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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 Unpublished memo, Pioneer Hi-Bred Company Papers.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.

Comment Michael J. Roberts

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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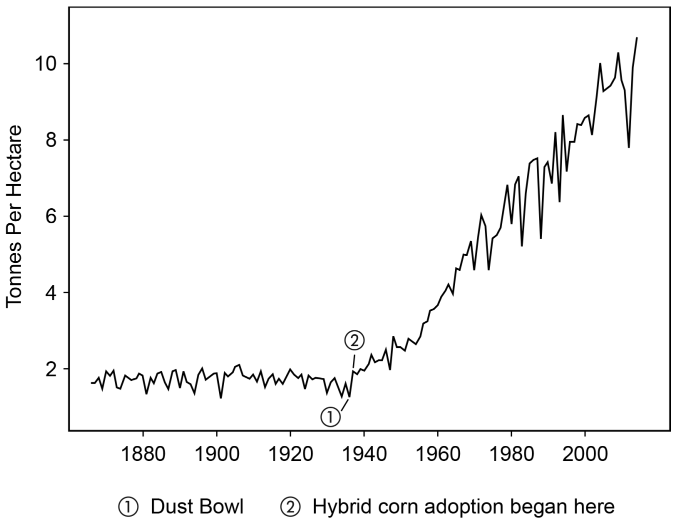

Fig. 3.C1 US corn yields, 1888–2014

Source: These data are from https://ourworldindata.org/crop-yields, which has graphs and data to show a more comprehensive presentation of global agricultural productivity growth. The data can also be obtained from USDA's National Agricultural Statistics Service (https://www.nass.usda.gov).

planted with crops, even 75 years ago, it seems unlikely that, without this innovation, there would be enough arable land on Earth to feed the current population. But with yield growth exceeding average population growth after hybrid corn adoption, the pressure on cropland expansion was greatly subdued. And more importantly, food prices fell even with soaring demand, sparing untold misery. Agriculture today comprises a tiny share of the gross domestic product (GDP) and is a sector we largely take for granted, mainly as a result of this remarkable technical change.

Meyers and Rhode follow up on a hypothesis put forward by Richard Sutch (2011) that hybrid adoption, and the ensuing "Green Revolution" of US and eventually global agriculture, was precipitated by devastating drought and crop failure associated with the Dust Bowl years of 1934 and 1936. In 1937, the year after the most devastating harvest in US history, hybrid corn gained its first substantial foothold, being used for over 40 percent of corn plantings in the most productive counties of Iowa and Illinois. While a productivity boost from hybrids had been discovered much earlier, the gains demonstrated in experimental trials were not enough to justify the high price of commercial seed. The vast majority of farmers still used open-pollinated seed retained from their last harvest, with a much lower opportunity cost.

Evidence presented by Sutch, further buttressed by more formal analyses of Meyers and Rhode, shows that early hybrid varieties not just were higher yielding than open-pollinated corn but also performed relatively well in drought conditions. This boost was especially evident in 1936. When combined with altered expectations stemming from the hottest and driest summers ever experienced in the Corn Belt region, this yield advantage appears to have been enough to entice a substantial number of farmers to purchase and plant commercially bred hybrids for the first time. This likely began in Iowa and central Illinois because these were the most productive areas, and if the productivity boost from hybrids was at least somewhat proportional (as opposed to additive), hybrids would be profitable there first. As adoption spread in later years, it seemed to stretch gradually from higher to lesser productive regions. To a first approximation, more farmers adopted hybrid corn as it became economic to do so, a key theme of Griliches's work.

The main novelty of Meyers and Rhode is their rediscovery and use of a data set collected by Griliches that includes early hybrid adoption rates for each crop reporting district (CRD), each of which is composed of about 10 contiguous counties. Most scholars have used only state-level data, which can obscure important within-state variation in weather, climate, and hybrid adoption rates. These new data allow for considerably more statistical power to test the idea that drought was a catalyst for early hybrid adoption. Meyers and Rhode also employ a formal regression analysis not attempted by Sutch.

A hopeful suggestion of Sutch, and of Meyers and Rhode, is that the prospect of devastating impacts of climate change on US (Schlenker and Roberts 2009) and global (Lobell, Schlenker, and Costa-Roberts 2011) agriculture may induce innovation and productivity growth that far surpasses nearer-term damages, much as the Dust Bowl seems to have done in the late 1930s. Matthew Kahn (2013) has a similar hopeful outlook. While I am generally persuaded by Sutch, Meyers, and Rhode that drought conditions of the late 1930s hastened the early adoption of hybrid corn, it is hard to know by how much this mattered for the long-run productivity trend. And while many point to genetically modified crops—including "drought-tolerant" varieties—as an emerging technology that could aid our adaption to climate change, I think there is good reason to be skeptical that these will impart a second Green Revolution as substantial as the one launched by hybrid corn.

In the next section, I briefly review some technical suggestions, some of which appear to have been adopted by the authors. In the third section, I step back to consider this chapter in the broader context of what we know about potential climate change impacts on agriculture more broadly and why the next Green Revolution, if it comes, may look quite different from the first.

3.C2 Technical Comments

3.C2.1 Measuring Drought

The key prediction variable that Meyers and Rhode considered in their first draft was the Palmer drought severity index (PDSI). This choice of measure is understandable given its prevalence. Drought is a complex thing to measure, for it depends on both supply and demand of soil moisture. Rainfall drives supply, while ground cover (plant type) and vapor pressure deficit (a lack of humidity) drive demand via evapotranspiration and evaporation. The PDSI was the first measure to account for both supply and demand of moisture, and it is based on ground cover of native grasses in Kansas, plus parametric assumptions calibrated by Palmer over 50 years ago (Palmer 1965). Unfortunately, the PDSI just does not predict corn yield outcomes very well.

In our experience, the single weather measure that best predicts corn yields is that of extreme heat—that is, growing degree days (GDDs) above 29°C (Schlenker and Roberts 2009). A quadratic in growing-season total precipitation and/or a measure of precipitation in July and August aid predictions, but only slightly. This extreme heat measure is highly correlated with average vapor pressure deficit in July and August, which suggests that the measure captures drought (Roberts, Schlenker, and Eyer 2013). A physiological model of corn plant growth and seed formation can predict outcomes slightly better, and this model considers the full chronological sequence of weather, corn evapotranspiration, and soil water balance, but it still cannot fully account for the impacts of extreme heat (Roberts et al. 2017). The notable sensitivity to extreme heat is a critical worry about climate change, and it looks like recent crop varieties, almost all genetically modified, are even more sensitive to it (Lobell et al. 2014; Roberts and Schlenker 2014), a point I will return to in the next section.

3.C2.2 Regression Model

Meyers and Rhode developed a model that predicted the log odds ratio of hybrid corn adoption as a function of previous season weather, CRD fixed effects, and a set of baseline 1930 (pre–Dust Bowl) characteristics to account for pre–Dust Bowl trends. The model seems fine as a first cut, but I had some concerns and suggestions. First, while the adoption of hybrid corn is a discrete choice and reversible in principle, the data suggest strongly that the decision is irreversible or nearly so. Thus a change in the adoption share is likely to be permanent. This suggests the use of differences in the log odds ratio instead of levels. Unit root tests could be employed as a formal test between levels and differences, but such tests are notoriously weak, so it may be best to simply report results for both levels and differences and perhaps consider a validation exercise that compares out-of-sample forecasts with actual adoption rates. Another approach may be to use a survival model wherein the dependent variable is the time until X percent of acreage in a crop district is planted with hybrid corn. To account for time-varying factors affecting survival time (like exogenous weather), the well-known Cox proportional hazard could be used.

3.C2.3 Zeros and Ones

To calculate the log odds ratio, Meyers and Rhode need to adjust the raw shares of hybrid and open-pollinated varieties, since these shares are often one or zero, and the log is undefined. In their initial paper, they added 0.001 to zeros and subtracted 0.001 from ones. This decision struck me as ad hoc, one that could cause high-leverage outliers that could bias regression results. Instead, it would be preferable to adjust all values by the same constant, not just the zeros and ones, so that the transformation of variables is consistent. This is sometimes called the Haldane-Anscombe correction. Better would be to make the adjustment an estimable parameter. For example, if Y is the share of acreage planted with hybrid corn and a is the adjustment parameter, log odds ratio then becomes $\log(Y + a) - \log(1 - Y + a)$, where a is a parameter to be estimated.

3.C2.4 Spatial Correlation

Climate, weather, soils, and many unobservable factors are all spatially correlated. Thus while weather can be a compelling instrument due to its exogeneity and near randomness in a fixed location when looking over appropriate time scales, regression errors tend to be highly spatially correlated. Meyers and Rhode cluster residuals by CRD, which accounts for serial correlation within CRDs, but residuals will still be correlated, and strongly so, for bordering CRDs. The CRD fixed effects only account for geospatial differences in mean outcomes. Within a year, however, all manner of unobservables and weather anomalies will be similar in nearby areas. Estimated standard errors will be too small. While it can be challenging to get standard errors right, when modeling crop yields in US agriculture, Wolfram Schlenker and I have found that clustering by state gives very similar standard errors as more sophisticated methods, such as Conley's method adapted for panel data.[1]

3.C2.5 Preadoption Productivity Differences

As noted earlier, Meyers and Rhode accounted for preadoption differences in productivity and other factors by interacting year fixed effects with variables from the 1930 Census of Agriculture. This strikes me as a sensible approach. The one concern I have is that a key control variable here is the 1930 yield, which is a rather transitory measure of productivity. It is important to recognize that crop yields vary tremendously from year to year and region to region, largely due to the weather, such that the yield outcome

1. To implement Conley's method adapted for panel data with independent time periods, originally used by Schlenker and Roberts (2009), see the code developed by Thiemo Fetzer (2014) and Solomon Hsiang (2010). The Conley approach may be less appropriate for data with serial correlation, such as hybrid adoption.

from any single year can be a poor reflection of anticipated or expected yield, which presumably drives decision-making. The added variance will likely cause attenuation bias of the control variable coefficient and therefore insufficiently account for preadoption productivity differences. Instead of using the outcome from this one census year, the authors could instead use average annual yield over the decade from 1920 through 1930. Annual-, county-, and crop district–level data are available from the US Department of Agriculture (USDA) to construct such a measure.

3.C2.6 Adoption Model, Yield Model, or Both?

Meyers and Rhode presented results from a regression model predicting hybrid corn adoption as a function of past weather. This approach seems reasonable. These results are nicely complemented by a working paper by Claire Palandri, David Popp, and Wolfram Schlenker (2019), who consider how hybrid corn adoption affected sensitivity to extreme heat, and I shared those preliminary results with Meyers, Rhode, and other attendees at the NBER workshop. Palandri, Popp, and Schlenker present regression results similar to what Meyers and Rhode also exhibit in their chapter. Both works show that hybrid adoption is associated with lower sensitivity to extreme heat, which seems consistent with the idea that the extreme drought conditions of the Dust Bowl years may have been a catalyst for adoption.

A key question I posed at the NBER workshop was whether the apparent drought resistance of early hybrids reflected in the postadoption observational data was the right magnitude to rationally provoke adoption in subsequent years. That is, can the adoption model and yield-response models be reconciled?

This question still needs answering. Careful development of the answer may be complicated. A critical piece concerns the way drought incidence in the 1930s changed expectations for future drought. Broadly speaking, weather looks approximately independent and identically distributed from one year to the next, so a severe drought in one year should not typically lead to altered expectations for the next year. The 1930s, however, were quite different, having several of the hottest and driest years on record in short succession.[2] Perhaps the appropriate way to tie the yield and adoption models together is to consider how much future expectations would have needed to change following the droughts of 1934 and 1936 in order to entice the rational adoption of hybrid corn. Another related question concerns how long diminished expectations would have needed to persist to continue influencing adoption in future years, as drought became less prevalent. Was drought an ongoing impetus for the expansion of hybrid corn or simply a catalyst in the initial year? These questions do not have clear answers, but it would seem that a rolling time series weather forecast, or perhaps even a

2. See the top panel of figure 2 in Palandri, Popp, and Schlenker (2019).

short-window moving average (over, say, a backward-looking five years), might give a reasonable proxy for expected weather.

3.C3 Lessons for Adaptation

While possible links between the Dust Bowl and the emergence of hybrid corn adoption are interesting and should be studied in greater depth, I think we ought to be circumspect about drawing lessons about adaptation to climate change today. The evidence brought to bear so far suggests that the hot and dry Dust Bowl years spurred the initial adoption of hybrid corn in Iowa and Illinois. At the same time, it is hard to see how hybrids would not have emerged anyway, if only a year or two later. Some of the analysis I suggest above may shed greater light on the enduring importance of extreme drought as a motive to adopt new technologies.

The trade-offs associated with the adoption of new crop varieties are quite different today. Many point to new genetically modified crops, and especially "drought-tolerant" varieties, as a viable means of adapting to climate change. The data, however, indicate that today's very-high-yielding corn varieties are *more* sensitive to extreme heat than past varieties (Lobell et al. 2014).

Growing drought sensitivity may be a testament to the success of seed development more generally. At a fundamental level, plant growth is Leontief, limited by the input in least supply. The critical inputs: sunlight, water, and nitrogen, which are the fundamental inputs to photosynthesis. Over time, crops have been bred to take the greatest advantage of the available resources to generate the maximum possible yield in each location (Cassman, Grassini, and van Wart 2010; Wright 2012). In earlier decades, the critical limiting input was nitrogen, which, even in rich soils, naturally occurs in much smaller quantities than became available after the Harbor-Bosch process made chemical fertilizer possible. Crop plants needed to be bred to manage higher nitrogen intake. The plants needed to be able to grow larger, stiffer, and with deeper roots to stand taller in higher planting densities. Thus early crop breeding led plants to have much higher *yield potential*, which crop scientists define as the maximum possible output given available sunlight and water, assuming a sufficient availability of nitrogen and no pest damage. Successive crop varieties were bred to fit the available sunlight and water in each area and to handle massive growth in fertilizer inputs.

Today, nitrogen is almost never the limiting factor; indeed, excess applications, applied just in case moisture and sunlight are sufficiently high, are the key reason for nutrient runoff into streams, lakes, and oceans, causing algae blooms and eutrophication (Babcock 1992; Tilman et al. 2002). And while today's plants have remarkable yield potential, the large plants with deep roots transpire much more water than crops from earlier generations or, for that matter, native grasses that underpin the PDSI. In more recent generations, genetically modified crops have aided management, making it easier to control weeds (glyphosate) and pests (BT strains), thereby helping farmers close the gap between yield outcome and yield potential. As a result, outcomes are more likely to be limited by other essential inputs, especially water. Thus one hypothesis is that earlier generations of hybrids grew yield outcomes mainly by growing yield potential, while later generations grew yield by closing the gap between realized yield and yield potential (Grassini, Yang, and Cassman 2009). Today, for many crops, and especially corn, crop scientists suggest that we are approaching the limit of what is possible (Van Wart et al. 2013).

Despite climate change, the highly productive Corn Belt has, so far, never experienced drought conditions nearly as severe as the 1930s. While the Midwest has experienced warming, it has mainly come during the winter and early spring, while summers have been relatively mild. Crop varieties have been bred to take the greatest advantage of the almost-ideal climate. While mild summers in the Corn Belt region have been a boon to US agricultural production, the region's vulnerability was evident during the unusually hot 2012 season, which came closer to Dust Bowl extremes (Boyer et al. 2013). Projections from climate models suggest that we have been lucky so far to have not experienced more years like 2012. More pointedly, I am not aware of any emerging technology that is likely to change the fundamentals of crop production the way hybrid corn did in the 1930s. At least for some crops, like corn, we are approaching the limits of photosynthesis (Grassini, Yang, and Cassman 2009). This suggests a new Green Revolution will require an altogether different approach.

Climate adversity and associated higher prices might push future innovation. But this will likely take time, as it always has. To my knowledge, at least since the adoption of hybrid corn and the birth of modern agriculture, productivity trends appear roughly linear over time and divorced from obvious inducing incentives, like prices or extreme events (Grassini, Eskridge, and Cassman 2013), with hybrid adoption a very notable exception. If we want to count on the idea that induced innovation will save us from climate change impacts, then I believe we need considerably more evidence to support this hopeful vision. To me, the prospect is daunting because "more than 90 per cent of the calories that feed humanity come from the handful of plants that our ancestors domesticated between 9500 and 3500 BC—wheat, rice, maize (called 'corn' in the US), potatoes, millet and barley" (Harari 2014, 78). Most aspects of our economy—energy, clothing, housing, retail trade, communication—have undergone multiple reinventions in history. Food production has not.

References

Babcock, B. A. 1992. "The Effects of Uncertainty on Optimal Nitrogen Applications." *Review of Agricultural Economics* 14 (2): 271–80.

Boyer, J., P. Byrne, K. Cassman, M. Cooper, D. Delmer, T. Greene, F. Gruis et al.

2013. "The US Drought of 2012 in Perspective: A Call to Action." *Global Food Security* 2 (3): 139–43.
Cassman, K. G., P. Grassini, and J. van Wart. 2010. "Crop Yield Potential, Yield Trends, and Global Food Security in a Changing Climate." In *Handbook of Climate Change and Agroecosystems*, edited by Daniel Hillel and Cynthia Rosenzweig, 37–51. London: Imperial College Press.
Fetzer, Thiemo. 2014. "Conley Spatial Hac Standard Errors for Models with Fixed Effects." trfetzer.com, last updated May 2015. http://www.trfetzer.com/conley-spatial-hac-errors-with-fixed-effects/.
Grassini, P., K. M. Eskridge, and K. G. Cassman. 2013. "Distinguishing between Yield Advances and Yield Plateaus in Historical Crop Production Trends." *Nature Communications* 4 (1): 1–11.
Grassini, P., H. Yang, and K. Cassman. 2009. "Limits to Maize Productivity in Western Corn-Belt: A Simulation Analysis for Fully Irrigate and Rainfed Conditions." *Agricultural and Forest Meteorology* 149:1254–65.
Griliches, Z. 1957. "Hybrid Corn: An Exploration in the Economics of Technological Change." *Econometrica* 25 (4): 501–22.
Harari, Y. N. 2014. *Sapiens: A Brief History of Humankind*. New York: Random House.
Hsiang, Solomon. 2010. "Standard Error Adjustment (OLS) for Spatial Correlation and Serial Correlation in Panel Data in (Stata and Matlab)." Fight Entropy, June 16, 2010. Version 3 update 2018. http://www.fight-entropy.com/2010/06/standard-error-adjustment-ols-for.html.
Kahn, M. E. 2013. *Climatopolis: How Our Cities Will Thrive in the Hotter Future*. New York: Basic Books.
Lobell, D. B., M. J. Roberts, W. Schlenker, N. Braun, B. B. Little, R. M. Rejesus, and G. L. Hammer. 2014. "Greater Sensitivity to Drought Accompanies Maize Yield Increase in the US Midwest." *Science* 344 (6183): 516–19.
Lobell, D. B., W. Schlenker, and J. Costa-Roberts. 2011. "Climate Trends and Global Crop Production since 1980." *Science* 333 (6042): 616–20.
Palandri, C., D. Popp, and W. Schlenker. 2019. "Hybrid Corn Adoption, Average Yields and Heat Sensitivity." Columbia University Center for Environmental Economics and Policy, Working Paper Series.
Palmer, W. C. 1965. *Meteorological Drought*. Vol. 30. Washington, DC: US Department of Commerce, Weather Bureau.
Roberts, M. J., N. O. Braun, T. R. Sinclair, D. B. Lobell, and W. Schlenker, W. 2017. "Comparing and Combining Process-Based Crop Models and Statistical Models with Some Implications for Climate Change." *Environmental Research Letters* 12 (9): 095010.
Roberts, M. J., and W. Schlenker. 2014. "The Evolution of Heat Tolerance of Corn: Implications for Climate Change." In *The Economics of Food Price Volatility*, edited by J.-P. Chavas, D. Hummels, and B. D. Wright, 81–90. Chicago: University of Chicago Press.
Roberts, M. J., W. Schlenker, and J. Eyer. 2013. "Agronomic Weather Measures in Econometric Models of Crop Yield with Implications for Climate Change." *American Journal of Agricultural Economics* 95 (2): 236–43.
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.
Sutch, R. 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 G. D. Libecap and R. H. Steckel, 195–223. Chicago: University of Chicago Press.

Tilman, D., K. G. Cassman, P. A. Matson, R. Naylor, and S. Polasky. 2002. "Agricultural Sustainability and Intensive Production Practices." *Nature* 418 (6898): 671–77.

Van Wart, J., K. C. Kersebaum, S. Peng, M. Milner, and K. G. Cassman. 2013. "Estimating Crop Yield Potential at Regional to National Scales." *Field Crops Research* 143:34–43.

Wright, B. D. 2012. "Grand Missions of Agricultural Innovation." *Research Policy* 41 (10): 1716–28.