



AgEcon SEARCH

RESEARCH IN AGRICULTURAL & APPLIED ECONOMICS

The World's Largest Open Access Agricultural & Applied Economics Digital Library

This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

Help ensure our sustainability.

Give to AgEcon Search

AgEcon Search

<http://ageconsearch.umn.edu>

aesearch@umn.edu

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

No endorsement of AgEcon Search or its fundraising activities by the author(s) of the following work or their employer(s) is intended or implied.

Staff Paper P24-03

May 2024

Staff Paper Series

Unpacking the Agricultural Black Box: The Rise and Fall of American Farm Productivity Growth

by

Philip G. Pardey and Julian M. Alston

Department of
**APPLIED
ECONOMICS**

INSTEPP
INTERNATIONAL
SCIENCE & TECHNOLOGY PRACTICE & POLICY

College of Food, Agricultural
and Natural Resource Sciences

UNIVERSITY OF MINNESOTA

ABSTRACT

Has the golden age of U.S. agricultural productivity growth ended? We analyze the detailed patterns of productivity growth spanning a century of profound changes in American agriculture. We document a substantial slowing of U.S. farm productivity growth, following a late mid-century surge—20 years after the surge and slowdown in U.S. industrial productivity growth. We posit and empirically probe three related explanations for this farm productivity surge-slowdown: the time path of agricultural R&D-driven knowledge stocks; a big wave of technological progress associated with great clusters of inventions; and dynamic aspects of the structural transformation of agriculture, largely completed by 1980.

Philip G. Pardey is Professor, Department of Applied Economics and director of International Science and Technology Practice and Policy (InSTePP) center, University of Minnesota, 248B Ruttan Hall 1994 Buford Avenue, St. Paul, MN 55108. E-mail: ppardey@umn.edu. Julian M. Alston is Professor, Department of Agricultural and Resource Economics, University of California-Davis, One Shields Avenue, Davis, CA 95616. E-mail: jmalston@ucdavis.edu. He is also director of the Robert Mondavi Institute Center for Wine Economics at UC Davis, a member of the Giannini Foundation of Agricultural Economics, and a research fellow at InSTePP.

Both authors contributed equally to this paper. The authors thank Matthew Andersen for his collaboration on prior work, which this paper deepens and extends, and are grateful for the excellent research assistance provided by Connie Chan-Kang, Yuan Chai, Mason Hurley, and Shanchao Wang. Trey Malone, Kevin Novan, Alan Olmstead, Paul Rhode, Scott Swinton, and Felicia Wu provided helpful comments and suggestions, as did other participants at various workshops and conferences, as well as two referees. The work for this project was partly supported by the University of California, the University of Minnesota (MIN-14-161), and the Giannini Foundation of Agricultural Economics.

Pre-publication version of Pardey, P.G. and J.M. Alston. "Unpacking the Agricultural Black Box: The Rise and Fall of American Farm Productivity Growth." *Journal of Economic History* 81(1)(2021): 114-155..

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. Since then, while the U.S. population continued to grow, the farm population declined to an estimated 4.50 million in 2017, just 1.39 percent of the total. Likewise, while the agricultural sector grew, its share of the total economy shrank from 17.4 percent of Gross Domestic Product (GDP) in 1910 to 0.8 percent in 2018. 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 the sector to produce much more marketable output with a little less land and a lot less labor.

Productivity grew rapidly. For example, Schultz (1956, p. 753) wrote: “From 1923 to 1929 only about one-half—or a little more—of the increase in farm output appears to have been achieved by additional inputs. ...[And] from 1940 to 1948 perhaps only a fifth to a fourth of the increase in output can be explained by additional inputs.” 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.”

Similar transformations have taken place around the world and food has become much cheaper in real terms in spite of having a much larger and richer global population to feed (Alston and Pardey 2014, 2019). In the second half of the twentieth century, in particular, global food supply grew faster than demand and real food prices fell significantly, alleviating hunger and poverty for hundreds of millions. Can that pattern be sustained in the twenty-first century, given that global demand for food is projected to grow by 70 percent from 2010 to 2050 (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 prospective path of farm productivity growth.

The recent significant slowing of the long secular decline in real food commodity prices—punctuated by spikes in mid-2008 and again from early 2011 to mid-2013—stimulated a renewed interest in questions about the long-term path of agricultural productivity. Has the “golden age” of U.S. agricultural productivity growth ended? In this article, we analyze the patterns of productivity growth revealed by detailed data encompassing more than a century of profound changes in American agriculture, and we dig into evidence on the underlying determinants of those patterns. Like studies of economy-wide productivity, this analysis entails working with indexes of aggregate inputs, outputs, and productivity, but here we emphasize indexes that are specific to the agricultural sector as a whole. Parts of the analysis go into less aggregative measures.

First, we present robust and compelling evidence of a structural slowing of productivity growth in U.S. agriculture, following a mid-century surge. As posited by Andersen et al. (2018), and reinforced by the new evidence we present here, rather than a constant rate of productivity growth the data are more consistent with a “big wave” surge in productivity growth peaking in the 1960s; a secular pattern in U.S. agricultural productivity similar to what others have found with reference to the economy as a whole, but with different timing (see, e.g., Field 2003; Gordon 2000, 2016). As discussed by Gordon (2000, p. 2) a surge in U.S. non-farm 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.” As we quantify briefly later, these farm and non-farm phenomena are clearly connected and the explanations could involve parallels.

Next, having settled the question of the existence, extent, and timing of a productivity surge and slowdown, we look “inside the black box” of the process and path of technological innovation in American agriculture during the twentieth century.¹ Like Gordon (2000, 2016), in his assessment of the big wave surge in U.S. non-farm productivity growth, we contemplate a corresponding big wave surge in agricultural productivity growth associated with great clusters of agricultural inventions.² We posit that the big wave of technological progress in agriculture through the middle of the century 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), making for a one-time transformation of U.S. agriculture that was largely completed by 1980.

This transformation entailed reductions in the number of farms and increases in both their size and specialization in production (Alston et al. 2010). We consider potential explanations for this productivity surge and slowdown, primarily related to either general public investments in agricultural research and development (R&D) or to specific innovations on farms. Both types of factors appear to have been involved, but with different timing. We present and assess a range of evidence on the time path of technological innovation and the associated changes in the size distribution of U.S. farms. Before doing that, we make the case that farm productivity growth

¹ The title of this paper pays homage to Nathan Rosenberg’s insightful 1982 volume *Inside the Black Box: Technology and Economics* and its 1994 sequel *Exploring the Black Box: Technology, Economics and History*.

² Rasmussen (1962) had a similar notion of technological clusters or sequential technological revolutions driving the arc of history regarding U.S. agriculture, noting that up to the time of his writing: “Two revolutions in American agriculture reflect the impact of technological change on farming during the past 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” (p. 578).

slowed following a surge in the third quarter of the twentieth century. To begin, we discuss the important step of creating the data we use to make that case.

FARM PRODUCTIVITY DATA

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, 2001, 2002, 2006a, 2006b, 2008), Gardner (2002), Dimitri, Effland, and Conklin (2005), and a host of others cited and discussed by Alston et al. (2010).³ Building on this foundation, we use newly created measures in longer-run series to quantify and interpret the evolving path of aggregate U.S. farm inputs, outputs, and productivity over most of the twentieth century and into the early twenty-first 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 productivity measures for the U.S. farm economy, stretching back a century or so.⁴ The InSTePP Production Accounts (version 5) consist of detailed state-specific data on inputs and outputs in U.S. agriculture for the period 1949–2007. Using these data we constructed Fisher

³ 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, Bakker, Crafts, and Woltjer (2019) for 1889–1941, 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. 362–64) for 1869–1960 (see also Rasmussen 1962, table 3), Loomis and Barton (1961, table 12) for 1910–1958, Kendrick (1973, table A-22) for 1929–1969, and Jorgenson, Gollop, and Fraumeni (1987, Appendix B) for 1948–1979. Others who have studied U.S. agricultural productivity growth with an emphasis on nineteenth century developments include Gallman (1972) and Weiss (1993) for the period 1800–1900, and Geib-Gundersen and Zahrt (1996) for 1800–1910.

⁴ The primary source of data used in this paper is the University of Minnesota International Science and Technology Practice and Policy (InSTePP) center Production Accounts, version 5, supplemented by earlier and other data from the United States Department of Agriculture (USDA) and various other sources, the details and treatment of which are briefly reviewed in Online 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/united-states. See Alston et al. (2010) for a detailed, book-length discussion of the spatial and regional patterns in the aggregative measures and their underlying elements.

ideal approximations to Divisia indexes of aggregate quantities of inputs and outputs for the farm sector in each of the 48 contiguous U.S. states, various multistate regions, and the United States as a whole. The highly disaggregated base data permitted the construction of indexes with adjustments for heterogeneity within major categories 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 analyze national, regional, and state-specific trends in multifactor productivity (*MFP*) and in several partial factor productivity (*PFPP*) measures for the period 1949–2007.⁵

Initial work with an earlier version of these data (e.g., Alston et al. 2010) provided evidence of a slowdown in productivity growth since 1990, but also raised some questions that require consideration of the prior history for which such detailed data on inputs, outputs, and productivity are not available. Hence, to place the post-WWII evidence in a longer-run setting, we backcast the InSTePP measures of national agricultural productivity to 1910, using year-on-year changes in the commensurate measures of *MFP* and quantities of land and labor compiled by the USDA.⁶ In a companion study to the present work, Andersen et al. (2018) applied a battery of measures to the resulting long-run *MFP* data, as well as various *PFPP* measures (such as labor productivity, land productivity, and yields per acre for various crops), to test for longer-term changes in productivity growth. 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 in plots of the data

⁵ Many of the environmental consequences of, or natural inputs to, agricultural production are rarely measured. Hence, rather than total factor productivity (*TFP*) we report estimates of *MFP* that include a less-than complete accounting of inputs and outputs, or measures of *PFPP* that express aggregate output, or part of output, relative to a particular input.

⁶ In the present work, we also try an alternative series compiled by using measures from Kendrick (1961, 1973) to backcast the InSTePP series.

and statistically significant after 1980. In this framework, the recent slowdown can be seen 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.

These findings are new and controversial. They conclude and largely settle our longstanding debate with USDA economists—see, for example, Ball, Wang, and Nehring (2010), Wang (2010), Ball, Schimmelpfenning, and Wang (2013), and Wang et al. (2015a, 2015b)—who maintained that U.S. farm productivity growth had not slowed since the 1950s. The present work arose in part from that debate. Here, using different procedures and some different data, we report new results that extend and reinforce the results from Andersen et al. (2018). We place these U.S. farm productivity patterns in the context of the changing structure of agriculture and the corresponding productivity patterns in the broader national economy, setting the scene for our deeper analysis of the main drivers of the farm productivity surge and slowdown.

U.S. FARM PRODUCTIVITY, 1910–2007

Our analysis begins with the most comprehensive but also most aggregative measure: data on national agricultural *MFP* over the longer period, 1910–2007. We describe the patterns in the data and the results from tests for a slowdown, constant growth, or a surge.⁷

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 463 in 2007, at a rate of 1.58 percent per year.⁸ Meanwhile, the index of the aggregate quantity of inputs (X) used in U.S. agriculture grew by

⁷ These data reflect some (mostly very minor) revisions to the series used by Andersen et al. (2018).

⁸ Sub-period specific MFP growth rates can be estimated either as the simple average of the annual MFP growth rates (the log-difference method) or as the slope coefficient from a regression of the MFP index (in natural logarithms) against a time trend. Throughout this paper, unless otherwise stated, all growth rates were calculated as first-differences of the relevant variables in natural logarithms.

just 0.16 percent per year, reflecting some increases in capital and materials inputs that offset the reductions in the use of land (after the late 1970s) and especially labor. Consequently, the measure of *MFP* ($MFP = Q/X$) grew at a rate of 1.42 percent per year (Figure 1). The implication is that U.S. agriculture produced 4.6 times as much aggregate output in 2007 as in 1910 without appreciably increasing the quantity of aggregate input.

[Figure 1 about here]

The long-run path was not always smooth. Year-to-year variations 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.⁹ To test for secular changes in productivity growth usually 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, which shows period-specific growth rates in U.S. aggregate agricultural input, output, and *MFP* as well as measures of land and labor productivity. As shown in Table 1, our measures of *MFP* and *PPF* growth have varied considerably 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, and relatively slow rates of growth since then.¹⁰

[Table 1 about here]

Using essentially the same data, Andersen et al. (2018) estimated logarithmic segmented trend models and polynomial trend models in which the linear logarithmic model, representing

⁹ Online Appendix Figure A-1 illustrates the phenomenon. 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., Andersen 2005; Andersen, Alston, and Pardey 2012b).

¹⁰ During the period 1950–1980, output grew by 2.0 percent per year and *MFP* grew by 2.13 percent per year.

constant exponential growth, is a nested special case. The hypothesis of the linear logarithmic model with a constant growth rate is strongly rejected, and their results (see also Online Appendix B) support the view that U.S. farm productivity growth has slowed in recent decades. But more than that, they also suggest that this slowdown came after a period of unusually rapid productivity growth. Multifactor productivity grew by 1.42 percent per year for 1910–2007, but this long-term average reflected a period of below-average growth at 0.83 percent per year for 1910–1950, above-average growth at 2.12 percent per year for 1950–1990, and again below-average growth at 1.16 percent per year for 1990–2007. State-specific data reinforce these findings.¹¹

Partial factor productivity measures reinforce the evidence from the multifactor productivity measures. Over the period 1910–2007, compared with *MFP*, the *PPF* of land grew more slowly, averaging 1.38 percent per year while the *PPF* of labor grew relatively rapidly, averaging 2.90 percent per year, as the labor intensity of farming was falling substantially (e.g., Alston et al. 2010, figure 3-14). U.S. agricultural land was 3.8 times more productive in 2007 than it was in 1910, and labor was 16.7 times more productive, reflecting the great exodus of farmers and other farm labor—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. Analysis of U.S. national average crop yields for barley, corn, oats, rice soybeans, and wheat back to the mid-nineteenth century indicates that the 1950s, 1960s, 1970s, and 1980s were decades of abnormally high rates of yield growth.¹²

¹¹ Online Appendix Table B-1 includes details on rates of growth in inputs, outputs, and *MFP* for the 48 contiguous states and for the United States over the 58 years spanning 1949–2007. These data reveal an economically and statistically significant slowing of *MFP* growth for any period that includes the years 1990–2007, compared with any prior period; and it is most pronounced for 1990–2007 compared with 1949–1990.

¹² Andersen et al. (2018) also report some evidence on the surge and slowdown in national average crop yields. Online Appendix B provides further details.

AGRICULTURAL MFP IN A NATIONAL MFP CONTEXT

The shifting sands of U.S. agricultural productivity growth were part and parcel of similar shifts in productivity growth in the broader economy. The long-run productivity performance of the U.S. economy has received considerable attention from economists, especially in the context of periodic concerns over slowdowns in economic growth, and the broad consensus is that national MFP growth slowed considerably since the 1960s after a mid-century surge.¹³ Comparatively little attention has been paid to the long-run productivity performance of the agricultural sector as an element of and compared with the economy as a whole. Of specific interest here is the linkage between the surge and slowdown in national MFP growth and the surge and slowdown we have identified in U.S. agricultural MFP growth.

A mechanistic relationship among sectors of the economy is implied by the arithmetic of productivity measures. Specifically, the growth rate of U.S. private business MFP (g_U) is a weighted average of the farm and non-farm MFP growth rates (g_F and g_N , respectively), where the weights are sector shares of the total quantity of inputs.¹⁴ That is:

$$g_U = s_F g_F + (1 - s_F) g_N.$$

Rearranging terms, the growth rate of U.S. private business MFP is equal to the growth rate of farm MFP plus the difference between the farm and non-farm MFP growth rates weighted by the non-farm share of aggregate inputs:

$$g_U = g_F + (1 - s_F) (g_N - g_F).$$

¹³ Notable contributors include Solow (1957), Kendrick (1958, 1961), Kuznets, Miller, and Easterlin (1960), Kuznets (1961, 1966), Jorgenson and Griliches (1967), Nordhaus et al. (1972), Gordon (2000, 2016), and Field (2003, 2011) as well as others referenced by Bakker, Crafts, and Woltjer (2019).

¹⁴ We define $MFP_U = (Q_U/X_U)$ where $Q_U = (Q_F + Q_N)$ and $X_U = (X_F + X_N)$. Hence, $MFP_U = s_F(Q_F/X_F) + (1 - s_F)(Q_N/X_N)$ where $s_F = X_F/(X_F + X_N)$. Treating shares as parameters yields the equations for instantaneous growth rates. A longer-run decomposition should account for changes in shares as well.

These equations illustrate the direct connections between growth in productivity of the farm sector and the broader (farm and non-farm) national economy. Less-direct connections reflect technology spillovers and factor movements. As noted by Kuznets (1961, p. 69) “if agriculture grows it makes a product contribution; if it trades with others it renders a market contribution; if it transfers resources to other sectors, these resources being productive factors, it makes a *factor* contribution” (emphasis in original). During the first half of the twentieth century, relatively rapid growth of the non-farm sector came partly at the expense of the farm sector—especially by attracting labor away from farms (Kendrick and Jones 1951)—with implications both for labor-saving innovations on farms and the growth rate of farm productivity as well as for the farm share of the total economy. In the early 1900s, agriculture accounted for one-third of the national economy: rural-urban migration mattered, and changes in agricultural productivity had meaningful impacts on national productivity measures.¹⁵ By the early 2000s, agriculture’s share of the economy had shrunk to the extent that changes in agriculture had little consequence for economy-wide measures of economic performance.

These connections are reflected in the measures of U.S. farm, non-farm, and aggregate (farm and non-farm) private business MFP growth reported in Table 2. The long-term aggregate and non-farm MFP series were created by splicing indexes from Kendrick (1961, 1973) to create annual indexes for 1899–1947, which, in turn, were used to backcast the corresponding series from BLS (2020) for 1948–2018. We include two measures of MFP growth for the farm sector. The first is the InSTePP-USDA series for 1910–2007, as depicted in Figure 1, which was created by using the historical USDA series to backcast the 1949–2007 InSTePP series from 1949 to

¹⁵ This transformation happened everywhere in the nation, but with different timing at the state and regional level and in different subsectors of the farming industry, thereby contributing to the movement of people and other resources between regions as well as between sectors. The details of these interregional-cum-intersectoral resource movements are a potentially important element of a more complete analysis of the transformation of American agriculture (e.g., Caselli and Coleman 2001).

1910. The second (InSTePP-Kendrick) uses indexes from Kendrick (1961, 1973) instead of the USDA to backcast the 1949–2007 InSTePP series from 1949 to 1890. The InSTePP-USDA series is preferred, but the latter is included because it is a longer series and directly comparable to the other (national and non-farm sector) series based on Kendrick for the years prior to 1948.

[Table 2 about here]

Several points may be drawn from Table 2. In the 1890s, overall private business MFP grew by 1.14 percent per year reflecting a slightly faster rate of growth in the farm sector, 1.27 percent per year, combined with a slower rate in the non-farm sector, 1.08 percent per year. Over the next two decades, however, negligible productivity growth in the farm sector—still a significant share of the economy—held the national aggregate MFP growth rate well below that for the non-farm sector. The long-term (1910–2007) annual average MFP growth rate for the farm sector was 1.42 percent per year, a little less than the aggregate private business sector rate of 1.54 percent per year. However, during the period 1910–1950, in the non-farm sector, MFP grew by 1.93 percent per year on average, more than twice the rate for the farm sector, 0.83 percent per year. For the subsequent period, 1950–2007, these roles were reversed: MFP grew by 1.83 percent per year in the farm sector but just 1.13 percent per year in the non-farm sector.

In Table 2, U.S. non-farm productivity growth accelerated in the 1910s and 1920s, peaking in the 1930s and 1940s, and began to slow appreciably in the 1950s, with a sharp drop in the 1970s. Hence, for the non-farm sector, annual average MFP growth rates exceeded the long-term (1910–2007) average for the decades of the 1910s through the 1940s and for the 1960s, and they have been below the long-term average from the 1970s on. Farm productivity followed a similar pattern, but two decades later, with above-average productivity growth rates for the decades of the 1930s through the 1980s. Combining these two elements, and noting the

further decline of the farm share of the total economy, helps account for the surge in aggregate MFP growth during the decades of the 1920s through the 1960s. Farm productivity growth rates remained high into the 1970s and 1980s, well above their non-farm sector counterparts, but by then the farm share of the economy had shrunk to just a few percent—too little to be of much consequence in sustaining the national productivity growth rate.

These informal impressions are confirmed by fitting a cubic polynomial trend model in logarithms to each of the data series summarized in Table 2 for the period 1910–2007. In each case the model fits the data fairly well (R^2 values of at least 0.98) and we can strongly reject the nested special case of a linear model with a constant exponential growth rate against the alternative of a cubic model that implies a surge and a slowdown.

At the start of the twentieth century, agriculture accounted for one-sixth of U.S. GDP, while employing a much larger share of the national labor force—more than one-third. Over the course of the twentieth century the rest of the economy grew much faster, and agriculture's share of GDP shrank by a factor of 15: from 15 percent in 1900–1910 to 1 percent in 2000–2007. Agriculture's contribution to GDP grew in real terms, although its share was shrinking. The farm sector share of the total labor force fell too, by a greater proportion, a factor of 24: from 34 percent in 1900–1910 to 1.4 percent in 2000–2007. Total private employment of labor increased fourfold, while employment of labor on farms shrank sixfold. Some of the associated movement of labor and resulting convergence in wage rates across sectors (e.g., Gardner 2002) entailed significant interregional movement of people (e.g., Caselli and Coleman 2001).

In what follows, we develop and discuss a range of evidence related to potential drivers of the twentieth century surge and slowdown in U.S. farm productivity. In the next three sections, respectively, we compare the timing of the surge and slowdown in productivity with the time

path of research-related knowledge stocks, the time path of uptake for different classes of on-farm innovation, and the timing of the structural transformation of the national farm economy. Finally, we briefly consider the potential effects of exogenous changes in the physical and regulatory environment that might have constrained agricultural productivity directly or done so indirectly by restricting the use of some technologies.

AGRICULTURAL R&D AND KNOWLEDGE STOCKS

Over the course of the twentieth century, following the closing of the physical frontier, American agricultural development and farm productivity growth were increasingly driven by organized agricultural R&D—especially in the public sector. A crucial development in the history of American agriculture was the establishment of institutions that fostered the improvement of agriculture through the development and adoption of new farming methods, and the improvement of farmers.¹⁶ In 1889, shortly after the Hatch Act was passed, federal and state appropriations totaled \$0.98 million; but by 2014, the total public (i.e., USDA and state agricultural experiment stations) agricultural R&D enterprise had grown to \$3.9 billion, an annual rate of growth of 6.4 percent (3.3 percent in inflation-adjusted terms). The U.S. private sector has spent a similar amount in recent years growing from \$54 million in 1950 (compared with \$56 million in public research that year) to \$9.4 billion in 2014 (Lee, Pardey, and Miller 2020). 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

¹⁶ Huffman and Evenson (1993, 2006) and Alston et al. (2010) document the legislative and other institutional changes that enabled the establishment of the USDA and the Land Grant Colleges with substantial support from state and federal governments. See also Alston and Pardey (2006).

growth (Pardey, Alston, and Chan-Kang 2013, figure 12). However, linking R&D and productivity is not straightforward or simple (e.g., Griliches 1988).

In conventional and widely applied models, current agricultural productivity depends on an agricultural R&D knowledge stock created from past investments in agricultural R&D over many years. As described and documented by Alston et al. (2010, 2011), Alston, Craig, and Pardey (1998), and others, it takes a long time for agricultural R&D to influence production (the lags in the creation of new knowledge and adoption of technology are long) and then it can affect production for a long time. However, the effective stock of agricultural knowledge becomes obsolete as new technologies embodying new knowledge are developed, or depreciates because of changes in the economic and environmental circumstances in which that knowledge or technology is used attributable to coevolving pests and diseases and changes in climate or relative prices.

Reflecting these ideas, Alston et al. (2010, 2011) estimated a model of U.S. state and national agricultural *MFP* as a function of a public agricultural R&D knowledge stock based on up to 50 years of past investments in public agricultural research and extension, with lag weights defined by a gamma lag distribution. The main competing model, proposed by Huffman and Evenson (1993, 2006), uses a shorter overall lag length (35 years) with a trapezoidal lag distribution shape. Alston et al. (2010, 2011) compared the trapezoidal lag model against their gamma lag distribution model and concluded that they were similar but the gamma lag distribution model was statistically preferred. In either case, it is proposed that current MFP_t depends on the current knowledge stock, K_t , which is a weighted sum of investments in R&D, R_{t-j} over a finite number of past years ($L_{max} = 50$ in the gamma lag model or 35 in the trapezoidal

model), where the lag weights, w_j are defined by the lag distribution model, and typically are scaled to sum to 1:¹⁷

$$MFP_t = f(K_t), \text{ where } K_t = \sum_{j=0}^{L_{max}} w_j R_{t-j}, \text{ and } \sum_{j=0}^{L_{max}} w_j = 1.$$

These models have in common that it is *growth* in the knowledge stock that begets growth in productivity. Given the finite overall lag between R&D and its contributions to the knowledge stock, if agricultural R&D spending is held constant over many years, eventually the knowledge stock also will be constant, irrespective of the precise structure of the lag weights. Hence, growth in productivity requires growth in R&D investments. It follows that, for changes in agricultural R&D spending to have caused the surge and slowdown in agricultural productivity growth, the path of R&D spending must have caused a surge and slowdown in the growth of the agricultural knowledge stock, with appropriate allowance for lengthy time lags.

To investigate this possibility, we computed estimates of public agricultural R&D knowledge stocks and examined their growth rates over time.¹⁸ Using data on U.S. public agricultural research investments for the period 1910–2007, deflated by InSTePP’s price deflator for such investments, we constructed the annual series of the two knowledge stocks: for 1939–2007 using the 50-year gamma lag distribution weights from Alston et al. (2010, 2011); and for 1924–2007 using the 35-year trapezoidal lag distribution weights from Huffman and

¹⁷ The typical specification assumes a linear relationship between $\ln(MFP_t)$ and $\ln(K_t)$. This implies that the growth in productivity is proportional to the growth in the knowledge stock, with a constant elasticity—typically less than one in published estimates.

¹⁸ These lag distribution models were estimated using the same or similar productivity data and, in effect, econometrically, they attribute as much as possible of the historical path of agricultural productivity to the path of the agricultural R&D knowledge stock. Therefore, in using these estimated weights as described, we are maximizing the odds of finding evidence that both the surge and slowdown in productivity are a consequence of agricultural R&D investments.

Evenson (1993, 2006). In the last two columns of Table 1 we report annual average growth rates in these two knowledge stock measures, by decade and by tercile. Unlike the corresponding growth rates of the indexes of output and productivity, these knowledge stocks do not exhibit a substantial surge in the period 1940–1980, but they do exhibit a secular slowdown. In fact, over the period 1910–2007, sub-period growth rates of the two knowledge stock measures decline monotonically by tercile and by decade within each tercile; the same is largely true of the real R&D spending measure on which those stocks is based. Such a progressive slowing of the growth of the knowledge stock would imply a steady, progressive slowing of the growth of agricultural productivity since the 1920s or 1930s. However, it cannot account for the mid-century surge.

Along with the consequences of a decades-prior slowdown in agricultural research investments, a slowdown in agricultural productivity growth might also reflect a change in the effectiveness of those investments. As documented by Pardey, Alston, and Chan-Kang (2013) the share of public agricultural R&D resources allocated to productivity-enhancing purposes shrank from about 69 percent in the early 1980s to about 56 percent by 2007—equivalent to a 20 percent reduction in the effective quantity of productivity-oriented R&D spending for a given total expenditure. This is a relevant consideration, but most of this shift has been relatively recent and too late to have contributed much to a productivity slowdown beginning a decade or two earlier, once we allow for R&D lags.

A second possibility is decreasing returns to agricultural R&D. It may be increasingly difficult to generate a further proportional gain in productivity on top of past productivity gains either (1) because we are getting closer to the biological potential of plants and animals (e.g., Fischer, Byerlee, and Edmeades 2014), (2) because we have to spend a larger share of the

research resources maintaining those past gains (e.g., Ruttan 1982), or (3) because the easy problems have already been solved. Bloom et al. (2020) attribute the post-WWII slowdown in U.S. agricultural Total Factor Productivity (TFP) growth (using USDA data) to a decline in research productivity. However, these authors measure research productivity as the annual rate of TFP growth per researcher, contemporaneously. They do not give any consideration to the stock-flow relationships whereby current research effort gives rise to increments to a stock of knowledge and enhanced productivity over an extended future period; nor any allowance for maintenance research requirements. Hence, the Bloom et al. (2020) model of knowledge production and the associated measure of research productivity are both misconstrued, leaving their findings open to challenge, especially in the context of agricultural R&D (see Alston and Pardey 2021 for details).

Moreover, studies of the rate of return to research investments provide direct evidence that contradicts the pessimistic view. Rao, Hurley, and Pardey (2019) report the results from a meta-analysis encompassing 492 studies published since 1958 that collectively reported 3,426 estimates of rates of return to agricultural R&D. They conclude that “the contemporary returns to agricultural R&D investments appear as high as ever” (Rao, Hurley, and Pardey 2019, p. 37). Improvements in the technology of science and in the human capital of scientific researchers have made research more productive, and it seems these gains in research productivity have been sufficient to offset any decline caused by other factors.

ADOPTION OF FARMING TECHNOLOGIES

More direct insight into the productivity consequences of innovation—whether facilitated by organized agricultural R&D or not—is provided by studying the time path of the uptake of major technologies on farms. One plausible hypothesis is that the progressive adoption of various

mechanical innovations, improved varieties, synthetic fertilizers, and other chemicals—each in a decades-long process—could have contributed to a sustained burst of faster-than-normal productivity growth throughout the third quarter of that century. On this view—like Gordon’s (2000) assessment of the big wave surge in U.S. *MFP*—we could account for the big wave surge in the rate of agricultural output and *MFP* growth in terms of the timing of waves of adoption by farmers of mechanical, biological, chemical, and, of late, information (or digital) technologies.

Dynamics of Agricultural Innovation

The long-term path can be envisioned as entailing a small number of large, discrete, but interrelated, meta-technological events—in the language of Hayami and Ruttan (1971). While each had its own time path and peaked at a different time, the different categories of innovation 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.

This rolling series of discrete meta-technological events gave rise to a comparatively smooth pattern of productivity growth as the technologies were progressively adopted and as farming systems were (re-)optimized to incorporate and accommodate them. In particular, for labor-saving mechanical innovations that entailed substantial economies of size, realizing the full cost-savings and productivity benefits required consolidating farms into larger units or reorganizing other structural elements (such as commodity mix, building infrastructure, farm management operations); adjustment processes that took time—perhaps decades—to work through. Thus, a peak in the adoption of some innovations might have been observed some years before the consequential increases in productivity were to be fully realized

Though somewhat smoothed, the consequent rate of agricultural productivity growth was not constant. The various interrelated changes coalesced into a surge of productivity growth

during the 1950s, 1960s, and 1970s as the cumulative adoption rates peaked. Subsequently, the associated rate of productivity growth slowed to a rate that could be sustained by more normal incremental rates of innovation. Importantly, some of this innovation might not have any apparent impact on observed productivity.

In agriculture, which relies on biological production processes, the relevant counterfactual productivity scenario is usually one in which environmental and economic circumstances may be changing such that, absent investment in R&D or innovation, productivity will eventually decline; maintenance research is necessary to sustain yields in the face of coevolving pests and diseases and climate change—the “Red Queen” effect in evolutionary biology (e.g., Olmstead and Rhode 2002). In this case, stagnant productivity can, in fact, represent a (significant perhaps) increase over the relevant counterfactual scenario of declining productivity. Similarly, innovations to substitute pest-resistant varieties for chemical pesticides might not show in measured farm productivity.

Major Farming Innovations

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 twentieth century (Figure 2). 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 (Figure 2, Panel A). Such innovations replaced horses and other draught animals with tractors (Olmstead and Rhode 2001)—a process that took off in the early 1900s and was not complete until the 1970s.

Biological innovations, in particular, improved crop varieties (Figure 2, Panel B) that were responsive to chemical fertilizers, took center stage a little later—although they were

clearly part of the story all along (Olmstead and Rhode 2008). The archetype example is hybrid corn which transformed agriculture in the American midwest. As a result of focused research over several decades (Alston et al. 2010, pp. 264–5) hybrid corn was introduced to farms in Iowa in the early 1930s, although it took until the 1960s for vastly improved hybrids to achieve 100 percent adoption across the United States (Griliches 1957; Dixon 1980; Hallauer and Miranda Filho 1981). These innovations laid the foundation for genetically modified (GM) hybrid corn varieties to be developed and adopted, beginning in 1996 (Fernandez-Cornejo et al. 2014).

[Figure 2 about here]

Similar, although typically not quite as dramatic, genetic innovations were common to many other 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 twentieth century (Olmstead and Rhode 2008). Changes in intellectual property rights applied to life forms encouraged private investments that drove much of the downstream genetic gains, especially more recently (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 WWII (Smith 1979; Alston and Pardey 2006). The early twentieth century invention of the Haber-Bosch process for the economical manufacturing of synthetic nitrogen fertilizer, in particular, was profoundly important for enhanced crop yields, especially when combined with complementary genetics and crop management practices. The U.S. on-farm adoption process for these fertilizers and associated varieties was mostly decades later. 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 systems and related precision production systems, satellites, remote- and ground-sensing, and the like. Adoption processes for these digital farming technologies are still in their early and slow stages, apart from relatively simple technologies, that involve neither large investments in specialized equipment or human capital nor major changes in farming systems and practices, such as global positioning system (GPS)-based remote-sensing and guidance systems (e.g., Alston and Pardey 2020).

As well as these on-farm changes, farmers benefited from 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 those related to rural electrification, telephone service, and irrigation projects (e.g., Beall 1940; Fischer 1987).¹⁹ These infrastructure improvements and other off-farm changes complemented on-farm innovations (e.g., Figure 2, Panel C).

A Mid-Century Surge in Technology Adoption?

Table 3 reports the growth in adoption rates (share of farmers or farm area adopting) for major examples of each of the main categories of innovation. Growth rates are reported for terciles of the century, 1920–2018. If the mid-century surge in productivity growth was

¹⁹ Johnson (1949, p. 19) maps the cross-state differences in the rate of uptake of rural electrification.

associated with a contemporaneous surge in adoption of innovations, we should see a surge in adoption in the middle tercile (1940–1980), compared with the first (1920–1940) and third (1980–2018) terciles. The patterns in Table 3 are consistent with Figure 2. Adoption of several major mechanical innovations and infrastructure improvements (tractors, trucks, electricity, and improved roads) was fastest in the first tercile, but for some complementary innovations (balers, combines, and conditioners) adoption accelerated in the second tercile. Likewise, for some major biological innovations (hybrid corn and use of fertilizer) adoption grew most rapidly in the first tercile. However, for other crop varietal technologies that came later, adoption accelerated in the second tercile (semi-dwarf wheat and rice) or even later (GM corn and soybeans).

[Table 3 about here]

Taken together, the data in Table 3 and as represented in Figure 2, are consistent with our story about a slowdown in the rate of adoption of innovations contributing to a slowdown in productivity, but they do not clearly concord with a surge in the middle tercile (1940–1980). However, for three reasons, the measured rate of adoption might not accurately reflect the ultimate consequences of these innovations. First, the share of farmers adopting or acres using an innovation might not well match the share of output produced using the technology. Second, economies of size and specialization associated with some of these innovations—especially mechanical innovations—meant that fully realizing the productivity potential required changes in the structure of agriculture and complementary off-farm assets and institutions. Third, it took time to make those structural changes because of the sticky nature of rural resources and the associated costs of change.

The upshot is that the productivity-enhancing consequences of innovation might lag considerably behind the evidence on initial adoption, which itself lags behind research

investment. The overall lag between investments in research and its ultimate economic impacts has several elements. First, comes the lag between investing in research and developing technology. Next, comes the lag between the release and initial adoption of technology and its ultimate impact on productivity. This lag is extended when we allow the role of work to adapt technology to better match particular contexts (e.g., as illustrated by the slow spatial diffusion of hybrid corn, particularly as its use extended beyond the corn belt). Last, comes the lag associated with the adjustment process. During this in-between time, in the middle of the twentieth century, while some farmers had adopted innovations and flourished, many others lagged and fell behind. Those who were slow to adjust and exit agriculture contributed to what became known as *the farm problem*.²⁰

STRUCTURAL TRANSFORMATION

The farm problem—excess capacity in agriculture, especially too many farmers—was eventually resolved through consolidation of farms into more economic-sized units, more specialized in particular outputs. This consolidation was enabled and promoted by the adoption of innovative technologies. Especially important were labor-saving machines that enabled considerable economies of size with respect to land and required much less labor to efficiently operate a larger farm area. It took time for the farm sector to absorb these changes and capitalize on the associated efficiencies. Hence, during the decades following the first introduction of those innovations, American agriculture faced a serious adjustment problem—how to move resources out from agriculture, especially labor, that were earning very low returns in farm production

²⁰ Sumner, Alston, and Glauber (2010) provide a concise review and cite several notable economists who have written on the issue, including Houthakker (1967) who wrote “The Farm Problem, it will be argued here, is primarily a problem of economic growth. To put it briefly: . . . economic growth requires a steady shift of labor and other resources from agriculture to other sectors. Since there is resistance to this shift, there are usually too many people in farming and as a result per capita farm income is depressed.” See also Gardner (1992, 2002).

where they were stuck.²¹ In this section we document the linkage between the structural adjustment process, and the surge and slowdown in farm productivity growth.

Labor-Saving Technologies

Much of the measured productivity gains, especially in the earlier period, can be attributed to mechanization. These were often labor-saving innovations that facilitated the consolidation of farms into many fewer and larger units. Total land in agriculture continued to increase until the early 1950s, but has trended down slowly since then. Meanwhile, average land per farm continued to increase as the number of farms shrank from its peak (6.8 million farms in 1935). In 1910, labor used in agriculture began to decline from its peak plateau (around 10.4 million labor years 1900–1910). The adoption of horses and mules, both to substitute for and complement human labor, transformed agriculture in the second half of the nineteenth century (Olmstead and Rhode 2001). At the turn of the century, the process of replacing animal power with machines had barely begun; in 1910, the United States had a total of 6.4 million farmers, farming 881 million acres using a total of 24 million horses and mules and just 1,000 tractors (Figure 3). Various mechanical innovations had been adopted in the latter nineteenth century and early twentieth century that were powered by horses, but the internal combustion engine really made its presence felt in the decades to come. The tractor, in particular, saved millions of acres of land and the work of many men and women.

[Figure 3 about here]

As shown in Figure 4 the stock of workhorses and mules on U.S. farms peaked in 1917 at 27 million animals (or 5.5 animals per 100 acres of improved land) dropping steadily to just 3.6

²¹ U.S. farm income support policies (e.g., Olmstead and Sumner 2006; Sumner, Alston, and Glauber 2010), introduced to address the farm problem, encouraged and enabled some farmers to stay in farming longer than they would have done otherwise, and in this way slowed and otherwise influenced the adjustment process.

million animals (0.8 per 100 acres of cropland) by 1957, and eventually to a low of 1.4 million in 1974.²² Numbers of equines have risen subsequently to more than 4 million, but these are mostly not workhorses and mules; more for recreational use.²³ This post-1917 pattern of change in the use of traction animals on farms is the mirror image of tractor use in U.S. agriculture. From just 50,000 tractors in 1917, the total grew to 4.6 million tractors in 1957. After a peak at 4.8 million, beginning some 10 years later the total number of tractors has fluctuated around a slight downward trend. This declining trend reflects several factors, including a decline in the total number of farms, an increase in the average size of farm tractors (thus enabling tractors to plow more land per season), and an increase in the provision of third-party contract tractor services.

[Figure 4 about here]

Machines were important in saving land from having to be used to produce feed for horses and mules. Olmstead and Rhode (2001, p. 665) report that “In 1939, 65 million acres of cropland were used to feed horses and mules, with all but 2 million acres devoted to farm stock. By 1960, only 5 million acres were needed.”²⁴ However, we suspect a larger driver of farm mechanization over the longer term was its labor-saving implications, motivated by high off-farm labor wage rates driven by innovation in the manufacturing industry and the associated broader economic growth (Kislev and Peterson 1982, 1996; Gardner 2002; Gordon 2016;

²² The 1917 Census reported no data on cropland. Instead, data were reported in terms of improved land, which includes all land regularly tilled or mowed, land in pasture which has been cleared or tilled, land lying fallow, land in gardens, orchards, vineyards, and nurseries, and land occupied by farm buildings. The first year of cropland data is 1924, where the intensity of traction animals is 5.95 animals per 100 acres of cropland.

²³ Citing USDA sources, Kilby (2007) reports that of surveyed farm operations that had horses in 1998, only 15.2 percent reported using them for farm or ranch work while 66 percent of the operations used them for recreational purposes.

²⁴ Johnson (1949, p. 45) noted that “The decrease in horses and mules of 15,000,000 animal units from 1920 to 1946 released land that could grow feed for an equivalent number of productive livestock (animals and their products that are produced for human use). The saving in grain alone amounted to about 16,000,000 tons in 1946—enough to feed 32,000,000 hogs to market weight.” On the other hand, part of the subsequent increase in use of synthetic fertilizers was to replace foregone horse manure.

MacDonald 2020).²⁵ A particular feature of this process was to move people and labor off farms, either entirely or through a substantial increase in part-time farming, and thereby to reduce the relative importance of labor as a farming input—a one-time transformation of agriculture that was largely completed by 1980.

Farm Numbers and Land per Farm

Taking our farm problem perspective, we might expect to see an acceleration of farm productivity growth associated with an acceleration in the rate of farmer exit, enabling the consolidation of farms into larger and more specialized operations (see also MacDonald, Hoppe, and Newton 2018). To check this idea, informally, we estimated cubic logarithmic trend models of the total number of farmers, using data for individual states, USDA regions, and the nation as a whole for the years 1910–2010. These models generally fit well, and they are consistent with an acceleration and slowdown in the rate of decline of farm numbers (i.e., the coefficients on the linear, quadratic, and cubic terms are all highly statistically significant and with the expected signs). Using these results, we solved for the inflection point, as an indication of the year of the peak rate of farm exit, as predicted by the model, and a 95 percent confidence interval around that year.

Table 4 summarizes estimates using state-level data for various spatial aggregates. The disaggregated statistics provide a regionally more nuanced interpretation of the aggregate picture in Figure 3. In each model referring to a particular spatial aggregate, the peak exit year is estimated with high precision (i.e., the 95 percent confidence interval is very narrow, often plus

²⁵ Cooper, Barton, and Brodell (1947, pp. 61–62) estimated that in 1910–1914 around 16 percent of all the “man-hours” used on farms was devoted to the feeding and care of horses and mules, but by 1945 the number of hours devoted to maintaining traction livestock fell by 62 percent so that the share of farm labor devoted to horses and mules was just 8 percent of the farm labor total. Offsetting this decline in labor use was the increase in labor required to service and maintain tractors and trucks, but this constituted less than 2 percent of overall farm labor use in 1945 according to Cooper, Barton, and Brodell (1947).

or minus one year) and, across aggregates, the estimates fall within a remarkably narrow range. Pooling the data across all 48 contiguous states, the year of peak exodus was 1959 (between 1958 and 1961 with 95 percent confidence). The spatial pattern is plausible. Across the nine USDA divisions, the year of peak exodus rate ranged from 1956 (New England) to 1964 (West North Central). In every region, the pattern is consistent with a surge in farm exodus in the 1950s and 1960s that conforms with the observed surge in *MFP*. Average acres per farm peaked a little later because—as shown for the nation as a whole in Figure 4—total land in farms continued to grow for a decade or two after the number of farms had begun to fall.²⁶

[Table 4 about here]

These national and regional averages and aggregates encompass highly diverse farm sizes and types, both changing over time.²⁷ Over time, farms became increasingly specialized in a narrower range of market goods. Many productive activities progressively shifted off farms—to be undertaken by specialized (pre-farm) agribusiness firms that nowadays produce farm machinery, seed, chemicals, energy, and other inputs (including contract services) that were once largely (and in some instances entirely) produced on-farm. Likewise farm households once made many food and fiber products that are now produced entirely off-farm by agribusiness firms in other (post-farm) sectors of the economy. These shifts have implications for where the lines are drawn in distinguishing between farms and other firms and thus between agriculture and the rest

²⁶ Issues surrounding the statistical definition of what is a farm are linked with issues about how to measure farm size since many of the USDA definitions, which themselves have changed from time to time, are based on a farm size criterion involving area or value-of-sales attributes.

²⁷ The USDA Economic Research Service has developed a typology for farms according to farm size measured using gross cash farm income (GCFI). Hoppe and MacDonald (2013) reported that in 2010 “small family farms” (GCFI < \$350,000) made up 91 percent (including residential/lifestyle, 43.5 percent and retirement farms, 16.6 percent) of all U.S. farms, and they operated on 55 percent of all U.S. farmland but produced only 21 percent of the total value of production.

of the economy. However, the available data on these shifts are limited, and we work with conventional measures based on statistical definitions of farms.²⁸

In 1920, the United States had 735 million acres on 6.4 million farms, at an average of 115.2 acres per farm. Few of those farms had more than 1,000 acres; 58.6 percent had less than 100 acres and used 17.0 percent of the total land in farms, while the other 41.4 percent that had more than 100 acres used 83 percent of the land. By 2012, the total number of farms had fallen by more than two-thirds compared with 1920. Now 8.2 percent of 2.1 million farms had more than 1,000 acres; 54.6 percent had less than 100 acres but these farms used only 4.4 percent of the land, while the other 45.4 percent with more than 100 acres used 95.6 percent of the land. Both tails of the distribution got fatter. Notably, more than 10 percent of today's farms have less than 10 acres, still, which is surprising given the general push toward larger and more specialized farms. But many of today's small farms are so-called hobby farms in the urban fringe, and many others at more commercial scale are part-time occupations for people for whom living on a farm is a life-style choice more than a way of making a living.

[Table 5 about here]

Because the distribution of land in farms is highly skewed, the simple average may be a misleading indicator of the rate of consolidation of farms. MacDonald (2020) demonstrates that the relatively constant number of acres per farm since 1980 reflects increases in both the numbers of very small farms and in the numbers of large farms. He suggests using changes in the midpoint rather than the mean of the distribution of farm size as a more informative indicator of

²⁸ The surveyed definition of a farm changed over time, but since 1974 consisted of "Any place from which \$1,000 or more of agricultural products were produced and sold, or normally would have been sold, during the census year." See Online Appendix Table C-1 for details.

the rate of farm consolidation.²⁹ Using this measure, he demonstrates that commodity-specific rates of farm consolidation were generally sustained over the three decades, 1987–2017, and were similar across producers of 55 crops and seven livestock products. While the simple average has barely budged, the midpoint of the distribution of farm size—whether measured in land per farm for cropping farms or numbers of animals for livestock producers—has grown significantly. MacDonald (2020) reports annual average growth rates for four commodity classes ranging from 3.01 to 3.59 percent. Thus, while data on the mean might be taken as indicating that structure of agriculture had stagnated since the 1980s, steady structural change and consolidation has continued, especially among the larger commercial farms that account for the bulk of farm production. This period 1987–2017 is some decades after the maximum rate of farm exit and consolidation revealed by the changes in numbers of farms and land per farm in Table 4.

The Farm Labor Force

Central to these changes in the structure of agriculture have been changes in the structure of the farm labor force, reflecting both labor push and pull phenomena (e.g., Kislev and Peterson 1996; MacDonald 2020). Growth in the non-farm demand for labor, driving up the opportunity cost of farmers' time as well as the cost of hired farm labor, pulled people out of farming, while technological changes on farms that permitted more to be produced with much less labor and more land per farm pushed people off the land. Farmers have responded to these incentives and opportunities by consolidating farms and substituting other inputs for labor, in part by

²⁹ The midpoint is the median of the distribution of *acres* (or *head* of livestock) by farm size (not the distribution of *farms* by farm size). Half of all acres (or head) are on farms that are larger than the midpoint.

developing and adopting labor-saving innovations that favored higher land-labor ratios and larger optimal farm sizes.

Figure 5 captures the main elements of these changes. In Panel A, total labor use in agriculture fell by two-thirds, from 20.5 billion hours in 1949 to 6.3 billion hours in 2007. Within this total, after accounting for the shift to part-time farming, operator labor fell by more than three-quarters, from 13.0 billion hours in 1949 to 3.5 billion hours in 2007, while the hired labor share increased from 19.8 to 31.7 percent. As farmers substituted other inputs—especially material inputs—for more expensive labor, the cost share of labor fell from more than 42 percent in 1949 to less than 30 percent in 2007 (Figure 5, Panel B). Labor still represented a large share of costs, however, since the reduction in labor use only partially offset the cost increases caused by the higher wage rates. One adjustment response of farmers has been to seek off-farm employment for at least one member of the household, which has been facilitated by the growth of the rural non-farm economy. Figure 5, Panel C illustrates. Between 1930 and 2012, the share of full-time farm operators fell from 70 to 40 percent and they increased their average number of days worked off-farm from 86.5 to 144.5.

[Figure 5 about here]

Compared with 1910, commercial farms are now much larger (in 2012, 70 percent of land was on farms exceeding 1,000 acres, up from 23 percent in 1920), and much less labor-intensive. Much of the agricultural transition took place in the middle of the century—between 1930 and 1970; it was associated with an acceleration in farm productivity growth, which has since returned to what seems to be a more normal, long-term rate commensurate with long-term productivity growth in the economy more generally.

PHYSICAL AND REGULATORY ENVIRONMENT

Some other environmental factors might also have contributed to the surge and slowdown of farm productivity growth, reinforcing the consequences of the factors discussed to this point. Specifically, climate change, invasive pests and diseases, evolving pesticide resistance, and declining natural resource stocks could all have contributed to a more challenging physical and economic environment for agricultural production, adding to the demands for maintenance research just to keep yields from falling and costs from rising. Among these possibilities, climate change is an unlikely explanation of the observed productivity patterns prior to 2007 since it has still barely begun to have tangible consequences for agricultural productivity in the United States. But other aspects of the economic environment for producers—including regulations governing production practices on farms—have become more difficult in ways that may help account for the observed phenomenon.

We do not have good data on the size of the associated effects, but the following claims are not controversial: (1) Some of the measured productivity growth reflected unmeasured consumption of stocks of various (often poorly priced) natural resources such that the surge was potentially in part a measurement error. (2) Following the dustbowl, natural resource conservation policies were introduced that internalized some environmental externalities. (3) Over time, environmental policies have been introduced that regulated technologies (especially pesticides and GMOs) and it has become progressively harder to introduce novel technologies that might entail negative externalities (e.g., hazards to human health or the environment). Moreover, state and federal governments are increasingly deregistering individual pesticides and regulating the use of other agricultural chemicals and veterinary medicines. (4) Other technological regulations imposed by government and food chain intermediaries have increasingly restricted production practices related to farm labor, food safety, animal welfare, and

the environment (e.g., Saitone, Sexton, and Sumner 2015). (5) Farmers increasingly have had to pay for varietal technologies they once received for free from public research agencies such that a greater share of the benefits from agricultural R&D are now captured by upstream agribusiness and life sciences firms.

Pesticides illustrate the main ideas here. The surge of farm productivity growth immediately following WWII was associated with a surge in the use of agricultural chemicals, especially synthetic fertilizers and pesticides (Alston and Pardey 2020). Conventional measures of productivity growth do not include adjustments for the negative externalities associated with these agricultural chemicals, and in this sense our measures overstate the true gains in productivity. The publication of Rachel Carson's *Silent Spring* in 1962 marks the beginning of the era of public awareness of the environmental consequences of agricultural pesticide use, and environmental regulation of agricultural production. Progressively over the decades since, a great many pesticides have been banned. A direct consequence of these regulations has been to reduce agricultural productivity—both measured and actual. Similar thinking applies to the development of intensive livestock production systems and the progressive, increasingly stringent regulation of the use of antibiotics, hormones, and other veterinary medicines, and regulation of other production practices. These and other regulations seek to protect human health, food safety, animal welfare, endangered species, and other environmental resources; consequences that do not show up in conventional productivity measures.

Together these aspects of the changing natural and regulatory environment confronting farmers might have contributed both to the measured surge (reflecting unmeasured externalities or unmeasured consumption of poorly priced natural resource stocks that contributed to overestimated productivity growth) and to the subsequent slowdown (reflecting the

consequences of regulations that internalized some of those costs). It is not easy even to guess at the empirical importance of these aspects, let alone measure them, but they are surely part of the story.

CONCLUSION

At issue in many minds is whether anything like the rapid growth in measured farm productivity during the third quarter of the twentieth century could be recaptured in the coming decades. Was this productivity surge (and the subsequent slowdown) a one-time phenomenon, or something that can be repeated with new waves of innovation in genetics, informatics, and robotics, which can save on costs of labor (which remain stubbornly large as a share of total costs) or other increasingly scarce inputs—especially land and water? More concisely: What might have accounted for the surge and slowdown in American farm productivity?

To address these questions, we examined three alternative (albeit related and not entirely mutually exclusive) explanations for the surge-slowdown phenomenon. First, conscious of the large literature linking investments in R&D to growth in agricultural productivity, we compared the time paths of growth in R&D knowledge stocks and growth in agricultural productivity. The two predominant models both imply progressively slowing growth in knowledge stocks that would, in turn, imply a progressively slowing rate of productivity growth. At face value, these R&D-knowledge stock trajectories cannot account for the third-quarter productivity surge in the twentieth century. On the other hand, we cannot rule out the possibility that the results from R&D spending became embodied in technologies adopted by farmers in ways and with timing that the econometric models did not fully capture. Of necessity, these models impose strong restrictions on the R&D lag structure and the structural parameters linking R&D knowledge

stocks and productivity; in particular, these aspects of the model structure are held constant and applied to data across many decades when much about R&D and agriculture changed.

A second, alternative but related, explanation is that a big wave of technological progress through the middle of the century contributed to a sustained burst of faster-than-normal productivity growth throughout the third quarter of that century. The innovations resulted from some combination of organized R&D and less-organized tinkering and inventing by farmers or other inventors, but we cannot confidently say much more than that. The normally difficult attribution problem in linking these factors to productivity patterns is made worse here by the role of the farm problem, which was both caused by and influenced the timing of the adoption of innovations and their eventual consequences for productivity, production, and prices for farm products and inputs.

Central to the story of these changes was the shift of labor off farms. Labor was pulled from agriculture by growth in the non-farm economy; it was also pushed by the adoption of labor-saving innovations on farms, induced by the increasing importance of labor as a farming cost and the value of innovation as a cost saver. Of course, not all farming innovation was labor-saving; but much was, and many innovations entailed economies of size that implied an increase in the efficient size of farms and a reduction in the number of farms. Our third potential explanation for the surge and slowdown in farm productivity centers on the dynamics of the structural transformation of the U.S. farm economy and the role of asset fixity (Johnson 1972) in slowing adjustment. This explanation is supported by our evidence that the agricultural transition gathered pace at the same time as the surge in productivity growth, after which both phenomena returned to more normal, long-term rates of change.

This structural transformation involved a one-time shift, to reduce the number of farmers and the total farm labor force by two-thirds or more. But it did not eliminate the cost of labor and does not mean we cannot have additional gains from labor (cost) saving innovation; nor does it mean we could not have another surge associated with, say, digital technology or genetics. However, it is hard to see scope for a second transformation of the American agriculture of comparable scale any time soon. We speculate that a surge in farm productivity, such as we have documented here for the United States, might be inherent in the economic transition from an agrarian to an industrial emphasis. Since that transition is necessarily a one-time phenomenon, in that sense, so too is the associated productivity surge and slowdown.

REFERENCES

- Alston, Julian M., Matthew A. Andersen, Jennifer S. James, and Philip G. Pardey. *Persistence Pays: U.S. Agricultural Productivity Growth and the Benefits from Public R&D Spending*. New York, NY: Springer, 2010.
- . “The Economic Returns to U.S. Public Agricultural Research.” *American Journal of Agricultural Economics* 93, no. 5 (2011): 1257–77.
- Alston, Julian M., Barbara J. Craig, and Philip G. Pardey. “Dynamics in the Creation and Depreciation of Knowledge, and the Returns to Research.” EPTD Discussion Paper No. 35, International Food Policy Research Institute, Washington, DC, August 1998.
- Alston, Julian M., and Philip G. Pardey. “Agricultural Productivity.” Essay in *Historical Statistics of the United States, Earliest Times to the Present: Millennial Edition*, edited by Susan B. Carter, Scott S. Gartner, Michael R. Haines, Alan L. Olmstead, et al. Cambridge: Cambridge University Press, 2006, pp. 4-19–4-27.
- . “Agriculture in the Global Economy.” *Journal of Economic Perspectives* 28, no. 1 (2014): 121–46.
- . “Transforming Traditional Agriculture Redux.” In *The Oxford Handbook of Structural Transformation*, edited by Célestin Monga and Justin Yifu Lin, ch. 16. Oxford: Oxford University Press, 2019.
- . “Innovation, Growth and Structural Change in American Agriculture.” NBER Working Paper No. 27206, Cambridge, MA, May 2020 .
- . “Are Ideas *Really* Getting Harder to Find? Concepts and Evidence from U.S. Agriculture.” Working Paper, International Science and Technology Practice and Policy Center, University of Minnesota, St. Paul, MN, 2021 (in process).
- Andersen, Mathew A. “Procylical Productivity Patterns in U.S. Agriculture.” Unpublished Ph.D. diss., Department of Agricultural and Resource Economics, University of California, Davis, 2005.
- . “Capital Use Intensity and Productivity Biases.” *Journal of Productivity Analysis* 37, no. 1 (2012b): 59–71.
- Andersen, Mathew A., Julian M. Alston, Philip G. Pardey, and Aaron Smith. “A Century of U.S. Farm Productivity Growth: A Surge Then a Slowdown.” *American Journal of Agricultural Economics* 100, no. 4 (2018): 1072–90.
- Atack, Jeremy. “On the Use of Geographic Information Systems in Economic History: The American Transportation Revolution Revisited.” *Journal of Economic History* 72, no. 2 (2013): 313–38.
- Bakker, Gerben, Nicholas Crafts, and Pieter Woltjer. “The Sources of Growth in a Technologically Progressive Economy: The United States, 1899–1941.” *Economic Journal* 129 (2019): 2267–94
- Ball, Eldon, David Schimmelpfenning, and Sun Ling Wang. “Is U.S. Agricultural Productivity Growth Slowing?” *Applied Economic Perspectives and Policy* 35, no. 3 (2013): 435–50.

- Ball, Eldon, Sun Ling Wang, and Richard Nehring. *Agricultural Productivity in the United States: Data Documentation and Methods*. Washington DC: USDA Economic Research Service, May 2010. Accessed July 2010 from <http://www.ers.usda.gov/data/agproductivity/methods.htm>.
- Barton, Glen T., and Martin R. Cooper. "Relation of Agricultural Production to Inputs." *Review of Economics and Statistics* 30, no. 2 (1948): 117–26.
- Barton, Glen T., and Donald D. Durost. "The New USDA Index of Inputs." *Journal of Farm Economics* 42, no. 5 (1960): 1398–410.
- Beall, Robert T. "Rural Electrification." In *USDA 1940 Agricultural Yearbook*. Washington, DC: United States Department of Agriculture, 1940, pp. 790–809.
- BEA (Bureau of Economic Analysis). "Table 6.8a-6.8d Persons Engaged in Production by Industry (A)" Obtained from National Income and Product Accounts Database. Washington, DC: Bureau of Economic Analysis, 2020a. Downloaded 26 June 2020. Available from https://apps.bea.gov/iTable/index_nipa.cfm.
- . "Table 1.3.5. Gross Value Added by Sector" Obtained from National Income and Product Accounts Database. Washington, DC: Bureau of Economic Analysis, 2020b. Downloaded 14 February 2020. Available from https://apps.bea.gov/iTable/index_nipa.cfm.
- Bloom, Nicholas, Charles I. Jones, John Van Reenen, and Michael Webb. "Are Ideas Getting Harder to Find?" *American Economic Review* 110, no. 4 (2020): 1104–44.
- BLS (U.S. Commerce Department, Bureau of Labor Statistics). "Historical Multifactor Productivity Measures (SIC 1948–87 linked to NAICS 1987–2019)." Washington, DC: Bureau of Labor Statistics, 2020. Accessed May 2020 from <https://www.bls.gov/mfp/mprdownload.htm>.
- Carter, Susan B., and Richard Sutch. "Self-Employed Persons, Unpaid Family Workers, and Domestic Service Employees by Industry: 1900–1960 [Lebergott]." In *Historical Statistics of the United States, Earliest Times to the Present: Millennial Edition*, edited by Susan B. Carter, Scott Sigmund Gartner, Michael R. Haines, Alan L. Olmstead, Richard Sutch, and Gavin Wright, table Ba910-921. New York: Cambridge University Press, 2006. <http://dx.doi.org/10.1017/ISBN-9780511132971.Ba652-103210.1017/ISBN-9780511132971.Ba652-1032>.
- Carson, Rachel. *Silent Spring*. Boston: Houghton Mifflin, 1962.
- Caselli, Francesco, and Wilbur J. Coleman II. "The U.S. Structural Transformation and Regional Convergence: A Reinterpretation." *Journal of Political Economy* 109, no. 3 (2001): 584–616.
- Cochrane, Willard W. *Farm Prices: Myth and Reality*. Minneapolis: University of Minnesota Press, 1958.
- . *The Development of American Agriculture: A Historical Analysis*, second edition. Minneapolis: University of Minnesota Press, 1993.
- Cooper, Martin R., Glen T. Barton, and Albert P. Brodell. *Progress of Farm Mechanization*.

- Miscellaneous Publication No. 630. Washington, DC: United States Department of Agriculture, 1947.
- Dimitri, Carolyn, Anne Effland, and Neilson Conklin. *The 20th Century Transformation of U.S. Agriculture and Farm Policy*. Economic Information Bulletin No. 3. Washington, DC: United States Department of Agriculture, Economic Research Service, 2005.
- Dixon, Robert. "Hybrid Corn Revisited." *Econometrica* 48, no. 6 (1980): 1451–61.
- Durost, Donald D., and Glen T. Barton. *Changing Sources of Farm Output*. Production Research Report No. 36. Washington, DC: United States Department of Agriculture, 1960.
- FAO (Food and Agriculture Organization of the United Nations). FAOSTAT. Rome: Food and Agriculture Organization of the United Nations, 2017. Available at <http://faostat.fao.org/site/291/default.aspx>.
- Fernandez-Cornejo, Jorge, Seth Wechsler, Mike Livingston, and Lorraine Mitchell. *Genetically Engineered Crops in the United States*. USDA Economic Research Report No. 162. Washington, DC: United States Department of Agriculture, 2014.
- Field, Alexander, J. "The Most Technologically Progressive Decade in the Century." *American Economic Review* 93, no. 4 (2003): 1399–413.
- . *A Great Leap Forward: 1930s Depression and U.S. Economic Growth*. New Haven & London: Yale University Press, 2011.
- Fischer, Claude S. "Technology's Retreat: The Decline of Rural Telephony in the United States, 1920–1940." *Social Science History* 11, no. 3 (1987): 295–327.
- Fischer, R. Anthony, Derek Byerlee, and Gregory O. Edmeades. *Crop Yields and Global Food Security: Will Yield Increase Continue to Feed the World?* Canberra: Australian Centre for International Agricultural Research, ACIAR Monograph No. 158, 2014.
- Fogel, Robert W. *Railroads and American Economic Growth: Essays in Econometric History*. Baltimore, MD: Johns Hopkins Press, 1964.
- Gallman, Robert E. "Changes in Total U.S. Agricultural Factor Productivity in the Nineteenth Century." *Agricultural History* 46, no. 1 (1972): 191–210.
- Gardner, Bruce L. "Changing Economic Perspectives on the Farm Problem." *Journal of Economic Literature* 30 (1992): 62–101.
- . *American Agriculture in the Twentieth Century: How It Flourished and What It Cost*. Cambridge: Harvard University Press, 2002.
- Geib-Gundersen, Lisa, and Elizabeth Zahrt. "A New Look at U.S. Agricultural Productivity Growth, 1800–1910." *Journal of Economic History* 56, no. 3 (1996): 679–86.
- Gordon, Robert J. "Interpreting the 'One Big Wave' in U.S. Long-Term Productivity Growth." NBER Working Paper No. 7752, Cambridge, MA, June 2000.
- . *The Rise and Fall of American Growth*. Princeton: Princeton University Press, 2016.
- Griliches, Zvi. "Hybrid Corn: An Exploration in the Economics of Technological Change." *Econometrica* 25, no. 4 (1957): 501–22.

- . “The Sources of Measured Productivity Growth: United States Agriculture, 1940–60.” *Journal of Political Economy* 71, no. 4 (1963): 331–46.
- . “Productivity Puzzles and R & D: Another Nonexplanation.” *Journal of Economic Perspectives* 2, no. 4 (1988): 9–21.
- Haines, Michael, Price Fishback, and Paul Rhode. “United States Agriculture Data, 1840–2012.” Ann Arbor, MI: Inter-university Consortium for Political and Social Research, 2018. Accessed on 2018-08-20. doi: doi.org/10.3886/ICPSR35206.v4.
- Hallauer, Arnel R., and J. B. Miranda Filho. *Quantitative Genetics in Maize Breeding*. Ames: Iowa State University Press, 1981.
- Hayami, Yujiro, and Vernon W. Ruttan. *Agricultural Development: An International Perspective*. Baltimore: Johns Hopkins University Press, 1971.
- Hoppe, Robert A., and James M. MacDonald. Updating the ERS Farm Typology, EIB-110, U.S. Department of Agriculture, Economic Research Service, April 2013.
- Houthakker, Hendrik. S. *Economic History for the Farm Sector*. Washington, DC: American Enterprise Institute, 1967.
- Huffman, Wallace E., and Robert E. Evenson. *Science for Agriculture: A Long-Term Perspective*. Ames: Iowa State University Press, 1993.
- . *Science for Agriculture: A Long-Term Perspective*, second edition. Ames: Blackwell Publishing, 2006.
- Johnson, Glenn L. *The Overproduction Trap in Agriculture*. Baltimore, MD: Johns Hopkins University Press, 1972.
- Johnson, Sherman. *Changes in American Farming*. USDA Miscellaneous Publication No. 707, Washington, DC: United States Department of Agriculture, Bureau of Agricultural Economics, December 1949.
- Johnston, Louis, and Samuel H. Williamson. “What Was the U.S. GDP Then?” Measuring Worth, 2020. Downloaded 6 February 2020. Available at <https://www.measuringworth.com/datasets/usgdp/>.
- Jorgenson, Dale W., and Frank M. Gollop. “Productivity Growth in U.S. Agriculture: A Postwar Perspective.” *American Journal of Agricultural Economics* 74, no. 3 (1992): 745–50.
- Jorgenson, Dale W., Frank M. Gollop, and Barbara Fraumeni. *Productivity and U.S. Economic Growth*. Amsterdam: North Holland, 1987.
- Jorgenson, Dale W., and Zvi Griliches. “The Explanation of Productivity Change.” *Review of Economic Studies* 34, no. 3 (1967): 249–83.
- Kendrick, John W. “Productivity Trends in Agriculture and Industry.” *Journal of Farm Economics* 40, no. 5 (1958): 1554–64.
- . *Productivity Trends in the United States*. Princeton: Princeton University Press, 1961.
- (assisted by Maude R. Pech). *Postwar Productivity Trends in the United States, 1948–1969*. New York: Columbia University Press for National Bureau of Economic Research, 1973. Available at <http://www.nber.org/books/kend73-1>.

- Kendrick, John W., and Carl E. Jones. "Gross National Farm Product in Constant Dollars, 1910–50." *Survey of Current Business*. Washington, DC: Department of Commerce, 1951.
- Kilby, Emily R. "The Demographics of the U.S. Equine Population." In *The State of the Animals 2007*, edited by Deborah J. Salem and Andrew N. Rowan, ch. 10. Washington, DC: Humane Society Press, 2007.
- Kislev, Yoav, and Willis Peterson. "Prices, Technology and Farm Size." *Journal of Political Economy* 90 (1982): 578–95.
- . "Economies of Scale in Agriculture: A Reexamination of the Evidence." In *Papers in Honor of D. Gale Johnson, Volume 2*, edited by John M. Antle and Daniel A. Sumner, ch. 10. Chicago: University of Chicago Press, 1996.
- Kuznets, Simon S. "The Role of Agriculture in Economic Development." *International Journal of Agrarian Affairs* 3, no. 2 (1961): 56–75.
- . *Modern Economic Growth: Rate, Structure, and Speed*. New Haven, CT: Yale University Press, 1966.
- Kuznets, Simon S., Ann R. Miller, and Richard A. Easterlin. *Analyses of Economic Change*. Vol. 2 of *Population Redistribution and Economic Growth, United States, 1970–1950*. Philadelphia, PA: American Philosophical Society, 1960.
- Lee, Kyuseon, Philip G. Pardey, and Steve Miller. "An Examination of U.S. Sectoral and Firm-level Investments in Food and Agricultural R&D, 1950–2017." InSTePP Working Paper, International Science and Technology Practice and Policy Center, University of Minnesota, St. Paul, MN, 2021 (in process).
- Loomis, Ralph A., and Glen T. Barton. *Productivity of Agriculture: United States, 1870–1958*. Technical Bulletin No. 1238. Washington, DC: United States Department of Agriculture, 1961.
- MacDonald, James M. "Tracking the Consolidation of U.S. Agriculture." *Applied Economic Perspectives and Policy*, 2020, doi.org/10.1002/aep.13056. Accessed 25 August 2020.
- MacDonald, James M., Robert A. Hoppe, and Doris Newton. *Three Decades of Consolidation in U.S. Agriculture*. EIB-189, U.S. Department of Agriculture, Economic Research Service, March 2018.
- Nordhaus, William D., Barry Bosworth, Robert Solow, and Beatrice N. Vaccara. "The Recent Productivity Slowdown." *Brookings Papers on Economic Activity* 1972, no. 3 (1972): 493–545.
- Olmstead, Alan L., and Paul W. Rhode. "The Transformation of Northern Agriculture from 1910 to 1990." In *Cambridge Economic History of the United States, Volume III, The Twentieth Century*, edited by Stanley L. Engerman and Robert E. Gallman, 693–742. New York: Cambridge University Press, 2000.
- . "Reshaping the Landscape: The Impact and Diffusion of the Tractor in American Agriculture, 1910–1960." *Journal of Economic History* 61, no. 3 (2001): 663–98.
- . "The Red Queen and the Hard Reds: Productivity Growth in American Wheat, 1800–1940." *Journal of Economic History* 62, no. 4 (2002): 929–66.

- . “Farms – Number, Population, Land, and Value of Property: 1850–1997 [Census years].” In *Historical Statistics of the United States, Earliest Times to the Present: Millennial Edition*, edited by Susan B. Carter, Scott Sigmund Gartner, Michael R. Haines, Alan L. Olmstead, Richard Sutch, and Gavin Wright, table Da19. New York: Cambridge University Press, 2006a.
- . “Farms—Number, Population, Land, and Value of Property: 1910–1999 [Annual].” In *Historical Statistics of the United States, Earliest Times to the Present: Millennial Edition*, edited by Susan B. Carter, Scott Sigmund Gartner, Michael R. Haines, Alan L. Olmstead, et al., table Da 6. Cambridge: Cambridge University Press, 2006b.
- . “Farms—Number, Population, Land, and Value of Property: 1910–1999 [Annual].” In *Historical Statistics of the United States, Earliest Times to the Present: Millennial Edition*, edited by Susan B. Carter, Scott Sigmund Gartner, Michael R. Haines, Alan L. Olmstead, et al., tables Da 4 and Da 5. Cambridge: Cambridge University Press, 2006c.
- . *Creating Abundance: Biological Innovation and American Agricultural Development*. New York: Cambridge University Press, 2008.
- Olmstead, Alan L., and Daniel A. Sumner. “Farm Policy.” Essay in *Historical Statistics of the United States, Earliest Times to the Present: Millennial Edition*, edited by Susan B. Carter, Scott Sigmund Gartner, Michael R. Haines, Alan L. Olmstead, et al. Cambridge: Cambridge University Press, 2006, pp. 4-31–4-38.
- Pardey, Philip G., and Julian M. Alston. “Replication: Unpacking the Agricultural Black Box: The Rise and Fall of American Farm Productivity Growth.” Ann Arbor, MI: Inter-university Consortium for Political and Social Research [distributor], 2020-01-09. <https://doi.org/10.3886/E130481V1>.
- Pardey, Philip G., Julian M. Alston, and Connie Chan-Kang. *Public Food and Agricultural Research in the United States: The Rise and Decline of Public Investments, and Policies for Renewal*. AGree Report. Washington DC: AGree, 2013.
- Pardey, Philip G., Matthew A. Andersen, Barbara J. Craig, and Julian M. Alston. Primary Data Documentation U.S. Agricultural Input, Output, and Productivity Series, 1949–2002 (Version 4). InSTePP Data Documentation. St. Paul, MN: International Science and Technology Practice and Policy Center, University of Minnesota, 2009.
- . “InSTePP United States Production Accounts, Version 5.” St. Paul, MN: International Science and Technology Practice and Policy, 2014. Available from www.instepp.umn.edu/united-states#Version%205.
- Pardey, Philip G., and Jason M. Beddow. *Agricultural Innovation: The United States in a Changing Global Reality*. CCGA Report. Chicago: Chicago Council on Global Affairs, 2013.
- Pardey, Philip G., Jason M. Beddow, Terrance M. Hurley, et al. “A Bounds Analysis of World Food Futures: Global Agriculture Through to 2050.” *Australian Journal of Agricultural and Resource Economics* 58, no. 4 (2014): 571–89.
- Peterson, Willis L. “Return to Poultry Research in the United States.” *Journal of Farm Economics* 49, no. 3 (1967): 656–69.

- Rao, Xudong, Terrance M. Hurley, and Philip G. Pardey. “Are Agricultural R&D Returns Declining and Development Dependent?” *World Development* 122 (2019): 27–37.
- Rasmussen, Wayne, D. “The Impact of Technological Change on American Agriculture, 1862–1962.” *Journal of Economic History* 22, no. 4 (1962): 578–91.
- Ruttan, Vernon W. *Agricultural Research Policy*. Minneapolis: University of Minnesota Press, 1982.
- Saitone, Tina L., Richard J. Sexton, and Danial A. Sumner. “What Happens When Food Marketers Require Restrictive Farming Practices?” *American Journal of Agricultural Economics* 97, no. 4 (2015): 1021–43.
- Schultz, Theodore W. “Reflections on Agricultural Production Output and Supply.” *Journal of Farm Economics* 38, no. 3 (1956): 748–62.
- Smith, Maryanna S. *Chronological Landmarks in American Agriculture*. Agricultural Information Bulletin No 425. Washington, DC: United States Department of Agriculture, Economics, Statistics, and Cooperatives Service, 1979.
- Solow, Robert M. “Technical Change and the Aggregate Production Function.” *American Economic Review* 39, no. 3 (1957): 312–20.
- Strauss, Frederick, and Louis H. Bean. *Gross Farm Income and Indices of Farm Production and Prices in the United States, 1869–1937*. USDA Technical Bulletin No. 703. Washington, DC: United States Department of Agriculture, 1940.
- Sutch, Richard. “Self-Employed Persons, Unpaid Family Workers, and Private Household Employees, by Industry: 1948–1999 [Current Population Survey].” In *Historical Statistics of the United States, Earliest Times to the Present: Millennial Edition*, edited by Susan B. Carter, Scott Sigmund Gartner, Michael R. Haines, Alan L. Olmstead, Richard Sutch, and Gavin Wright, table Ba922-933. New York: Cambridge University Press, 2006.
- Sumner, Daniel A., Julian M. Alston, and Joseph W. Glauber. “Evolution of the Economics of Agricultural Policy.” *American Journal of Agricultural Economics* 92, no. 2 (2010): 403–23.
- United Nations Statistics Division. UN National Accounts Main Aggregates Database. New York: United Nations, 2020. Accessed 4 February 2020 from <http://unstats.un.org/unsd/snaama/introduction.asp>.
- U.S. Bureau of the Census. “Historical Statistics of the United States, 1789–1957- Chapter A Wealth and Income, Series A 154-164: National Income.” U.S. Department of Commerce. Washington, DC: GPO, 1949. Downloaded 14 February 2017 from http://www.census.gov/library/publications/1949/compendia/hist_stats_1789-1945.html.
- . “Historical Statistics of the United States: Colonial Times to 1970.” U.S. Department of Commerce. Washington, DC: GPO, 1975.
- . “1969 United States Census of Agriculture. General Information: Procedures for Collection, Processing, Classification. Volume II General Report. April 1973. Washington, DC: Government Printing Office.
- . “1974 Census of Agriculture – United States Summary and State Data, Volume I Part

- 51.” U.S. Department of Commerce. Washington, DC: GPO, 1977.
- . “Census of the United States: Agriculture.” U.S. Department of Commerce. Washington, DC: GPO, various years.
- USDA (United States Department of Agriculture). “States by Census Region and Division.” Washington, DC: USDA, Economic Research Service, 2019. Downloaded from www.ars.usda.gov/northeast-area/beltsville-md-bhnrc/beltsville-human-nutrition-research-center/docs/regions.
- USDA-ERS (United States Department of Agriculture, Economic Research Service). *Economic Indicators of the Farm Sector: Production and Efficiency Statistics, 1981*. ECIFS 1-3, Washington, DC: USDA, Economic Research Service, 1983.
- USDA-NASS (United States Department of Agriculture, National Agricultural Statistical Service). “Farms and Land in Farms.” Washington, DC: USDA-NASS Agricultural Statistical Boards, February 1999. Downloaded from <https://downloads.usda.library.cornell.edu/usda-esmis/files/5712m6524/gh93h204z/n870zt29p/FarmLandIn-02-26-1999.pdf>.
- . “Farms and Land in Farms 2013 Summary.” Washington, DC: USDA-NASS, May 2014a. Downloaded from <https://downloads.usda.library.cornell.edu/usda-esmis/files/5712m6524/fq977x84m/6m311r61b/FarmLandIn-05-28-2014.pdf>.
- . “2012 Census of Agriculture. United States Summary and State Data. Volume 1 Geographic Area Series Part 51 AC-12-A-51. Washington, DC: United States Department of Agriculture, May 2014b. Available at https://www.nass.usda.gov/Publications/AgCensus/2012/Full_Report/Volume_1,_Chapter_1_US/.
- . “Farm Operations” Obtained from Quick Stats 2.0 Database. Washington, DC: United States Department of Agriculture, 2019. Downloaded 9 January 2019. Available from <http://quickstats.nass.usda.gov/>.
- . Census of Agriculture. Washington, DC: United States Department of Agriculture, various years.
- Wang, Sun Ling. “Is U.S. Agricultural Productivity Growth Slowing?” *Amber Waves* 8, no. 3 (2010): 6. Available at www.ers.usda.gov/Amberwaves/.
- Wang, Sun Ling, Paul Heisey, David Schimmelpfennig, and Eldon Ball. *Agricultural Productivity Growth in the United States: Measurement, Trends, and Drivers*, ERR-189, U.S. Department of Agriculture, Economic Research Service, July 2015a.
- . “U.S. Agricultural Productivity Growth: The Past, Challenges, and the Future.” *Amber Waves* Feature, September 2015b.
- Weiss, Thomas. “Long-Term Changes in US Agricultural Output Per Worker, 1800–1900.” *Economic History Review* 46, no. 2 (1993): 324–41.
- Wright, Brian D., and Philip G. Pardey. “The Evolving Rights to Intellectual Property Protection in the Agricultural Biosciences.” *International Journal for Technology and Globalization* 2,

no. 1/2 (2006): 12–29.

TABLE 1
ANNUAL AVERAGE GROWTH RATES IN U.S. AGRICULTURAL OUTPUT, *MFP*, AND LABOR
AND LAND *PFP*, AND IN AGRICULTURAL R&D SPENDING AND STOCKS 1910–2007

<i>Period</i>	Productivity Indexes					Public Ag. R&D Spending and Stocks		
	<i>Output</i>	Multifactor	Labor	Land	R&D Spending	R&D Stocks		
						Trap	Growth	
						Ratio ¹	Rate ²	
<i>(Percent per Year)</i>								
1910–1920	1.54	0.21	0.00	0.70	1.71	0.6	8.9	
1920–1930	0.24	0.07	0.18	0.09	0.98	0.70	6.8	
1930–1940	0.51	0.71	0.88	0.78	0.05	0.83	5.2	
1940–1950	0.89	0.47	0.60	0.10	0.73	0.81	9.4	
1950–1960	0.17	0.25	0.37	0.24	0.85	0.93	8.3	
1960–1970	0.60	0.69	0.19	0.44	0.46	0.60	8.3	
1970–1980	0.22	0.46	0.71	0.14	0.08	0.73	2.7	
1980–1990	0.63	0.08	0.03	0.86	0.49	0.20	3.3	
1990–2000	0.72	0.25	0.94	0.90	0.40	0.35	7.5	
2000–2010	0.15	0.03	0.83	0.84	1.08	0.27	5.6	

191	1	0	2	0	4	5	4.9
0–1950	.29	.83	.16	.62	.12	.60	9
195	1	2	4	1	2	3	3.7
0–1990	.91	.12	.07	.92	.72	.62	3
199	1	1	1	1	0	2	2.2
0–2007	.48	.16	.90	.88	.22	.01	7
191	1	1	2	1	2	3	3.5
0–2007	.58	.42	.90	.38	.86	.89	7

Notes: All figures are annual average growth rates for the respective periods calculated by the log-difference method.

¹ Data on trapezoidal-lag knowledge stocks are available from 1925. Thus, for the periods 1920–1930, 1910–1950, and 1910–2007, growth rates are for 1925–1930, 1925–1950, and 1925–2007, respectively.

² Data are gamma-lag knowledge stocks available from 1939. Thus, for the periods 1910–1950 and 1910–2007, growth rates are for 1939–1950 and 1939–2007 respectively.

Sources: Growth rates of productivity indexes were calculated by the authors using the InSTePP Production Accounts, version 5, augmented with data from USDA-ERS (1983). Growth rates of R&D spending and knowledge stocks were calculated by the authors using the InSTePP public agricultural R&D series for the United States.

TABLE 2
ANNUAL AVERAGE U.S. FARM, NON-FARM AND TOTAL PRIVATE BUSINESS MFP GROWTH
RATES, 1890–2007

Period	Private Business Sector MFP Growth				Agricultural	Labor		
	A	Fa		F	GDP as a	P	F	
	Aggregate Farm and Non-Farm	N on-Farm	(InStePP-U SDA)	(InStePP- Kendrick)	Share of GDP	Private Business Farm	Share of Total	
	<i>(Percent per Year)</i>				<i>(Percent)</i>	<i>(Million Labor Years)</i>		<i>(Percent)</i>
1890–1900	1.14	1.08		1.27	14.9	10.4	27.5	37.9
1900–1910	0.86	1.14		0.02	15.0	10.4	31.3	33.5
1910–1920	1.26	1.61	0.21	-0.67	15.8	10.1	36.9	27.4
1920–1930	1.60	1.56	-0.07	0.96	9.9	9.4	40.9	23.1
1930–1940	2.29	2.52	1.71	1.52	7.5	9.0	39.7	22.9
1940–1950	2.31	2.05	1.47	1.26	7.3	7.9	49.8	15.9
1950–1960	1.68	1.31	2.25	2.25	4.8	5.9	55.0	0.8
1960–1970	2.05	1.76	1.69	1.69	2.8	3.9	59.7	0.6
1970–1980	0.96	0.88	2.46	2.46	2.5	2.9	71.4	0.1
1980–1990	0.75	0.55	2.08	2.08	1.7	2.3	86.7	0.7

199									1
0–2000	1.04	0.97	1.25	1.25	1.3	1.8	103.0		.7
200									1
0–2007	1.42	1.39	1.03	1.03	1.0	1.6	115.1		.4
191									2
0–1950	1.87	1.93	0.83	0.77	10.2	9.1	41.9		2.3
195									4
0–2007	1.31	1.13	1.83	1.83	2.4	3.2	80.1		.8
191									1
0–2007	1.54	1.46	1.42	1.39	5.6	5.6	64.4		2.0

Notes: Shading indicates the decades with growth rates above the long-term (1910–2007) average. MFP growth rates of the respective periods calculated by the log-difference method. Labor includes the number of full-time equivalent employees plus the number of self-employed persons and unpaid family workers.

Sources: Growth rates of productivity indexes were calculated by the authors using the InSTePP Production Accounts, version 5 (1949–2007), augmented with data from USDA-ERS (1983) or Kendrick (1961, 1973) and BLS (2020). Labor data were calculated by the authors using data on persons engaged in production from BEA (2020a), on unpaid family workers from Carter and Sutch (2006) and Sutch (2006), and on engaged persons from Kendrick (1961). Agricultural GDP as a share of GDP is authors' calculations based on GDP data from Johnston and Williamson (2020), and AgGDP data from the United Nations (2020), BEA (2020b), and U.S. Bureau of Census (1949).

TABLE 3
GROWTH RATES IN ADOPTION OF SELECTED INNOVATIONS BY TERCILE, 1920–2018

Innovation Shares	192 0–1940	1940–1 980	19 80–2018
Mechanical Innovations	<i>(Percent per Year)</i>		
Farms using tractors	9 .2	3 .4	– 0.3
Farms with automobiles	3 .3	0 .5	– 1.4
Farms with motor trucks	9 .9	4 .2	– 0.4
Farms with balers	3 .5	5 .9	0 .3
farms with combines	3 .5	5 .9	– 1.1
Crop farms with conditioners	3 .5	4 .6	2 .0
Biological and Chemical Innovations			
Corn acreage planted to hybrids	7 8.0	6 .9	
Corn acreage planted to GE varieties			1 6.4
Soybean acreage planted to GE varieties			1 6.5
Semi-dwarf wheat area		1 9.9	2 .1
Semi-dwarf rice area		8 8.0	1 5.2
Wheat area, varieties released post-1920	3 0.9	2 .5	0 .0

	3	2	0
Cropland acres using fertilizer	.5	.3	.7
<hr/>			
Infrastructure Innovations			
	7	2	0
Farms with electricity	.8	.8	.1
	–	2	0
Farms with telephones	2.2	.7	.7
	4	1	0
Farms located on improved roads	.7	.1	.0
	4	2	0
Total cropland irrigated	.2	.4	.8

Notes: Shading indicates the tercile with the fastest annual rate of innovation uptake.

For all machinery variables, irrigation and fertilizer, we assumed a share of 0 percent in 1900 and interpolated the data between 1900 and the first year of data available from the Agricultural Census. For GE corn and GE soybeans, we assumed a share of 0 percent in 1980 and interpolated between 1980 and 1996 (first year of data available). For electricity and telephone, we assumed 100 percent of farms had electricity and telephones in 2018 and we interpolated between the last year of data available and 2018. For improved roads, we carried over the 1959 estimate (last year of data available to 2018).

Share of farms using tractors: Last year of data is 2012, so for 1980–2018, growth rates refer to 1980–2012. Share of farms with automobiles: Last year of data is 1982, so for 1980–2018, growth rates refer to 1980–1982. Share of farms with motor trucks: Last year of data is 2012, so for 1980–2018, growth rates refer to 1980–2012. Share of farms with balers: Last year of data is 2012, so for 1980–2018, growth rates refer to 1980–2012. Share of farms with conditioners: Last year of data is 1992, so for 1980–2018, growth rates refer to 1980–1992. Share of corn planted to hybrids: For the 1920–1940 period, growth rates refer to 1933–1940; for the 1940–1980 period, growth rates refer to 1940–1960. Area share of wheat to semi-dwarf wheat: Last year of data is 2016, so for 1980–2018, growth rates refer to 1980–2016. Area share of rice to semi-dwarf rice: Last year of data is 2005, so for 1980–2018, growth rates refer to 1980–2005. Area share of wheat with varieties released after 1920: Last year of data is 2016, so for 1980–2018, growth rates refer to 1980–2016. Share of cropland using fertilizer: Last year of data is 2012, so for 1980–2018, growth rates refer to 1980–2012. Share of irrigated cropland in total cropland: Last year of data is 2012, so for 1980–2018, growth rates refer to 1980–2012.

Source: See Figure 2.

TABLE 4
YEARS OF PEAK RATES OF CHANGE IN U.S. FARM NUMBERS AND FARM SIZE, 1910–2012

U.S. Region	Number of States	Estimated Year of Maximum Growth Rate (Inflection Point)					
		Total Number of Farms: 95% Confidence Interval			Average Farm Size (Acres/Farm): 95% Confidence Interval		
		2.5%	Estimate	97.5%	2.5%	Estimate	97.5%
U.S. Statistical Division							
New England	6	1954	1956	1958	1951	1953	1956
Middle Atlantic	3	1952	1957	1963	1953	1956	1959
Mountain	8	1954	1957	1960	1917	1932	1947
West South Central	4	1957	1959	1962	1954	1957	1959
Pacific	3	1959	1961	1964	1954	1955	1957
South Atlantic	8	1958	1961	1964	1956	1958	1959
East North Central	5	1961	1962	1964	1959	1961	1963
East South Central	4	1961	1962	1963	1959	1960	1961
West North Central	7	1961	1964	1968	1955	1960	1965
USDA Region							
Northeast	9	1953	1956	1960	1952	1954	1956
West	11	1955	1958	1961	1930	1940	1950
South	16	1959	1961	1963	1957	1958	1959
Midwest	12	1961	1963	1965	1956	1960	1965
United States							
Contiguous states	48	1958	1959	1961	1951	1954	1956

Sources: Created by the authors based on pooled estimates of cubic trend models using state-level data in logarithms for all of the states within the respective U.S. region. Regions are defined in USDA (2019). Regression results are reported in Online Appendix Table D-5.

TABLE 5
DISTRIBUTION OF LAND IN FARMS AND NUMBER OF FARMS IN THE UNITED STATES
BY AREA PER FARM COHORTS, 1870–2012

	Land in									
	Farms				Farms				Total	
	10 Acres	50 Acres	100 Acres	1,000 Acres	10 Acres	50 Acres	100 Acres	1,000 Acres	Land in Farms	F arms
<i>(Percentage)</i>								<i>(Millio n Acres)</i>	<i>(Th ousands)</i>	
870					.7	9.7	8.0	9.9	—	2 ,660
880					.5	9.3	5.1	9.3	—	4 ,009
890					.3	8.9	3.5	9.3	—	4 ,565
910					.3	5.4	8.0	9.2	—	6 ,362
920	.17	.0	7.0	6.9	.5	5.7	8.6	9.0	735.2	6 ,381
925	.23	.1	7.1	5.7	.9	7.9	0.2	9.0	924.3	6 ,372
930	.19	.7	5.7	2.0	.7	7.5	9.4	8.7	986.8	6 ,289
935	.29	.6	5.5	0.6	.4	9.6	0.7	8.7	1,054.5	6 ,812
940	.25	.7	3.5	5.7	.3	7.5	8.7	8.4	1,060.9	6 ,097
945	.25	.1	1.4	9.7	0.1	8.4	8.1	8.1	1,141.6	5 ,859

											5
950	.21	.6	0.1	7.3	.0	6.5	5.9	7.7	1,158.6		,382
											4
954	.20	.9	.4	4.1	0.1	5.5	3.6	7.3	1,158.2		,782
											3
964					.8	6.0	3.1	5.4	—		,158
											2
987	.07	.2	.5	7.6	.8	8.5	3.4	1.9	964.5		,088
											1
992	.07	.2	.3	4.9	.6	8.8	3.5	1.0	945.5		,925
											1
997	.07	.2	.5	3.9	.0	9.5	5.0	0.8	931.8		,912
											2
002	.09	.7	.3	3.1	.4	4.9	1.0	1.7	938.3		,129
											2
007	.12	.8	.5	2.3	0.6	8.7	4.4	2.2	922.1		,205
											2
012	.11	.8	.4	0.8	0.6	8.6	4.6	1.8	914.5		,109

Note: Percentages calculated by authors from reported distributions of farm numbers and area.

Source: Authors' calculations using data from Haines, Fishback, and Rhode (2018).

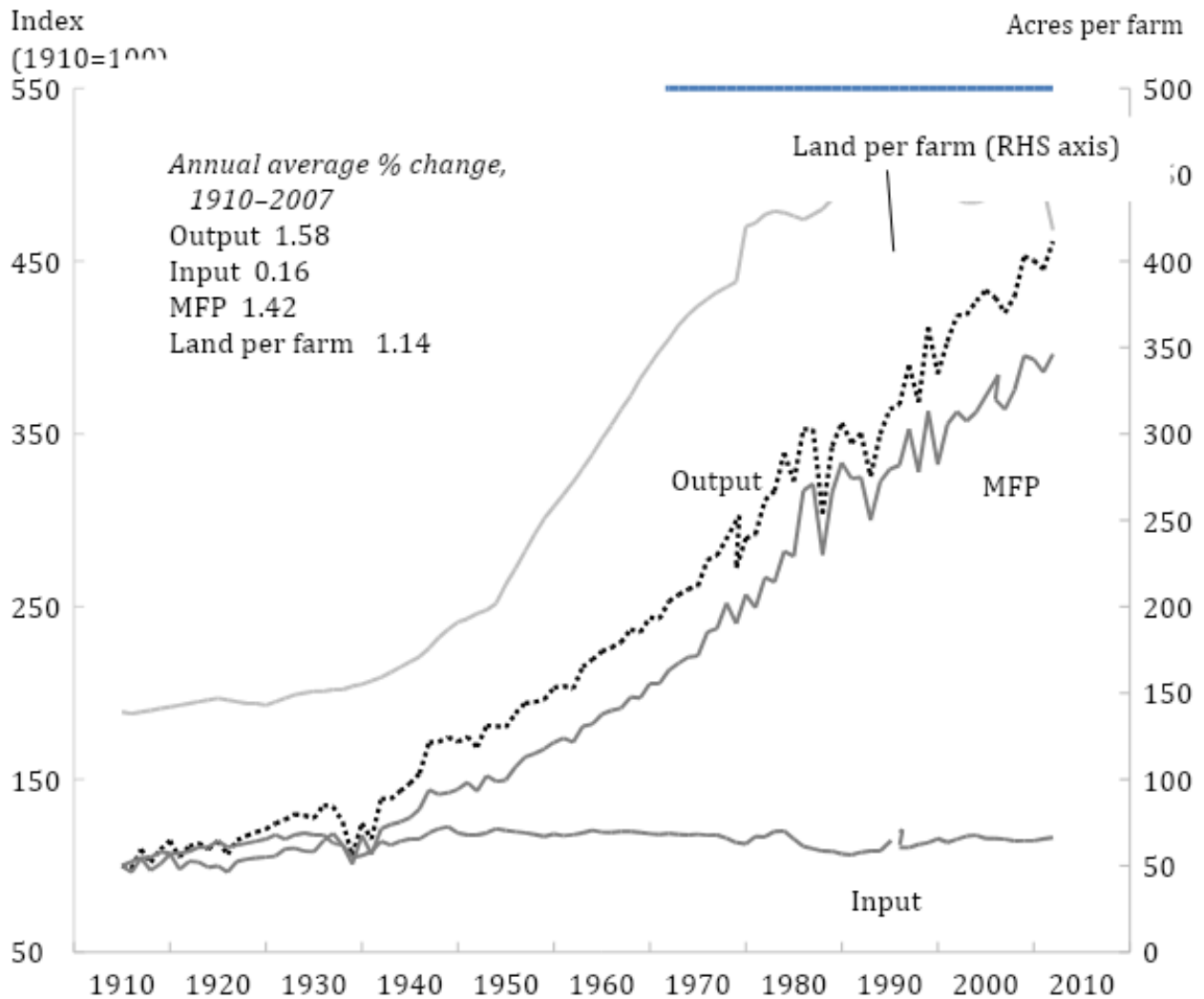
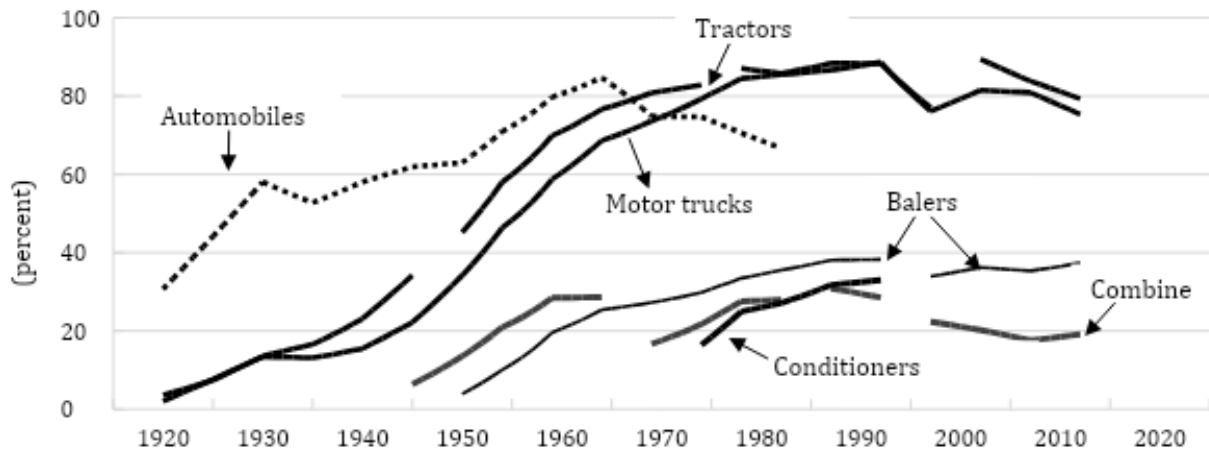


FIGURE 1
QUANTITY INDEXES OF OUTPUT, INPUT, AND MFP, U.S. AGRICULTURE, 1910-2007

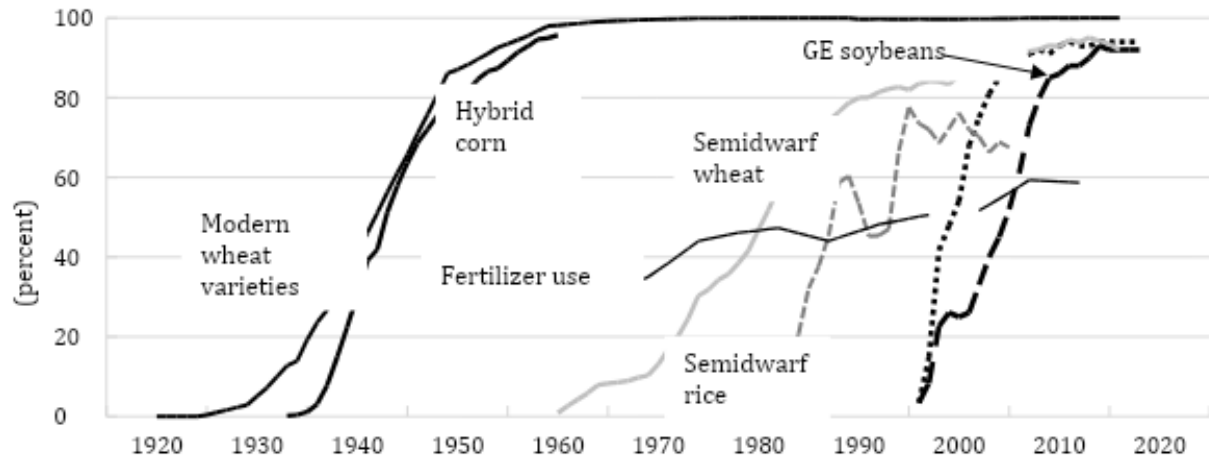
Notes: All of the series refer to the left axis except for land per farm (right axis). The sudden decline in land in farms in 1993 reflects a change in the definition of farms (USDA-NASS 1999, p. 13) that had the measured number of farms increasing by 4.5 percent from 1992 to 1993. We omitted the 2007 estimate as USDA-NASS (2014a, p. 21) reported 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 were calculated by the authors using the InSTePP Production Accounts, version 5 augmented with data from USDA-ERS (1983). Number of farms and land in farms are from Olmstead and Rhode (2006a, series D19 and D6 series) for 1910 to 1997 and from USDA-NASS (2019) for 1998 to 2007.

Panel A: Mechanical Innovations



Panel B: Biological and Chemical Innovations



Panel C: Infrastructure Innovations

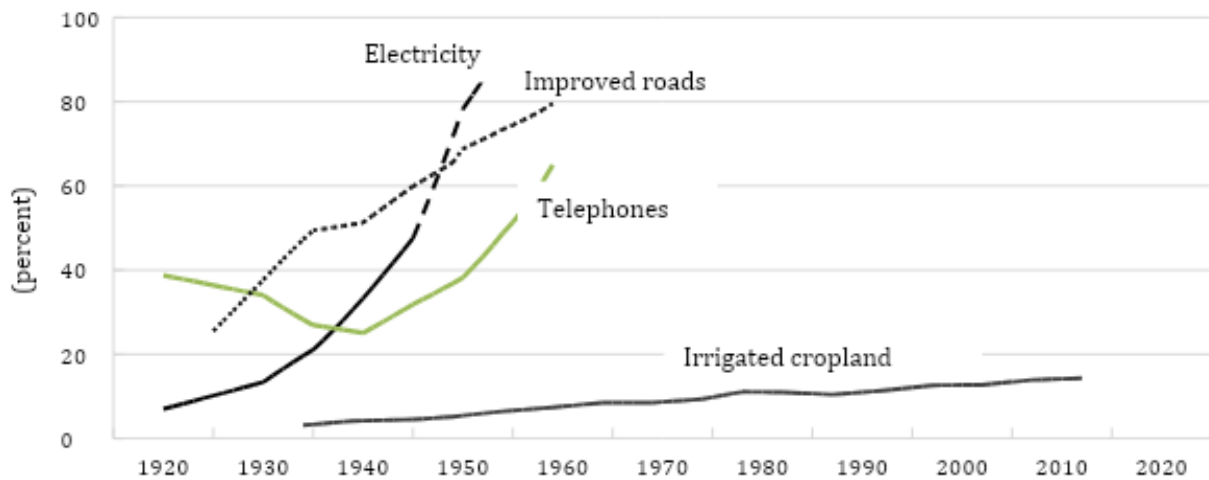


FIGURE 2
55

ADOPTION PATHS FOR SELECTED MAJOR U.S. FARMING INNOVATIONS, 1920–2018

Notes: For automobiles, motor trucks, tractors, electricity, and telephone, the data represent the shares of farms using the designated technology. For balers, conditioners, and combines, the data represent the shares of crop farms using the designated technology. For fertilizer, the data represent the share of cropland with fertilizer application. **Tractors:** From 1920 to 1945, tractors include wheel, crawler, and garden; from 1950 to 1969, tractors include wheel and crawler; from 1978 to 1997, tractors include wheel tractor only; from 2002 to 2012, tractors include wheel and crawler. **Automobiles:** A drop in the number of automobiles is observed in 1969 and thereafter indicative of a structural change in this measure. See USDA-NASS *Census of Agriculture* (1969, p. 11) for details. **Combines:** From 1945 to 1964, combines include pull type and self-propelled; from 1969 to 1982 only self-propelled combines are included; from 1987 to 1992, all types of combine are included; from 1997 onwards, only self-propelled combines are included. **Balers:** From 1950 to 1992, data refer to pickup balers; from 1997 to 2012, data refer to hay balers. **Conditioners:** Data refer to mower conditioners. **Fertilizer:** From 1954 to 1997 fertilizers do not include lime whereas from 2002 to 2012 lime is included. Manure is excluded in all years. From 1978 to 2012, acres on which fertilizers were applied are reported for cropland only, pastureland, and total (i.e., cropland and pastureland). In 1959, 1964, 1969, and 1974, however, data were reported for pastureland and total acres fertilized. Thus, acres of cropland fertilized were estimated for those years by subtracting acres of pastureland fertilized from total acres fertilized. In 1954, only data on total acres fertilized was available. Thus, we estimated the area of cropland fertilized in 1954 by applying the share of cropland fertilized in 1959 to the 1954 cropland area.

Sources: Mechanical and infrastructure innovations data as well as fertilizer data were developed by authors based on estimates from the U.S. Census of Agriculture (Bureau of Census and USDA-NASS, various years). Data for intercensus years were linearly interpolated. Data on hybrid corn are from Alston et al. (2010); GE soybeans and GE corn data are from USDA-NASS “June Agricultural Survey” from 2000 to 2018 and available at www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-us/. Areas of semidwarf wheat and rice, and area of wheat varieties released after 1920 are unpublished data from InSTePP.

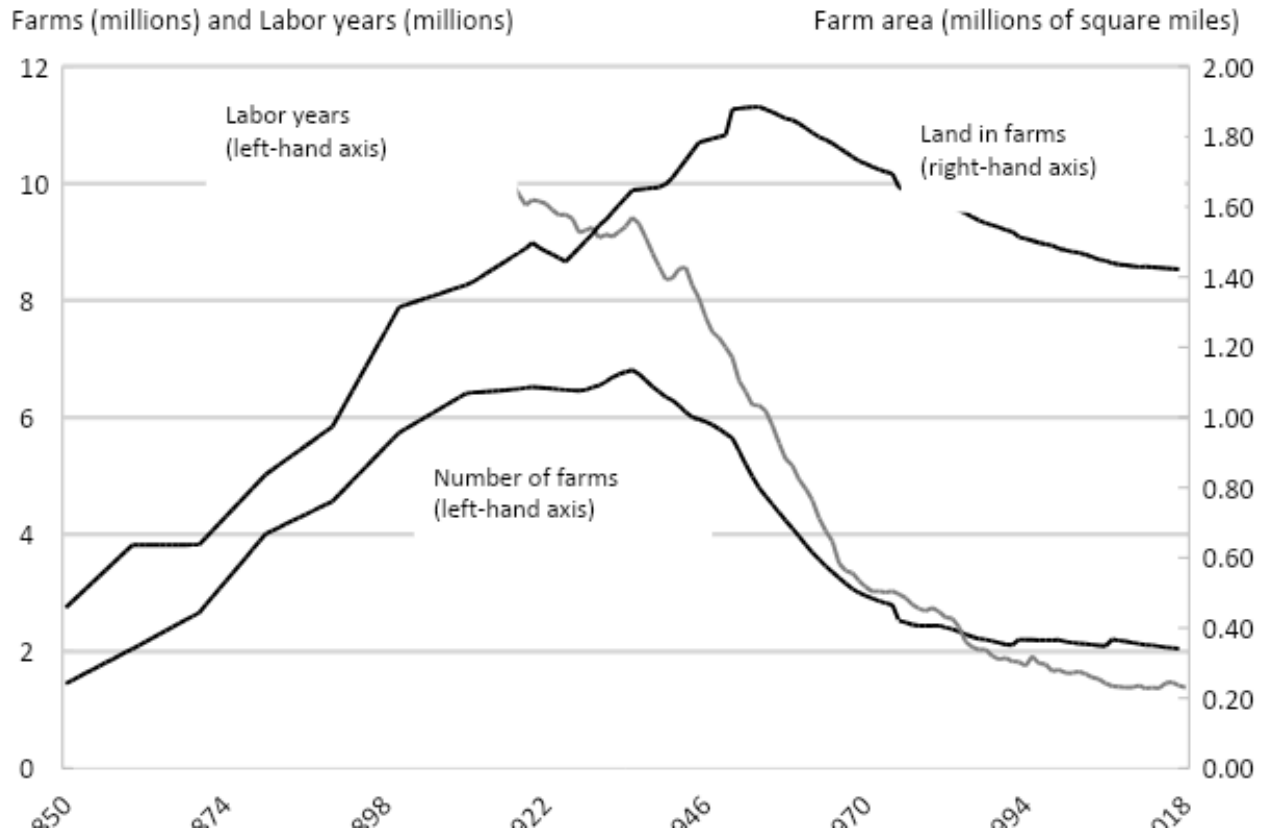


FIGURE 3
U.S. FARM AREA, FARM LABOR, AND FARM NUMBERS, 1850–2018

Note: For number of farms, intercensal values were estimated using a linear interpolation when no value was reported.

Sources: 1850, 1860, 1870, 1880, 1890, and 1900 values for numbers of farms and land in farms are from the U.S. Bureau of the Census (1975, series K-4 and K-5). The 1910 value for land in farms is from series K-5 of the same resource. Number of farms (1910–1999) and land in farms (1911–1999) are from Olmstead and Rhode (2006c, series Da4 and Da5, respectively). For both numbers of farms and land in farms, values for 2000–2018 are from USDA-NASS (2019). Labor data were calculated by the authors using data on persons engaged in production from BEA (2020a), on unpaid family workers from Carter and Sutch (2006) and Sutch (2006), and on engaged persons from Kendrick (1961).

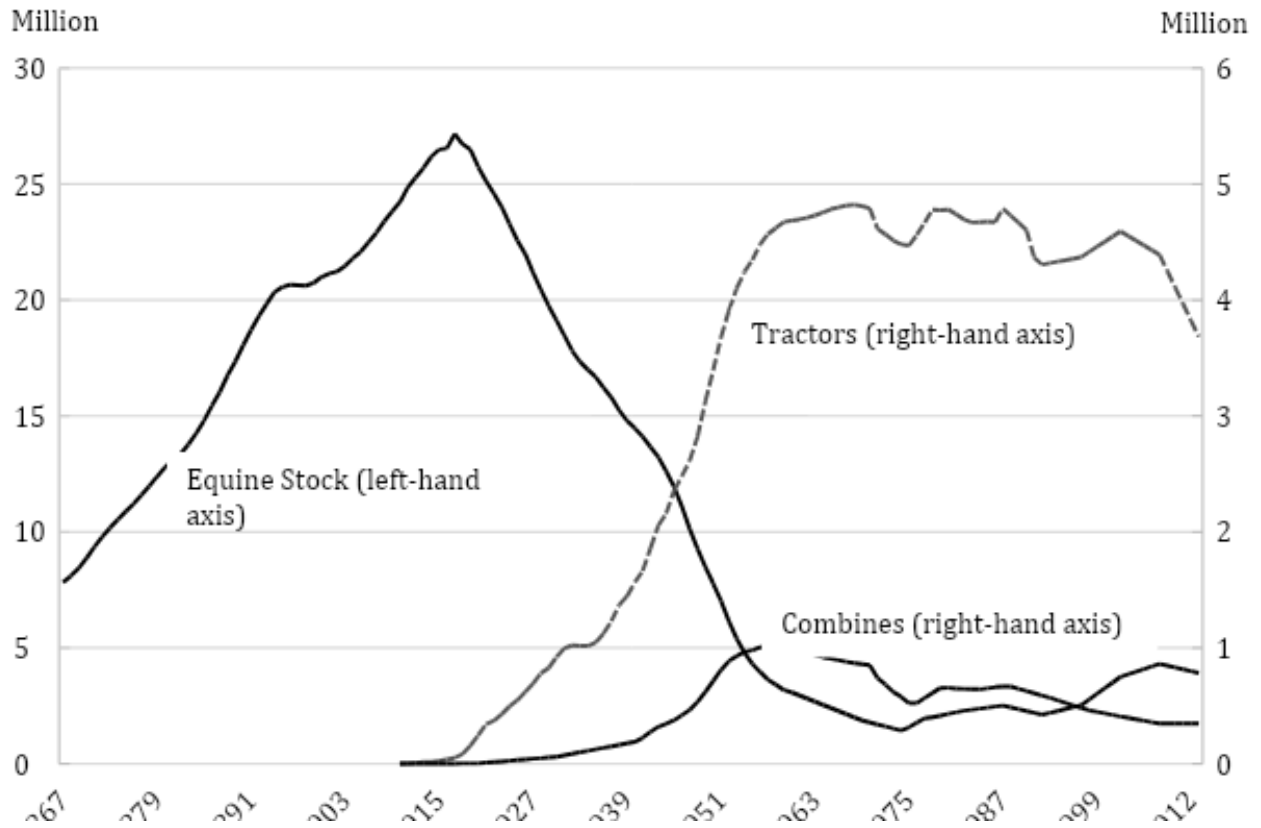
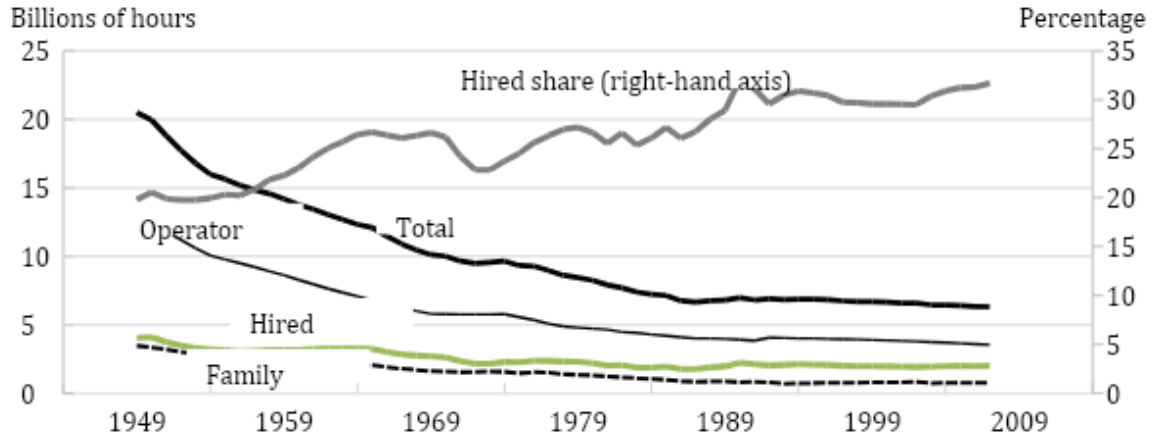


FIGURE 4
 AMERICAN AGRICULTURAL MECHANIZATION, 1867–2012

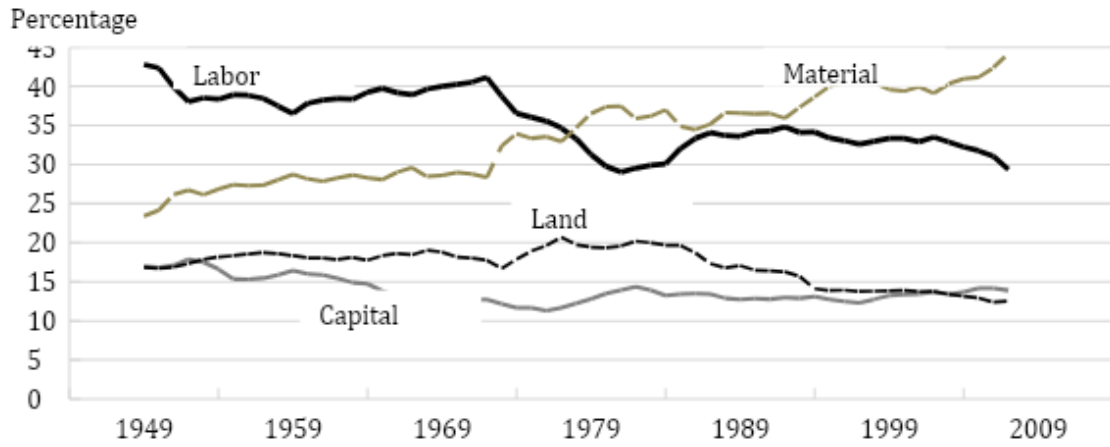
Note: See Alston et al. (2010, p. 29) for details on equine stock.

Sources: Equine stock: 1867–2002 from Alston et al. (2010); 2007 and 2012 from USDA-NASS (2019). Other values were linearly interpolated. Tractors: 1910–1990 from Alston et al. (2010); 1991–2007 from FAO (2017); 2012 from USDA-NASS (2014b, table 48); 2008–2011 were linearly interpolated. Combines: 1910–2002 from Alston et al. (2010); 2007 and 2012 from USDA-NASS (2014b, table 48); 2003–2006 were linearly interpolated.

Panel A: Structure of labor



Panel B: Labor and other cost shares



Panel C: Part-time farm operators

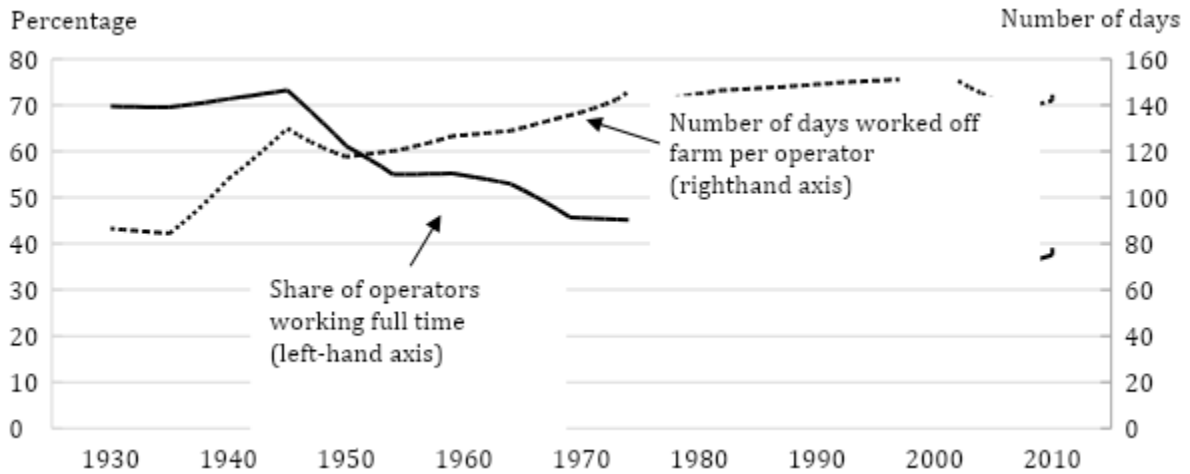


FIGURE 5

LABOR USE IN U.S. AGRICULTURE, 1949–2012

Notes: In all Census years up to 1997, the reported number of operators was equal to the total number of farms. From 2002 onwards, this is no longer true. The Census collected information on the total number of operators. Therefore, if a farm had more than one operator, it was counted accordingly. In all census years up to 1997, data are reported in terms of operators by days worked off-farm cohorts (e.g., 0 days, 1–49 days, 50–99 days, etc.). For 2002, 2007, and 2012, data are reported in terms of cohorts of days worked off-farm by the principal operator. In 1974, data were collected only for individual or family operations (sole proprietorships) and partnerships. Thus, corporations and other types of organizations (e.g., cooperative, prison farms, grazing associations, and Indian reservations) were excluded (for more details, see U.S. Bureau of Census 1977, Appendix A, page A4). In all other years, data on days worked off-farm were collected for all types of farms. To calculate the average number of days worked off-farm per operator, we proceeded as follows. First, the total number of days worked off-farm in each cohort was estimated by multiplying the mid-point number of days worked off farm in each cohort (e.g., 25 days for 1–49 days, 75 days for 50–99 days, etc. and 200 days for 200 and more) by the corresponding total number of operators. The total number of days worked off farms was obtained by summing the estimated number of days worked off-farm across cohorts. The number of days worked off-farm per operator is given by the total number of days worked off-farm divided by the total number of operators. Data for intercensal years were estimated by linear interpolation. The total number of operators working full time was estimated by subtracting the number of operators working off-farms from the total number of operators.

Sources: Data for Panels A and B are from the InSTePP Production Accounts, version 5. Data for Panel C were developed by authors based on U.S. Bureau of Census data (various years).