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The Rise and Fall of U.S. Farm Productivity Growth, 1910–2007

by

Julian M. Alston, Matthew A. Andersen, and Philip G. Pardey

Department of Applied Economics

INSTEPP International Science & Technology Practice & Policy

College of Food, Agricultural and Natural Resource Sciences

University of Minnesota

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Julian M. Alston, Matthew A. Andersen and Philip G. Pardey

Julian M. Alston
Professor, Department of Agricultural and Resource Economics
Director, Robert Mondavi Institute Center for Wine Economics
1 Shields Avenue
University of California
Davis, CA 95616 U.S.A.
Phone: (530) 752-3283
Email: julian@primal.ucdavis.edu
Web: http://agecon.ucdavis.edu/people/faculty/julian-alston/

Matthew A. Andersen
Associate Professor, Department of Agricultural and Applied Economics
1000 E. University Ave.
University of Wyoming
Laramie, WY 82071
Phone: (307) 766-3401
Email: mander60@uwyo.edu
Web: http://www.uwyo.edu/agecon/about us/facultystaff/faculty pages/matt andersen.html

Philip G. Pardey
University of Minnesota
Director, International Science and Technology
Practice and Policy (InSTePP) center
Professor, Applied Economics
248B Ruttan Hall
1994 Buford Ave
St Paul, MN 55108 U.S.A.
Phone: (612) 625-2766
Email: ppardey@umn.edu
Web: http://faculty.apec.umn.edu/ppardey/

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The Rise and Fall of U.S. Farm Productivity Growth, 1910–2007

ABSTRACT. Some studies have reported a slowdown in U.S. farm productivity growth, but the prevalent view among economists is to reject or downplay the slowdown hypothesis, implying that the rates of productivity growth experienced over the past half century can be projected forward. We set out to resolve this issue, which matters both for understanding the past and anticipating the future. Using newly compiled multifactor and partial-factor productivity estimates, developed for the purpose, we examine changes in the pattern of U.S. agricultural productivity growth over the past century. We detect sizable and significant slowdowns in the rate of productivity growth. Across the 48 contiguous states for which we have very detailed data for 1949–2007, U.S. multifactor productivity (*MFP*) growth averaged just 1.18 percent per year during 1990–2007 compared with 2.02 percent per year for the period 1949–1990. *MFP* in 44 of the 48 states has been growing at a statistically slower rate since 1990. Using a longer-run national series, since 1990 productivity growth has slowed compared with its longer-run growth rate, which averaged 1.52 percent per year for the entire period, 1910–2007. More subtly, the historically rapid rates of *MFP* growth during the 1960s, 1970s and 1980s can be seen as an aberration relative to the long-run trend. A cubic time-trend model fits the data very well, with an inflection around 1962. We speculate that a wave of technological progress through the middle of the twentieth century—reflecting the progressive adoption of various mechanical innovations, improved crop varieties, synthetic fertilizers and other chemicals, each in a decades long process—contributed to a sustained surge of faster-than-normal productivity growth throughout the third quarter of the century. A particular feature of this process was to move people off farms, a one-time transformation of agriculture that was largely completed by 1980.

Keywords: U.S. agriculture, multifactor productivity, land and labor productivity, crop yields

One hundred years ago, U.S. agriculture played a much different role in the economy than it does today. In 1916, the farm population peaked at 32.5 million, 31.9 percent of the total U.S. population (Alston et al. 2010a). Since then, while the U.S. population continued to grow, the farm population declined to 4.6 million in 2013, just 1.5 percent of the total.[1] A dramatic transformation of agriculture, with farms becoming much larger and more specialized, was achieved through the progressive introduction and adoption of a host of technological innovations and other farming improvements that enabled much more to be produced with less land and a lot less labor. Productivity grew rapidly. Echoing Schultz (1956) and Griliches (1963), Jorgenson and Gollop (1992, p. 748) concluded "There is little doubt that productivity growth is the principal factor responsible for postwar [1947–1985] economic growth in agriculture, accounting for more than 80 percent of the sector's growth."[2]

Similar transformations have taken place around the world, especially in the higher-income countries; and, partly driven by the changes in the United States, food has become much cheaper in real terms in spite of having a much larger and richer global population to feed. In the second half of the 20th century, in particular, global food supply grew faster than demand and real food prices fell significantly, alleviating hunger and poverty for hundreds of millions around the world (e.g., Alston and Pardey 2014).[3] Can that pattern, or anything like

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[1] The U.S. government ceased providing estimates of farm population (i.e., rural civilians living on farms regardless of occupation) in 1991. This 2013 estimate was formed by multiplying the average number of people per farm living on farms during 1987–1991 by the number of farms in 2013 obtained from USDA-NASS (2015). The farm population share was formed by dividing the result by the corresponding U.S. population obtained from U.S. Bureau of Census (2015).

[2] For example, Schultz (1956, p. 753) wrote: "From 1923 to 1929 only about one-half—or a little more—of the increase in output appears to have been achieved by additional inputs. During the depression years, 1930 to 1940, none of the increase in output seems to be explained by additional inputs. … The war years called forth substantially more output, yet from 1940 to 1948 perhaps only a fifth to a fourth of the increase in output can be explained by additional inputs."

[3] The United States was a significant factor in the global developments both directly as an important agricultural producer and indirectly as a source of technologies that other countries adopted (e.g., see Pardey and Alston 2010).

it, be sustained in the 21st century, given that global demand for cereals is projected to grow by about 70 percent from 2010 to 2050 (Rosegrant, Fernandez, and Sinha 2009; Pardey et al. 2014)? The answers to today's questions about the future of food will depend, as they did in the past, fundamentally on the future path of farm productivity growth.

The recent spikes of food commodity prices, peaking in mid-2008 and again in early 2011, have stimulated a renewed interest in questions about the long-term path of agricultural productivity, and emerging, but contested, evidence suggests that U.S. farm productivity growth has significantly slowed. Has the "golden age" of U.S. agricultural productivity growth ended? The national and global economic stakes are high, since sustaining a comparatively rapid rate of farm productivity growth is key to U.S. farmers remaining competitive in world markets, and global food supplies and prices depend directly and indirectly on U.S. farming innovations.[4]

Concerns about a slowdown in the pace of productivity growth in the U.S. economy as a whole, or sectors of the economy, are not new. In a retrospective, Nordhaus (2004, p. 1) noted that "… the [U.S.] productivity slowdown of the 1970s has survived three decades of scrutiny, conceptual refinements, and data revisions. The slowdown was primarily centered in those sectors that were most energy-intensive, were hardest hit by the energy shocks of the 1970s, and therefore had large output declines." Economists had mixed views at the time as to whether the U.S. economy in fact experienced a productivity slowdown during the 1970s; and, if so, about the timing of the onset, the amplitude, and the duration of the slowdown.

[4] The United States itself accounts for significant shares of global production in major food and feed crops. In 2010–12 it was second-ranked for total agricultural output at 10.1 percent of global output by value; first-ranked for maize (34.6 percent of total output), soybeans (33.4 percent), poultry (18.9 percent), and beef (18.0 percent); and second-ranked for sorghum dairy, and pork (FAO 2014).

Likewise, economists have various views about the existence, nature, extent and likely duration of a slowdown in U.S. (and global) agricultural productivity growth. Economists at the U.S. Department of Agriculture—a widely cited source of data and research on agricultural productivity—have consistently rejected the hypothesis of a slowdown. Specifically, Ball, Wang and Nehring (2010, p. 3) reported that "… statistical analysis of the [USDA] data does not provide evidence of a longrun productivity slowdown." Similarly, Wang (2010, p. 6) observed "…statistical analyses of ERS productivity accounts through 2008 did not reveal a corresponding slowdown in long-term rates of [U.S.] agricultural productivity growth." In contrast, Alston et al. (2010a, pp. 120–121) concluded "There can be little doubt that the InSTePP *MFP* data exhibit evidence of a slowdown in multifactor productivity growth in the period 1990–2002 compared with the previous period [1949–1990]." More recently, Ball, Schimmelpfennig and Wang (2013) reported having found a structural shift in the path of agricultural productivity in 1974, concluding that productivity grew at an annual average rate of 1.71 percent per year prior to the breakpoint and 1.56 percent per year after. More broadly, the predominant view among economists and in U.S. government reports, is to reject or downplay the slowdown hypothesis both in the United States and in a global context (e.g., see Fuglie 2010, and various chapters in Fuglie, Wang and Ball 2012). In this paper we challenge that conventional wisdom. Using a range of productivity measures and assessment methods we find robust and compelling evidence of a structural slowing of productivity growth in U.S. agriculture, and offer two potential rationales.

DATA RESOURCES

The long-run path of U.S. agricultural inputs, outputs, innovations and productivity has been the subject of a rich literature, including works by Cochrane (1958, 1993), Olmstead and Rhode (2000, 2006a, 2006b, 2008), Gardner (2002), Dimitri, Effland, and Conklin (2005) and a host of others cited and discussed by Alston et al. (2010a), but this literature did not address the issue of a productivity slowdown in the recent era.[5] Those studies that have addressed the issue of a recent slowdown—such as Alston, Babcock and Pardey (2010b), Alston et al. (2010a), Ball, Wang and Nehring (2010) and Ball, Schimmelpfennig and Wang (2013)—relied on evidence since 1949. In what follows, in addition to conducting further analysis using post-World War II data, we use several new, longer-run, series of productivity measures, constructed specifically for the purpose, to explore the evolving path of U.S. farm productivity growth over most of the 20th century and into the early 21st century.

Measuring productivity is a difficult task; detecting and interpreting changes in productivity growth rates can be even more difficult. The measures used matter. We developed a range of *MFP* and *PFP* measures for the U.S. farm economy stretching back a century or more, to investigate the nature of productivity growth over time. First, we updated the InSTePP production accounts, which consist of very detailed state-specific data, for the period 1949–2007, on inputs and outputs in U.S. agriculture.[6] Using these data we

[5] Historical compilations of national indexes of inputs, outputs, and productivity in U.S. agriculture are reported by Strauss and Bean (1940) for the period 1869–1937, Barton and Cooper (1948, Chart 8) for 1910–1945, Barton and Durost (1960) for 1910–1939, Durost and Barton (1960) for 1870–1955, Kendrick (1961, pp. 362–364) for 1869–1960 (see also Rasmussen 1962, Table 3) and Loomis and Barton (1961, Table 12) for 1910–1958. Others who have studied U.S. agricultural productivity growth with an emphasis on 19th century developments include Gallman (1972) and Weiss (1993) for the period 1800–1900, and Geib-Gundersen and Zhart (1966) for 1800–1910.

[6] The primary source of data used in this paper is the InSTePP Production Accounts, Version 5, supplemented by earlier and other data from various USDA sources, the details and treatment of which are briefly reviewed in the

constructed Fisher ideal approximations to Divisia indexes of quantities of inputs and outputs for each of the 48 contiguous U.S. states and the United States as a whole. The highly disaggregated base data permitted the construction of indexes with adjustments for heterogeneity of inputs (e.g., age and horsepower of tractors in the capital stock or age and education of farm operators in the labor input) and outputs at the state and national levels.

These quality-adjusted state-specific indexes can be used to estimate and analyze national and state-specific trends in multifactor productivity (*MFP*) and in several partial factor productivity (*PFP*) measures (specifically, land, labor, capital and materials) for the period 1949–2007.[7] Initial work with an earlier version of these data (e.g., see Alston et al. 2010a) provided evidence of a slowdown in productivity growth since 1990, but this work also raised some questions that require consideration of the prior history for which we do not have such detailed data available on inputs, outputs, and productivity. Hence, to place the post-World War II (WWII) evidence in a longer-run setting, we backcast the InSTePP measures of national agricultural productivity to 1910, using commensurate land, labor and *MFP* measures compiled by the USDA (see Appendix A for details). We apply a battery of measures to the resulting *MFP* data, as well as various *PFP* measures, to test for changes in productivity growth over the longer term. These analyses, as well as analyses using the more-detailed data after 1948, consistently reveal a phenomenon of accelerating growth peaking in the 1960s or 1970s, followed by a progressive slowdown, visibly apparent after 1990. In this

Appendix A. See Pardey, et al. (2009) for a more complete description of the InSTePP Production Accounts which are available at www.instepp.umn.edu/datasets.

[7] In the present context, as in many others, we are most interested in total factor productivity (*TFP*) since it is an encompassing measure that represents the full quantity of resources used to produce the total quantity of output produced. However, for most practical purposes we have incomplete measures of outputs and inputs, especially in agriculture where many of the environmental consequences of, or natural inputs to, agricultural production are rarely measured. We are thus forced to rely on *MFP* estimates that include less than a complete accounting of inputs and outputs, or *PFP* measures that express output relative to a particular input.

framework, the recent slowdown can be seen to some extent as a return to a more-normal long-run average growth rate, following a period of abnormally high rates in the period of the 1950s through the 1980s.

U.S. FARM PRODUCTIVITY, 1910–2007

Our analysis begins with the most comprehensive but also most aggregative measure: using our new data on national agricultural *MFP* over the longer period, 1910–2007. We describe the patterns in the data and then apply various procedures to test for a slowdown.

Multifactor Productivity Measures

Over the course of the century, the index of the aggregate quantity of output (*Q)* from U.S. agriculture grew from 100 in 1910 to 461 in 2007, at an average fitted exponential growth rate of 1.69 percent per year. Meanwhile, the index of the aggregate quantity of inputs (*X*) used in U.S. agriculture grew at an average fitted exponential growth rate of just 0.03 percent per year, reflecting some increases in capital and materials inputs that offset the reductions in use of land (after the late 1970s) and especially labor. Consequently, the measure of *MFP* ($MFP = Q/X$) grew at an average fitted exponential growth rate of 1.66 percent per year (Figure 1). The implication is that U.S. agriculture produced 4.6 times as much agricultural output in 2007 as in 1910 without appreciably increasing the quantity of aggregate input. Over the same period, the *PFP* of land grew more slowly, averaging 1.35 percent per year while the *PFP* of labor grew relatively rapidly, averaging 2.90 percent per year, as the labor intensity of farming was falling substantially. U.S. agricultural land was 4.8 times more productive in 2007 than it was in 1910, and labor was 18.4 times more productive, reflecting the great exodus of farm labor out of agriculture—even after appropriate adjustment for the partially offsetting improvements to land (mainly irrigation) and the enhanced educational status and work experience (increased age) of farm operators.

[Figure 1: *Output, Input, MFP, Labor PFP, Land PFP and Land per Farm, 1910–2007*]

The long-run path of these various productivity measures was not always smooth. Substantial year-to-year variation in *MFP*, and the associated year-to-year variation in aggregate output (and to a much lesser extent measured aggregate input use) make it difficult to discern the onset, magnitude and duration of a productivity slowdown (e.g., see Appendix Figure A-1).[8] To test for secular changes in productivity growth entails comparing longer sub-periods in which some of the year-to-year variation is smoothed out—for instance, the data are summarized by decade in Table 1. As these data indicate, our measures of *MFP* and *PFP* growth have varied substantially from decade to decade, with relatively high rates of growth during the period 1950–1980, when the rate of growth of aggregate output was also relatively high (1.87 percent per year for the period 1950–1980, and 2.03 percent per year for *MFP* for the same period). But findings regarding productivity growth over sub-periods may depend on the choice of where to divide the data (measures may be sensitive to starting and ending points), as well as choices about how to measure growth rates and whether to measure them in absolute or percentage changes, in yields per acre or in partial- or multi-factor productivity indexes. In addition, they may depend on the econometric and statistical techniques used, as discussed next before we turn to a formal assessment of structural changes in the rates of productivity growth.

[8] Year-to-year variations in measured productivity growth might reflect the influences of short-term, transient factors such as weather, crop pests, or policy changes; they might also be the result of measurement errors such as those associated with variable capital utilization rates (e.g., see Andersen 2005; Andersen, Alston and Pardey 2011).

[Table 1. *Annual Growth Rates in U.S. Output, MFP and PFP, 1910–2007*]

Perron (1989), Zivot and Andrews (1992), and Hansen (1992 and 2001) devised and applied methods for testing for a unit root (i.e., non-stationarity) when a structural break may be present in the underlying series. These studies indicate that commonly used unit root tests, such as a Dickey-Fuller test, may be inappropriate in the presence of structural breaks. A Dickey-Fuller test provides strong indications that our index of *MFP* is non-stationary.[9] However, an alternative possibility is that our *MFP* series is in fact stationary around a deterministic trend that has a structural break somewhere in the series, and we have to distinguish between these alternatives. Zivot and Andrews (1992) developed a statistical approach to distinguish between a unit root process and a trend stationary process with a structural break of unknown timing, which we refer to as the *ZA*-test. This test allows for a break in either the level or the trend of the underlying series, or both.

In our application of the *ZA*-test, the null hypothesis is that the *MFP* series in natural logarithms has a unit root, while the alternative hypothesis is that the series is stationary around a deterministic trend, with a structural break of unknown timing in its level and trend. Under the alternative hypothesis, standard tests for a unit root might be inappropriate. The *ZA*-test procedure involves segmenting the entire sample into different periods at each observation and performing a series of one-sided *t*-tests of the null hypothesis of a unit root. The observation (year) with the minimum calculated (negative) *t*-statistic provides the strongest evidence against the null hypothesis, and represents the most likely candidate for a

[9] We performed a Dickey-Fuller test for whether *MFP* (in natural logarithms) follows a unit-root process. The null hypothesis is that *MFP* contains a unit root, and the alternative is that *MFP* was generated by a stationary process. We failed to reject the null hypothesis of a unit root (p-value = 0.94); however, after taking the first-difference in logs, we strongly rejected the null hypothesis of a unit root in the series (p-value = 0.00).

breakpoint in the series.[10] Figure 2 plots the estimated breakpoint *t*-statistics for the *MFP* series in natural logs for the period 1910–2007 with a five percent trim. The largest (negative) *t*-statistic occurs for the breakpoint year of 1979. However the calculated *t*-statistic for this test, –3.38, is less than the 5 percent critical value of –5.08, so we do not reject the null hypothesis of a unit root in the series.[11]

[Figure 2: *Zivot-Andrews Breakpoint t-statistics on MFP Series, 1913–2006*]

According to the *ZA*-test, a one-time structural break in the series does not appear to exist. However, this does not rule out the possibility of a gradual decline in recent decades in the level or growth rate of a fundamentally non-stationary time series. The findings from the Dickey-Fuller and *ZA* tests suggest that we should work with a stationary variant of the productivity series, the first differences of the logs (i.e., the annual rate of growth) of *MFP* (as plotted in Figure A-1), to assess whether the growth in U.S. agricultural productivity has slowed. To do so, we adopted and expanded on a procedure Nordhaus (2004) used to test for periods of a slowdown in U.S. productivity growth. This "rolling regressions" procedure is parsimonious and allows for the identification of periods of slowdown using a stationary productivity growth series.

We first applied a modified version of Nordhaus' rolling regressions approach, whereby we assessed differences in the average rates of U.S. agricultural *MFP* growth for periods before and after a breakpoint date. To do this we regressed annual observations of the rate of growth of *MFP* for the period 1911–2007 on a constant term and an indicator variable

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[10] The asymptotic critical values for the *t*-tests are provided in Zivot and Andrews (1992). The *ZA*-test requires trimming the data on both ends by a certain percentage of the overall sample; typically 1 percent, 5 percent, or 10 percent is chosen. In practice the results from our analysis are invariant to the choice of a 1, 5 or 10 percent trim.

[11] We also performed the *ZA*-test assuming a break in the intercept (not trend), as well as a break in the trend (not intercept), and in each case found that we do not reject the null hypothesis of a unit root.

that was assigned a value of zero for each year prior to a breakpoint and one thereafter. Breakpoints were set at each year from 1920 to 2006, and a rolling series of dummy variables was constructed accordingly. The estimated coefficients on the dummy variables for the different breakpoints are plotted in Figure 3, Panel a.[12] These coefficients measure the difference in the average annual rate of productivity growth between the years before and after the corresponding breakpoint.[13]

[Figure 3: *Estimated Coefficients on Dummy Variables for Breakpoints and Time Intervals of MFP Growth Rates, 1910–2007*]

For the first 50 years or so of the series beginning in 1910, the breakpoint coefficients plotted in Panel a of Figure 3 are positive numbers, indicating that productivity grew more rapidly after each breakpoint compared with the period before it. The generally downward slope of the sequence of coefficients implies that, over time, the increase in the growth rate of *MFP* after the breakpoint was generally diminishing, albeit with some temporary reversals. In contrast, for the series of breakpoints following the late 1970s, the dummy variable coefficients are generally negative, indicating that, for each breakpoint, productivity was slower after the breakpoint than before it—clear evidence of a slowdown in *MFP* in the more-recent years. The breakpoint for 2007 is an exception and reflects an outlier effect; setting

[12] Nordhaus (2004, p. 4) wrote, "It is tempting to perform statistical significance tests on these series. However, it is clear that the underlying series have non-stationary variances, are not normally distributed, and are inappropriate for standard tests because of the overlapping samples. The best approach is probably to examine the pattern of results."

[13] For example, take the year 1925, with an indicator variable equal to zero for 1911–1924 and one for 1925–2007. The estimated coefficient on the indicator variable from the 1925 breakpoint regression (1.52) is simply the average fitted *MFP* growth rate for 1925–2007 (1.74) minus the average fitted growth rate for 1911–1924 (0.22). In this case the estimates indicate that *MFP* grew by 1.52 percent per year faster from 1925 forward, compared with the years before 1925.

aside this atypical terminal observation results in an outlier effect in the opposite direction as can be seen in the dotted line in Figure 3, Panel a.[14]

We also tried the specific rolling regressions procedure used by Nordhaus (2004). In this instance the indicator variable was assigned a value of one for each year in a five- or fifteen-year interval, and zero for all other years in the sample.[15] The terminal year for each interval was stepped back through the data, beginning in 2007, and the estimated dummy coefficients for the rolling series are plotted in Panels b and c of Figure 3. Here the coefficients indicate the difference between the average annual rate of *MFP* growth for the interval ending in the year shown, and for all other years in the sample.

Consider a five-year rolling interval and the estimated results for the interval ending in 1925. To obtain the 1925 coefficient estimates we set the indicator variable equal to one for all the years in the five-year interval ending in 1925 (i.e., 1921–1925) and zero for all the other years in the sample. The estimated coefficient on the indicator variable indicates the magnitude by which average productivity growth for the specified five-year interval differs from the average productivity growth for the other years in the sample (i.e., 1911–1920 and 1926–2007).[16] The results from five- and fifteen-year interval analysis serve to reinforce the breakpoint analysis, indicating a slowdown in productivity growth in the latter decades of the

[14] Breakpoint estimates can be sensitive to the choice of endpoint, especially at the tail end of the sample when the small number of observations on one side of the breakpoint makes the coefficient estimates vulnerable to outlier effects. U.S. *MFP* jumped by 2.53 percent from 2006 to 2007—an abnormal rate, well above the long-run average rate of growth of 1.52 percent per year over the period 1910–2007, and no doubt reflecting a response to the commodity price spikes in that year.

[15] We also applied the same procedure for a ten-year interval with no appreciable difference in the qualitative nature of the results.

[16] For example, the average productivity growth rate for the interval 1921–1925 was 0.30 percent per year, and the average for the other years in the sample 1911–1920 and 1926–2007 was 1.59 percent per year. The estimated coefficient on the indicator variable for 1925 is –1.29, indicating that in the period 1921–1925 *MFP* grew by 1.29 percent per year more slowly on average than during the periods 1911–1920 and 1926–2007 (i.e., 0.30 – 1.59 = –1.29).

sample, but they also suggest a period of comparatively slow productivity growth in the early decades of the 20th century.

Given a null hypothesis of constant growth, it is informative to plot the logarithm of *MFP* against time: constant productivity growth implies a linear path, i.e., $d\ln MFP/dt$ is constant. In Figure 4, Panel a, the path of ln*MFP* is clearly (visibly) non-linear. To parsimoniously characterize the patterns in these data we estimated polynomial trend models in which the linear model, representing constant exponential growth, is a nested special case. A cubic polynomial trend model (the gray line) fits the data (the black line) very closely, and the quadratic and cubic terms are individually statistically significant; the hypothesis of the linear model with a constant growth rate is strongly rejected (see Table 2, Column 3). The estimated parameters of the cubic model imply an accelerating rate of *MFP* growth over the years prior to 1963 and slowing productivity after 1963 (the estimates imply an inflection point—the year of the maximum growth rate—in 1963, with a 95 percent confidence interval between 1961 and 1964). This cubic function is consonant with the patterns of the sub-period-specific growth rates in Table 1—faster rates in the 50 years centered on 1963 (i.e., the 1940s through 1980s, especially in the middle of that period) and slower rates in the earlier decades (i.e., 1910–1930) and more recently (1990–2007).

[Figure 4: *A Cubic Trend Model of Productivity Indexes in Natural Logarithms, 1910–2007*]

[Table 2. *Cubic Trend Models of MFP and PFP in Natural Logarithms, 1910–2007*]

The results in Figure 4, Panel a (see also Appendix Figure B-1) and Table 2, Column 3, support the view proposed by Alston et al. (2010a) that U.S. farm productivity growth has slowed in recent decades, in the context of the post-war period (i.e., since 1950). But more than that, they also suggest that this slowdown was relative to a period of unusually high productivity growth in the middle of the full sample period, 1910–2007. In the context of that longer time series, the period 1947–1985 studied by Jorgenson and Gollop (1992), was a period of comparatively rapid and fairly steady productivity growth—compared with both the prior period 1910–1946 and the subsequent period 1986–2007.

In addition, it can be seen that the middle 1980s were characterized by relatively volatile productivity patterns—probably the consequences of unusual weather conditions in some years (e.g., drought in 1982-83; see Boken, Cracknell and Heathcote 2005) and farm policy in some others (the "payment-in-kind" program introduced in 1983 and other significant changes wrought by the 1985 Farm Bill; see Olmstead and Sumner 2006). This volatility makes findings regarding a slowdown potentially sensitive to the choice of break-point within the 1980s, though productivity growth seems clearly to have been slower after 1990 than before 1980. Since 1990, *MFP* grew by 1.18 percent per year, which is less than the average rate of growth of 1.52 percent per year for 1910–2007, and substantially less than the rate for several preceding decades. Conscious of potential end-point effects, we also calculated the annual average rate of growth for various periods, beginning in different years, 1985–1995 but all ending in 2007. The average annual percentage growth rates ranged from 0.67 to 1.46 (and from 0.50 to 1.40 if the terminal year was 2006), all below the long-run average rate of growth.

As a type of robustness check on these results, we estimated the same cubic model applied to the USDA-ERS "TFP" measures available at (USDA-ERS 2013) for 1948–2011, that were backcast to 1910 using the same procedure as we used for the InSTePP series to create a comparable long-run series, 1910–2007. The estimation results are reported in Table 2, Column 4. The cubic model also fits the long-run TFP series very well and rejects the simpler (including linear) forms. The quadratic and cubic coefficients are statistically significant, indicating a statistically significant acceleration and slowdown with an inflection in 1978 (see Appendix Figure B-2). The same cubic model estimated using data just for the shorter period, 1949–2007, for which we have much more detailed information on inputs, outputs, and productivity, also indicates a slowdown but with different timing—an inflection in 1971 using our (InSTePP) MFP data versus 1982 using the USDA TFP data (Table 2, Columns 5 and 6). Whilst the specific findings vary with the base data used (InSTePP versus USDA ERS) and time periods studied (beginning in 1910 versus 1949) the general findings are consistent: statistically significant evidence of an acceleration and slowdown, with an inflection between 1960 and 1985.

Partial Factor Productivity Measures: Land and Labor

Table 1 shows period-specific growth rates in U.S. aggregate agricultural input, output, and *MFP* as well as measures of partial factor productivity (*PFP*) for both land and labor. In Appendix C we lay out the links between *TFP* and *MFP* measures (and as a limiting case, *PFP* measures) that we can use to draw inferences about *TFP* from patterns of *MFP* and *PFP* growth. With these *PFP-MFP-TFP* relationships in mind we turn to an empirical assessment of long-run trends in land and labor productivity as well as selected national-average U.S. crop yields for which data are available well back into the 19th century.

Figure 4 shows plots of logarithms of land productivity (Panel b) and labor productivity (Panel c). In each case, as for *MFP*, a cubic polynomial trend model (the dashed line) fits the data (the solid line) very closely, and the quadratic and cubic terms are individually statistically significant; the hypothesis of the linear model with a constant growth rate is again strongly rejected (see Table 2). However, the patterns are quite different between land and labor productivity. In the case of labor, the pattern shows a clear acceleration and slowdown with an inflection centered on 1960, whereas for land, a clear acceleration in the early decades is not mirrored by a corresponding slowdown in the later decades. The estimated inflection point of 1974 has a relatively wide 95 percent confidence interval and, visually, we see only weak if any indications of a slowdown at any time after 1950.

As for *MFP*, we also applied the breakpoint and interval regression methods to these two productivity metrics for data spanning the period 1910–2007.[17] In Figure 5, Panels a and b report the results of the breakpoint analysis for land and labor productivity, respectively, and panel c reports the 15-year interval analysis for both land and labor productivity. The breakpoint coefficients plotted in Panel a reveal that in most periods, land productivity grew faster, on average, after than before each breakpoint (i.e., most estimated coefficients are positive). This is consistent with the plot in Figure 4, panel b, in which land productivity accelerated before 1950 after which it grew at a fairly constant trend rate. As the breakpoint moves toward the end of the sample, the gap in pre- and post-breakpoint growth rates becomes more variable and begins to widen, most notably after 2000. This pattern reflects the abnormal production year in 2007, when U.S. aggregate output jumped (by 3.47 percent that year) in response to spiking commodity prices. Productivity increases in that single year increasingly dominate the average growth rate in post-breakpoint periods as the number of observations following the breakpoint shrinks. The breakpoint analysis for the sample period 1910–2006 is plotted as a dotted line in Figure 5, Panel a, where setting aside the observation

[17] The *ZA*-tests discussed above were conducted on the land and labor productivity series for the period 1910–2007, and the minimum *t*-statistic (–5.83) was found for the breakpoint year of 1933 for land productivity. The *t*-statistic exceeds the 1 percent critical *t*-statistic of –5.57, indicating that we should reject the null hypothesis of a unit root. The breakpoint year for labor productivity was 1977, with an estimated *t*-statistic of –3.18, indicating that we should not reject the null hypothesis of a unit root.

for 2007 mutes the tendency for the trend rate of growth in land productivity to rebound in more recent years.

[Figure 5: *Estimated Coefficients on Dummy Variables for Breakpoints and Time Intervals of PFP Growth Rates, 1910–2007*]

In keeping with the plots of labor productivity in Figure 4, Panel b, the pattern of breakpoint regression coefficients in Figure 5, Panel b indicates that the pace of labor productivity growth slowed during the first half of the 20th century in tandem with a slowing of the rate of decline in labor use in agriculture (Alston et al. 2010a, chapter 3).[18] Throughout the time period, the estimated coefficients tend to decrease as the breakpoint is moved to later years. Labor productivity grew more slowly in periods after the breakpoint for breakpoints later than 1965, except for 2007, again a reflection of an anomalous end-point (year 2007) effect. If we set aside the observation for 2007, the trend rate of growth in labor productivity is slower for all years after 1965 (Figure 5, Panel b).

The interval results in Figure 5, Panel c, reinforce the insights gleaned from the breakpoint analysis in Panels a and b, as well as the results from the cubic trend models as plotted in Figure 4. Fifteen-year interval productivity growth rates for land were below the long-run average until the beginning of WWII. After remaining well above average for about 10 years, beginning in 1952, interval growth rates hovered around the long-run average through to the end of the sample. The pattern for labor is similar in the early years but quite different after 1950. Labor productivity grew more slowly than average for each of the fifteen-year windows terminating in years after 1992, just as it did for the fifteen-year

[18] As Alston et al. (2010a, pp. 40–41) observed "To account for the general shift toward more days spent off farm...[in forming the InSTePP series we estimated]...the average number of hours operators worked off farm relative to the hours in a full-time farm year. In 2002, part-time farmers worked 61% of their total work hours off farm, compared with 31% in 1930."

intervals terminating in years prior to 1942. The slower-than-average growth rates in the beginning and ending years of this 97-year sample bracket a period from 1942 to 1992 when the fifteen-year interval growth rates in labor productivity consistently exceeded the rest-of-sample growth rates. In Panel c, the gap between the interval and the rest-of-sample labor productivity growth rates is around –2 percent to –3 percent per year through to the mid-1930s, after which it generally increases up to 1950 and generally diminishes over time after 1960, to become increasingly negative after 1992.

Partial Factor Productivity Measures: Crop Yields

A comparable analysis of U.S. national average crop yields—yet another partial factor productivity measure—for barley, corn, oats, rice soybeans, and wheat back to the mid-19th century indicates that the decades of the 1950s, 1960s, 1970s and 1980s were generally decades of abnormally high rates of yield growth. More complete details are provided in Appendix B, but to summarize, the period of abnormally high *MFP* growth began a little later and was shorter lived, spanning the 1970s and 1980s. Prior to 1935, the rate of growth in crop yields was, with some minor exceptions (for rice and soybeans), generally below the rate since then.[19] And, again like the *MFP* evidence, rates of yield growth for all six crops since 1990 are more in line with the average rate of growth in yields over the entire period 1867–2009, well below the rapid rates of the 1960s and 1970s. Notably, the more recent rates of growth in crop yields are generally similar to the corresponding rates of growth in *MFP*. For example, the comparatively slower rates of growth of crop yields since 1990 ranged between

[19] The annual rate of growth in rice yields changed little after 1935 (from 1.64 to 1.31 percent per year), and the exceptionally high 3.62 percent per year trend rate of growth of soybean yields prior to 1935 likely reflects a small sample phenomenon (in that we only have soybean yield observations beginning in 1924).

0.62 and 1.75 percent per year, with five of the six crops experiencing yield gains of less than 1.40 percent per year; and with a simple average among all crops of 1.00 percent per year for 1990–2009 and 1.17 for 1990–2007.[20] The corresponding rate of growth in *MFP* was 1.18 percent per year for 1990–2007. In this instance, at least for the period 1990–2007, a simple average of the crop-specific *PFP* measure provides a reasonable approximation to the broad path of the corresponding *MFP* measure that is a more encompassing measure of productivity.

Cubic trend models fitted to all of these national productivity measures—be they *MFP*, labor or land *PFPs*, or crop yields generally indicate a significant slowdown in productivity growth with an inflection in the early- to mid-1960s (see Appendix B). In Table 3 we report the point estimates and 95 percent confidence intervals for the inflection point (the year of maximum annual productivity growth) for each of those measures and, to evaluate the possibility that the early years might have been influential, using a range of subsamples for *MFP*.

[Table 3: *Estimated Inflection Points in Cubic Trend Models for Various Productivity Measures*]

The evidence presented above on the changing trajectory of productivity growth in U.S. agriculture is reliant on primal measures of productivity. Drawing on the duality between real commodity prices and primal productivity measures described by Jorgenson and Griliches (1967), Alston and Pardey (2014) pointed out that the progressive slowing of the rate of decline in real commodity prices over the past four decades or so (transiting to an upward drift in these relative prices in more recent years, even prior to the commodity price spike of 2007–2008) is consistent with a secular slowdown in the growth rate of *MFP*. To the

[20] The individual average annual growth rates for wheat, corn, barley, oats, soybeans, and rice during the years 1990–2007 were 1.15, 1.44, 1.17, 0.56, 1.42, and 1.26 percent per year, respectively.

extent that U.S. farmers' terms of trade are determined in global markets, they will reflect global, not just U.S. agricultural productivity growth, which might not have slowed as much or with the same timing. Even so, in terms of both their extent and timing, the relative price movements are broadly consistent with a slowdown in productivity growth as documented here using the primal measures for U.S. agriculture alone.

STATE-SPECIFIC PRODUCTIVITY PATTERNS, 1949–2007

The analysis using national aggregate data back to 1910 provides compelling evidence of a slowdown in the growth of agricultural *MFP* in recent decades, following a period of unusually rapid growth in MFP during the third quarter of the 20th century. Here we use more detailed state-specific evidence on input, output, and *MFP* indexes for the period 1949–2007 to gain a sense of the structure of productivity change among U.S. states, and to test more formally for a slowdown since 1990.

Diverse Patterns of Change in Inputs, Outputs, and Productivity

The national aggregate data are quite informative but they do mask remarkable diversity among the states in their production and productivity patterns over the period 1949–2007 (see Appendix D). All states had positive *MFP* growth. Some states had both inputs and outputs growing (e.g., California and Idaho), and some had both falling (e.g., Massachusetts and New Jersey); however, the majority of states had the quantity of output growing against a declining quantity of aggregate inputs. Clear evidence of a recent productivity slowdown can be seen in distributions of annual state-specific *MFP* growth rates over ten-year periods since 1949 (Appendix Figure D-2). Aggregate input growth was generally higher in 1990–2007 compared with 1949–1990 (and notably so for most western states), whereas output growth generally slowed after 1990. These reinforcing input and output trends contributed to the pervasive slowdown in *MFP* growth.

Given the very substantial differences in paths taken by agricultural input, output and productivity among the 48 contiguous states, albeit with a predominant pattern of slower productivity growth since 1990, we might reasonably expect to find diversity among the states in the timing, duration, and extent of shifts in their productivity patterns. To explore this aspect, as for the national aggregate data for 1910–2007, we estimated cubic polynomial trend models using these state-specific data for 1949–2007. The cubic model generally rejects the simpler (including linear) forms, and the preponderance of states show clear evidence of a slowdown in productivity growth in the latter years of the sample (detailed results are available in Appendix D, in particular see Appendix Figures D-1, D-2, and D-3).[21]

In Table 2, Column 7 we report the results for a cubic trend model estimated by ordinary least squares, pooling the state-specific data, which is equivalent to estimating individual state models subject to the restriction that the parameters are the same for every state.[22] The estimates suggest a slowdown with an inflection in 1969 and a narrow 95 percent confidence interval. In Figure 6, the box and whiskers plots of distributions of the predicted state-specific MFPs (in logarithms) reveal a general pattern that is consistent with the plot in Figure 4 of the national average MFP (in logarithms) over the same period. Overlaid on that

[21] Some notable exceptions are among the mid-western states (such as Illinois, Indiana, Iowa and Minnesota) where the paths suggest constant (or even slightly accelerating) growth. These are states where corn and soybean production predominate; two crops that have sustained comparatively rapid rates of growth in national average yields in recent years compared with prior decades (Appendix Table B-2).

[22] The estimated parameters are identical to those that would be obtained by estimating the 48 individual state-specific models, without imposing that restriction, and then taking the simple average of each coefficient (since they are linear models with the same explanatory variables). The predicted MFP from this model is accordingly the average of the predicted state-specific MFP indexes from the unrestricted models and at the same time a prediction of the simple average of the state-specific MFP indexes.

plot, the fitted model from Table 2, column 7, closely tracks the mean of the observed 48 state-specific MFP growth rates, which exhibits a sharper slowdown than the model applied to the national index of MFP.

[Figure 6: *Observed and Predicted Average State-Specific and National MFP, Natural Logarithms*]

The slowdown in U.S. agricultural *MFP* is also apparent in measures of *PFP*s using our more detailed state-level data. In Table 4, over the period 1949–2007, in U.S. agriculture the productivity of labor, land, capital, and materials grew at average annual rates of 3.37 percent, 1.88 percent, 1.62 percent, and –0.09 percent, respectively; the materials result reflects the very substantial substitution of materials inputs for other inputs, especially labor. Over the period 1990–2007, the corresponding partial productivity growth rates for labor, land, capital, and materials were 1.90, 2.17, 0.46, and 0.55 percent per year respectively. A substantial slowdown is evident in the growth rates of productivity of both labor and capital. Materials productivity grew more rapidly over 1990–2007, reflecting a slower rate of increase in the use of materials input in this period compared with the several decades immediately following WWII. Appendix Table D-1 provides state-specific details on the same measures that echo these findings in the national data.

[Table 4: *Annual Growth Rates in Partial Productivity Measures, Various Sub-Periods*]

Statistical Tests for a Slowdown using State-Specific Data

In conducting a formal statistical test for a slowdown in state-specific *MFP* we were conscious of the possibility that different measures may imply different findings. For this reason, we tried two methods for estimating the growth rate. The first method for estimating the growth rate used the simple average of the annual state-specific estimates of *MFP* growth, calculated as annual differences of the series (in natural logarithms). The second used a regression of each state-specific *MFP* index (in natural logarithms) against a time trend, such that the estimated coefficient on the time trend provides an estimate of the average annual proportional growth in the *MFP* index. We computed these alternative measures for various time periods, and then conducted statistical tests of the differences in the state-specific growth rates before and after the split points. The results are reported in Table 5. In every case with either measure the tests indicate a substantial and statistically significant (in all cases but one at well less than 1 percent) slowing of *MFP* growth for any period that includes the years 1990–2007 compared with any prior period. The slowdown is most pronounced for 1990–2007 compared with 1949–1990.

[Table 5: *Statistical Tests for a Slowdown in MFP Growth*]

"ONE BIG WAVE" IN U.S. FARM PRODUCTIVITY GROWTH?

The evolving productivity patterns that we analyze reflect dramatic changes in U.S. agricultural production over the past 100 years; changes in what is being produced, where and how; changes in the nature of farms and farming; and changes in the infrastructure, markets, policies and other aspects of the institutional environment within which farmers operate. Central to many of those changes have been a host of innovations and other investments made by farmers, in some cases enabled by public and private investments in science and technology.

It is not easy to attribute elements of the observed productivity patterns to particular causes, partly because many influences are in play but also because the lags between investment in innovation and observed outcomes are generally very long—50 years or more in some cases—and variable. A period of relatively rapid productivity growth in the 1970s and 1980s could be a reflection of investments made in the 1930s and 1940s; and a slowdown in the 1990s could be showing that the additional gains to be drawn from those earlier investments were beginning to peter out. The particular shape of the productivity path, however, is suggestive that something significant was substantially different about the period between 1950 and 1990, especially the middle of that period.

In broad terms, the surge and subsequent slowdown in U.S. agricultural productivity mirrors the surge and slowdown in U.S. nonfarm productivity, but with different timing. As discussed by Gordon (2000, p. 2) a surge in U.S. nonfarm productivity growth after 1913 "…ushered in the glorious half century between World War I and the early 1970s during which U.S productivity growth was faster than before or after." These phenomena are no doubt connected, involving the fact that the farm sector was a much larger part of the total economy in the early years than now, and the explanations could involve parallels. While we do not offer a formal assessment, we present two potential views of the agricultural productivity surge.

Over the course of the 20th century, following the closing of the frontier, American agricultural development and farm productivity growth were increasingly driven by organized agricultural R&D. On that view, the evolving path of productivity patterns to a great extent will therefore have been driven by the prior path of investments in science and in the development and adoption of innovations. But the lags between agricultural research investments and their main contributions to farm productivity growth are variable, though typically very long—averaging in the range of 35–50 years in econometric studies that measure the links, such as Huffman and Evenson (1993 and 2006) and Alston et al. (2011).

A slowdown in agricultural productivity growth could reflect a decades prior slowdown in agricultural research investments or a change in the effectiveness of those investments for any of a variety of possible reasons (e.g., decreasing returns, coevolving pests and diseases, changes in climate, or a (re-)allocation of R&D resources to non-productivity purposes). In 1889, shortly after the Hatch Act was passed, federal and state appropriations totaled $0.98 million; but by 2009, the total public agricultural R&D enterprise had grown to $4.89 billion, an annual rate of growth of 7.8 percent (4.0 percent in inflation-adjusted terms). The U.S. private sector has spent a similar amount in recent years growing from $68 million in 1950 (compared with $56 million in public research that year) to $6.8 billion in 2009 (Pardey et al. 2015). However, the rate of growth of total public and private spending on agricultural R&D has slowed in recent decades, with a shrinking share devoted to research oriented toward enhancing farm productivity, which might have contributed to the observed slowdown in productivity growth.

An alternative (not necessarily entirely incompatible) view comes from looking at the path of the innovations and associated changes in the size and structure of U.S. farms that drove the farm productivity patterns. This view, like Gordon's (2000) assessment of the "big wave" surge in U.S. *MFP*, accounts for the corresponding "big wave" surge in the rate of agricultural output growth in terms of the timing of "great clusters" of inventions. In the case of agriculture, these clusters include "mechanical," biological," "chemical," and "information" technologies. Although the resulting productivity patterns are comparatively smooth, the long-term path can be envisioned as entailing a small number of large, discrete, but interrelated, "meta-technological" events.[23] The envelope of this rolling series of discrete

[23] Rasmussan (1962) referred to agricultural innovation prior to 1962 in terms of a series of revolutions: "Two revolutions in American agriculture reflect the impact of technological change on farming during the past

meta-technological events gave rise to a comparatively smooth pattern of productivity growth as the technologies were progressively adopted and, eventually, became widely used.[24] But the consequent rate of productivity growth was not constant. The various interrelated changes coalesced into a surge of productivity growth during the 1960s, 1970s and 1980s. After the extent of uptake of these transformative "meta-technologies" peaked, the associated rate of productivity growth began to stall, or at least slow to a rate that could be sustained by more normal incremental innovation.

Much of the measured productivity gains, especially in the earlier period, can be attributed to mechanization. Mechanical innovations transformed U.S. agriculture with a series of innovations including tractors, mechanical reapers, (pulled and, eventually, self-propelled) combines and related bulk handling equipment. Such innovations first replaced horses and other draught animals in the early part of the 20th century with tractors (Olmstead and Rhode 2001)—a process that was not complete until the 1970s—and later replaced most of the people employed in agriculture. As well as these on-farm changes, farmers benefited from the development of improved technology for long-distance transportation of farm output, including refrigeration and preservation technologies, coupled with investment in roads, railroads, and other public infrastructure (Fogel 1964; Atack 2013). Public infrastructure investments that contributed considerably to agricultural productivity include

century. The first revolution saw the change from manpower to animal power, and centered about the Civil War. The second revolution saw the change from animal power to mechanical power and the adaptation of chemistry to agricultural production. It centered around the post-World War II period. The transition from animal power to mechanical power is virtually complete (Rasmussen, 1962, p. 578)."

[24] While each had its own time path and peaked at a different time, the different types of innovation—mechanical, biological, chemical, and information systems—were all being made to some extent throughout the full period of our data, albeit with a shifting emphasis, as demonstrated by Olmstead and Rhode (2008) with respect to biological innovation.

those related to rural electrification, telephone service, and irrigation projects (e.g., see Beall 1940; Fisher 1987).

Biological innovations, in particular improved crop varieties that were responsive to chemical fertilizers, took center stage a little later—although they were clearly part of the story all along. In particular, as a result of focused research over several decades (see Alston et al. 2010a, pp. 264-5) hybrid corn was introduced to farms in Iowa in the early 1930s, though it took until the 1960s for vastly improved hybrids to achieve 100 percent adoption throughout the United States (Dixon 1980). Varietal improvement has continued. These innovations, with others, laid the foundation for genetically modified hybrid corn varieties to be developed and adopted, beginning in 1996 (Fernandez-Cornejo et al. 2014). Similar, though generally not quite as dramatic, genetic innovations were common to many agricultural crop and livestock species (especially poultry, see Peterson 1967), and contributed to the rapid rise of yields and aggregate productivity during the second half of the 20th century (Olmstead and Rhode 2008).

Changes in intellectual property rights applied to life forms helped encourage the private investments that drove much of the genetic gains (Wright and Pardey 2006). In parallel with these genetic changes was the development of modern agricultural chemicals, including various fertilizers, pesticides, herbicides, antibiotics, and hormones, much of which took shape after World War II (Smith 1979; Alston and Pardey 2006). These were also largely private innovations and interlinked with private and public investment in complementary varietal innovations (e.g., herbicide-tolerant crop varieties) (Pardey and Beddow 2013). More recently, much agricultural innovation has emphasized information technologies, including various applications of computer technologies, geographic information and related precision production systems, satellites, remote sensing, and the like.

One plausible hypothesis, then, is that the transformation of agriculture in the 20th century involved a series of interlinked, one-time events, not to be repeated. We posit that the big wave of technological progress through the middle of the century—reflecting the progressive adoption of various mechanical innovations, improved varieties, synthetic fertilizers and other chemicals, each in a decades long process—contributed to a sustained burst of faster-than-normal productivity growth throughout the third quarter of that century. A particular feature of this process was to move people off farms (either entirely or involving a substantial increase in part-time farming) and replace them with machines and chemicals, a one-time transformation of agriculture, which was largely completed by 1980. As shown in Figure 7, the adoption processes for several major classes of agricultural innovations were undertaken over periods of several decades, with many of those processes coming to full fruition during the middle third of the 20th century. Many of these were labor-saving innovations that facilitated the consolidation of farms into many fewer and larger units. The pattern of land per farm is remarkably similar in shape to the pattern of *MFP* (see Figure 1 and Alston et al. 2010a, Figure 2–5, p. 17). The acceleration and slowdown in the growth in average farm size, in particular, is closely correlated with the slowdown in farm productivity.

[Figure 7: *Adoption Paths for Selected Major U.S. Farming Innovations, 1920–2012*]

CONCLUSION

At issue in many minds is whether anything like the rapid farm productivity growth of the middle twentieth century could be recaptured in the coming decades. Over the most recent 20 or so years of our data, the annual average rate of *MFP* growth was half the rate of the previous two to three decades and well below the average rate throughout the twentieth century. More subtly, and of equal importance, the statistics assembled here suggest the relatively rapid productivity growth experienced during the 1960s, 1970s and 1980s could be construed as an aberration, while the post-1990 rates of productivity growth have fallen well below the longer-run trend rate of growth.

One interpretation of this evidence emphasizes agricultural science and related public policy. The lags between investing in R&D and reaping the productivity growth dividends from those investments are long, spanning many decades (Alston et al. 2010a and 2011). The stand-out productivity decades of the 1960s, 1970s and 1980s were preceded by almost a century of sustained growth and accumulation of human, institutional, and scientific capital (Pardey, Alston and Ruttan 2010). Real investments in public agricultural R&D grew on average by 3.87 percent per year from 1953 to 1970, substantially faster than the corresponding rate of growth of agricultural output (an index of which grew by 1.67 percent per year over this period). Conversely, the precursor to the post-1990 slowdown in U.S. agricultural productivity growth was a slowdown in the growth of total spending on agricultural R&D, starting in the late 1970s, and a reduction in the share spent on productivity-enhancing agricultural research and development (Pardey, Alston and Chan-Kang 2013; Alston et al. 2010a).

Another interpretation looks to the transformation of agriculture to shed most of its labor and replace horses, mules, and people with machines and other inputs purchased off the farm—including energy, agricultural chemicals, and proprietary genetically engineered plant varieties that assist in the management of pests and weeds—resulting in many fewer farms, much less labor and much more land per farm. This process of transformation is largely complete, at least in the sense that average land per farm is no longer growing much, such that the scope for further gains from this source is more limited—although some further consolidation continues to take place and new technologies such as robotics and informatics will continue to substitute for some labor. On the first interpretation it ought to be possible to restore farm productivity growth by significantly increasing the growth of expenditure on farm productivity-enhancing research, but keeping in mind the ever-increasing demand for maintenance research simply to prevent productivity from falling; on the second, it is less clear whether the rapid growth rates of the 1960s and 1970s could be restored, even with a significant and sustained acceleration of such spending.

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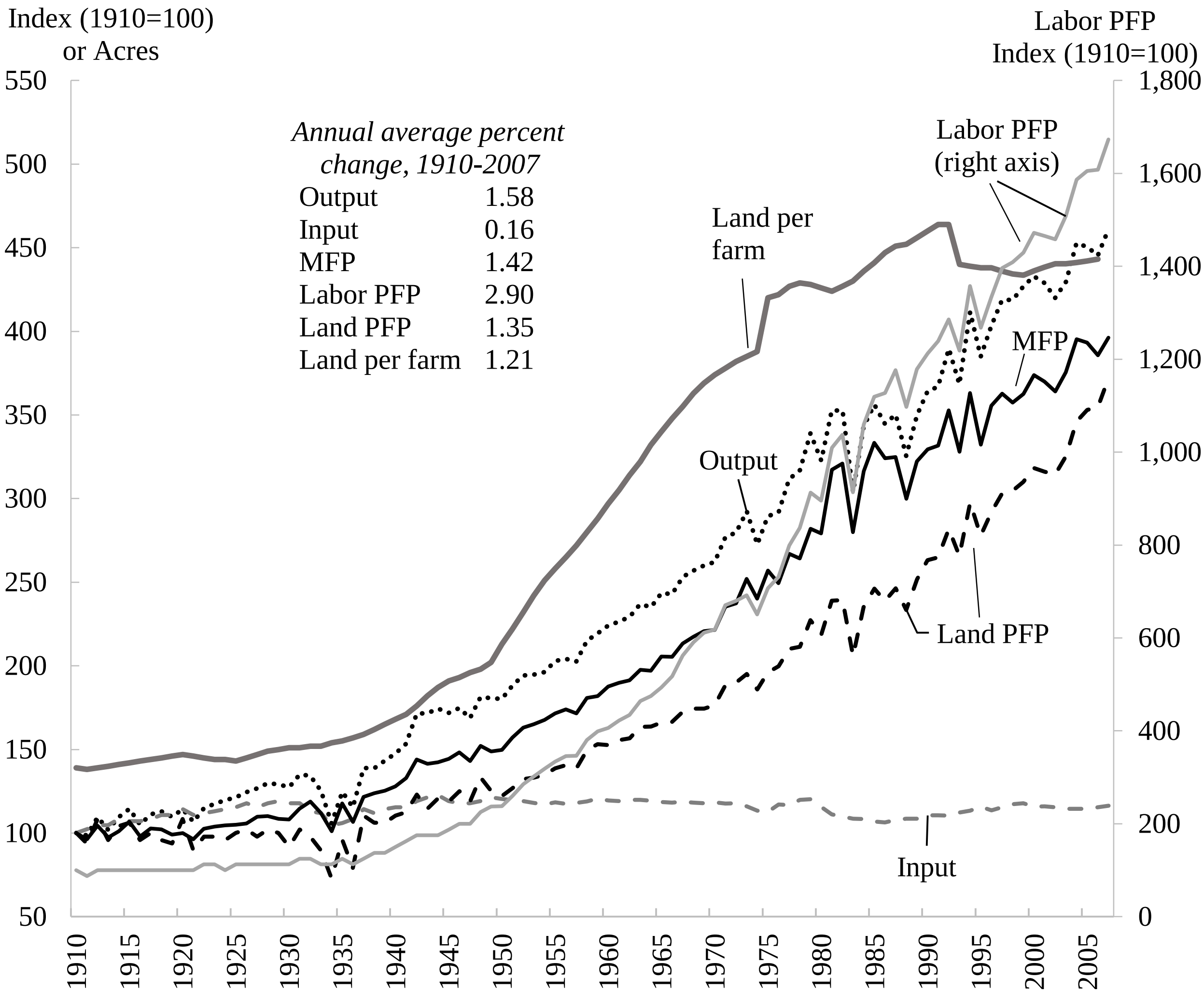


Figure 1

Output, Input, MFP, Labor PFP, Land PFP, and Land per farm, 1910–2007

Notes: All series refer to left axis except for Labor PFP (right axis). The sudden decline in the land in farms in 1993 is due to a change in the definition of farms (see USDA-NASS 1999) that had the number of farms increasing by 4.5 percent from 1992 to 1993. We omitted the 2007 estimate as USDA-NASS (2014, p.21) report a sudden increase in the reported number of farms (by 5.3 percent from 2006 to 2007) attributed to "…methodological changes that allowed NASS to more accurately count small farms in the 2007 census" with a commensurate large drop in the average acres per farm from 443 in 2006 to 418 in 2007.
Sources: Index numbers calculated by the authors using Version 5 of the InSTePP Production Accounts. Number of farms and land in farms from Olmstead and Rhode (2006a, series D19 and D6 series) for 1910 to 1997 and from USDA-NASS (2015) for 1998 to 2007.

Table 1

Annual Average Growth Rates in U.S. Output, MFP and PFP, 1910–2007

		Productivity Indexes		
Period	Output	Multifactor	Labor	Land
		Percent per year		
1910 – 1920	1.33	0.00	0.00	0.80
1920 – 1930	1.10	0.79	1.18	-1.67
1930 – 1940	1.46	1.67	2.88	1.86
1940 – 1950	1.99	1.58	4.60	1.00
1950 – 1960	2.18	2.26	5.37	2.24
1960 – 1970	1.56	1.66	4.19	1.44
1970 – 1980	2.08	2.32	3.71	2.14
1980 – 1990	1.21	1.66	3.03	1.86
1990 – 2000	1.73	1.26	1.94	1.90
2000 – 2007	0.90	0.83	1.83	2.23
1910 – 1950	1.47	1.01	2.16	0.50
1950 – 1990	1.76	1.97	4.07	1.92
1990 – 2007	1.39	1.08	1.90	2.04
1910 – 2007	1.58	1.42	2.90	1.35

Notes: All figures are annual averages.
Source: Calculated by the authors using Version 5 of the InSTePP Production Accounts augmented with data from USDA-ERS (1983).

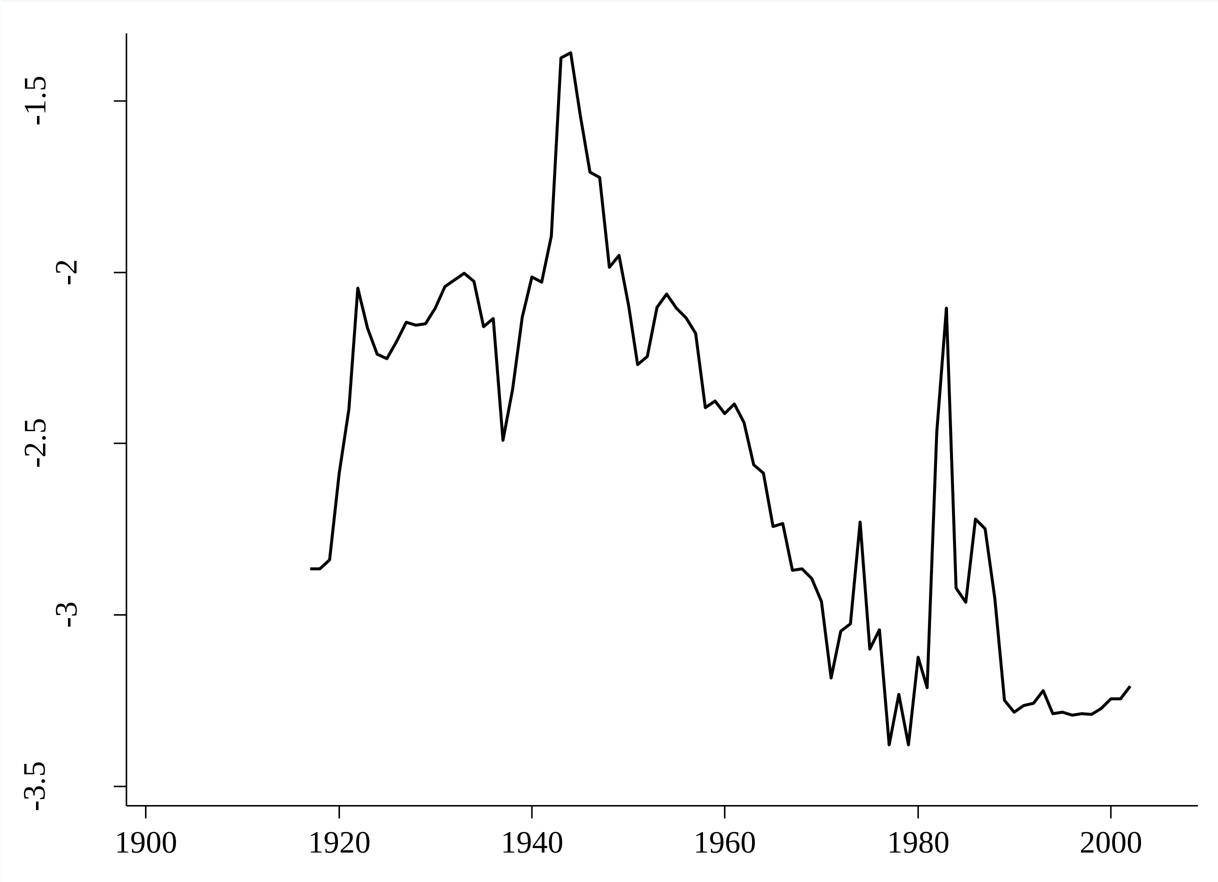
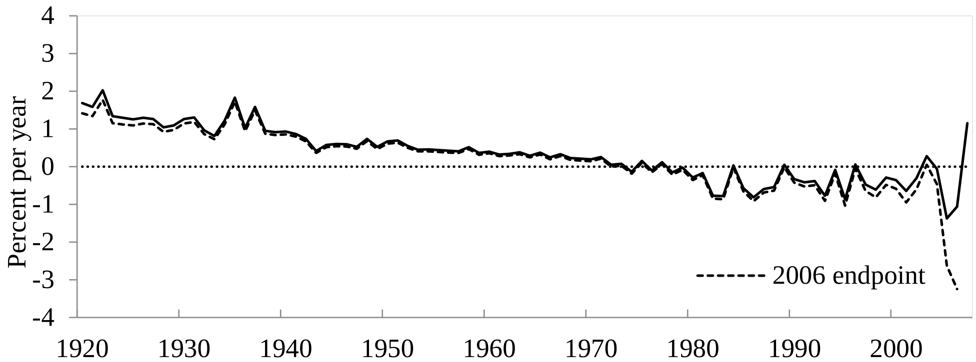


Figure 2

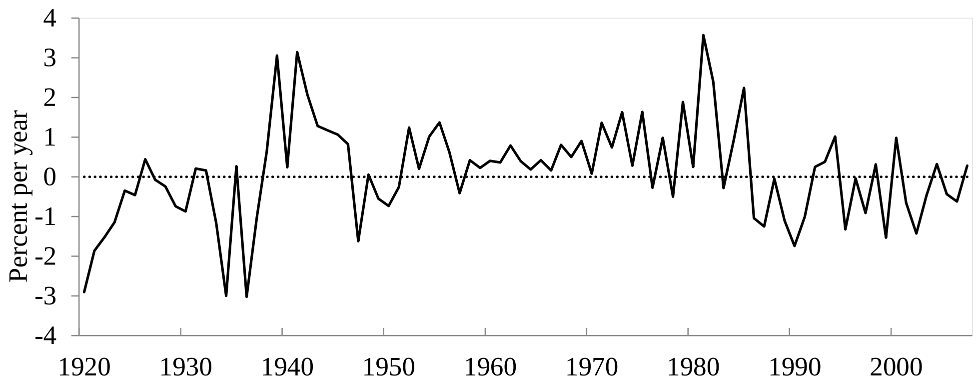
Zivot-Andrews Breakpoint t-statistics on natural log of MFP Series, 1917–2002

Notes: Zivot-Andrews breakpoint *t*-statistics were obtained using STATA 12 assuming a break in the level and trend with a five percent trim and two lags of the dependent variable. The minimum breakpoint *t*-statistic is in 1979.
Source: Calculated by the authors using Version 5 of the InSTePP Production Accounts augmented with data from USDA-ERS (1983).

Panel a: Breakpoint



Panel b: 5-year interval



Panel c: 15-year interval

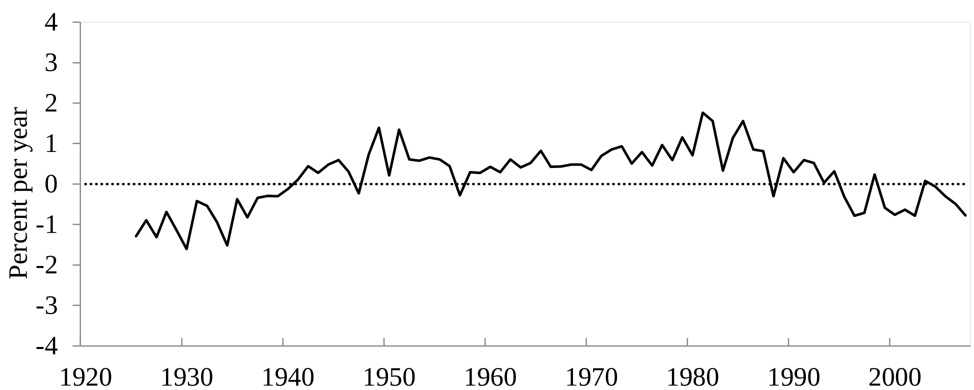
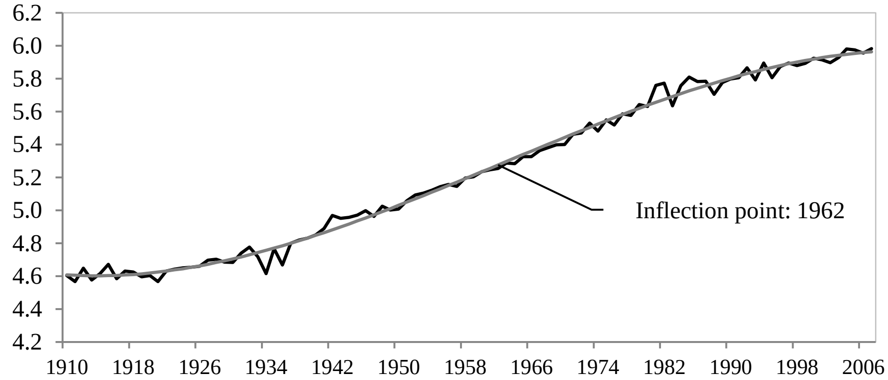


Figure 3

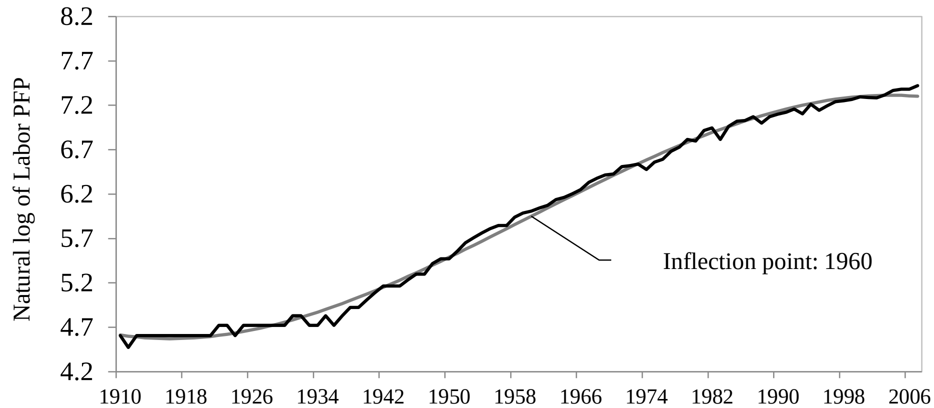
Coefficients on Dummy Variables for Breakpoints and Time Intervals of *MFP* Growth Rates, 1910–2007

Notes: The dashed line in Panel a represents coefficient estimates obtained when data from 2007 are excluded. Coefficient estimates in Panel a represent the estimated increase (or decrease) in *MFP* growth after the year noted. Coefficient estimates in Panels b and c represent the estimated differences in *MFP* growth during the time period of the length specified relative to all other years outside that time period. Coefficients are graphed against the last year in the time period.
Source: Calculated by the authors using Version 5 of the InSTePP Production Accounts augmented with data from USDA-ERS (1983).

Panel a: MFP (in natural logarithms)



Panel b: Labor PFP (in natural logarithms)



Panel c: Land PFP (in natural logarithms)

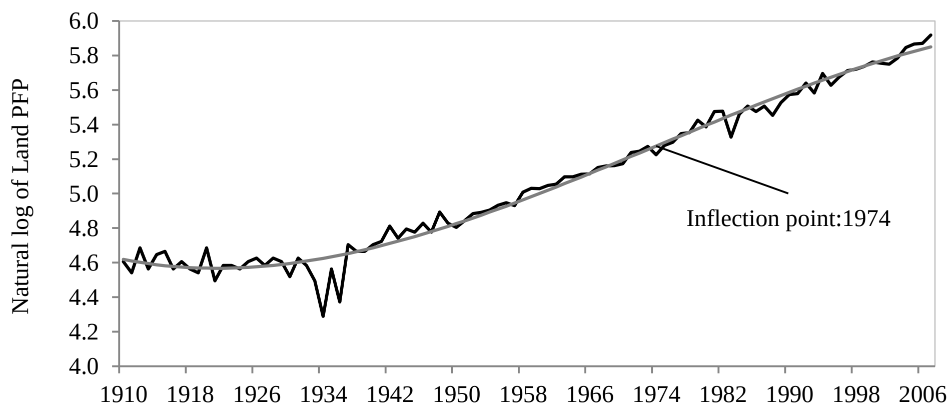


Figure 4
Cubic Trend Models of Productivity Indexes in Natural Logarithms, 1910–2007

Source: Calculated by the authors using Version 5 of the InSTePP Production Accounts augmented with data from USDA-ERS (1983).

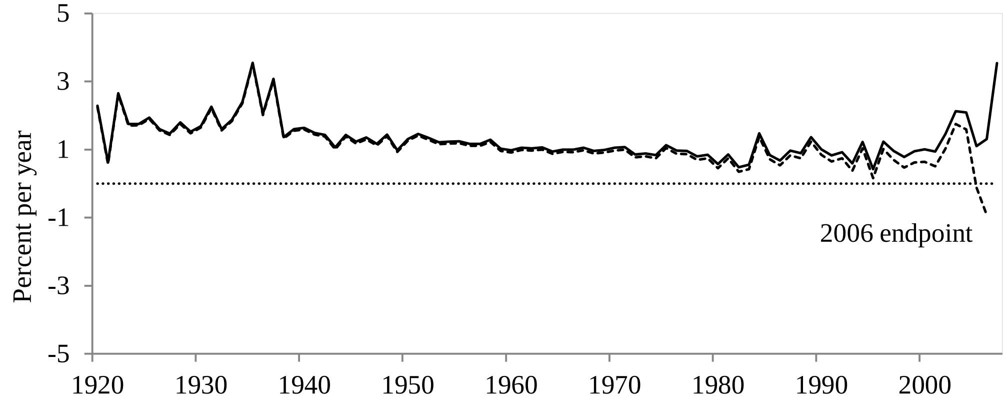
Table 2

Cubic Trend Models of MFP and PFP in Natural Logarithms, 1910–2007

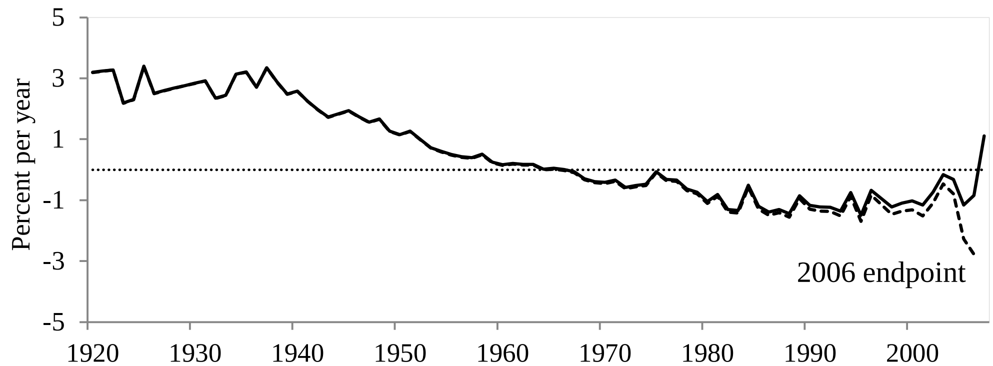
	1910–2007				1949–2007			1948–2011
	PFP				National		State	National
	Land	Labor	MFP	TFP	MFP	TFP	MFP	TFP
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
t	-1.04×10^{-2}***	-1.63×10^{-2}***	-4.10×10^{-3}***	3.62×10^{-3}***	1.44×10^{-2}***	9.55×10^{-3}***	1.46×10^{-2}*	6.06×10^{-3}**
	(2.29×10^{-3})	(2.34×10^{-3})	(1.40×10^{-3})	(1.50×10^{-3})	(2.70×10^{-3})	(2.92×10^{-3})	(1.44×10^{-3})	(2.54×10^{-3})
t^2	4.70×10^{-4}***	1.24×10^{-3}***	4.69×10^{-4}***	1.96×10^{-4}***	3.33×10^{-4}*	2.33×10^{-4}**	3.41×10^{-4}*	3.64×10^{-4}*
	(5.36×10^{-5})	(5.47×10^{-5})	(3.28×10^{-5})	(3.38×10^{-5})	(1.04×10^{-4})	(1.13×10^{-4})	(5.54×10^{-5})	(9.04×10^{-5})
t^3	-2.42×10^{-6}***	-8.15×10^{-6}***	-2.92×10^{-6}***	-9.46×10^{-7}***	-4.83×10^{-6}*	-2.08×10^{-6}***	-5.54×10^{-6}*	-3.50×10^{-6}*
	(3.56×10^{-7})	(3.63×10^{-7})	(2.18×10^{-7})	(2.16×10^{-7})	(1.14×10^{-6})	(1.23×10^{-6})	(6.07×10^{-7})	(9.14×10^{-7})
Intercept	4.63***	4.63***	4.61***	4.57***	4.59*	4.60*	4.62*	3.71*
	(2.63×10^{-2})	(2.68×10^{-2})	(1.61×10^{-2})	(1.80×10^{-2})	(1.89×10^{-2})	(2.04×10^{-2})	(1.00×10^{-2})	(1.92×10^{-2})
R^2	0.98	1.00	0.99	0.99	0.99	0.99	0.85	0.99
Number of observations	98	98	98	102	59	59	2,832	64
Inflection year	1974	1960	1962	1978	1971	1985	1969	1982
95% confidence interval	[1969, 1979]	[1959, 1961]	[1961, 1964]	[1969, 1987]	[1967, 1975]	[1975, 1996]	[1966, 1971]	[1979, 1985]

Notes: Trend is year minus 1909. The inflection years were calculated by adding 1909 to the estimated inflection points, rounded to the nearest whole year.
*** Statistically significant at one percent; ** statistically significant at five percent; * statistically significant at ten percent.
Source: Calculated by authors using Version 5 of the InSTePP production accounts augmented with data from USDA-ERS (1983).

Panel a: Land *PFP* breakpoint



Panel b: Labor *PFP* breakpoint



Panel c: Land and labor *PFP* 15-year interval

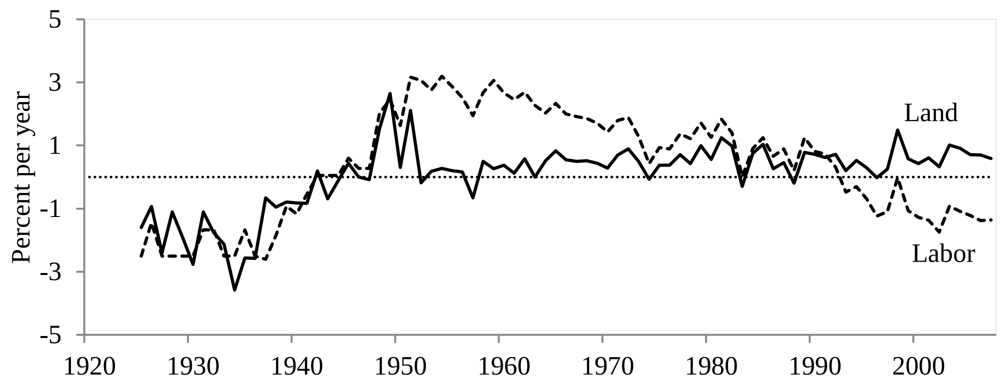


Figure 5

Coefficients on Dummy Variables for Breakpoints and Time Intervals of PFP Growth Rates, 1910–2007

Notes: The dashed lines in Panels a and b represent coefficient estimates obtained when data from 2007 are excluded. Coefficient estimates in Panels a and b represent the estimated increase (or decrease) in *PFP* growth after the year noted. Coefficient estimates in Panel c represent the estimated differences in *PFP* growth during the 15-year time period relative to all other years outside that time period. Coefficients are graphed against the last year in the time period.
Source: Calculated by the authors using Version 5 of the InSTePP Production Accounts augmented with data from USDA-ERS (1983).

Table 3

Estimated Inflection Points for Crop Yields and Productivity Indexes

Productivity Measure	Data Period	Year of Inflection (Maximum Growth Rate)		
		Point Estimate	95 Percent Confidence Interval	
			Lower Bound	*Upper Bound*
Crop yields				
Wheat	1910–2009	1962	1960	1964
Corn	1910–2009	1963	1961	1964
Barley	1910–2009	1965	1962	1968
Oats	1910–2009	1962	1959	1966
Rice	1910–2009	1962	1959	1964
Soybeans†	1924–2009	1975	1969	1981
Productivity indexes				
MFP	1910–2007	1962	1961	1964
MFP	1920–2007	1962	1960	1964
MFP	1930–2007	1961	1957	1965
MFP	1940–2007	1968	1965	1970
MFP	1950–2007	1967	1960	1975
Labor	1910–2007	1960	1959	1961
Land	1910–2007	1974	1969	1979

Notes: The yield data were converted from bushels per acre to pounds per acre using conversion factors obtained from USDA-NASS (2000, pp. v-vii) of 48, 56, 32, 60, and 60 pounds per acre respectively for barley, corn, oats, soybeans, and wheat. The rice data were reported in pounds per acre. All the inflection points represent the first year of deceleration, except for soybeans where the inflection point represents an acceleration in yield. Each of the estimated inflection points is statistically significantly different from zero at the one percent level of significance.
† The soybean data are from 1924-2009 and the inflection point represents the year where the second derivative changed from negative to positive.
Source: Yield data from USDA-NASS (2010) and productivity data from Version 5 of the InSTePP Production Accounts augmented with data from USDA-ERS (1983).

Table 4

Annual Growth Rates in Partial Productivity Measures, Various Sub-periods

	Labor		Land		Capital		Materials		MFP	
Period	National	48 states	National	48 states	National	48 states	National	48 states	National	48 states
					Percent per year					
1949–1960	4.88	4.87	1.82	2.28	1.30	1.30	-1.99	-1.79	1.89	2.04
1960–1970	4.19	4.35	1.44	1.91	2.20	2.14	-1.76	-1.16	1.69	1.98
1970–1980	3.71	2.90	2.14	1.63	1.61	1.26	1.60	1.32	2.46	2.01
1980–1990	3.03	2.93	1.86	2.20	3.39	2.84	0.87	1.08	2.08	2.07
1990–2000	1.94	1.50	1.90	1.90	1.09	0.69	0.48	0.05	1.25	0.83
2000–2007	1.83	1.05	2.23	1.78	-0.43	-1.30	0.65	0.70	1.08	0.58
1949–2007	3.37	3.06	1.88	1.96	1.62	1.29	-0.09	-0.03	1.78	1.65
1949–1990	3.98	3.79	1.82	2.01	1.87	2.10	-0.36	-0.18	2.02	2.02
1990–2007	1.90	1.31	2.17	1.85	0.46	-0.13	0.55	0.32	1.18	0.73

Notes: The growth rate estimates designated "National" were calculated from the respective U.S. national series. The estimates designated "48 state" are the 48-state average of the respective growth rates.
Source: Calculated by the authors from Version 5 of the InSTePP Production Accounts.

Table 5

Statistical Tests for a Slowdown in MFP Growth

Time Period	During Period	After Period	Difference	P-value
	(Annual average percent change)			
Using differences in logarithms				
1949–1960	2.04	1.55	0.48	0.002
1949–1970	2.01	1.44	0.58	0
1949–1980	2.01	1.23	0.78	0
1949–1990	2.02	0.73	1.29	0
1949–2000	1.79	0.58	1.21	0
1949–2007	1.65	–	–	–
Using regression of logarithms				
1949–1960	2.04	1.60	0.43	0.007
1949–1970	1.88	1.33	0.55	0
1949–1980	1.96	0.85	1.12	0
1949–1990	2.04	0.68	1.37	0
1949–2000	1.87	0.98	0.89	0.011
1949–2007	1.72	–	–	–

Notes: The p-values are for an unpaired data t-test of the difference between the means when comparing the annual averages for different periods (assuming unequal variances). The p-values for the regressions were calculated by including intercept dummies and slope dummies for the trend variable in the regressions for the 'after' period, and then testing if the slope dummy on trend was statistically significantly different from zero.
Source: Calculated by the authors using Version 5 of the InSTePP Production Accounts.

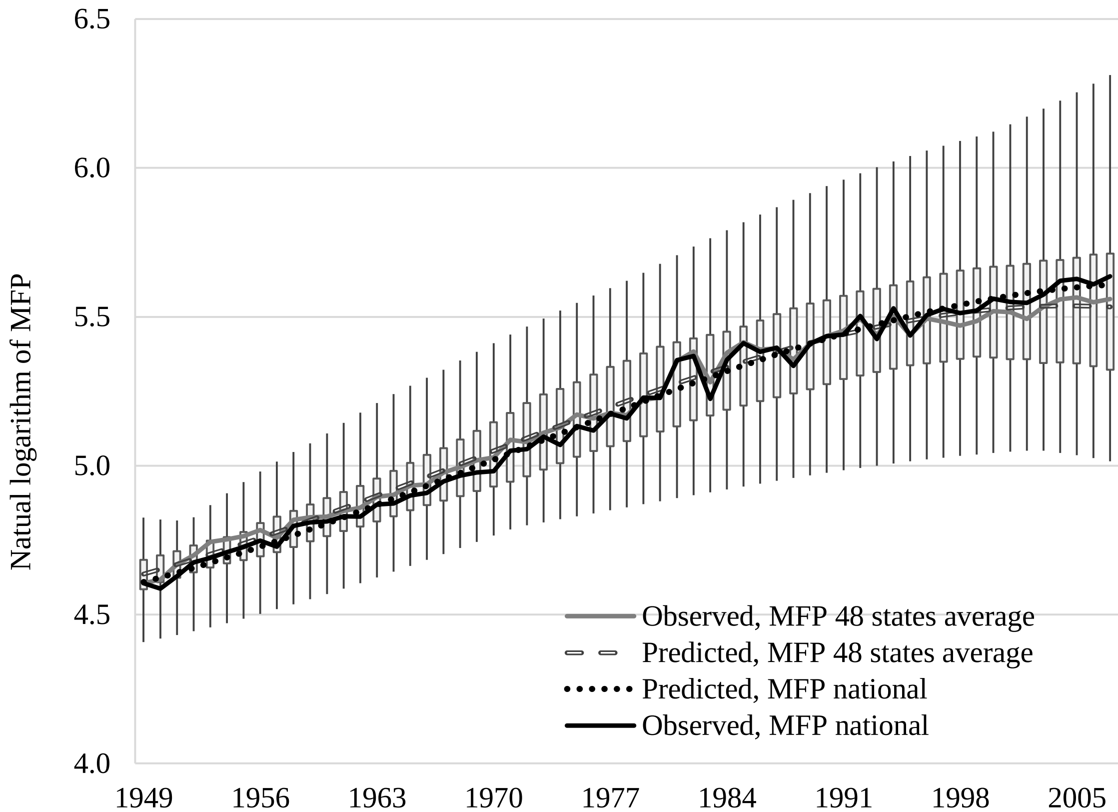


Figure 6

Observed and Predicted Average State-Specific and National MFP, Natural Logarithms

Notes: The lines on the linearized distribution for each year indicate the respective predicted maximum and minimum state values, the upper bound on the box is the 75th percentile and the lower bound is the 25th percentile. *Source*: Calculated by the authors using Version 5 of the InSTePP Production Accounts.

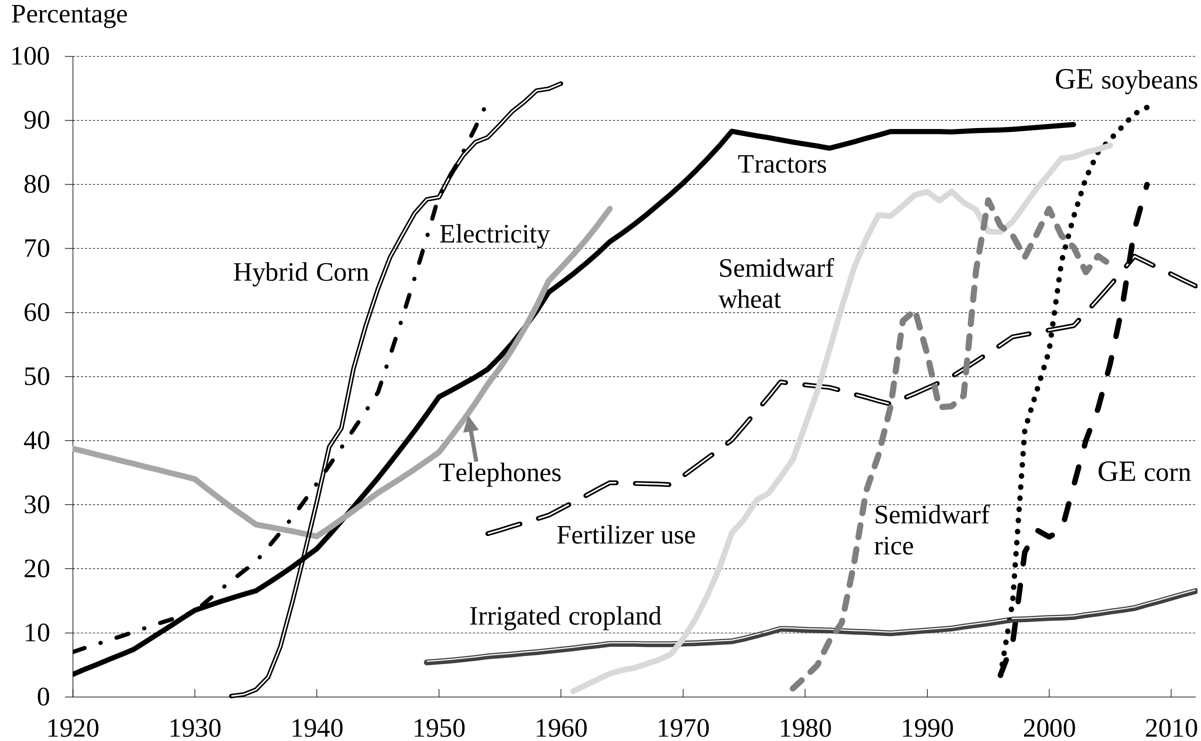


Figure 7

Adoption Paths for Selected Major U.S. Farming Innovations, 1920–2012

Notes: For 1969 and 1974, acres on which fertilizer was applied were available only for farms with sales of $2,500 or more only. For 1978, data are reported for all farms as well as for farms with $2,500 or more of sales. We used the 1978 ratio of acres with fertilizer application from farms with sales of $2,500 or more to All farms to infer data for 1969 and 1974. For 1997, 2002, 2007, and 2012 estimates of fertilizer use are available for cropland only (excluding pastureland), as well as for pastureland. For 1954 and 1959, estimates include pasture but for all the other years, it is not clear whether pastureland is included in the acreage receiving fertilizers. We assumed that the acreage with fertilizer application reported in the Census data prior to 1997 refers to total (crop and pasture) acreage. To estimate fertilizer application on cropland only prior to 1997, we used the average ratio of fertilizer use on pastureland relative to cropland for the years 1997, 2002, 2007, and 2012.
Sources: Tractors, electricity, telephones, Hybrid corn, GE corn, and GE soybeans from Alston et al. (2010). Irrigated cropland: 1949 to 2007; Shares calculated using Cropland and Irrigated cropland data from InSTePP production account version 5: 2008 to 2011; Linear interpolation: 2012; Share of irrigated cropland in total cropland calculated using irrigated cropland and total cropland acreage from USDA-NASS (2015). Fertilizer use: 1954 from 1954 Census of Agriculture; 1959 from 1959 Census of Agriculture; 1964 from 1964 Census of Agriculture; 1969 and 1974 were estimated based on data from the 1974 and 1978 Census of Agriculture reports, see notes below; 1978 from 1978 Census of Agriculture; 1982, 1987, and 1992 from 1992 Census of Agriculture; 1997, 2002, 2007, and 2012 from 1997, 2002, 2007, and 2012 Ag Census downloaded from NASS Quickstat 2.0 database. Missing data were linearly interpolated. Semi-dwarf wheat and rice areas are from Chan-Kang and Pardey (2012a and b).

Appendixes

APPENDIX A: DATA DETAILS AND SOURCES

U.S. Input, Output and Multifactor Productivity, 1910–2007

Estimates of U.S. national and state-level aggregate input, output, and multifactor productivity for the period 1949–2007 are included in a recently updated version of the InSTePP Production Accounts. The previous version, version 4, of these Production Accounts spanned the period 1949–2002, and a summary of the sources and construction details of that series is given in Alston et al. (2010a, pp. 127–133). The methods and data sources used to update the accounts from 2003 to 2007 are an extension of those used to construct version 4 of this series.

1949–2007 Series

Version 5 of the InSTePP Production Accounts consists of state-specific measures of the prices and quantities of 74 categories of outputs and 58 categories of inputs for the 48 contiguous U.S. states. The 58 categories of inputs are grouped into four broad categories: land, labor, capital, and materials inputs. The land input is subdivided into service flows from three basic types of land, namely: pasture and rangeland, non-irrigated cropland, and irrigated cropland. The price weights used for aggregation of the land input are annual state- or region-specific cash rents for each of the three land types. The labor data consist of 30 categories of operator labor by age and education cohort, as well as family labor and hired labor. State-specific wages were obtained for the hired and family labor, whereas implicit wages for operators were developed using national data on income earned by "rural farm males," categorized by age and educational attainment.

Capital inputs include seven classes of physical capital and five classes of biological capital. A physical inventory method, based on either counts of assets purchased or assets in place, was used to compile the capital series as described in some detail in Andersen, Alston, and Pardey (2011) and Pardey et al. (2009).[25] In addition, we adjusted inventories of the physical capital classes to reflect quality change over time, depending on the nature of the data available and the service flow profile of each capital type. Rents for capital items were taken to be specific

[25] The capital series was identified as a particular source of discrepancies between the InSTePP measures of multi-factor productivity growth and the counterpart measures published by the USDA (see, for instance, Ball, Butault, and Nehring 2001). These discrepancies are more pronounced for particular states and subperiods than for the aggregate U.S. series over the full period for which both measures are available (see Andersen, Alston, and Pardey 2011 and 2102 for details and discussion).

fractions of the purchase price, fractions that varied among capital types. Purchase prices were assumed to reflect the expected present value of real capital services over the lifetime of the specific type of capital.

Eleven types of materials inputs are included in this data set. Apart from fertilizers, measured as quantities of elemental nitrogen, phosphorous, and potash, the purchased input quantities were implicit quantities derived by dividing state-specific expenditure totals by the corresponding national average price. The miscellaneous category was preaggregated and included a list of disparate inputs, such as fencing, irrigation fees, hand tools, veterinary services, and insurance costs, among others. In this category, state-specific prices were available only for electricity; all other input prices were national prices or price indices based on national prices paid by farmers.

The agricultural input data come from a host of sources, most importantly from various issues of the U.S. Census of Agriculture. Most of the input data are constructed using Census estimates that are supplemented with annual data from numerous other sources, including the USDA-ERS, the Association of Equipment Manufacturers (AEM), and the Census of Population. For example, Census estimates of operator labor on farms were disaggregated by age and education cohort using data from the ERS Agricultural Resource Management Survey. Also, Census data on the counts of tractors and combines used in production were disaggregated into different horsepower and width classifications using proprietary data from the AEM.

In the disaggregated form, the output data cover 74 output categories, including 16 field crops, 22 fruits and nuts, 22 vegetables, implicit quantities of greenhouse and nursery products, 9 livestock commodities, and 4 miscellaneous items that include implicit quantities of machines rented out by farmers, and Conservation Reserve Program (CRP) acreage. The commodity-specific prices used as weights to form aggregate output are state-specific prices received by farmers for all commodities, except machines for hire and greenhouse and nursery products, which use national average prices.

The major sources of the price and quantity data for agricultural outputs are annual estimates from the Economic Research Service (ERS) and National Agricultural Statistics Service (NASS) of the U. S. Department of Agriculture (USDA). The estimates come principally from two publications, *Agricultural Statistics* and *Statistical Bulletins*, supplemented with NASS and USDA occasional commodity reports.

Bias from the procedure used to aggregate inputs and outputs can be kept to a minimum by choosing an appropriate index, carefully selecting value weights for all inputs and outputs, and disaggregating inputs and outputs as finely as possible. The InSTePP indexes of quantities and prices of output and input were formed using a Fisher discrete approximation to a Divisia index for the years 1949 through 2007. An index of multifactor productivity for each state and the nation was then constructed as the ratio of the index of aggregate output to the index of aggregate input using state-specific price and quantity data to form the national aggregate. In this way we adjusted for compositional or quality variation as described by Craig and Pardey (1996).

1910–1948 Series

Laspeyres indexes of aggregate input, output and multifactor productivity for the period 1910–1981 are reported in USDA, ERS (1983, Table 69). We recalculated these indexes with a base year of 1949=100 and spliced the series with 1949–2007 InSTePP Fisher indexes of inputs, outputs and productivity.

U.S. Land and Labor Productivity, 1910–2007

We report partial factor productivities (PFPs) that express the same index of aggregate output relative to an index of the corresponding quantity of a particular input, land or labor.

1949–2007 Series

To form indexes of land and labor productivity for the period 1949–2007, we divided the Fisher index of U.S. aggregate agricultural output by the corresponding Fisher indexes of aggregate land and labor use in U.S. agriculture, using the data described above from version 5 of the InSTePP production accounts.

1910–1948 Series

An index of aggregate labor productivity for U.S. agriculture for the period 1910–1984 was taken from USDA, ERS (1983, Table 45). This represents an index of the amount of farm output per hour in agriculture. An index of aggregate land productivity for U.S. agriculture for the period 1910–1981 was taken from USDA, ERS (1983, Table 13). This represents an index of crop production per acre in agriculture. We recalculated these indexes with a base year of 1949=100 and spliced the series with 1949–2007 InSTePP indexes of labor *PFP* and land *PFP*.

U.S. National Average Crop Yields, 1866–2009

National average yields represent total annual U.S. crop production divided by the corresponding harvested area taken from USDA-NASS (2010).

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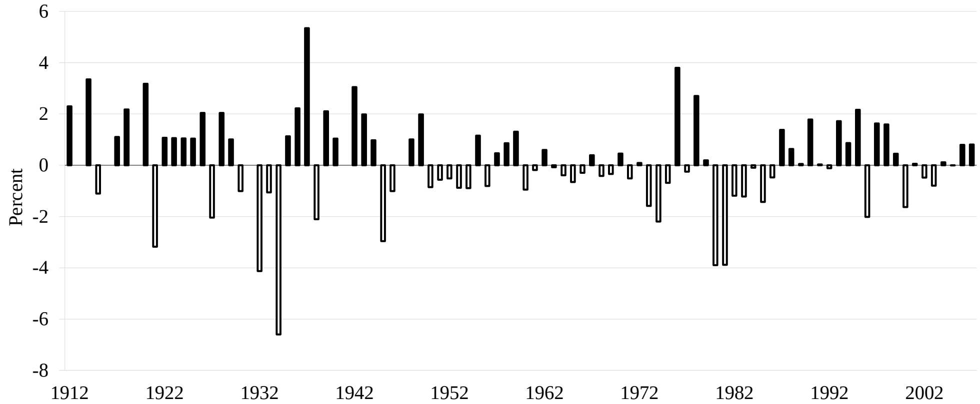
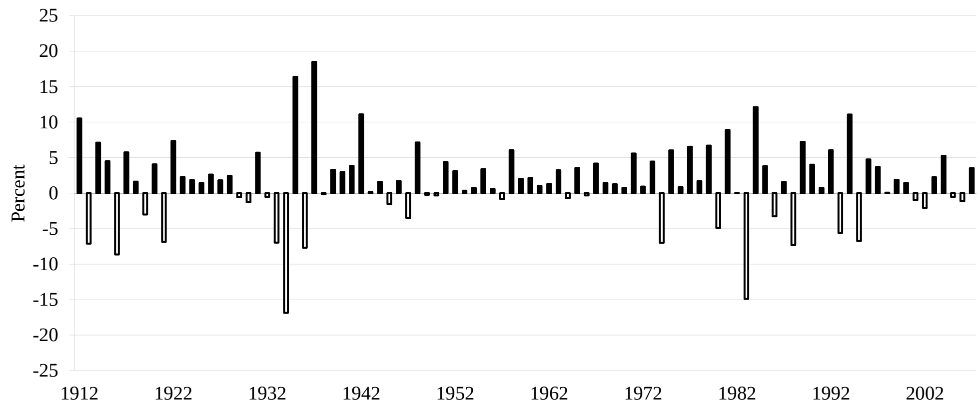
USDA-NASS (U.S. Department of Agriculture, National Agricultural Statistical Service). "Crop Production Historical Track Records" Washington, D.C.: USDA, National Agricultural Statistical Service, 2010. Available at http://usda.mannlib.cornell.edu/usda/current/htrcp/htrcp-04-12-2010.txt (accessed October 2010).

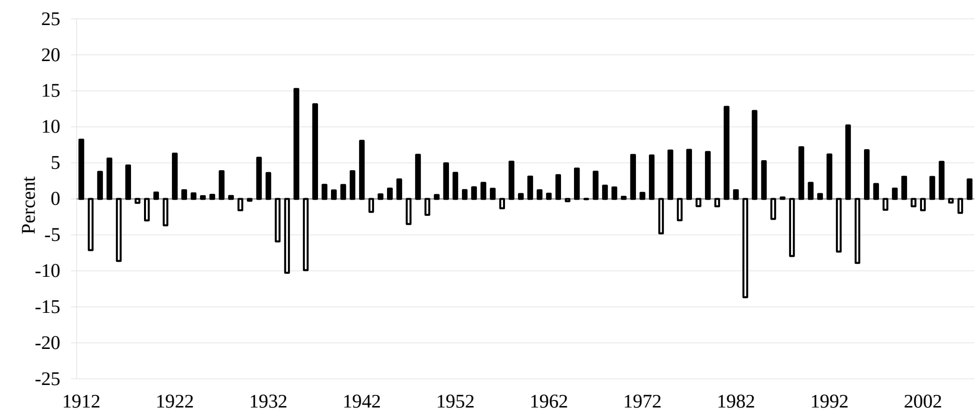
Panel a: Input growth



Panel b: Output growth



Panel c: MFP growth



Appendix Figure A-1

Year-to-Year Changes in Input, Output and *MFP*, 1910–2007

Notes: Annual year-to-year growth rates were calculated as differences in the natural logs.
Source: Calculated by the authors using Version 5 of the InSTePP Production Accounts augmented with data from USDA-ERS (1983).

APPENDIX B: SUPPLEMENTARY EVIDENCE ON STRUCTURAL CHANGES IN GROWTH RATES OF U.S. MFP (1920–2007) AND CROP YIELD (1867–2009)

Multifactor Productivity

Appendix Figure B-1 plots 5-, 10-, 15-, and 25-year moving average measures of *MFP* growth rates against time, every fifth year for 1922–2007, along with the fitted values for quadratic trend models fitted to the moving average growth rates, all compared with the long-run average growth rate of 1.64 percent per year for the period for 1922–2007. The fitted models are all negative parabolas, with their maxima between 1960 and 1980 (moving forward in time as the period of the moving average increases, as would be expected). In the years prior to 1940 the plotted moving average growth rates are all below the long run average; likewise for the years after 1995. And in the middle years, 1950–1985, the plotted moving average growth rates are all above average with one exception, 1957, which might reflect the effects of U.S. involvement in the Korean War as well as several severe droughts in the 1950s.

[Appendix Figure B-1: *Annual Average MFP Growth for Various Periods and Time Intervals, 1922–2007*]

We estimated a cubic trend regression model of U.S. agricultural *MFP* applied to USDA-ERS data for the period 1948-2011 obtained from USDA-ERS (2013). The results indicate a statistically significant slowdown, with an inflection at 1981 (see text Table 2 and Appendix Figure B-2).

[Appendix Figure B-2: *A Cubic Trend Model Fitted to USDA ERS MFP Estimates, 1948–2011*]

Appendix Figure B-3 shows the results of a breakpoint and a 15-year interval rolling regression analysis of U.S. agricultural land *PFP*, land *PFP*, and *MFP*, for the period 1910–2007.

[Appendix Figure B-3: *Estimated Coefficients on Dummy Variables for Breakpoints and 15-year Time Intervals of MFP Growth Rates, 1910–2007*]

Crop Yields

Appendix Figure B-4 shows the U.S. national average yields for barley, corn, oats, rice soybeans, and wheat back to the mid-19th century. A visual inspection suggests a structural change in the U.S. crop yields during the mid-1930s, but it is less obvious how rates of growth in crop yields have fared in recent decades. According to these USDA, NASS yield estimates, on average over the entire period, soybean and rice yields grew by around 1.6 percent per year and corn yields grew by 1.34 percent per year, while yields of wheat, barley and oats all grew at rates below 1.0 percent per year (Appendix Table B-2,). Setting aside soybeans (where we only have 11 observations prior to 1935) and rice, prior to 1935 the yield growth rate was low or negligible. Thereafter (i.e., for 1936–2009), yields for all six crops grew by more than 1.0 percent per year, with corn being the standout: corn yields grew by 2.60 percent per year on average for 1935–2009. Rice yields grew at the same rate before and after 1935 (1.60 percent per year).

[Appendix Figure B-4: *Yields for Six Field Crops, 1867–2009*]

[Appendix Table B-2: *Crop Yields, and Absolute and Proportional Changes in Yields, 1867–2009*]

A substantial (but not statistically significant) slowdown in the growth of crop yields after 1990 is apparent for each crop, which suggests that the rate of growth of U.S. crop yields slowed substantially during the period 1990–2009 (1.17 percent per year, averaging across all six crops) compared with 1935–1990 (1.81 percent per year). However, this conclusion is sensitive to the choice of terminal points for the periods being compared, and especially so given the year-to-year (often weather-induced) volatility in crop yields.

To address this potential problem, Appendix Figure B-5 reports the results of a rolling regression interval analysis for the (logarithms of the) average national yields of these six major field crops in the United States. The figure shows how *proportional* rates of growth in the crop yields for these six crops have changed over time. These plots indicate the difference in the average annual growth rate over a 15-year interval, relative to the average growth rate for the other years, in each time series. Setting aside the rather truncated soybean time series, this evidence indicates that the (15-year) rate of growth in yields for barely, corn, oats, rice and wheat has slowed in the recent several decades relative to the immediately preceding decades.

[Appendix Figure B-5: *Estimated Coefficients on Dummy Variables for 15-Year Intervals of U.S. Crop Yield Growth, 1881–2009*]

These results indicate that the decades of the 1950s, 1960s, 1970s and 1980s were generally decades of abnormally high rates of yield growth during a longer period spanning the late 19th century and the entire 20th century. The period of abnormally high *MFP* growth began a little later and was shorter lived, spanning the 1970s and 1980s. Up to 1935, the rate of growth in crop yields was, with some minor exceptions (for rice and soybeans), generally below the rate since then.[26] And, again like the *MFP* evidence, rates of growth for all six crop yields since 1990 are more in line with the average rate of growth in yields over the entire period 1867–2009, well below the rapid rates of the 1960s and 1970s. Cubic trend regression models also indicate a slowdown in the proportional growth rate (Appendix Figure B-6).

[Appendix Figure B-6: *Cubic Trend Regression Models of U.S. Crop Yield, 1881–2009*]

Notably, the more recent rates of growth in crop yields are generally similar to the corresponding rates of growth in *MFP*. For example, the comparatively slower rates of growth of crop yields since 1990 ranged between 0.62 and 1.75 percent per year, with five of the six crops experiencing yield gains of less than 1.40 percent per year; and with a simple average among all crops of 1.00 percent per year for 1990–2009 and 1.17 for 1990–2007.[27] The corresponding rate of growth in *MFP* was 1.18 percent per year for 1990–2007. In this instance, an average of the crop-specific *PFP* measure provides a reasonable approximation to the broad path of the corresponding *MFP* measure that is of greater interest.

An alternative perspective on crop yield growth is the absolute (as distinct from the proportional) increment in crop yields per year. Since 1935, corn has both the highest proportional rate of yield growth (2.60 percent per year, middle section of Appendix Table B-2) and the highest absolute rate of yield growth (106.7 pounds per acre per year, lower section of Appendix Table B-2). Oats have the slowest proportional rate of growth (1.25 percent per year since 1935), and the smallest absolute gain (only 16.2 pounds per acre per year) on average.[28]

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[26] Notably, the annual rate of growth in rice yields before and after 1935 was little changed (1.64 percent per year and 1.31 percent per year, respectively), and the exceptionally high 3.62 percent per year trend rate of growth of soybean yields prior to 1935 may, at least in part, reflect a small sample phenomenon (in that we only have soybean yield observations beginning in 1924).

[27] The individual average annual growth rates for wheat, corn, barley, oats, soybeans, and rice during the years 1990–2007 were 1.15, 1.44, 1.17, 0.56, 1.42, and 1.26 percent per year, respectively.

[28] In many policy contexts, the relevant measure is proportional growth in yields, and sustaining proportional growth requires ever-increasing absolute growth. Hence, a slowdown in proportional growth could be associated with a constant (or even increasing) rate of absolute growth in yield.

References

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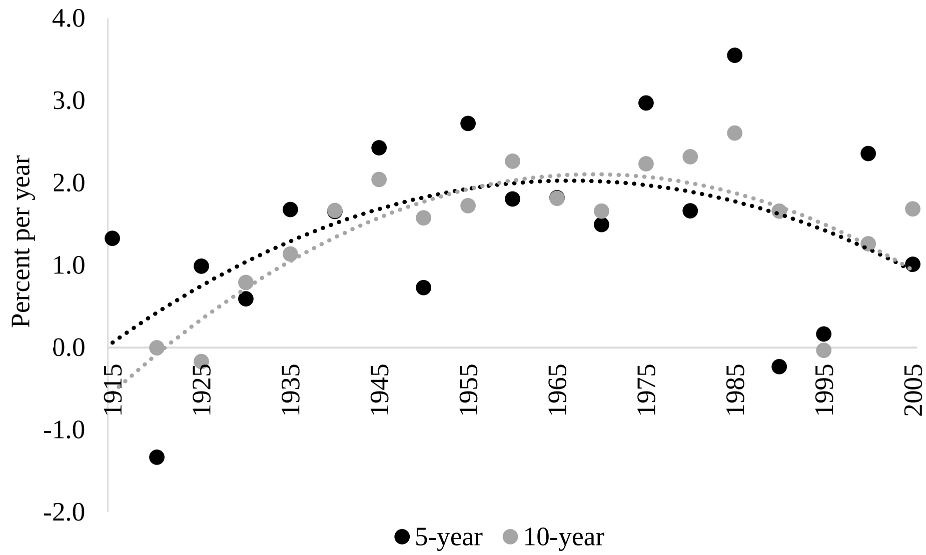
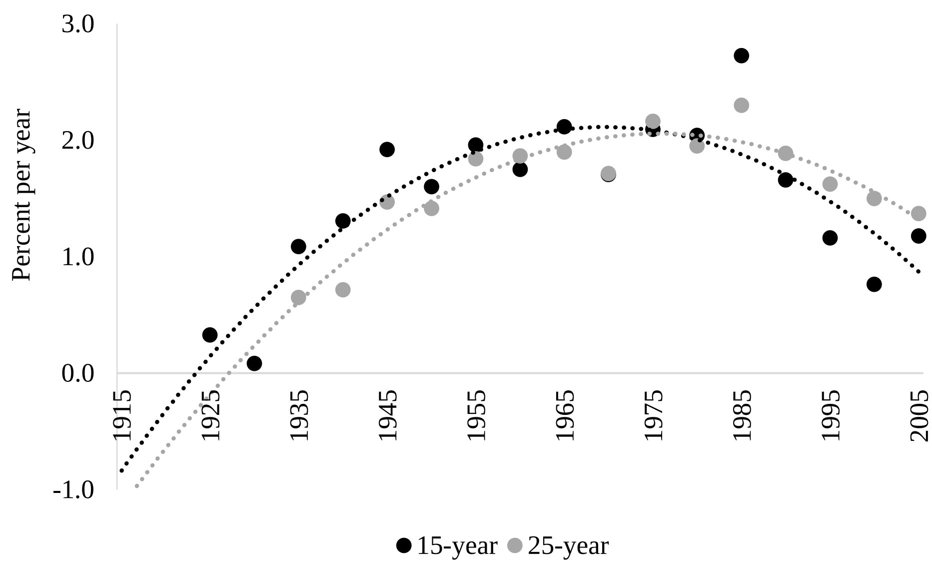
Panel a: 5-year and 10-year moving average growth rates



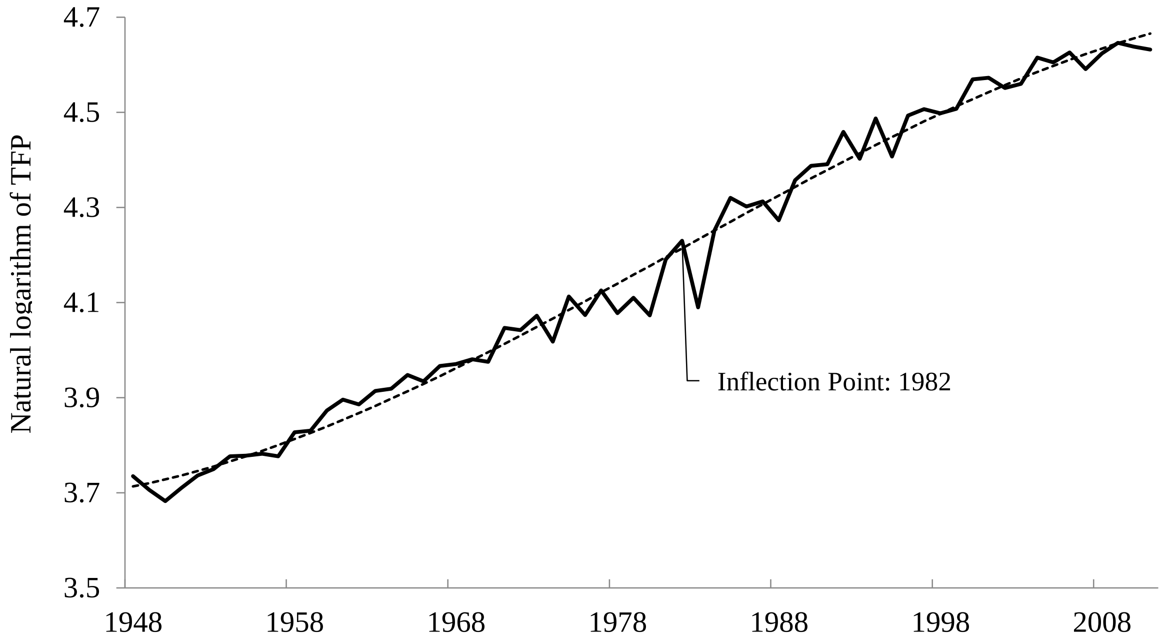
Panel b: 15-year and 25-year moving average growth rates



Appendix Figure B-1

Moving average of annual MFP growth by different intervals with quadratic trend lines

Notes: In panel a, darker points indicate 5-year moving average growth rates with the period terminating in the year the points are plotted. The lighter shaded points represent 10-year moving averages. The dashed lines are a quadratic line of best fit through the respective points. In panel b, darker points indicate 15-year moving average growth rates with the period terminating in the year the points are plotted. The lighter shaded points represent 25-year moving averages. The dashed lines are a quadratic line of best fit through the respective points.
Source: Authors estimates using InSTePP Production Accounts, Version 5 augmented with data from USDA-ERS (1983).

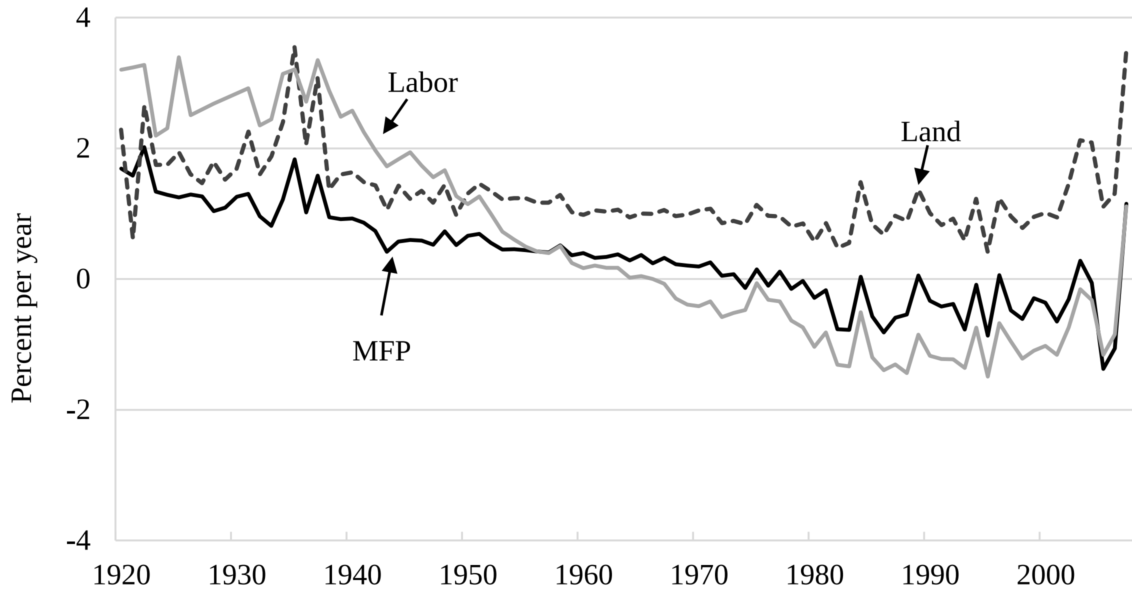


Appendix Figure B-2

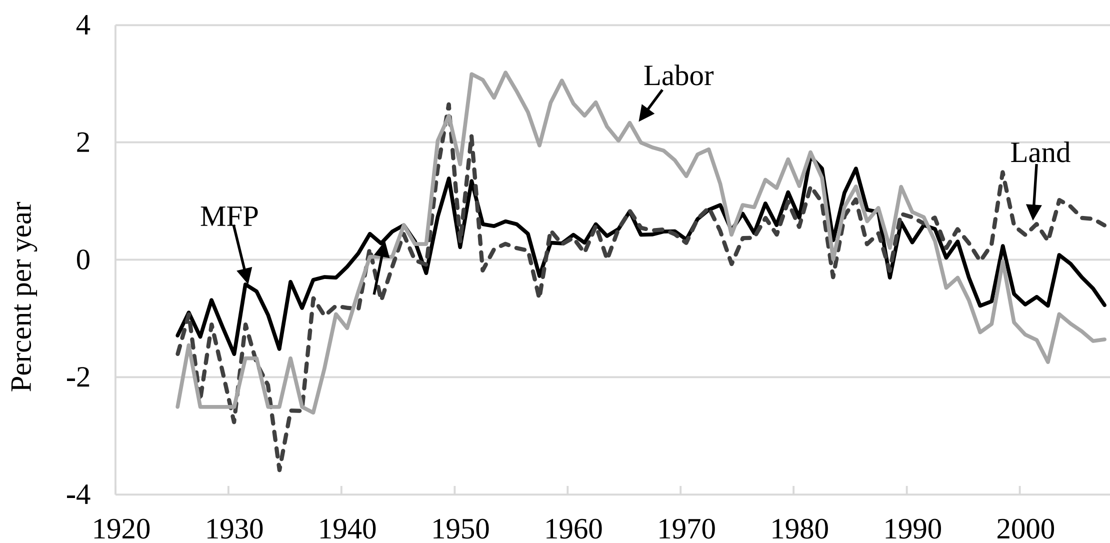
Natural logarithm of TFP with cubic trend line, 1948-2011

Source: The TFP indexes are from the USDA-ERS (2013).

Panel a: Breakpoint



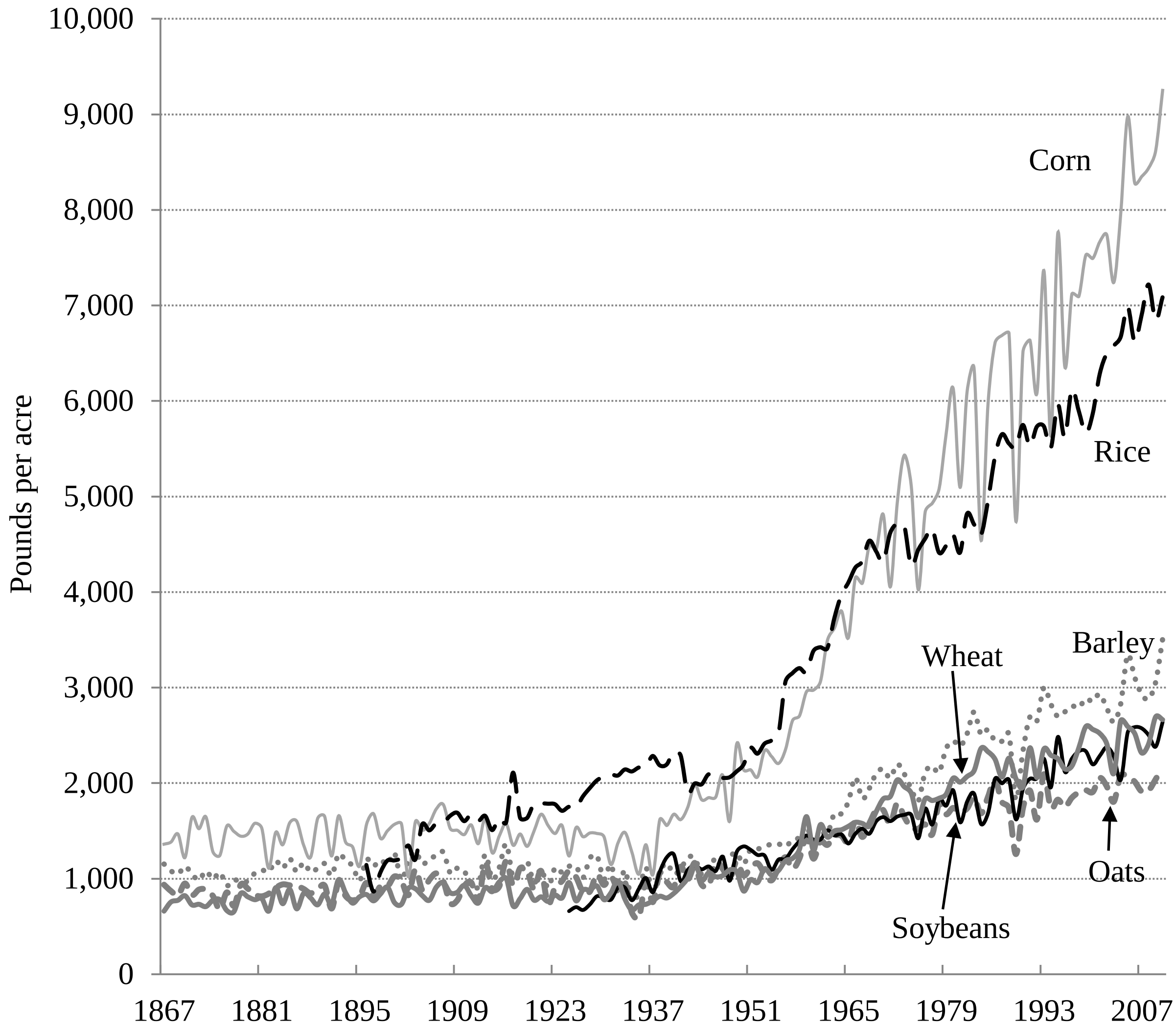
Panel b: 15 year interval



Appendix Figure B-3

Estimated Coefficients on Dummy Variables for Breakpoints and 15-year Time Intervals of MFP Growth Rates, 1910–2007

Notes: Coefficient estimates in Panel a represent the estimated increase (or decrease) in the rate of productivity growth after the year noted. Coefficient estimates in Panel b represent the estimated differences in productivity growth during the 15-year time period relative to all other years outside that time period. Coefficients are plotted against the last year in each successive time period.
Source: Calculated by the authors using Version 5 of the InSTePP Production Accounts augmented with data from USDA-ERS (1983). .



Appendix Figure B-4

Yields for Six Field Crops, 1867–2009

Notes: The yield data were converted from bushels per acre to pounds per acre using conversion factors obtained from USDA-NASS (2000, pp. v-vii) of 48, 56, 32, 60, and 60 pounds per acre respectively for barley, corn, oats, soybeans, and wheat. The rice data were reported in pounds per acre. All the inflection points represent the first year of deceleration, except for soybeans where the inflection point represents an acceleration in yield. Each of the estimated inflection points is statistically significantly different from zero at the 1 percent level of significance.
Sources: Yield data from USDA-NASS (2010).

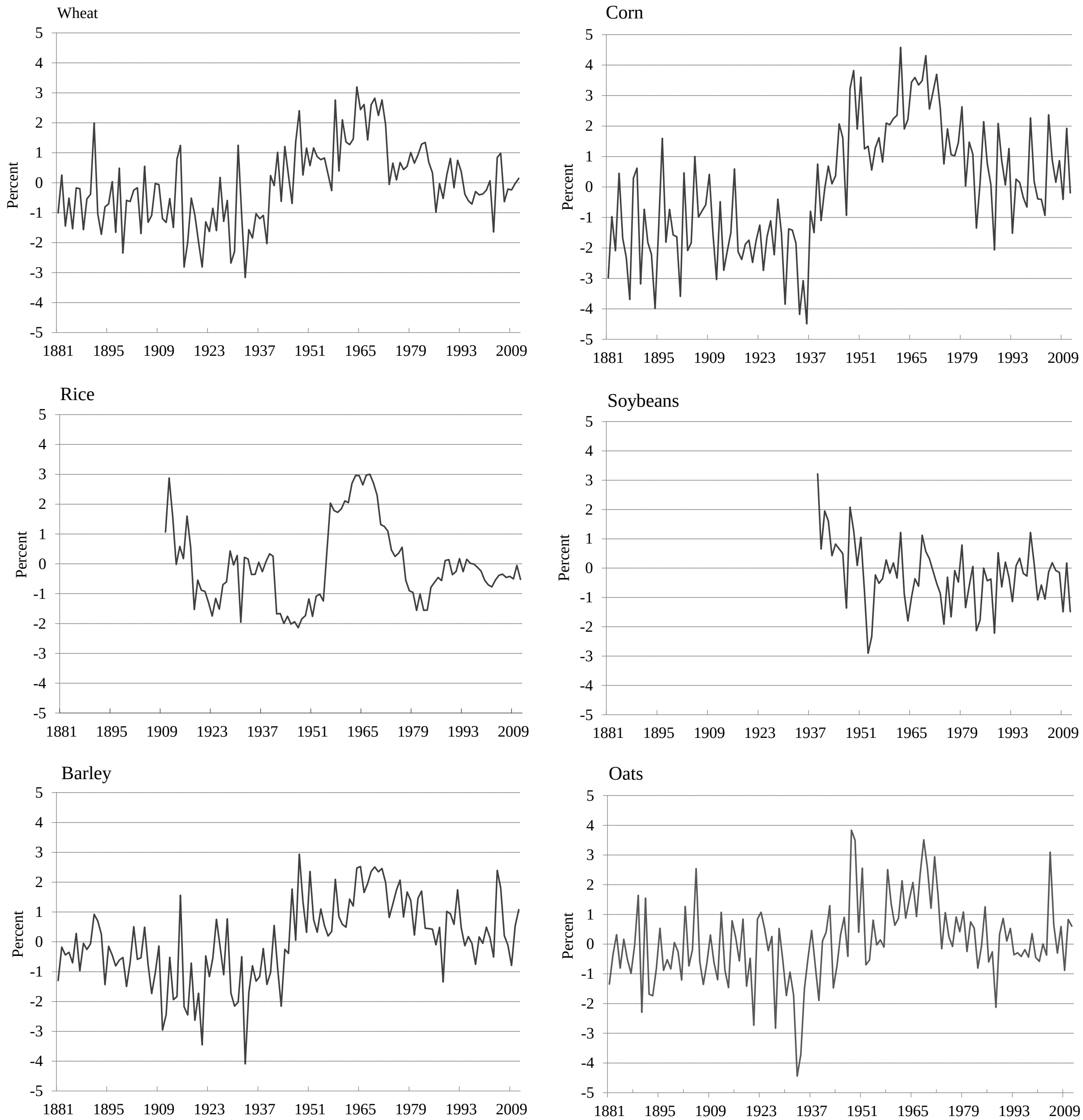
Appendix Table B-2

Crop Yields, and Absolute and Proportional Changes in Yields, 1867–2009

	Barley	Corn	Oats	Rice	Soybeans	Wheat
Crop Yield						
			(pounds per acre)			
1867	1,152	1,361	938	1,144	660	660
2009	3,504	9,251	2,163	7,085	2,640	2,664
Entire period	1,581	3,138	1,226	3,382	1,563	1,294
Through 1935	1,090	1,452	904	1,671	804	812
1935–2009	2,033	4,688	1,523	4,330	1,677	1,736
Average rate-of-change						
			Average annual percentage change			
Entire period	0.78	1.34	0.58	1.60	1.58	0.98
Through 1935	-0.05	-0.01	0.04	1.60	3.62	0.15
1935–2009	1.55	2.60	1.09	1.60	1.30	1.75
1935–1990	1.61	2.89	1.25	1.70	1.29	2.14
1990–2009	1.39	1.75	0.62	1.31	1.34	0.62
1950s	1.31	3.59	2.21	3.67	0.80	4.59
1960s	3.23	2.80	1.25	2.99	1.28	1.72
1970s	1.49	2.29	0.74	-0.45	-0.08	0.78
1980s	1.21	2.64	1.26	2.25	2.52	1.65
1990s	0.85	1.44	0.66	1.28	1.11	0.61
2000–09	1.98	2.09	0.57	1.34	1.60	0.62
Average yield gain			*Pounds per acre per year*			
Entire period	16.4	55.2	8.6	52.1	30.7	14.0
Through 1935	-0.6	-0.1	0.4	25.7	84.0	1.0
1935–2009	32.3	106.7	16.2	66.4	22.1	26.1
1935–1990	28.7	96.0	17.4	61.0	18.9	29.8
1990–2009	42.7	137.6	12.6	81.9	31.3	15.5
1950s	18.2	92.4	27.5	105.2	10.8	57.6
1960s	56.6	99.1	18.6	119.5	19.2	29.4

1970s	33.1	104.2	12.2	-20.5	-1.2	15.0
1980s	30.7	154.0	22.7	111.6	45.6	36.0
1990s	24.0	103.0	13.1	75.2	24.0	15.0
2000–09	63.5	176.1	12.1	89.3	39.3	16.0

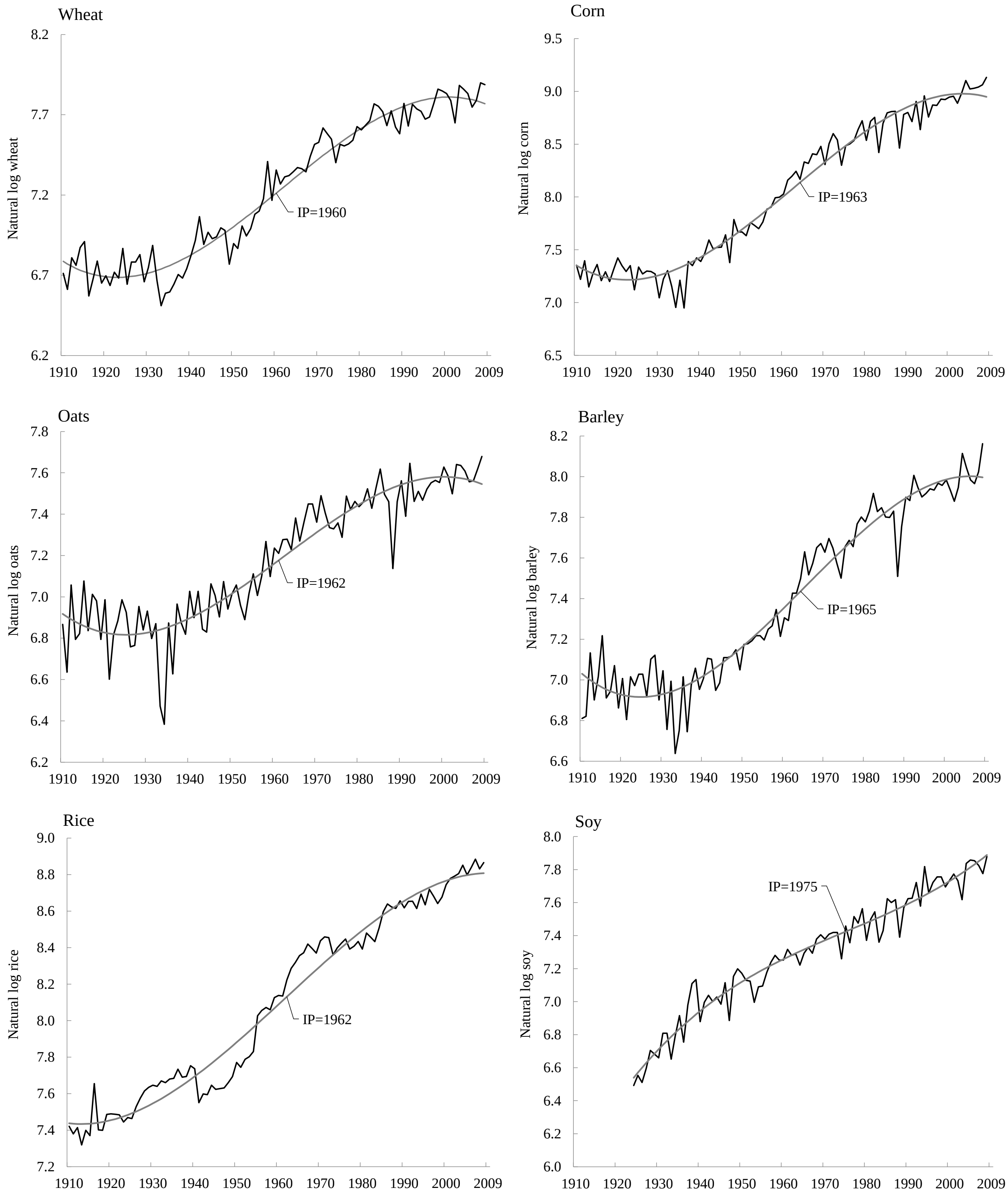
Notes: See Appendix figure B-4.
Sources: Yield data from USDA-NASS (2010).



Appendix Figure B-5

Estimated Coefficients on Dummy Variables for 15-Year Intervals of U.S. Crop Yield Growth, 1881–2009

Notes: Coefficient estimates represent the estimated differences in yield growth during the 15-year time period relative to all other years outside that time period. Coefficients are graphed against the last year in the time period.
Source: Calculated by the authors using yield data from USDA-NASS (2010).



Appendix Figure B-6

Cubic Trend Regression Models of U.S. Crop Yield, 1881–2009

Notes: The yield data were converted from bushels per acre to pounds per acre using conversion factors obtained from USDA-NASS (2000, pp. v-vii) of 48, 56, 32, 60, and 60 pounds per acre respectively for barley, corn, oats, soybeans, and wheat. The rice data were reported in pounds per acre. All the inflection points represent the first

year of deceleration, except for soybeans where the inflection point represents an acceleration in yield. Each of the estimated inflection points is statistically significantly different from zero at the one percent level of significance.
Source: Yield data from USDA-NASS (2010).

APPENDIX C: LINKS AMONG PARTIAL, MULTI- AND TOTAL FACTOR PRODUCTIVITY MEASURES

How well does an *MFP* or *PFP* measure approximate *TFP*? The main ideas can be illustrated with some simple mathematics.[29] Let us define total output Q as the sum of the quantities of outputs *included* in *MFP*, Q_i, and the outputs *excluded* from *MFP*, Q_e (where $Q_e / Q = q_e$), and total input X as the sum of the quantities of *included* inputs, X_i, and *excluded* inputs, X_e (where $X_e / X = x_e$), such that the measures of *TFP* and *MFP* are

$$MFP = \frac{Q_i}{X_i}, \tag{1}$$

$$TFP = \frac{Q}{X} = \frac{Q_i + Q_e}{X_i + X_e}. \tag{2}$$

Taking logarithmic differentials of equations (1) and (2) gives measures of growth rates of *MFP* and *TFP*. Taking the difference between the logarithmic differentials gives an equation for the difference between growth in *TFP* and growth in *MFP* as follows:

$$\begin{aligned} d\ln TFP - d\ln MFP &= d\ln\left(Q_i + Q_e\right) - d\ln\left(X_i + X_e\right) - d\ln\left(Q_i\right) + d\ln\left(X_i\right) \\ &= q_e\left(d\ln Q_e - d\ln Q_i\right) - x_e\left(d\ln X_e - d\ln X_i\right). \end{aligned} \tag{3}$$

Thus the discrepancy depends on the relative importance of the excluded quantities of outputs and inputs (q_e and x_e), and on the differences in the growth rates between the included and excluded quantities of outputs and inputs.

Importantly, if the excluded quantities of outputs and inputs are growing at the same rates as their included counterparts, the *MFP* measure grows at the same rate as the *TFP* measure. If the growth rates are different, however, the *MFP* growth rate will be different, with the difference increasing with the relative importance of the excluded outputs and inputs unless by chance the distortions in the outputs and inputs offset one another. For instance, in the United States, the purchased inputs category has been a relatively rapidly growing category of inputs. All other categories have been shrinking, especially operator labor. The greenhouse and nursery products category has been by far the fastest growing category of outputs (see Alston et al. 2010a for

[29] This appendix draws on material presented in Alston, Babcock and Pardey (2010).

details). If we were to exclude purchased inputs, we would understate growth in inputs, and therefore overstate growth in productivity. Conversely, if we were to exclude greenhouse and nursery products we would understate output growth and understate productivity growth. If we were to exclude both purchased inputs and nursery and greenhouse products, the net effect may be to increase or decrease the measured productivity growth depending on the relative importance of the two biases.

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APPENDIX D: STATE-SPECIFIC MFP GROWTH

Appendix Table D-1 includes state-specific details on rates of growth in inputs, outputs, and *MFP* for the 48 contiguous states and for the United States as a whole over the 58 years, 1949–2007, and for each decade within that period.[30] Appendix Figure D-1 plots the average annual growth rate of agricultural output against the corresponding annual average growth rate of agricultural input, state by state, and for the 48-state aggregate. Points on the 45-degree line that pass through the origin have output growing at the same rate as input and thus have zero *MFP* growth. All states had positive *MFP* growth, with all points above and to the left of the 45-degree line through the origin. Some states had both inputs and outputs growing (e.g., California and Idaho), some had both falling (e.g., Massachusetts and New Jersey), but the majority had output growing against a declining input quantity. In a few (mostly northeastern) states, *MFP* growth reflected a contraction in input use that outweighed declining aggregate output. The 45-degree line in Appendix Figure D-1 that passes through the observation for the national aggregate cuts the vertical axis at 1.78 percent per annum, the national aggregate annual average productivity growth rate. A point above that line indicates a relatively fast output growth rate for the given input growth rate (or a relatively fast reduction in inputs for a given rate of output growth). We can think of the points above the line as reflecting faster-than-average *MFP* growth.

[Appendix Table D-1: *State-Specific Input, Output, and Productivity Growth, 1949–2007*]

[Appendix Figure D-1: *Input versus Output Growth Rates, by State, 1949–2007*]

Clear evidence of a recent productivity slowdown can be seen in Appendix Figure D-2, which shows distributions of annual state-specific *MFP* growth rates over ten-year periods since 1949. Each of the distributions refers to a particular period, and the data are the state-specific averages of the annual *MFP* growth rates for the period, a total of 48 growth-rate statistics. By inspection, it can be seen that the general shape and position of the distribution of state-specific *MFP* growth rates seems reasonably constant across periods until the last two, 1990–2000 and 2000–2007, when both distributions shift substantially to the left, indicating a widespread slowdown in state-specific productivity growth. Aggregate input growth was generally higher in 1990–2007 compared with 1949–1990 (and notably so for most western states), whereas output

[30] The periods are decades beginning in the year ending in zero except for the first period, which includes one extra year, and the last which is truncated by three years to 2007.

growth generally slowed after 1990. These reinforcing input and output trends contributed to the pervasive slowdown in *MFP* growth.

[Appendix Figure D-2. *Distribution of Average Annual MFP Growth Rates across States, by Decade*]

The plots in Appendix Figures D-1 and D-2 display the very substantial differences in paths taken by agricultural input, output and productivity among the 48 contiguous states, albeit with a predominant pattern of slower productivity growth since 1990. Appendix Table D-2 includes the results of cubic trend regression models estimated for each of the 48 U.S. states and various sub regions and these are plotted, state-by state, in Appendix Figure D-3.

[Appendix Table D-1. *Cubic Trend Regressions of State-Specific and Regional MFP, 1949–2007*]

[Appendix Figure D-3. *Cubic Trend Regressions of State-Specific MFP, 1949–2007*]

Appendix Table D-1

State-Specific Input, Output and Productivity Growth Rates, 1949–2007

	Input	**Output**	**MFP**	**1949-1960**	**1960–1970**	**1970–1980**	**1980–1990**	**1990–2000**	**2000-2007**
Alabama	-0.52	1.76	2.28	3.37	2.29	2.58	3.40	0.83	0.58
Arizona	1.11	2.27	1.16	1.45	0.70	3.17	0.67	1.72	-1.63
Arkansas	-0.02	2.77	2.80	3.12	3.59	2.81	3.13	1.99	1.84
California	0.83	2.60	1.77	1.66	2.22	2.84	1.01	1.10	1.77
Colorado	0.53	1.86	1.33	1.54	1.98	1.81	2.33	0.29	-0.53
Connecticut	-1.49	0.07	1.56	2.54	2.09	0.77	2.16	-1.09	3.30
Delaware	0.36	2.58	2.22	3.83	2.66	1.02	3.02	0.61	1.89
Florida	1.13	2.34	1.21	0.97	2.12	4.07	-0.37	2.58	-3.47
Georgia	-0.03	2.65	2.69	4.02	2.65	2.17	3.00	2.08	1.81
Idaho	0.76	2.81	2.05	1.70	2.92	2.64	2.82	1.33	0.45
Illinois	-0.19	1.43	1.62	1.47	0.08	2.61	2.62	1.49	1.37
Indiana	-0.28	1.43	1.71	1.48	0.55	2.87	2.15	1.56	1.64
Iowa	0.09	1.71	1.62	1.10	0.97	2.80	1.11	1.84	2.13
Kansas	0.28	2.04	1.76	3.48	0.44	1.22	2.55	1.61	0.80
Kentucky	-0.54	0.44	0.98	1.32	1.55	1.95	1.69	-0.74	-0.33
Louisiana	-0.66	1.36	2.02	1.05	4.32	1.96	1.68	1.70	1.30
Maine	-1.45	0.30	1.75	3.47	4.73	-1.38	2.06	0.37	0.75
Maryland	-0.26	1.65	1.91	2.71	2.82	1.30	2.71	1.14	0.17
Massachusetts	-1.83	-0.72	1.11	2.97	3.18	1.99	-0.39	-0.76	-1.24
Michigan	-0.44	1.34	1.78	0.94	2.34	3.69	1.51	0.87	1.26
Minnesota	-0.09	1.81	1.90	1.88	1.41	2.67	2.10	1.97	1.15
Mississippi	-0.83	2.11	2.94	3.86	3.90	1.42	2.58	2.58	3.28
Missouri	-0.26	1.12	1.37	1.64	0.58	1.96	0.76	1.63	1.73
Montana	0.23	1.35	1.12	1.81	2.00	0.94	1.56	-0.60	0.88
Nebraska	0.46	2.51	2.05	2.41	1.41	2.06	3.43	0.92	2.00
Nevada	0.19	1.04	0.86	0.89	0.94	1.48	-0.13	1.56	0.19
New Hampshire	-1.65	-0.44	1.21	3.31	3.66	-0.54	0.92	-0.01	-0.92
New Jersey	-1.19	-0.16	1.03	2.22	1.00	0.89	2.09	-0.14	-0.43
New Mexico	0.79	2.42	1.63	1.05	2.15	1.45	1.63	3.01	0.11
New York	-1.17	0.42	1.59	1.81	1.92	1.88	1.78	-0.01	2.39
North Carolina	-0.47	1.99	2.46	2.34	2.67	3.14	3.90	1.60	0.58
North Dakota	-0.14	2.22	2.36	2.19	1.63	2.00	5.01	0.92	2.45
Ohio	-0.46	1.14	1.60	1.22	0.92	3.57	1.59	1.47	0.52

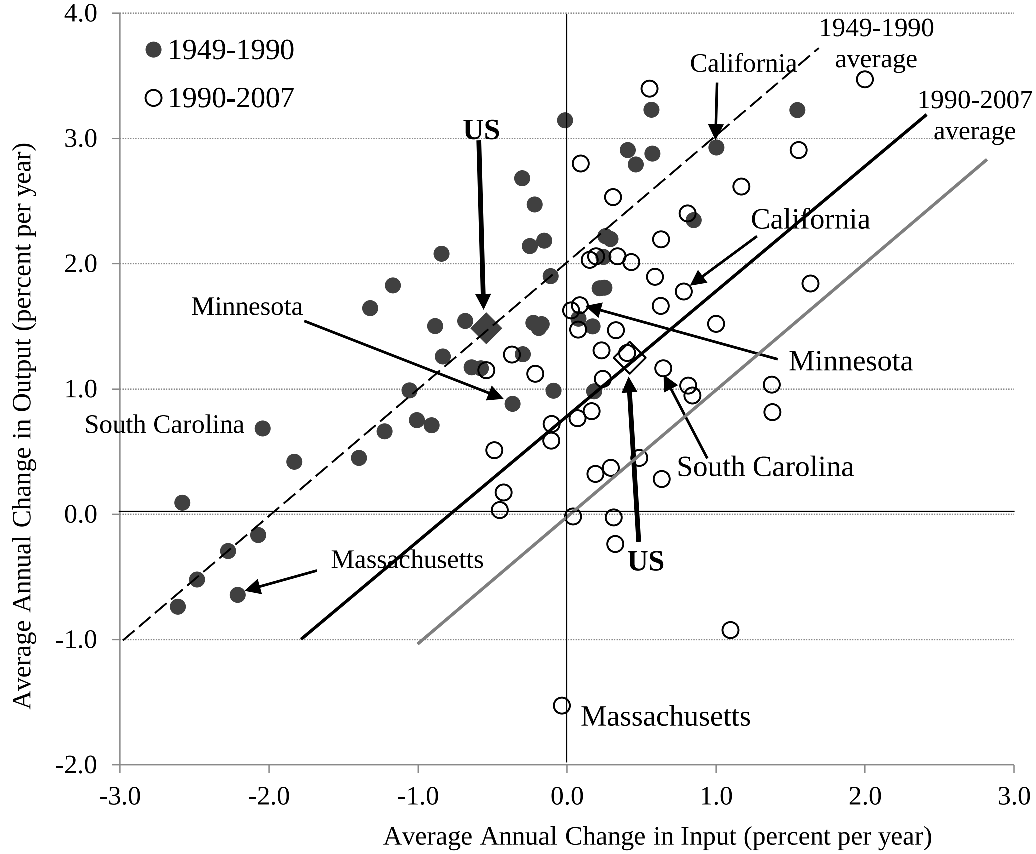
Appendix Table D-1 *(continued)*

State-Specific Input, Output and Productivity Growth Rates, 1949–2007

	Input	**Output**	**MFP**	**1949-1960**	**1960–1970**	**1970–1980**	**1980–1990**	**1990–2000**	**2000-2007**
Oklahoma	0.09	1.26	1.16	2.01	0.33	2.90	1.43	-0.25	0.19
Oregon	0.32	1.98	1.66	1.41	1.90	2.68	1.29	0.99	1.74
Pennsylvania	-0.60	1.30	1.90	2.04	2.20	2.80	2.54	0.38	1.20
Rhode Island	-1.51	-0.34	1.17	2.68	2.79	1.01	4.22	-3.78	-0.59
South Carolina	-1.23	1.00	2.23	1.82	3.10	3.03	3.05	1.84	-0.13
South Dakota	-0.01	2.03	2.04	2.96	1.59	1.33	3.41	1.69	0.79
Tennessee	-0.68	0.51	1.19	1.55	1.26	3.17	1.08	-0.84	0.75
Texas	0.33	1.61	1.29	0.39	1.01	1.39	2.62	1.00	1.44
Utah	0.01	1.09	1.08	1.89	2.38	0.06	2.63	1.19	-2.94
Vermont	-1.07	0.43	1.50	2.71	3.08	0.62	1.05	0.14	1.19
Virginia	-0.56	0.75	1.31	1.33	1.51	1.86	3.56	-0.61	-0.25
Washington	0.45	2.40	1.95	0.71	2.76	3.79	2.13	1.38	0.65
West Virginia	-1.34	-0.12	1.22	1.95	0.83	2.68	2.46	-0.13	-1.33
Wisconsin	-0.31	1.03	1.33	1.49	1.37	1.97	1.48	1.03	0.33
Wyoming	0.07	0.58	0.51	2.06	0.71	1.21	0.22	0.51	-2.78
U.S. 48 states average	-0.28	1.37	1.65	2.04	1.98	2.01	2.07	0.83	0.58
U.S. national	-0.07	1.70	1.78	1.89	1.69	2.46	2.08	1.25	1.08

Source: Calculated by the authors using Version 5 of the InSTePP Production Accounts.

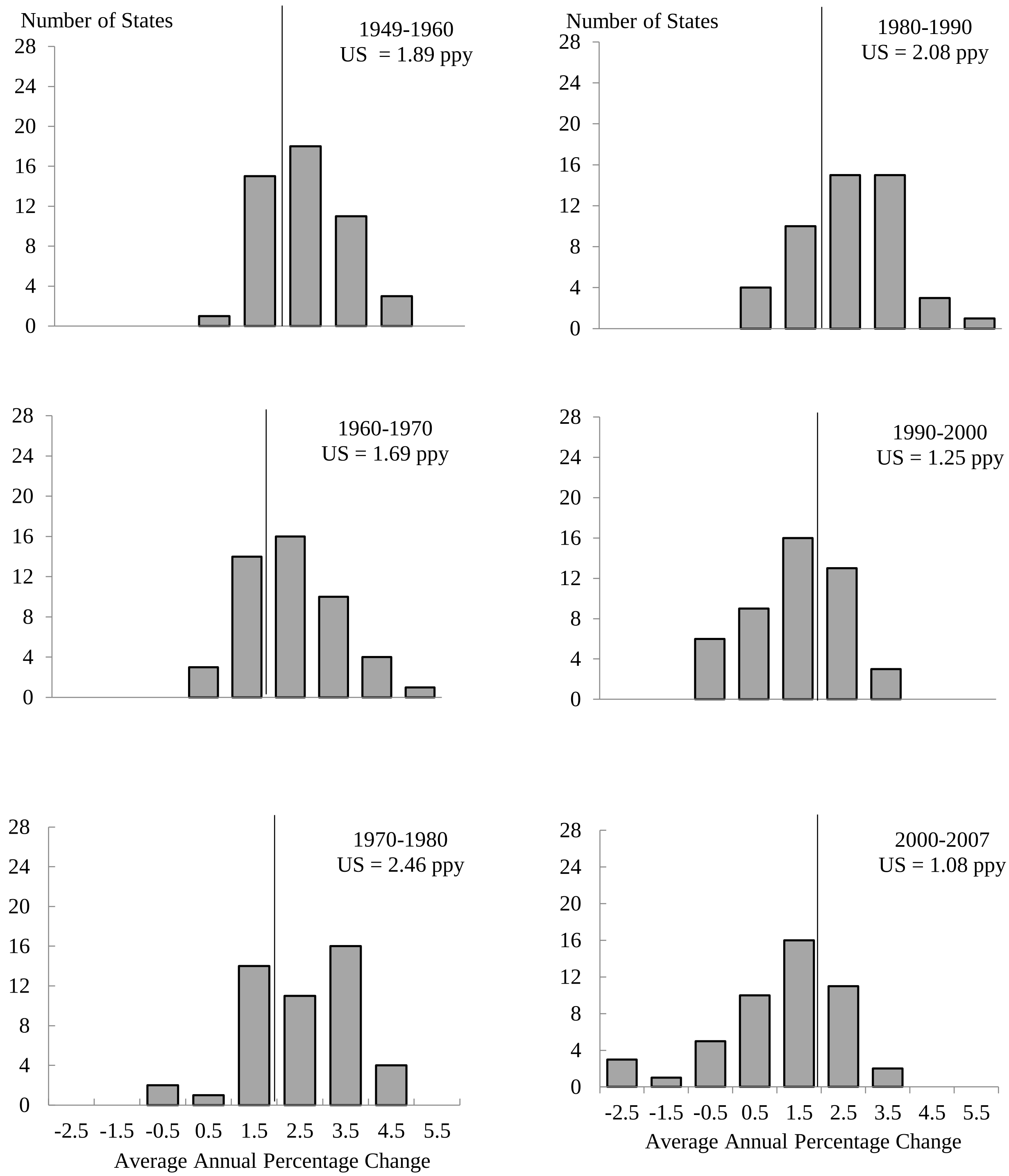
Appendix Figure D-1



Input versus Output Growth Rates, by State, 1949–1990 and 1990–2007

Notes: States lying above or below the respective 45 degree line have MFP growth rates above and below the respective U.S. period averages. The dashed line represents the U.S. average for the period 1949-1990; the solid dark line the US average for the period 1990-2007. States lying above the solid gray line have positive rates of MFP growth for either period.

Source: Calculated by authors from Version 5 of InSTePP Production Accounts.



Appendix Figure D-2

Distribution of Average Annual MFP Growth Rates across States, by Decade

Notes: ppy designates percent per year. The vertical line represents the 48-state average of the 1949-2007 MFP, growth rates, which is 1.65 percent per year.
Source: Calculated by authors from Version 5 of InSTePP Production Accounts.

Appendix Table D-2

Cubic Trend Regressions of State-Specific and Regional MFP, 1949–2007

State	t	t^2	t^3	constant
Alabama	3.356E-02***	1.105E-04	-4.790E-06**	4.551E+00***
	5.436E-03	*2.096E-04*	*2.300E-06*	*3.798E-02*
Arizona	-1.089E-02**	1.070E-03***	-1.230E-05***	4.759E+00***
	5.251E-03	*2.024E-04*	*2.220E-06*	*3.669E-02*
Arkansas	4.343E-02***	-1.057E-04	-2.310E-06	4.472E+00***
	4.337E-03	*1.672E-04*	*1.830E-06*	*3.030E-02*
California	1.438E-02***	3.158E-04	-5.050E-06**	4.620E+00***
	4.983E-03	*1.921E-04*	*2.110E-06*	*3.482E-02*
Colorado	6.530E-03	7.531E-04***	-1.080E-05***	4.524E+00***
	4.900E-03	*1.889E-04*	*2.070E-06*	*3.423E-02*
Connecticut	2.183E-02***	-2.652E-04	1.700E-06	4.719E+00***
	7.232E-03	*2.788E-04*	*3.060E-06*	*5.053E-02*
Delaware	4.423E-02***	-5.277E-04**	2.520E-06	4.564E+00***
	5.485E-03	*2.115E-04*	*2.320E-06*	*3.832E-02*
Florida	-1.998E-03	9.708E-04***	-1.280E-05***	4.726E+00***
	6.713E-03	*2.588E-04*	*2.840E-06*	*4.690E-02*
Georgia	3.690E-02***	-2.650E-05***	-2.750E-06	4.600E+00***
	4.929E-03	*1.900E-04*	*2.080E-06*	*3.444E-02*
Idaho	7.520E-03**	6.600E-04***	-7.930E-06***	4.672E+00***
	3.287E-03	*1.267E-04*	*1.390E-06*	*2.297E-02*
Illinois	1.408E-02**	7.250E-05***	-5.710E-07	4.575E+00***
	6.621E-03	*2.553E-04*	*2.800E-06*	*4.626E-02*
Indiana	1.027E-02*	1.912E-04	-1.290E-06	4.603E+00***
	5.364E-03	*2.068E-04*	*2.270E-06*	*3.747E-02*
Iowa	1.178E-02**	5.620E-05	3.870E-07	4.583E+00***
	5.438E-03	*2.097E-04*	*2.300E-06*	*3.800E-02*
Kansas	2.322E-02***	-7.830E-05	5.990E-08	4.556E+00***
	7.434E-03	*2.866E-04*	*3.140E-06*	*5.194E-02*
Kentucky	1.326E-02**	3.915E-04*	-7.640E-06***	4.563E+00***
	5.649E-03	*2.178E-04*	*2.390E-06*	*3.947E-02*
Louisiana	2.217E-02***	3.896E-04	-7.480E-06***	4.536E+00***
	6.220E-03	*2.398E-04*	*2.630E-06*	*4.345E-02*
Maine	6.545E-02***	-1.353E-03***	9.290E-06***	4.502E+00***
	5.333E-03	*2.056E-04*	*2.250E-06*	*3.726E-02*
Maryland	2.663E-02***	9.410E-05	-3.780E-06**	4.583E+00***
	3.826E-03	*1.475E-04*	*1.620E-06*	*2.673E-02*
Massachusetts	2.526E-02***	1.084E-04	-6.710E-06***	4.701E+00***
	5.544E-03	*2.137E-04*	*2.340E-06*	*3.873E-02*
Michigan	6.595E-03	7.121E-04***	-9.010E-06***	4.578E+00***
	4.897E-03	*1.888E-04*	*2.070E-06*	*3.422E-02*
Minnesota	1.168E-02**	2.800E-04	-2.660E-06	4.612E+00***
	5.767E-03	*2.223E-04*	*2.440E-06*	*4.029E-02*
Mississippi	5.562E-02***	-8.460E-04***	7.070E-06***	4.522E+00***
	5.944E-03	*2.292E-04*	*2.510E-06*	*4.153E-02*
Missouri	2.034E-02***	-2.048E-04	1.650E-06	4.550E+00***

	5.651E-03	*2.178E-04*	*2.390E-06*	*3.948E-02*
Montana	1.066E-02	2.024E-04	-4.100E-06	4.724E+00 ***
	8.342E-03	*3.216E-04*	*3.530E-06*	*5.828E-02*
Nebraska	3.298E-03	7.743E-04***	-8.760E-06***	4.670E+00***
	5.212E-03	*2.009E-04*	*2.200E-06*	*3.641E-02*
Nevada	-8.333E-04	3.655E-04*	-4.040E-06*	4.666E+00***
	5.421E-03	*2.090E-04*	*2.290E-06*	*3.787E-02*
New Hampshire	5.226E-02***	-1.223E-03***	9.180E-06***	4.636E+00***
	4.322E-03	*1.666E-04*	*1.830E-06*	*3.019E-02*
New Jersey	1.676E-03	6.027E-04**	-8.690E-06***	4.729E+00***
	6.432E-03	*2.480E-04*	*2.720E-06*	*4.494E-02*
New Mexico	5.392E-03	5.912E-04***	-6.280E-06***	4.522E+00***
	4.006E-03	*1.545E-04*	*1.690E-06*	*2.799E-02*
New York	9.705E-03**	3.250E-04*	-4.500E-06**	4.668E+00***
	4.334E-03	*1.671E-04*	*1.830E-06*	*3.028E-02*
North Carolina	-7.686E-03	1.603E-03***	-1.890E-05***	4.729E+00***
	5.830E-03	*2.247E-04*	*2.460E-06*	*4.073E-02*
North Dakota	1.728E-02*	4.391E-04	-6.300E-06	4.612E+00***
	1.031E-02	*3.974E-04*	*4.360E-06*	*7.201E-02*
Ohio	-8.817E-04	7.770E-04***	-8.650E-06***	4.627E+00***
	5.260E-03	*2.028E-04*	*2.220E-06*	*3.675E-02*
Oklahoma	1.476E-02*	3.782E-04	-6.700E-06**	4.446E+00***
	6.065E-03	*2.338E-04*	*2.560E-06*	*4.237E-02*
Oregon	9.081E-03**	3.635E-04**	-4.480E-06***	4.647E+00***
	3.815E-03	*1.471E-04*	*1.610E-06*	*2.666E-02*
Pennsylvania	8.150E-03	7.665E-04***	-1.060E-05***	4.639E+00***
	5.302E-03	*2.044E-04*	*2.240E-06*	*3.704E-02*
Rhode Island	-1.103E-02	1.754E-03***	-2.520E-05***	4.835E+00***
	1.038E-02	*4.003E-04*	*4.390E-06*	*7.254E-02*
South Carolina	7.510E-03	1.053E-03***	-1.390E-05***	4.642E+00***
	5.925E-03	*2.284E-04*	*2.500E-06*	*4.140E-02*
South Dakota	1.839E-02**	7.930E-05	-1.310E-06	4.655E+00***
	6.980E-03	*2.691E-04*	*2.950E-06*	*4.877E-02*
Tennessee	7.447E-03	7.114E-04***	-1.090E-05***	4.591E+00***
	6.259E-03	*2.413E-04*	*2.640E-06*	*4.373E-02*
Texas	9.844E-03*	4.411E-04**	-5.890E-06***	4.398E+00***
	5.101E-03	*1.966E-04*	*2.160E-06*	*3.564E-02*
Utah	5.931E-03	3.871E-04*	-5.100E-06**	4.715E+00***
	4.743E-03	*1.828E-04*	*2.000E-06*	*3.314E-02*
Vermont	4.258E-02***	-7.099E-04***	4.140E-06**	4.553E+00***
	3.786E-03	*1.459E-04*	*1.600E-06*	*2.645E-02*
Virginia	-9.100E-03**	1.270E-03***	-1.600E-05***	4.690E+00***
	4.320E-03	*1.666E-04*	*1.830E-06*	*3.019E-02*
Washington	-1.778E-03	1.096E-03***	-1.330E-05***	4.661E+00***
	4.608E-03	*1.777E-04*	*1.950E-06*	*3.220E-02*
West Virginia	-1.041E-02	1.131E-03***	-1.340E-05***	4.771E+00***
	6.520E-03	*2.513E-04*	*2.760E-06*	*4.555E-02*
Wisconsin	9.532E-03**	2.524E-04*	-3.490E-06**	4.637E+00***
	3.910E-03	*1.508E-04*	*1.650E-06*	*2.732E-02*

Wyoming	8.207E-03*	1.744E-04	-3.790E-06*	4.703E+00***
	4.710E-03	*1.816E-04*	*1.990E-06*	*3.291E-02*

*Note*s: Standard errors in italics. The symbol * denotes statistically significantly different from zero at the 10 percent level of significance, ** at 5 percent, and *** at 1 percent.

Appendix Table D-3

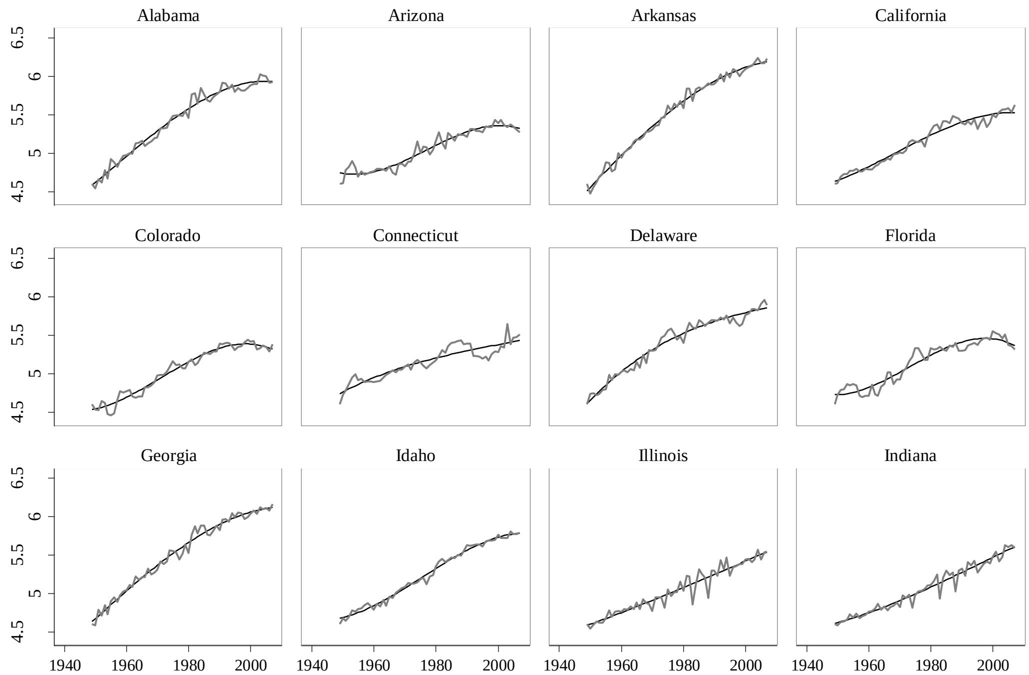
Inflection Point Estimates, by State, 1949–2007

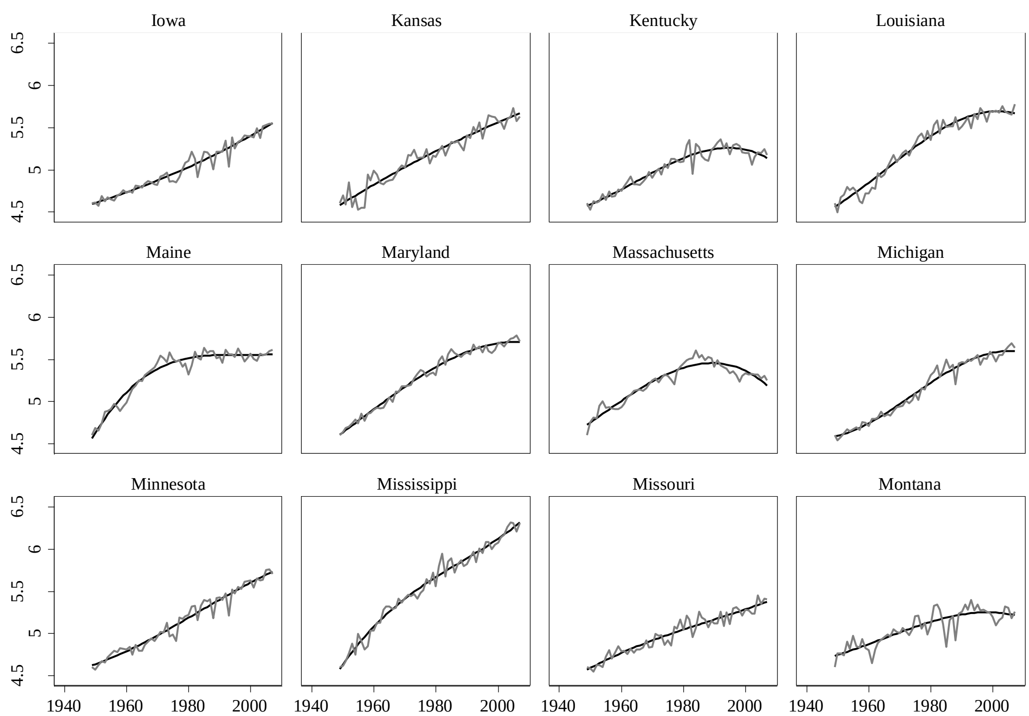
State	*Pt. est.*	*IP*	95_{low}	95_{hi}	R^2	*Shape*
Alabama	7.70 *10.97*	1956	1934	1978	0.9770	*inconclusive*
Arizona	29.09*** *0.92*	1977	1975	1979	0.9342	*deceleration*
Arkansas	-15.25 *36.13*	1933	1860	2005	0.9895	*inconclusive*
California	20.83*** *4.35*	1969	1960	1978	0.9592	*deceleration*
Colorado	23.29*** *1.61*	1971	1968	1975	0.9616	*deceleration*
Connecticut	52.03 *40.62*	2000	1919	2081	0.8332	*inconclusive*
Delaware	69.87* *37.00*	2018	1944	2092	0.9671	*acceleration*
Florida	25.34*** *1.52*	1973	1970	1976	0.9142	*deceleration*
Georgia	-3.21 *25.41*	1945	1894	1996	0.9831	*inconclusive*
Idaho	27.73*** *0.96*	1976	1974	1978	0.9884	*deceleration*
Illinois	42.36 *65.32*	1990	1859	2121	0.9252	*inconclusive*
Indiana	49.27 *34.88*	1997	1927	2067	0.9550	*inconclusive*
Iowa	-48.46 *467.00*	1900	964	2835	0.9475	*inconclusive*
Kansas	435.36 *21250.02*	2383	-40203	44969	0.9260	*inconclusive*
Kentucky	17.07*** *4.33*	1965	1956	1974	0.9132	*deceleration*
Louisiana	17.37*** *4.77*	1965	1956	1975	0.9608	*deceleration*
Maine	48.55*** *4.66*	1997	1987	2006	0.9488	*acceleration*
Maryland	8.31 *9.53*	1956	1937	1975	0.9826	*inconclusive*
Massachusetts	5.39 *8.77*	1953	1936	1971	0.9122	*inconclusive*
Michigan	26.34*** *1.42*	1974	1971	1977	0.9717	*deceleration*
Minnesota	35.12*** *6.55*	1983	1970	1996	0.9592	*deceleration*
Mississippi	39.86*** *3.92*	1988	1980	1996	0.9774	*acceleration*
Missouri	41.44**	1989	1953	2026	0.9171	*acceleration*

	18.08					
Montana	16.46 *12.41*	1964	1940	1989	0.7376	*inconclusive*
Nebraska	29.46*** *1.26*	1977	1975	1980	0.9713	*deceleration*
Nevada	30.17*** *2.83*	1978	1973	1984	0.8160	*deceleration*
New Hampshire	44.40*** *3.03*	1992	1986	1998	0.9223	*acceleration*
New Jersey	23.11*** *2.66*	1971	1966	1976	0.8371	*deceleration*
New Mexico	31.39*** *1.39*	1979	1977	1982	0.9813	*deceleration*
New York	24.05*** *3.15*	1972	1966	1978	0.9581	*deceleration*
North Carolina	28.29*** *0.69*	1976	1975	1978	0.9785	*deceleration*
North Dakota	23.24*** *5.81*	1971	1960	1983	0.9107	*deceleration*
Ohio	29.94*** *1.28*	1978	1975	1981	0.9583	*deceleration*
Oklahoma	18.81*** *4.68*	1967	1957	1976	0.9342	*deceleration*
Oregon	27.07*** *2.08*	1975	1971	1979	0.9736	*deceleration*
Pennsylvania	24.15*** *1.63*	1972	1969	1975	0.9668	*deceleration*
Rhode Island	23.22*** *1.47*	1971	1968	1974	0.8286	*deceleration*
South Carolina	25.24*** 1.24	1973	1971	1976	0.9748	*deceleration*
South Dakota	20.16 *24.82*	1968	1918	2018	0.9354	*inconclusive*
Tennessee	21.70*** *2.34*	1970	1965	1974	0.9252	*deceleration*
Texas	24.96*** *2.59*	1973	1968	1978	0.9583	*deceleration*
Utah	25.30*** *2.69*	1973	1968	1979	0.9350	*deceleration*
Vermont	57.23*** *10.71*	2005	1984	2027	0.9656	*acceleration*
Virginia	26.52*** *0.69*	1975	1973	1976	0.9655	*deceleration*
Washington	27.46*** *0.82*	1975	1974	1977	0.9769	*deceleration*
West Virginia	28.19*** *1.09*	1976	1974	1978	0.9094	*deceleration*
Wisconsin	24.10*** *3.66*	1972	1965	1979	0.9590	*deceleration*

Wyoming	15.33* *8.13*	1963	1947	1980	0.8124	*deceleration*

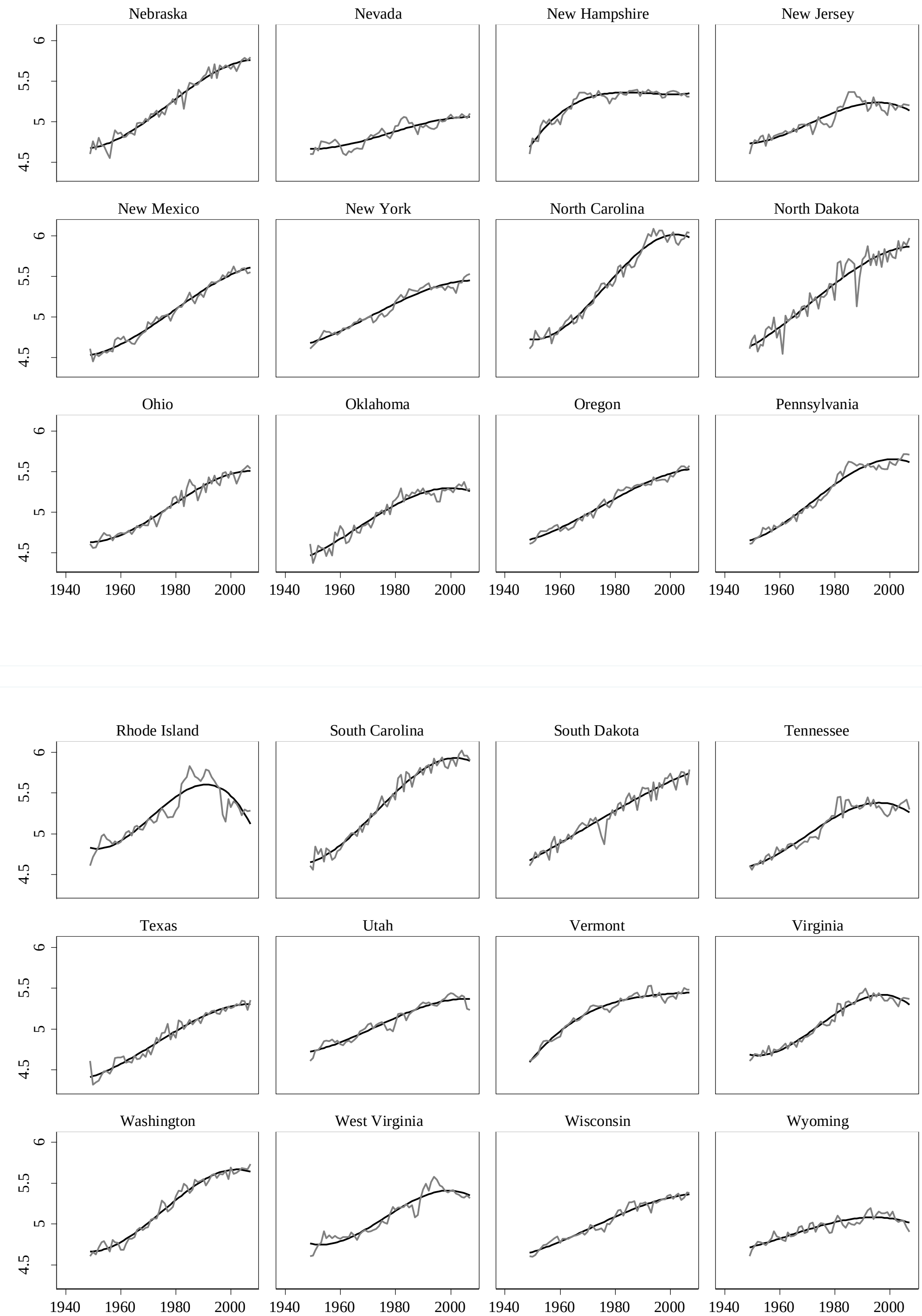
Notes: Standard errors in italics. Thirty states indicated statistically significant deceleration in *MFP*, 6 states indicated statistically significant acceleration in *MFP*. The estimated inflection points for 12 states were not statistically significantly different from zero. The average inflection point for the 30 states with statistically significant deceleration in *MFP* is 1974, and the 95 percent C.I. is [1968, 1981]. The symbol * denotes statistically significantly different from zero at the 10 percent level of significance, ** at 5 percent, and *** at 1 percent. If indicated shape is inconclusive, we cannot identify a statistically significant inflection point within the sample range. Deceleration indicates a statistically significant change from a convex to a concave shape at the point of inflection, and acceleration from a concave to a convex shape.





Appendix Figure D-3

Cubic Trend Regressions of the Natural Logarithm of State-Specific MFP, 1949–2007



Appendix Figure D-3 (continued)

Cubic Trend Regressions of the Natural Logarithm of State-Specific MFP, 1949–2007