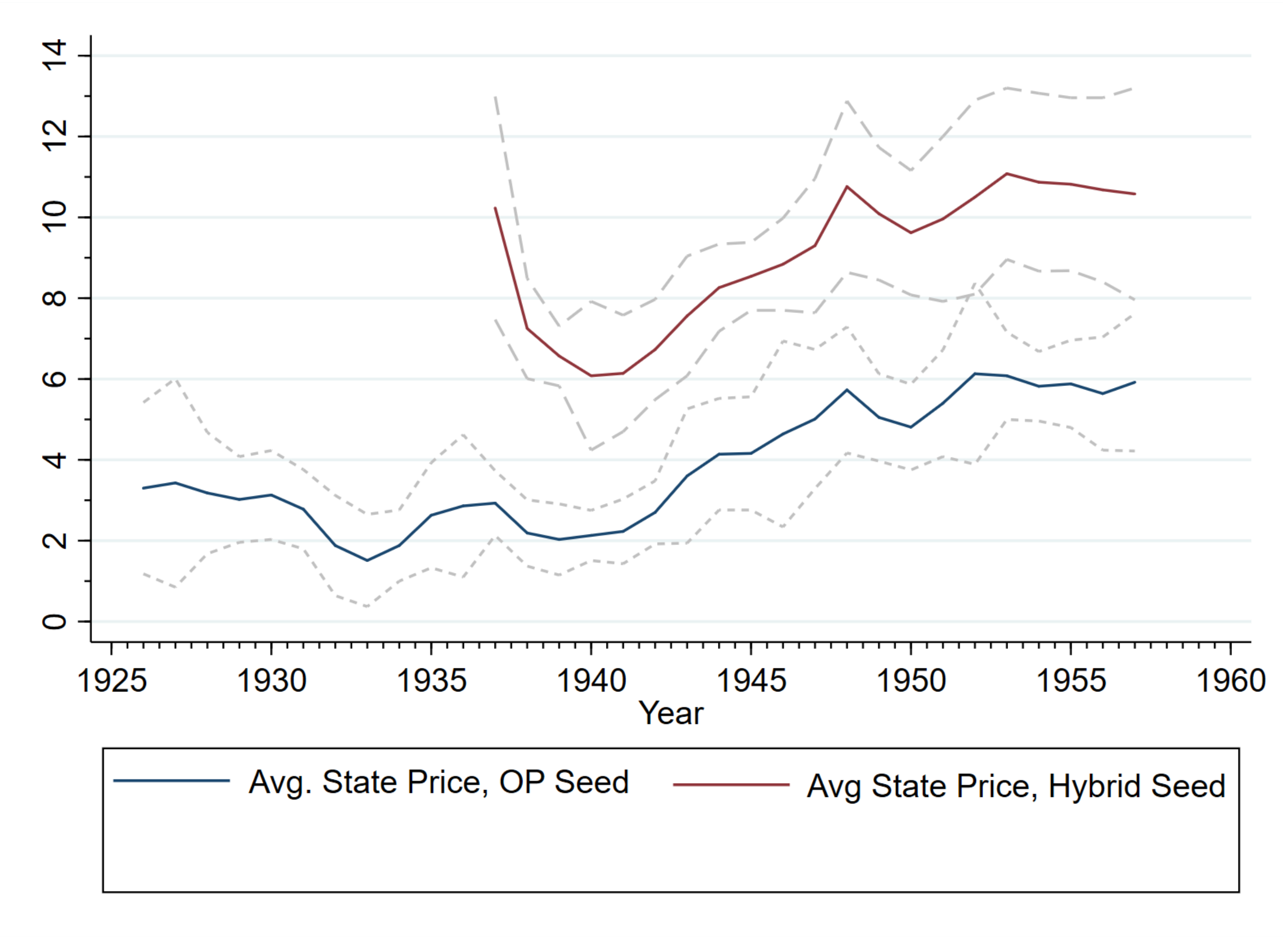

Figure 1. Nominal Prices ($) of Open-Pollinated (OP) and Hybrid Corn Seeds with Two Standard Deviation Bands. Source: USDA (1963). Prices paid by farmers for seed: spring season averages, 1926-1961: September 15 prices, 1949-1961 by states and United States. Statistical Bulletin No. 328. GPO: Washington, DC.

[6] 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.

Griliches tabulated but did not use USDA data on the prices (per bushel) of hybrid and open-pollinated seed by state (Box 59).[7] 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). Griliches' 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 did not rely on the hybrid corn price alone, but the hybrid seed price relative to other prices, for example, relative to the price of open-pollinated seed. In Figure 1, the average price of hybrid seed at the state level is approximately between two or three 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).[8] Again, he argued the cross-state variation is negligible. The coefficient of variation of seeding rates in bushels per acre was around 18.7 percent.

The path-breaking work of Griliches inspired a vigorous scholarly response (see Skinner and Staiger 2007). Ryan and Gross (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. In a series of papers, fellow rural sociologists debated with Griliches about the forces driving diffusion (Skinner and Staiger 2007, 254). Dixon (1980) observed that the diffusion process

[7] Griliches relied on a USDA publication entitled "Seed Crops." These are essentially the same as in USDA (1963).
[8] These data were based on USDA, *Agricultural Statistics*, 1945, 1949, 1950.

continued through the late 1950s and 1960s beyond the ceiling levels that Griliches employed. Dixon reanalyzed the extended annual state-level data, considering that diffusion to reach nearly 100 percent almost everywhere by the end of the period. Griliches' modeling approach has also been criticized. David (2003) has cogently argued that it lacks micro-foundations; the logistic form is simply assumed, not derived from an underlying economic model. Rural sociologist Everett Rogers (2010) observed that Griliches abstracted from the contagion-like learning effects that are commonly used to justify the logistic form.

Richard Sutch (2008; 2011) revisited the early diffusion of hybrid corn, emphasizing the role of adverse weather shocks. 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. He 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.[9] It was the adverse weather shocks of the mid-1930s, in combination with propaganda from the USDA (headed by hybrid corn pioneer Henry A. Wallace), that convinced Midwestern farmers to adopt the new seed. Sutch (2008) notes the conflict of interest that Henry A. Wallace faced serving as Secretary of the USDA while being the owner of Pioneer, one of the leading commercial seed companies (other leadings hybrid producers at the time included DeKalb, Funk Farms, and Pfister). 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 restriction.

[9] Sutch (2008) notes commodity prices were low and that seed was expensive. His description does not address the subsidies hybrid seed producers gave farmers to adopt hybrids. One strategy used by 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.

Narrative evidence suggests farmers readily noticed that hybrid corn 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 Cornbelt in the 1930s and argued that 1936 drought hastened the adoption of hybrids through learning effects. Sutch was hampered by the lack of geographically decentralized data. He was unable to identify records on hybrid and open-pollinated seed productivity prior to 1936. This is well after commercial hybrids entered the market and taken hold in Iowa and Illinois. With our new data (or more accurately, newly recovered old data), we seek to address these issues afresh and study hybrid performance starting in the late 1920s.[10]

Hybrid Corn and Weather Data

The data used in this empirical inquiry comes from two primary sources. The first source is information on hybrid corn adoption derived from unpublished USDA data and notes contained in Zvi Griliches' archival collection held at the Special Collections Library at Harvard University.[11] Data on hybrid corn diffusion by state are available in USDA's *Agricultural Statistics*. These data, on the percentage of maize acreage planted with hybrid seed, have been available to scholars for many years. Griliches' data provide information at the Crop Reporting District (CRDs) level. These more detailed records-- drawn from a grid of roughly nine entries per state-- are based unpublished data from the USDA's Agricultural Marketing Service. In addition to the diffusion data that Griliches used in his statistical analysis, his archival record include data on yields of hybrid and open-pollinated varieties by CRDs. We have recovered these series for use for the first time since the 1950s. We also gather additional data from experimental trials in Iowa. These trials compared the relative

[10] We thank Richard Sutch for making us aware the CRD-level diffusion data were available in the Griliches archives at Harvard.

[11] Papers of Zvi Griliches, ca. 1930-2000. Collection Identifier: HUGFP 153. Harvard Library. 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 at the National Agricultural Library.

performance of hybrid seeds to open-pollinated seeds from 1928 to 1942. The second data source is the measurement of temperature and precipitation from Wolfram Schlenker's Detailed Daily Weather Data for the Contiguous United States. Combining these two data sources together 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 and Year Level.[12]

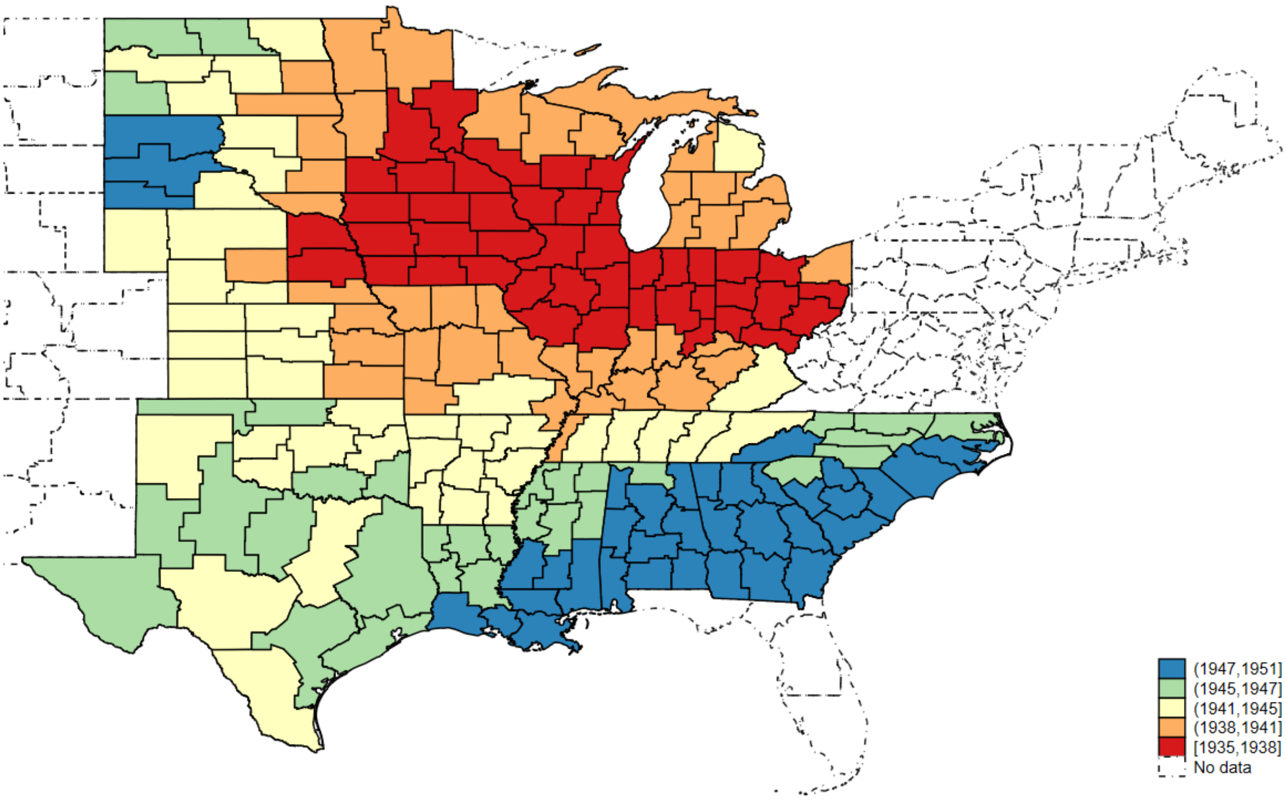

Figure 2. Crop Reporting District Map, Years When Hybrid Corns Exceed 10% of Planted Corn. Source: Compiled from Zvi Griliches' Archival Records.

Data on Hybrid Corn from Zvi Griliches' Archival Records

The technology of hybrid corns spread to the Southeast U.S. and periphery of the Corn Belt more than a decade after Pioneer Hi-Bred seed company launched its first commercially successful

[12] Crop Reporting Districts are relatively equivalent to contemporary Agricultural Statistics Districts.

hybrid seed in 1931. Figure 2 visualizes how hybrid corn rapidly diffused across the U.S. Corn Belt and United States in the years following its initial introduction.

The crop reporting district diffusion data were compiled from a set of hand-written spreadsheets for the 1944-1955 period (Box 58), from typed sheets for all the CRDs in United States in 1959 (Box 60) and for Ohio CRDs for the 1935-1954 period (Box 58), and from very carefully marked diffusion graphs drawn by Griliches's own hand (Box 58). The graphs indicate the annual rate of diffusion by crop reporting district for each state on a 100-point (or finer) scale covering the period from first diffusion to 1954/55. The numbers derived from the graphs match exactly those from available non-graphical sources.[13] In addition, the records of Griliches include maps of CRD data from the Agricultural Adjustment Administration 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.

Griliches collected data on the differential yields achieved by hybrid seed relative to open-pollinated seed. The data include the results of state yield trials and AAA surveys, and well as some yield data are at the sub-state level (Boxes 57, 60).[14] 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 are short because little open-pollinated seed was grown after the mid-1940s. Griliches used the AMS series chiefly in summary form. Note these data do not allow direct measurement of the effects of the weather shocks (e.g. droughts) of the mid-1930s.

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[13] We have data for the northeastern states from 1945 on. However, this data does 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 of other archival sources.

[14] The sub-state regions covered do not always translate directly into CRDs.

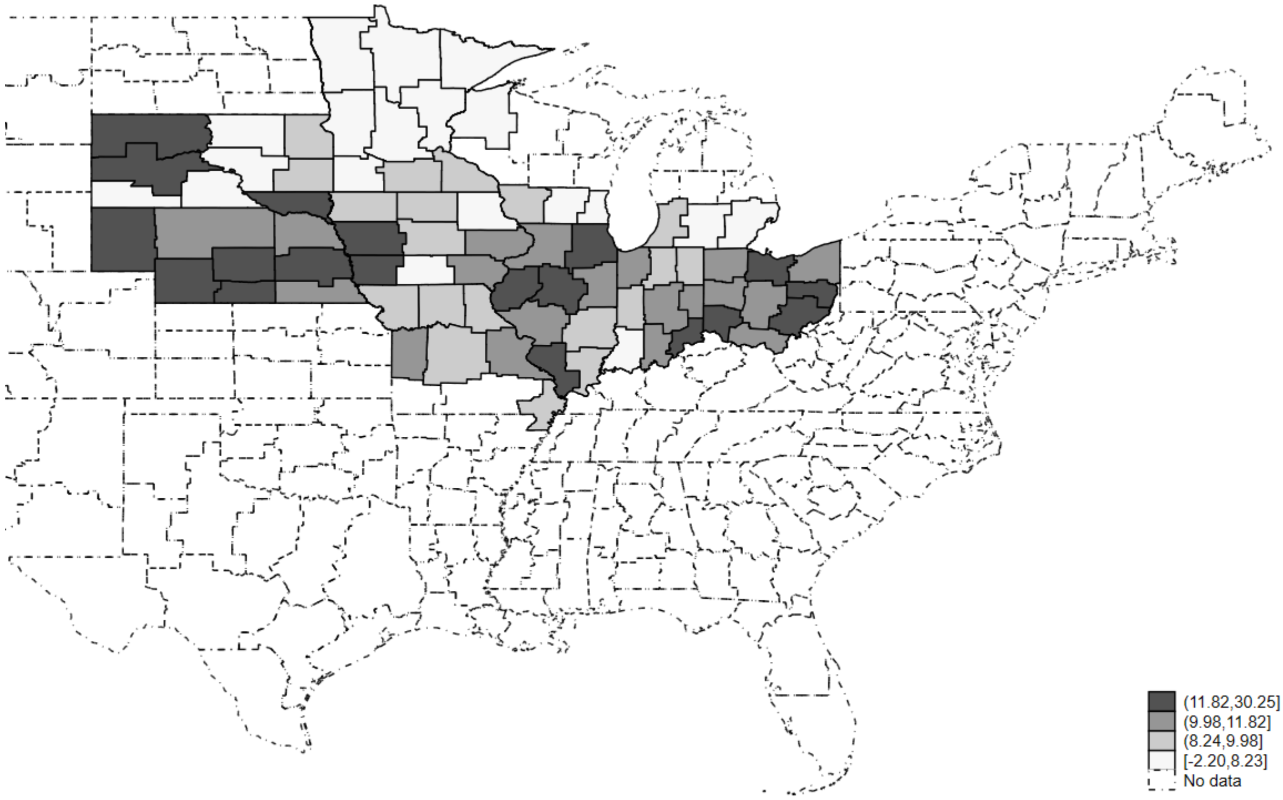

Figure 3. Average Hybrid Minus Average Open-Pollinated Corn Yield per Acre, quartiles, 1937-1941. Source: Griliches' Archival Records.

Thus, Griliches' 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 to 1941. Figure 3 presents the regions this data covers 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 an CRD. These identicals are more consistently documented in Griliches' archival records. The identical data are reported from 1939 to 1953 and have broader geographic coverage than the alternative yield data and are presented in Figure 4. With both the seed type yield specific data and identicals data there is a broad geographic coverage. The tradeoff with these data is their cover a time period almost a decade after hybrids had initially entered the market. To study the earlier time period, we compile experimental farm data from Zuber and Robinson (1941;1942). These records report the yield ratio of hybrids to open-pollinated varieties in Iowa from 1928 to 1942.[16]

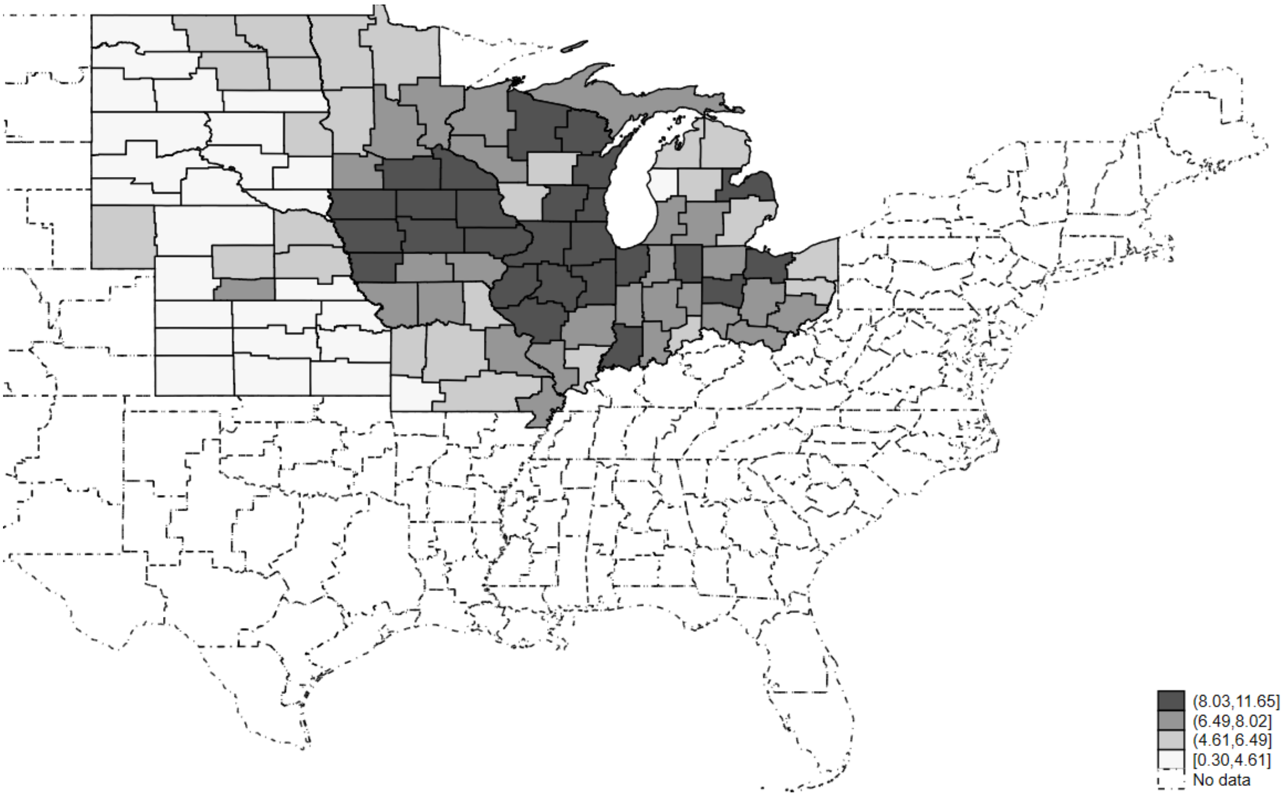

Figure 4. "Yield Identicals" per Acre, quartiles, 1939-1953. Source: Griliches' Archival Records.

Daily Weather Data for Contiguous United States

The source of temperature and precipitation data used in this analysis derives from gridded weather data compiled and provided by Wolfram Schlenker (Columbia University) and Michael Roberts (University of Hawaii). The data is based on the PRISM weather dataset and is an updated

[16] Sutch (2011) described ratios from Iowa Corn Yield Tests as representing all varieties tested. But the data are in fact for section varieties, the subset of varieties entered into tests in all three districts in a section. Records from Iowa reports average yield for all and section varieties for 1928 to 1932 ratios for all and the section subset are reported. The average hybrid to open-pollinated yield ratio was 1.1069 for all varieties entered but 1.095 for section varieties. A further issue with the test data in the location of the test districts and trial locations changes (marginally) over time. How these inconsistencies affect the comparison is unclear, a priori.

version used in Schlenker and Roberts (2009). The raw data consists 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 daily temperature along with daily total precipitation. We then construct growing degree days in accordance to agronomically observed heat sensitivity in corn yields, heat in excess of 29 degrees Centigrade (Schlenker and Roberts 2009, Schauberger et al. 2017). For each growing season, defined as lasting from April 1 to September 30, we calculated the total number of Moderate Growing Degree Days and Extreme Growing Degree Days.

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

Equation 1 defines a Growing Degree Day, GDD, as the average daily temperature calculated between the daily maximum temperature, T_{max}, and daily minimum temperature, T_{min}, minus some base temperature, T_{base}. A Growing Degree Day 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 and 29 degrees Centigrade during the growing season as Moderate Growing Degree Days. This calculation assumes a base temperature of 10 degrees Centigrade. We sum days with average temperatures in excess of 29 degrees Centigrade as Extreme Growing Degree Days (and assume a base temperature of 29 degrees in this summation). In addition to these heat measures, we also total the amount of precipitation during the growing season.

Tables 1 and 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 does coincide with the end of the Dust Bowl drought waves. The yield identical data ranges from 1939 to 1953, has broader geographic coverage, and more variability in its 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 between hybrid and open-pollinated corns grown on the same farm of 6 bushels per acre. Table 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% between 1926 and 1941. This average is consistent with Griliches claims.[17]

Empirical Method and Results

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

2) $$y_{it} = \theta_1 MGDD_{it} + \theta_2 EGDD_{it} + \delta_1 Prec_{it} + \delta_2 Prec^2 + \alpha_i + \gamma_t + \varepsilon_{it}$$

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}, denotes the ratio of hybrid yields divided by open-pollinated yields. These outcomes are regressed on moderate and extreme degree days, $MGDD_{it}$ and $EGDD_{it}$. Annual growing season precipitation, $Prec_{it}$, and the squared value of precipitation measure the effects rainfall has upon corn yields. Time invariant effects specific to each CRD are controlled for 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},

[17] 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 likely not representative of the farm population and achieved yields substantially higher than those commonly prevailing.

are clustered at the state (or CRD) level to account for potential correlation in the errors shared across CRDs from the same state.

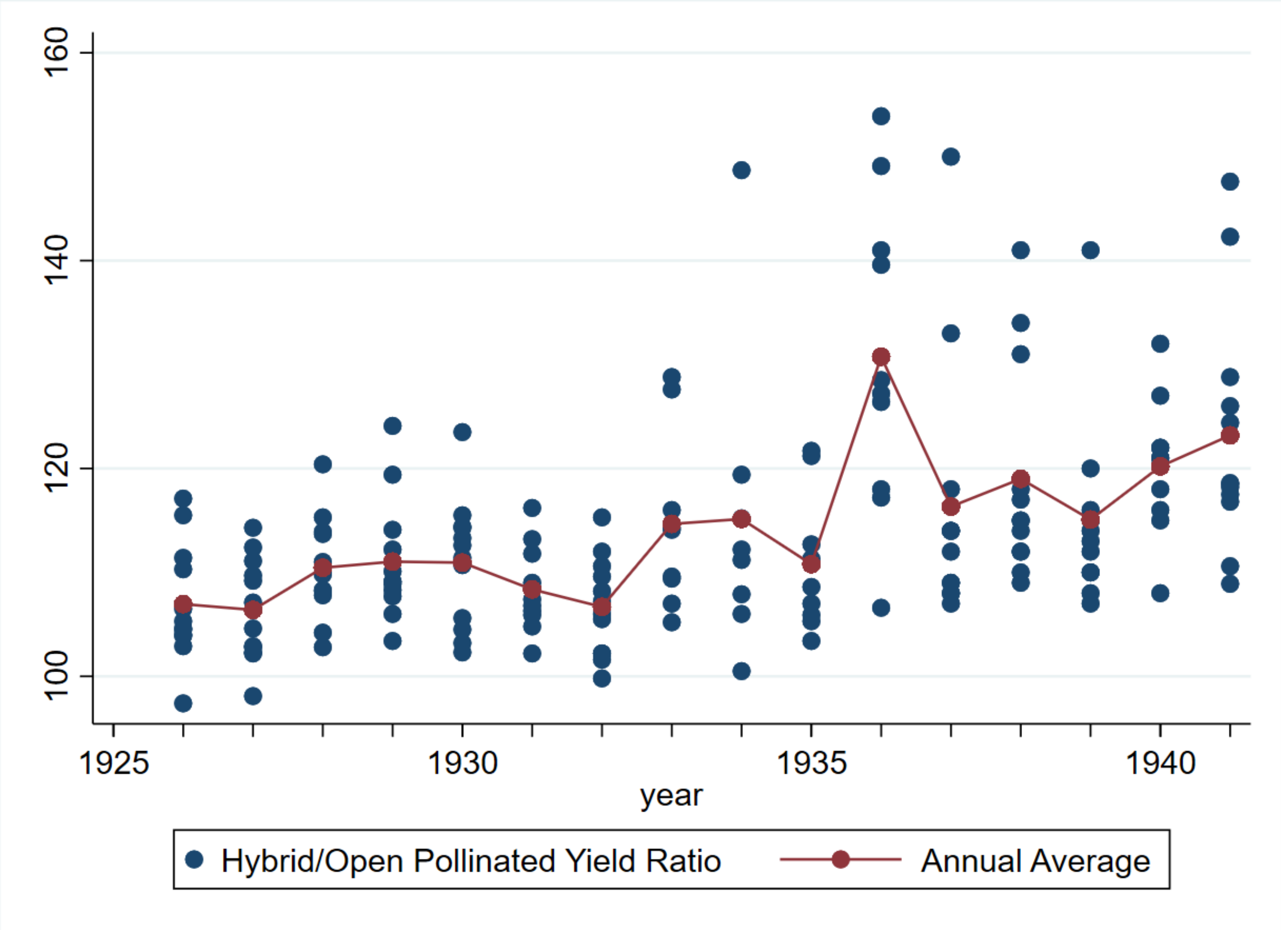

Figure 5. Hybrid to Open-Pollinated Corn Yield Ratios, Iowa Trials Data, 1926-1941. Source: Authors' tabulation

Iowa Experimental Farm Results, 1926 to 1942

Much of the foundational work developing commercial hybrid corn seeds occurred in Iowa. We use experimental farm data from Zuber and Robinson (1941;1942) to study the relationship between temperature 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 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 start to shift upwards in 1936. Both the floor and average of the ratios also increases until 1942. The last year yields for open pollinated corns are reported in Iowa stations is 1942. This is because hybrid corn seed technology had come to dominate corn production in Iowa by that time.

In Table 4 we regress the Iowa yield ratio against the temperature and precipitation data. We find results that are consistent with Richard Sutch's (2011) and rural sociologists' arguments about the role drought played in diffusion. Specification (1) finds that moderate growing degree days decrease the relative performance of hybrids and the effect is statistically significant at the 1% level. A 100 unit increase in moderate growing degree days decreases the ratio by 2.3. The effect of moderate growing degree days is sensitive to the choice of quadrative time trends versus year fixed effects. The coefficients for extreme growing degree days show that the relative performance of hybrids increased during periods of extreme heat. In specification (1) a 100 unit increase in extreme growing degree days increases the ratio by 21.5 and by 41.7 in specification (2). In both specifications the coefficients are statistically significant at the 1% level. These results support that narrative accounts that hybrid corns performed much better than open pollinated corns during period of drought.

Variety Specific Yield and Yield Identical Regressions

Columns (1), (2), and (3) in Table 5 report the effects of temperature and precipitation 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 corn yields increase for both hybrid and open-pollinated corns under moderate GDD. However, the regression coefficients essentially identical and suggest that 100 additional moderate GDD increase corn yields by approximately 6.7% (the coefficients are statistically significant at the 1% level). Column (3) presents some evidence that hybrid corns perform better relative to open-pollinated corns. The yield gap between the two hybrid and open-pollinated varieties increases with additional moderate GDD with a 100 unit increase in moderate GDD increasing the yield gap by 0.48% (this result is statistically significant at the 5% level when standard errors are clustered at the CRD level). The results for yield identicals in column (4) corroborate this result and suggest a 100 unit increase in moderate GDD increase the yield gap by 0.42% (this result is statistically significant at the 10% level under both state and CRD clustered errors).

Extreme growing degree days negatively affect both the performance of hybrid and open-pollinated corns. According to columns (1) and (2) in Table 5, a 100 unit increase in extreme GDD reduces hybrid corn yields per acre by approximately 51.3% and reduces open-pollinated corn yields by 66.2% (both coefficients statistically significant at the 5% 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 growing degree days reduce the performance of hybrids relative to open-pollinated corns. An additional 100 extreme GDD reduces the yield identical by 30.4% (this effect is statistically significant at the 5% and 1% level 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 6, 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 growing degree days. The statistical significance for the negative effect of extreme growing degree days on the yield identical also attenuates. For the hybrid and open pollinated corn yields this specification change does not appear to change yield sensitivity to extreme growing degree days. Using year fixed effects does not substantively change the coefficients and statistical significance of extreme growing degree days in specifications (1) and (2).

Discussion and Conclusion

If hybrid corns exhibited a unique tolerance toward extreme heat and drought, then we would expect that the difference between hybrid and open-pollinated corn yields to increase in periods of extreme heat. We uncover two distinct patterns in the data regarding hybrid yield performance relative to open-pollinated yield performance. For crop reporting districts in Iowa from 1928 to 1942, extreme temperature increases the yield performance of hybrid seeds relative to open-pollinated seeds. This evidence is consistent with Richard Sutch's and the rural sociologists claims regarding the drought tolerant nature of hybrids. In Iowa, hybrid corns out performed their open-pollinated contemporaries. The patterns we uncover are consistent with a scenario where farmers preferences for drought tolerance drove hybrid adoption.

We find contrasting results using yield data from a later time period and with a broader geographic coverage. Using the yield specific data and the yield identicals we find evidence more consistent with Griliches assessment. We do not find strong evidence that extreme temperature increased the performance of hybrid corns relative to open pollinated corns in the years after the Dust Bowl droughts. The evidence from the regression analysis indicates that the difference in yields between hybrids and open-pollinated corns increases during moderate GDD. Extreme heat resulting from daily average temperatures in excess of 29 degrees Centigrade do not appear to increase the relative difference in hybrid and open-pollinated corns. Evidence using the yield "identicals" from the unpublished USDA manuscripts indicate that the difference in hybrid and open-pollinated corn yields decreases with additional extreme GDD. This evidence suggests that hybrid corns improved overall yields relative to open-pollinated corns during normal and advantageous growing conditions, but that this increased yield performance attenuates during periods of extreme heat exposure.

On one hand our evidence support's Griliches' notion that hybrid seeds increased productivity in corns overall rather than principally during droughts. Such results indicate that the main benefit that hybrid seeds provided in mitigating the adverse effects of extreme temperature come from their overall increase in yields. This increase in yields cushions the adverse effects of drought. On the other hand, evidence from Iowa experimental farms supports the narrative accounts presented by historians and rural sociologists.

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Appendix Figures

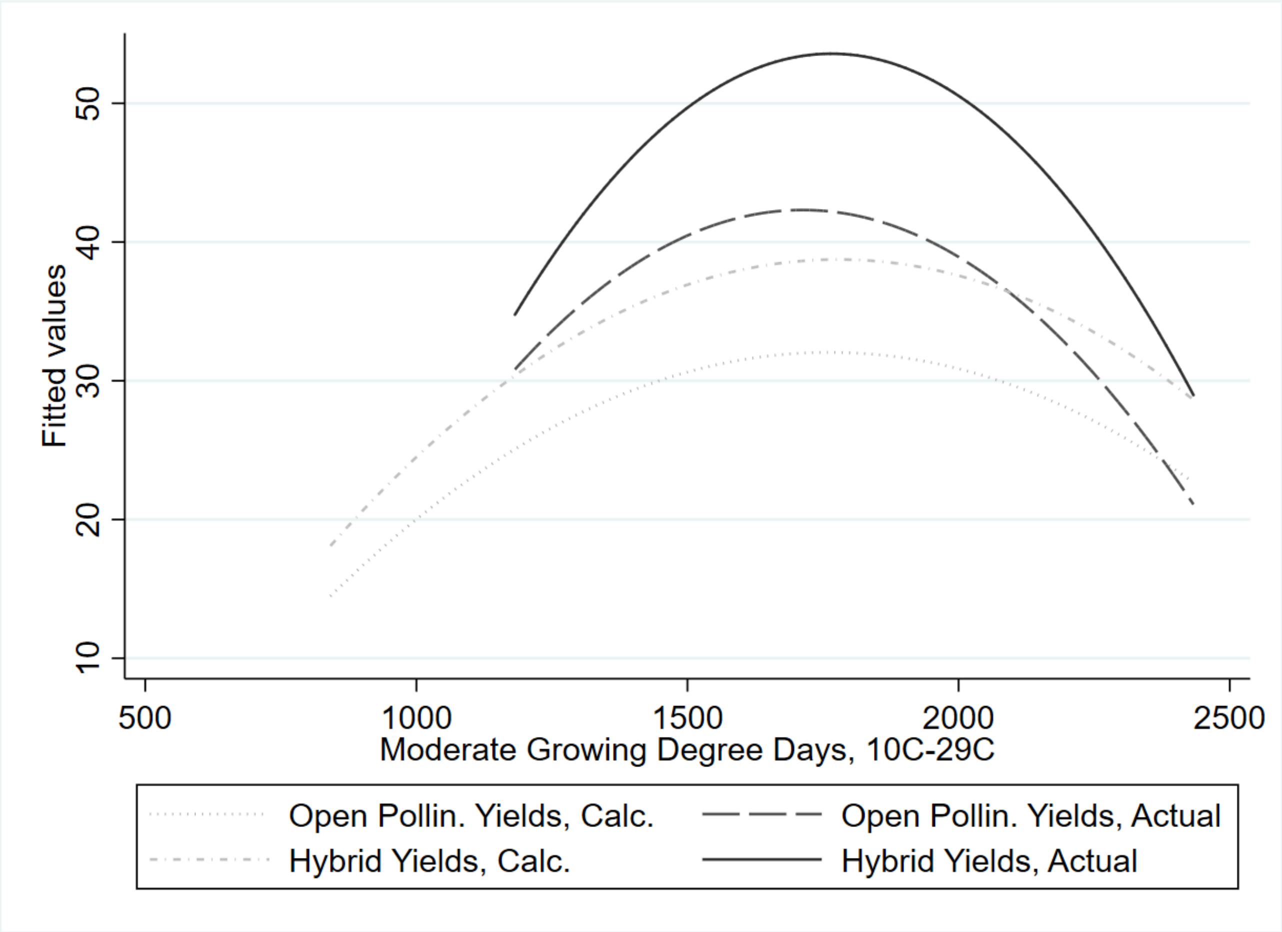

Figure A1. Moderate Growing Degree Days and Fitted Quadratic Lines for Constructed and Actual Hybrid and Open-Pollinated Corn Yields. Source: Authors' Calculations.

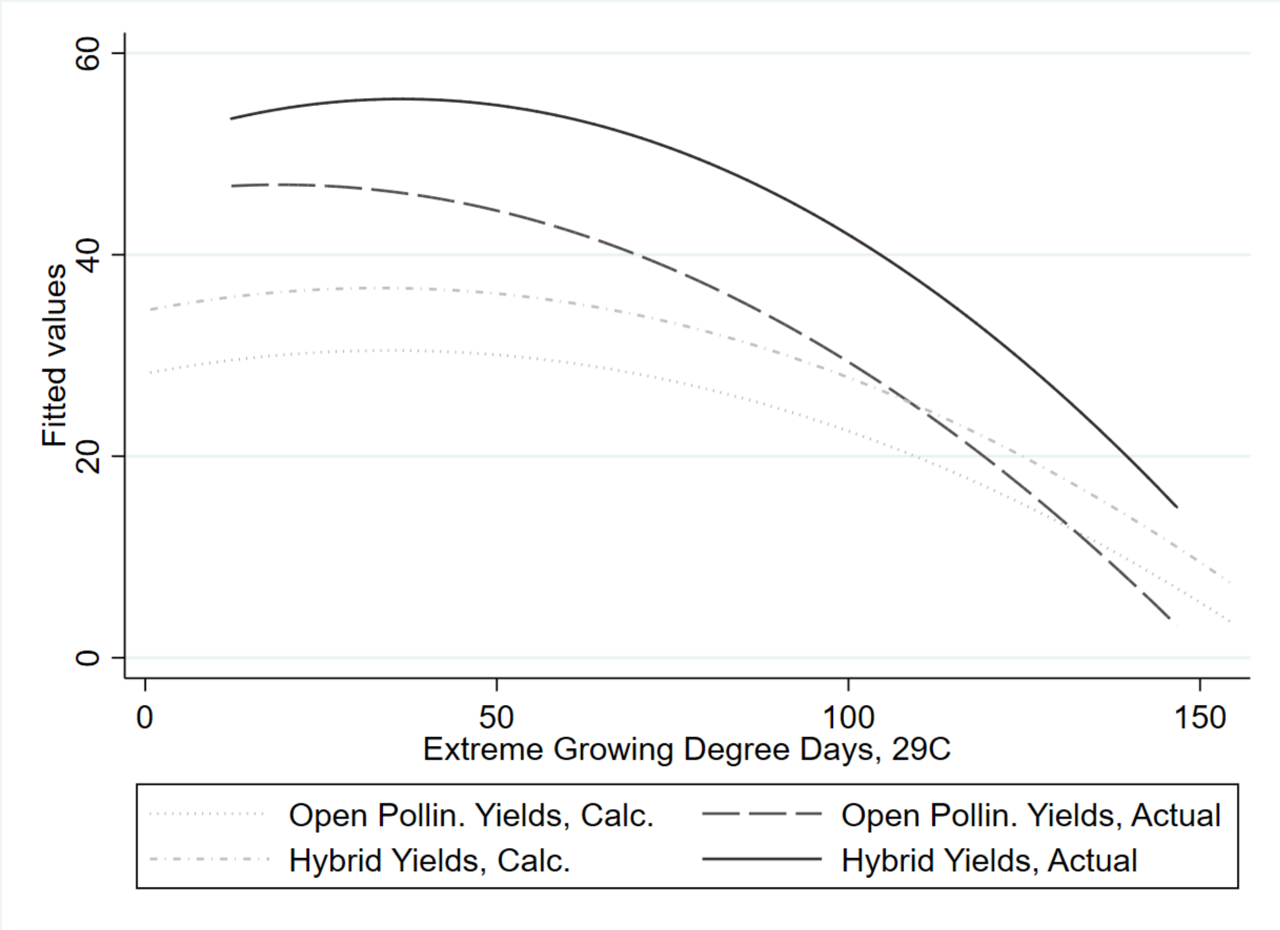

Figure A2. Extreme Growing Degree Days and Fitted Quadratic Lines for Constructed and Actual Hybrid and Open-Pollinated Corn Yields. Source: Authors' Calculations.

In Figures A1 and A2, we plot fitted quadric lines to the data to highlight the relationship between moderate and extreme GDD 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 Quickstats 2 program, the yield "identical", and information on share of acreage planted as hybrid corn.[18] This descriptive evidence suggests that hybrid performance increases more

[18] The formulas used to construct the data are $Yield_{op} = Yield_{total} - Share_{hybrid} * Identical$ and $Yield_{hy} = Yield_{op} + Identical$, where $Yield_{total}$ is the overall average yield in a CRD from Quickstats and $Share_{hybrid}$ is the fraction of acreage planted as hybrid seed.

under moderate growing degree days than open-pollinated corns. It also suggests that the difference in yields is either fixed or decreasing in response to extreme growing degree days.

Table 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 Growing Degree Days	211	1773.318	228.086	1181.853	2433.123
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	1939.787	1.103	1937	1941

Table 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 Growing Degree Days	989	1581.220	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	1944.219	3.876	1939	1953

Table 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 Growing Degree Days	170	1688.860	155.203	1289.026	2091.285
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	1933.565	4.740	1926	1941

Table 4. Iowa Hybrid and Open-Pollinated Corn Ratios, 1926-1941

	(1) Iowa Yield Ratio	(2) Iowa Yield Ratio
Moderate GDD, 10^0 - 29^0 C	-0.02343***	-0.02925
	(0.00867)	(0.03604)
Extreme GDD, > 29^0 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	1926-1941	1926-1941
N	177	177
Adj. R^2	0.391309	0.487914

Robust standard errors are in parentheses.

* p<0.10 ** p<0.05 *** p<0.01

Table 3. Regression Results, Effect of Temperature Stress on Corn Yields, Quadratic Time Trends

	(1) ln(Hybrid Yield Per Acre)	(2) ln(Open-Pollinated Yield Per Acre)	(3) ln(Yield Difference)	(4) ln(Yield Identical)
Moderate GDD, 10^0 - 29^0 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, > 29^0 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	1937-1941	1937-1941	1937-1941	1939-1953
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 Crop Reporting District are in brackets.

* p<0.10 ** p<0.05 *** p<0.01

Table 4. Alternative Specification, Regression Results, Effect of Temperature Stress on Corn Yields, Year Fixed Effects

	(1) ln(Hybrid Yield Per Acre)	(2) ln(Open-Pollinated Yield Per Acre)	(3) ln(Yield Difference)	(4) ln(Yield Identical)
Moderate GDD, 10^0 - 29^0 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, 29^0 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	1937-1941	1937-1941	1937-1941	1939-1953
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 Crop Reporting District are in brackets.

* p<0.10 ** p<0.05 *** p<0.01