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Agricultural Productivity Growth in the United States: Measurement, Trends, and Drivers

Sun Ling Wang, Paul Heisey, David Schimmelpfennig, and Eldon Ball

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Abstract

U.S. agricultural output more than doubled between 1948 and 2011, with growth averaging 1.49 percent per year. With little growth in total measured use of agricultural inputs, the extraordinary performance of the U.S. farm sector was driven mainly by increases in total factor productivity (TFP—measured as output per unit of aggregate input). Over the last six decades, the mix of agricultural inputs used shifted significantly, with increased use of intermediate goods (e.g., fertilizer and pesticides) and less use of labor and land. The output mix changed as well, with crop production growing faster than livestock production. Based on econometric analysis of updated (1948-2011) TFP data, this study finds no statistical evidence that longrun U.S. agricultural productivity has slowed over time. Model-based projections show that in the future, slow growth in research and development investments may have only minor effects on TFP growth over the next 10 years but will slow TFP growth much more over the long term.

Keywords: U.S. agriculture, total factor productivity, TFP, labor productivity, land productivity, productivity slowdown, public R&D, private R&D, extension, infrastructure, public research.

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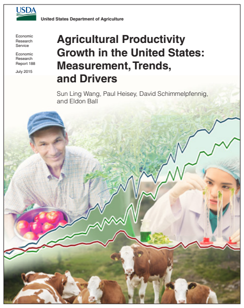

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Agricultural Productivity Growth in the United States: Measurement, Trends, and Drivers

Sun Ling Wang, Paul Heisey, David Schimmelpfennig, and Eldon Ball

What Is the Issue?

Since 1948, total U.S. agricultural output more than doubled. Over the same period, the U.S. population also more than doubled. The ability of the farm sector to feed far more people today while using less farmland than six decades ago is attributed to increases in agricultural productivity. However, slowing growth in U.S. crop yields during 1990-2000 has raised concerns about a possible productivity slowdown in the U.S. farm sector. Slower growth in productivity could affect food prices, food security, and the environment as farmers intensify use of land and chemicals to produce more output.

This study examines changes and trends in U.S. agricultural inputs (e.g., land and labor), output (e.g., crops and livestock), and productivity over the last six decades and the drivers behind productivity changes. In particular, it attempts to answer questions about a possible productivity slowdown and the ability of the U.S. farm sector to sustain productivity over the long term.

What Did the Study Find?

Between 1948 and 2011, U.S. agricultural output grew at 1.49 percent per year. With little growth in total input use (0.07 percent per year) during the period, the extraordinary performance of the U.S. farm sector was driven mainly by productivity growth, at an annual rate of 1.42 percent (as measured by total factor productivity (TFP)—output per unit of total inputs).

Changes in input use. Though total annual use of agricultural inputs changed little since 1948, the mix of inputs used shifted significantly, with increased use of intermediate inputs (e.g., fertilizer and pesticides) and decreased use of labor and land. Over time, the prices of farm machinery, energy, chemicals, and purchased service inputs (e.g., custom machine work) all fell relative to the price of farm labor. The declines were large—between 1948 and 2011, the relative price of agricultural chemicals fell by three-quarters while the relative prices of farm machinery, purchased services, and energy fell by about two-thirds. The drop in relative input prices encouraged farmers to substitute chemicals, purchased services, energy, and machinery use for labor.

Changes in output. The output mix for U.S. farms changed as well over the period, with crop production growing faster than livestock production. The share of farm production revenue attributed to crops increased from 52 to 56 percent between 1948 and 2011, while the share for livestock dropped from 47 to 39 percent and the share for other farm-related output increased from 1 to 5 percent. Relative prices among agricultural outputs also changed. Overall, the farm prices of fruits/nuts and vegetables/melons during the period rose relative to the prices of other crops. Prices of poultry and eggs grew much slower than prices of other livestock products. Shifts in consumers' diet preferences and uneven technical changes in production among agricultural commodities could be contributing factors behind those relative price changes.

Partial factor productivity versus total factor productivity. Partial factor productivity, such as crop yield (or land productivity) and labor productivity, measures average outputs per unit of a single factor. Over the study period, U.S. crop yields and labor productivity grew substantially. For example, soybean yields doubled, corn yields grew more than fourfold, and labor productivity increased by nearly 16 times from 1948 to 2011. However, an increase in a partial factor measure of productivity may not necessarily be caused by technical change but could be attributed to the increased use of other inputs. Total factor productivity measures the contribution from all inputs in production and can be a more informative measure in understanding changes in overall agricultural productivity. From 1948 to 2011, TFP grew by about 150 percent.

Is agricultural productivity slowing? Some studies suggest U.S. agricultural productivity has slowed by comparing decadal productivity growth rates. Yet, TFP estimates can fluctuate considerably from year to year, largely in response to weather events and other transitory factors. Using arbitrary dates (such as by decade) to break down the sample and make comparisons could give misleading information regarding a productivity slowdown. This study uses historical TFP time series data (1948-2011) to evaluate this issue. Analysis reveals an upward shift in TFP after 1985 and finds no statistical evidence of a productivity slowdown over the last six decades.

Changes in drivers of agricultural productivity. Investments in public and private agricultural research are the major factors driving technological change that leads to TFP growth. Public research and development (R&D) investments grew rapidly in real (inflation-adjusted) terms from 1948 to the early 1980s but grew much more slowly and variably since. In 2009, real public R&D investments began to decline, and by 2012, they were nearly 6 percent lower than in 1982. Private R&D investment, however, has been growing faster than public R&D investment. From 1982 to 2010, private agricultural input research grew by over one-third in real (inflation-adjusted) terms. While extension services can enhance the dissemination of new technology, extension full-time-equivalent staffs (FTE) declined by more than 20 percent between 1980 and 2010 nationally, with program diversity and different rates of decline across regions.

Future productivity growth scenarios. Based on model estimates with alternative public R&D investment assumptions, future TFP growth is not expected to be affected much by the decline in public R&D investment in the short term (within 10 years). However, in the long term, TFP growth may slow at a greater rate. For example, from 2010 to 2050, if annual public research expenditures remain unchanged in nominal (unadjusted for inflation) terms, the annual rate of TFP growth is expected to fall from the historical average of 1.42 percent to 0.86 percent in 2050. Furthermore, it will become increasingly difficult for TFP to catch up even if public R&D investments increase again because there is typically a long lag between a research investment and the resulting TFP growth.

How Was the Study Conducted?

This study draws mainly from ERS's agricultural productivity accounts, which provide data on TFP and estimates of input use and output in the U.S. farm sector during 1948-2011. The study also uses data from several other sources, including USDA's National Agricultural Statistics Service and National Institute of Food and Agriculture, the U.S. Bureau of Economic Analysis, and the U.S. Bureau of Labor Statistics. Productivity slowdown tests were conducted using time series data and techniques that enable one to detect structural breaks.

Agricultural Productivity Growth in the United States: Measurement, Trends, and Drivers

Introduction and Objectives

The United States is one of the world's largest agricultural producers. It has the third largest population in the world and the second largest amount of arable agricultural land area. It is also ranked in the top two in agricultural commodity exports and agricultural commodity imports (FAO, 2015). The United States not only helps feed the world but is also a significant consumer of agricultural commodities.

Although its population has more than doubled in the last six decades, the United States now uses about 25 percent less farmland than it did in 1950 (USDA-NASS, 2014). The ability to feed far more people with much less farmland is attributed to increases in agricultural productivity. While yield, or land productivity, and labor productivity are useful productivity estimates, they are partial, or single-factor, measures that attribute all changes in agricultural production to the use of land or labor, respectively. Increases in yield or labor productivity, however, may stem from increased use of other inputs, such as agricultural chemicals, and not necessarily as a result of technical improvement. Total factor productivity (TFP), a more complete measure of productivity, accounts for the contributions of all inputs and is a better measure of overall long-term technical change.

It is important to distinguish between these measures—output per person, per hour worked, per acre of land, or per unit of all factors of production combined—when estimating productivity because each has different policy implications. In general, growth-oriented policy is aimed at affecting the potential trend of output growth (Solow, 1993), which has been mainly driven by TFP growth in the U.S. farm sector in the post-World War II (WWII) period.

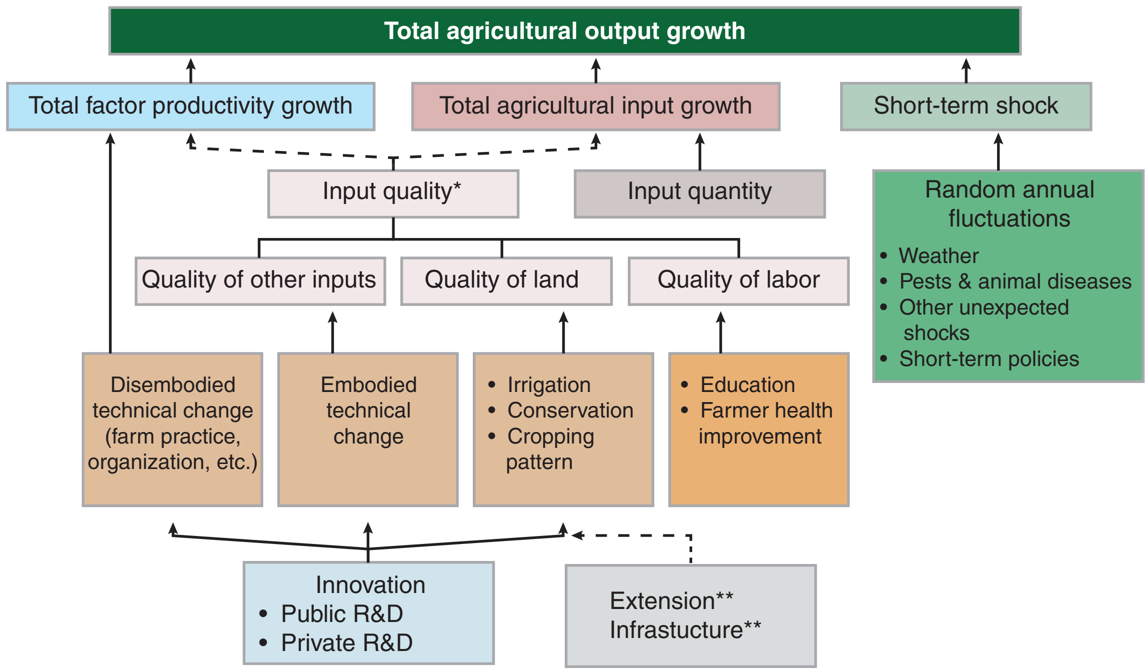
The sources of long-term growth in agricultural output are input growth and TFP growth (fig. 1). Although output growth can be affected by adverse weather events, pests or animal diseases, business cycles, or other factors in the short term, it often returns to its previous trend over time. The factors causing short-term fluctuations in agricultural output differ from those affecting long-term trends and generally call for different policies.

Jorgenson and Griliches (1995) assert that, in addition to measuring TFP growth, one should also try to understand and measure the sources of productivity growth. Jorgenson and Griliches, among others, have made efforts to measure input quality changes and incorporate quality-adjusted inputs in TFP measurement. In this approach, input changes include changes in quality—such as labor quality, land quality, and quality embodied in other inputs, such as agricultural chemicals, and farm machinery—as well as changes in quantity. Still, measures of input quality depend on data availability. The dotted lines in the upper part of the figure indicate that input quality can affect measures of either TFP or agricultural inputs.

No matter how input quality change is categorized, researchers generally agree that one of the major factors driving longrun productivity growth—including both embodied and disembodied

Figure 1

Sources of agricultural output growth



* Indicates that the direction of input quality depends on how TFP and input are defined and measured.
** Indicates that "extension activity" and "infrastructure" could enhance the dissemination of knowledge to improve input quality and farmers' operation skill.
Source: USDA, Economic Research Service.

technical changes[1]—is innovation that results from research funded by both public and private sectors. Extension activities[2] and some public infrastructure, such as roads, electricity, and telecommunications, can enhance the dissemination of new technologies and techniques to farmers, reduce marketing costs, and, thus, influence longrun productivity growth. Irrigation is also a form of infrastructure, but it directly affects land quality and is identified separately in figure 1.

In the last two decades, slower growth in crop yields has turned the spotlight on global as well as U.S. agricultural production and has raised concerns about a possible slowdown in agricultural productivity growth and an increase in food insecurity. When growth in real U.S. public agricultural research funding, which has historically driven innovation, began slowing in the 1980s, concerns about slowing U.S. productivity growth were raised anew. If research and innovation slow and productivity growth slackens, the inability to keep pace with increasing global commodity demand could lead to price increases, which would particularly affect low-income populations in developing countries that already spend much of their income on food. Slower agricultural productivity growth could also affect the environment as farmers intensify use of land and chemicals to produce more output in response to higher prices.

[1]Embodied technical change (ETC) originally referred to the technological advances embodied in the capital goods that make equipment work faster or better in some way. This term can be applied to other inputs when the quality of that input is improved. Disembodied technical change is technical change not associated with any particular input.

[2]Extension activities include a range of communications aimed at providing technical guidance to farmers, such as farm practice demonstration, workshops, State and county specialists' farm visits, publications, and online information.

This study addresses four key questions of interest to both researchers and policymakers:

1. What are the trends in U.S. agricultural output, input, and productivity growth since WWII and how have the compositions of agricultural output and input shifted over time?

2. What are the differences between partial factor productivity and TFP and why does the measurement matter?

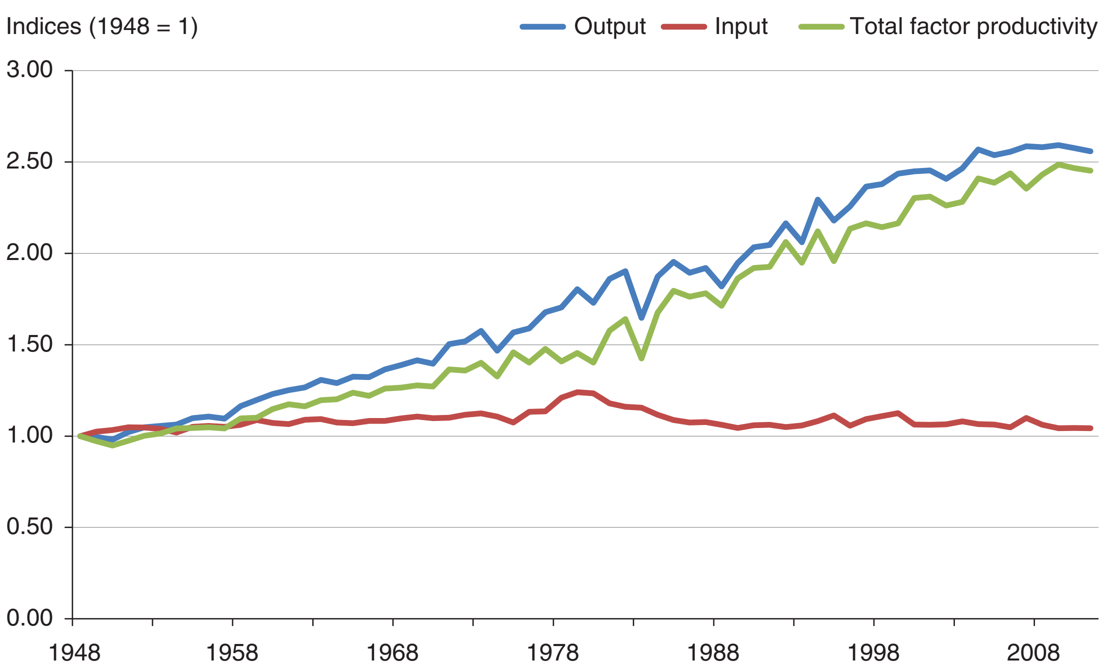
3. Is U.S. agricultural productivity growth slowing?

4. How can the United States sustain agricultural productivity growth in the long run?

To answer these questions, we use the ERS agricultural productivity accounts to examine the nature and sources of agricultural productivity growth from 1948 to 2011. According to these accounts, U.S. agricultural output has more than doubled in this period. With little growth in aggregate input use, the impressive performance in U.S. farm production is driven mainly by TFP growth (fig. 2).

USDA has been monitoring U.S. agricultural productivity for decades. In 1960, USDA introduced multifactor productivity measurement into the Federal statistical system. Today, ERS routinely publishes TFP measures based on a sophisticated system of farm production accounts. Its TFP model relates the growth rates of multiple outputs to the cost-share weighted growth rates of labor, capital (including land), and intermediate inputs. The annual TFP growth is the difference between growth in aggregate output and aggregate input. The dataset provides statistics on TFP, along with

Figure 2
Agricultural productivity growth accounted for most output growth between 1948 and 2011



Source: USDA, Economic Research Service productivity accounts.

estimates of 10 outputs and 12 inputs. This study draws on data from the most recent ERS national productivity accounts (1948-2011) (see box "How Does ERS Measure Agricultural Output, Input, and Total Factor Productivity in the U.S. Agricultural Productivity Accounts" and USDA-ERS (2013)).

How Does ERS Measure Agricultural Output, Input, and Total Factor Productivity in the U.S. Agricultural Productivity Accounts?

ERS constructs aggregates of output and inputs as implicit quantities based on the Törnqvist indexes approach over detailed output and input information. Indexes of output—including meat animals, dairy products, poultry and eggs, food grains, feed crops, oil crops, vegetables and melons, fruits and nuts, other crops, and other farm-related outputs—are formed by aggregating over agricultural goods and services using revenue-share weights based on shadow prices.[1] Indexes of inputs—including durable equipment, service buildings, land, inventories, hired labor, self-employed, farm origin input, energy, fertilizer and lime, pesticides, purchased services, and other intermediate goods—are formed by aggregating over individual agricultural inputs using cost-share weights.

The changing demographic characteristics of the agricultural labor force are used to construct a quality-adjusted index of labor input. Similarly, much asset-specific detail underlies the measure of capital input. The construction of a measure of capital input begins with estimating the stock of capital for each component of capital input. For depreciable assets, the capital stocks are the cumulation of past investments adjusted for discards of worn-out assets and loss of efficiency of assets over their service life. Indexes of capital input are then formed by aggregating over the various capital assets using cost-share weights based on asset-specific rental prices. The land stock is adjusted by quality differences across counties and States. Törnqvist indexes of energy consumption are calculated by weighting the growth rates of petroleum fuels, natural gas, and electricity by their shares in the overall value of energy inputs. Agricultural chemicals—including fertilizers and pesticides—as well as purchased contract labor services are adjusted for their quality changes over time using the hedonic method.

The total factor productivity (TFP) index is measured as the ratio of aggregate output over aggregate input. Therefore, TFP *growth* can be measured as the difference between output growth and input growth. For further information, see www.ers.usda.gov/data-products/agricultural-productivity-in-the-us/findings,-documentation,-and-methods.aspx.

[1]The shadow price is the price farmers actually receive or face for each commodity. It reflects the market value, the Government subsidy, and/or Government tax (or tax rebate) for that commodity.

Trends and Compositional Shifts in U.S. Agricultural Outputs and Inputs

Over the last six decades, the U.S. farm sector has undergone structural, organizational, and technological changes, with agricultural production shifting to larger and more specialized farms and farmers relying more heavily on contracting to manage their risk (Hoppe et al., 2007, O'Donoghue et al., 2011, and MacDonald et al., 2013). Structural and organizational change may also interact with technological change (see Huffman and Evenson (2006), MacDonald et al. (2013), and Fernandez-Cornejo (2014) for crops; and Huffman and Evenson (2006), McBride and Key (2013), and MacDonald (2014) for livestock). Besides adopting new technologies, applying more efficient practices, increasing farm size, and becoming more specialized, the farm sector has also experienced significant shifts in both output composition and input use. The combined changes in resources, preferences, and technology have altered the relative prices of inputs and the profitability of outputs. Farmers today use more capital and chemicals and less labor and land than they did in 1948. They purchase more services for tasks that they used to perform themselves. The mix of items that farms produce has also changed: far more acreage is devoted to soybeans and far less goes to oats and cotton; and changing consumer diets have led to large increases in production of poultry and fruits and vegetables. Changes in the mix of outputs and inputs affect how the farm sector is organized and the sources of TFP growth.

Trends and compositional shift in agricultural outputs: 1948-2011

Farm output includes primary agricultural products and certain secondary activities that are closely linked to agricultural production, such that information on production and input use cannot be separately observed. Secondary activities (alternatively, farm-related output) includes recreation activities,[3] the imputed value[4] of employer-provided housing, land rentals under USDA's Conservation Reserve Program (CRP),[5] and services such as custom machine work and custom livestock feeding. Table 1 shows output growth[6] in three major categories—livestock, crops, and farm-related output—and changes in the composition of livestock revenue and crop revenue over the last six decades.

U.S. agricultural output has more than doubled (up 156 percent) since 1948. Yet, the growth trends in farm commodities differ, and the revenue shares of individual commodities in total farm output have shifted over time. From 1948 to 2011, aggregate output grew at an average annual rate of 1.49 percent, with the crop sector growing faster than the livestock sector. The growth of crops accelerated and surpassed the growth of livestock in the mid-1970s, due partly to faster growing foreign

[3]Farm-based recreation includes hunting, fishing, horseback riding, and other onfarm activities that provide income to farmers. See Brown and Reeder (2007) for more details.

[4]There is no actual rent earned or paid regarding the employer-provided housing. Yet, to reflect farmers' production or expense, the value of employer-provided housing was estimated using the market value of housing rental rate.

[5]The Conservation Reserve Program (CRP) is a land conservation program established by the 1985 Food Security Act and is administered by USDA's Farm Service Agency. The goal of the program is to re-establish valuable land cover to help improve water quality, prevent soil erosion, and reduce loss of wildlife habitat. CRP is the largest Federal program idling cropland, offering annual rental payments to farm owners and operators who voluntarily retire environmentally sensitive cropland under 10- to 15-year contracts.

[6]In ERS's productivity accounts, the implicit quantities of output and input are measured as nominal values deflated by their corresponding price indices (in 2005 dollars). The implicit quantity is therefore a "real value" in constant dollars.

Table 1
Farm output growth and changes in revenue shares

	Total changes	Annual growth rate	Total revenue shares[3]	
	1948-2011	1948-2011	1948	2011
	Percent			
Total output[1]	156	1.49	100	100
Livestock and products	130	1.32	47	39
Meat animals	98	1.08	21	20
Dairy	109	1.17	10	9
Poultry and eggs	617	3.13	9	9
Crops	163	1.54	52	56
Food grains	84	0.97	7	4
Feed crops	129	1.32	24	24
Oil crops	604	3.10	3	10
Vegetables and melons	178	1.62	4	5
Fruits and nuts	265	2.05	3	6
Other crops[2]	449	2.70	2	6
Farm-related output	380	2.49	1	5

[1]Total output includes "livestock and products," "crops," and "farm-related output." Farm-related outputs includes secondary output, such as recreation activities, custom machine work, and custom livestock feeding.
[2]Other crops include sugar crops, maple, seed crops, miscellaneous field crops, hops, mint, greenhouse and nursery, and mushrooms.
[3]Because some minor products are not reported in the table, the sum of revenue shares from the components will not sum up the subcategory's share in total revenue.
Source: USDA, Economic Research Service productivity accounts.

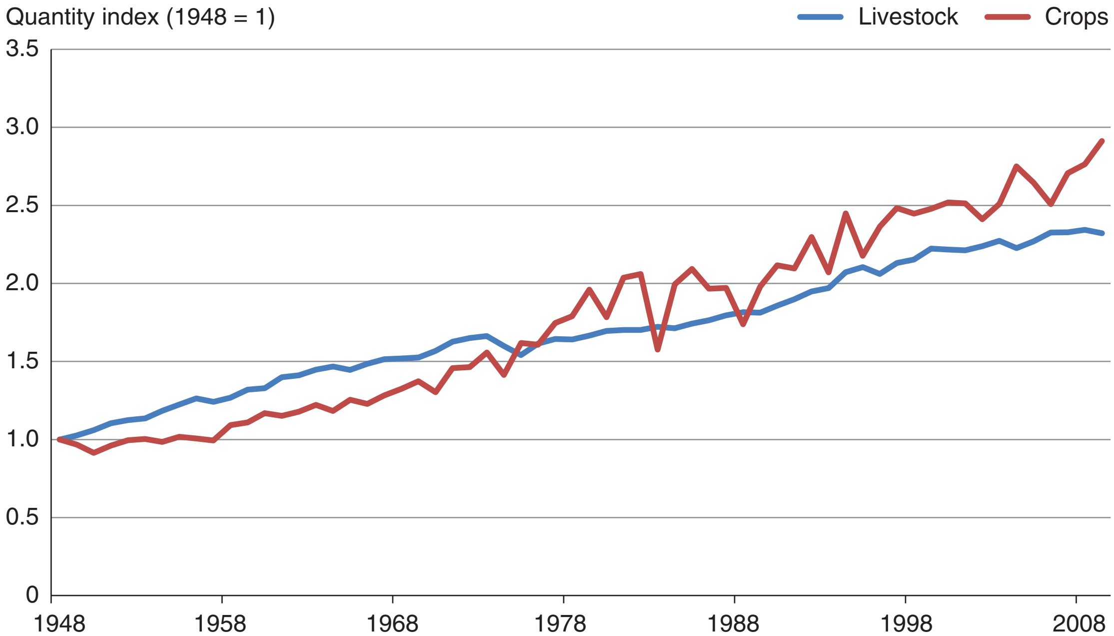
demand for crop exports relative to livestock exports (USDA-FAS, 2014). As a result, the crop revenue share of total farm production increased from 52 to 56 percent, the livestock share dropped from 47 to 39 percent, and the farm-related output share grew by 4 percentage points between 1948 and 2011. In general, crop production fluctuates more than livestock (fig. 3) as it is more sensitive to adverse weather events.

Livestock

Although livestock's revenue share of total farm production declined, the real value of livestock still grew by 130 percent from 1948 to 2011, with poultry and eggs growing much faster than meat animals (including cattle, hogs, and lamb) and dairy products. Among the three subcategories of livestock analyzed (see table 1), meat animals accounted for the largest share of production: 45 percent of the total livestock revenue share in 1948 and 50 percent in 2011. Yet, the poultry subcategory had the most rapid growth due largely to changes in technology and consumer preferences: in 2011, total poultry and egg production was more than seven times its level in 1948 (real value) (see table 1 and figure 4), with an average annual growth rate exceeding 3 percent. The production of some miscellaneous products—such as honey and wool—has declined over the period, resulting in a greater decrease in livestock's total revenue share than can be inferred from the trends mentioned here.

Figure 3

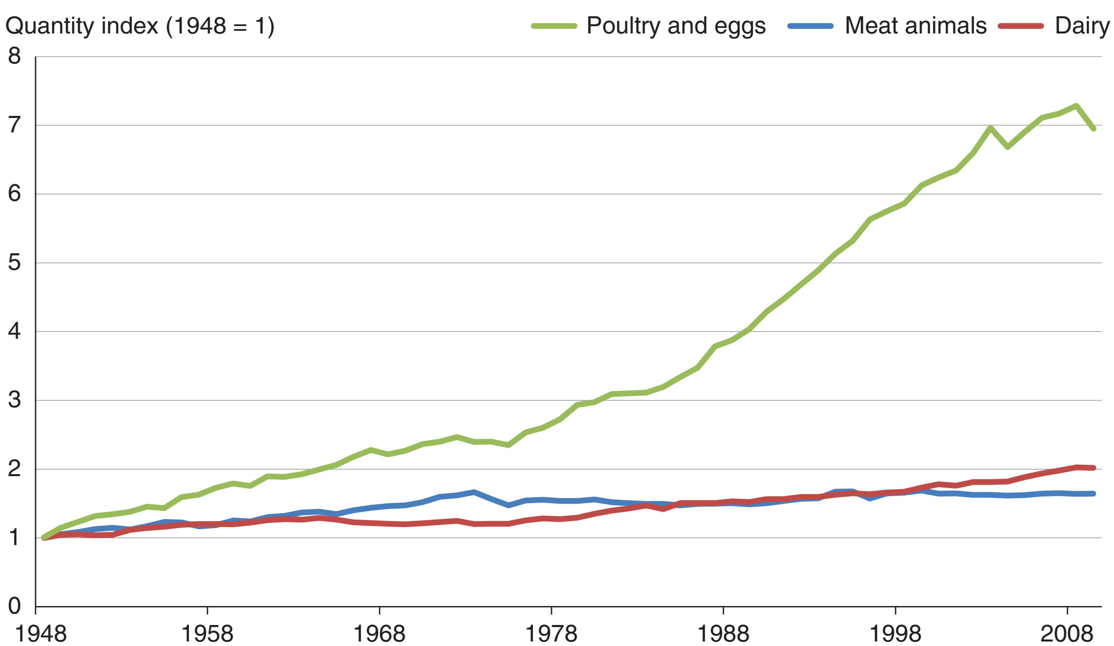
U.S. crop output has grown faster and more variably than livestock output since the 1970s



Source: USDA, Economic Research Service productivity accounts.

Figure 4

U.S. poultry and egg output has grown much more rapidly than dairy and meat animal output over the past 60 years

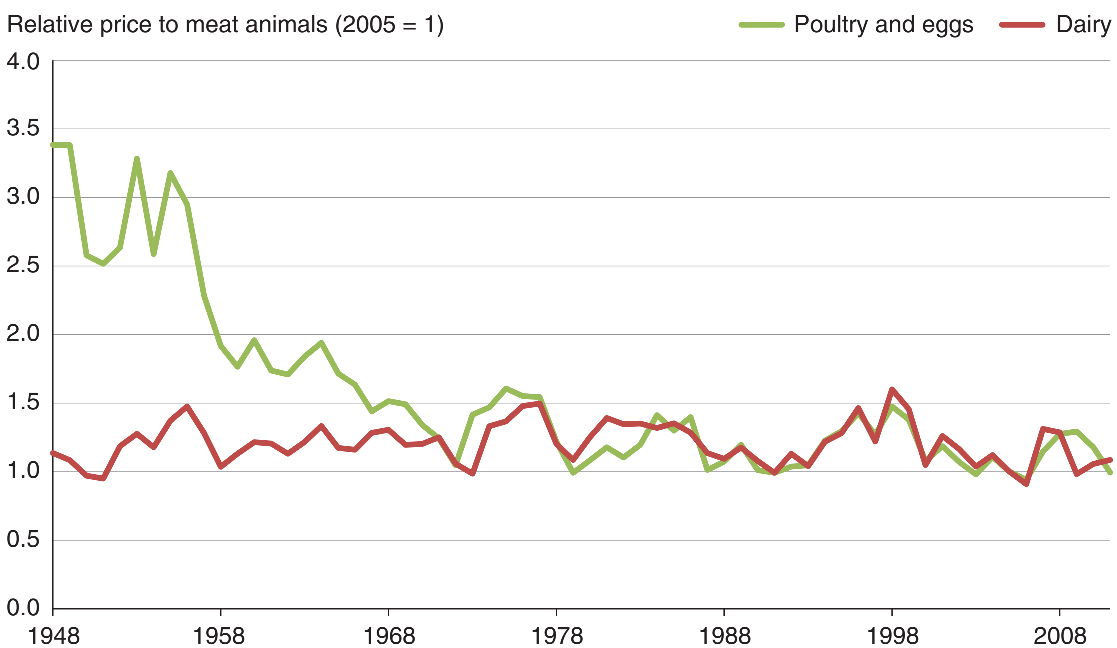


Source: USDA, Economic Research Service productivity accounts.

Relative commodity prices changed over time and account for some of the shift in revenue shares (fig. 5). In particular, prices of poultry and eggs grew much slower than prices of other livestock products, resulting in a sharp drop in the price of poultry and eggs relative to meat animals between 1948 and 1970. Since then, price trends for the three major groups have generally followed a common longrun trend. The relative price changes can be partially due to advances in animal and poultry genetics, which have been faster in poultry than in hogs and cattle. The genetic base for poultry is relatively narrow and the biological production cycle is much shorter than that for other meat animals (Ward, 2014).

Advances in animal housing, feed, pharmaceuticals, and management have also made it possible for large, confined or semi-confined poultry operations to be profitable and to crowd out many of the small and medium-sized operations (Huffman and Evenson, 2001; McBride and Key, 2013; and MacDonald, 2014). The continued growth of poultry production after 1970 also reflects increased demand, often in response to new products and product differentiation led by vertically integrated firms (Ward, 2014; and MacDonald, 2014) without major changes in relative prices.

Figure 5
Relative price of poultry and eggs output to other livestock products declined more rapidly before the 1970s



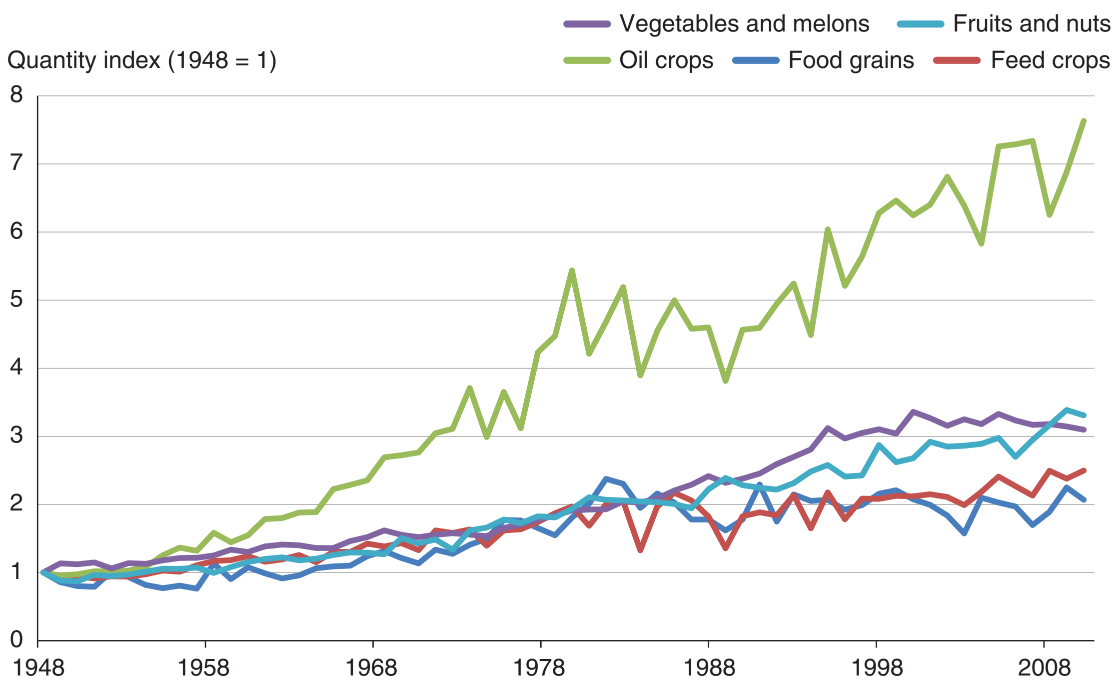
Source: USDA, Economic Research Service productivity accounts.

Crops

From 1998 to 2011, production of oil crops grew at the highest average rate (3.1 percent per year) among all crops analyzed (see table 1, fig. 6). The major oil crops are soybeans, cottonseed, sunflower seed, canola, rapeseed, and peanuts. Soybeans account for about 90 percent of U.S. oilseed production and are also one of the most important U.S. field crops next to corn. Soybean production goes overwhelmingly to animal feed. In 1948, soybean planted area was 12 million acres. By 2011, it had increased to 75 million acres. The large increases in soybean planting were driven by innovations in soy production and processing and growth in poultry and egg production, which boosted demand for oilmeals in feed consumption. With the highest growth in the crop sector, the oil crop share of total crop revenue increased from 6 to 17 percent from 1948 to 2011. As a result, oil crops are now the second largest subcategory in the crop sector. The crop revenue shares for vegetables and melons, as well as for fruits and nuts, also grew in response to increasing consumer demand over time.

Contrarily, in 2011, total production of food grains for human consumption was only 84 percent higher than in 1948. The slower growth for food grains production than for other crops may reflect changes in consumers' dietary preferences, which shifted to a less carbohydrate-heavy diet over time. Feed crops constitute the largest subcategory in the crop sector. Nonetheless, with slower growth, feed crops' share of total crop revenue declined from 46 percent in 1948 to 42 percent in 2011. The slowing growth in feed demand is related to a composition shift in livestock production in addition to productivity gains (FAO, 2012). As poultry requires lower quantities of cereals feed per kilogram of meat than other meat animals, feed crop demand slowed when poultry production grew more rapidly than production of other livestock. In addition, over 40 million acres were shifted from

Figure 6
Oil crop output increased over sevenfold over the past 60 years, faster than all other U.S. crop outputs



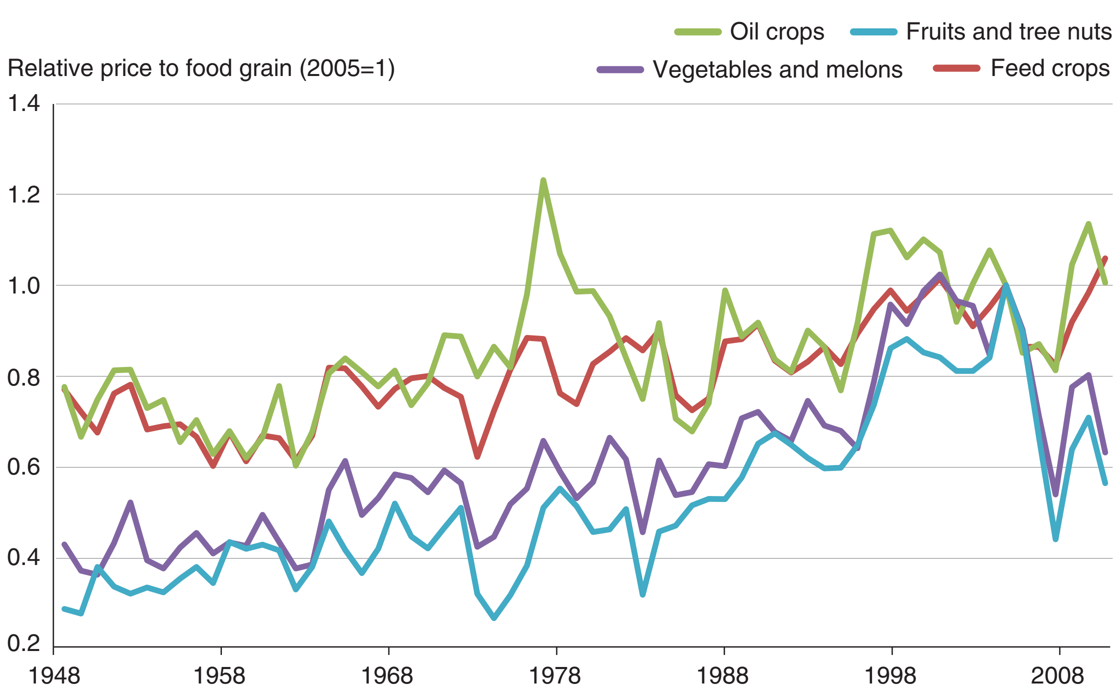
Source: USDA, Economic Research Service productivity accounts.

oats production to soy production as farm operations continued to switch from horses and mules to tractors, reducing the need for feed oats and hay. This offset the growth in other feed crop production (MacDonald et al., 2013).

Over the post-WWII period, the prices of fruits/nuts and vegetables/melons rose much faster than those of food grains, feed crops, and oil crops (fig. 7). Several factors may account for these changes. First, over time, U.S. consumers have gradually shifted their diets from grain-based food to higher intakes of fruit and vegetables, as the latter have been shown to be an important part of a healthful diet (Pollack, 2001). This shift has increased demand for fruit and vegetable production. However, genetic improvement is slower for tree fruits and nuts as many of these crops have a longer bearing period than shorter life cycle food grains and feed crops. Scorza (2001) notes specific problems in the development of new tree fruit cultivars, including "generation cycles of 3-20 years." As with fruit, vegetable breeding has to focus not only on yield but also on quality traits, and vegetable production may be particularly constrained by diseases and pests (Dias and Ryder, 2011). All of these factors could have contributed to prices of fruits/nuts and vegetables/melons increasing faster than prices for other crops.

The prices of oil crops, food grains, and feed crops moved much closer together than did those of the other crop categories and were relatively stable between 1985 and 2005. Crop prices started escalating after 2005 in response to strong export demand as well as domestic biofuel demand. The prices of food grains, feed crops, and oil crops rose to new nominal highs in 2008, increasing by 127, 88, and 85 percent, respectively, between 2005 and 2008. As a result, the relative prices of fruits/nuts and vegetables/melons dropped dramatically during that period. While prices subsequently declined in 2009-10, they rebounded and reached record highs in 2011-12.

Figure 7
Most crop prices increased faster than food grain prices except for recent years



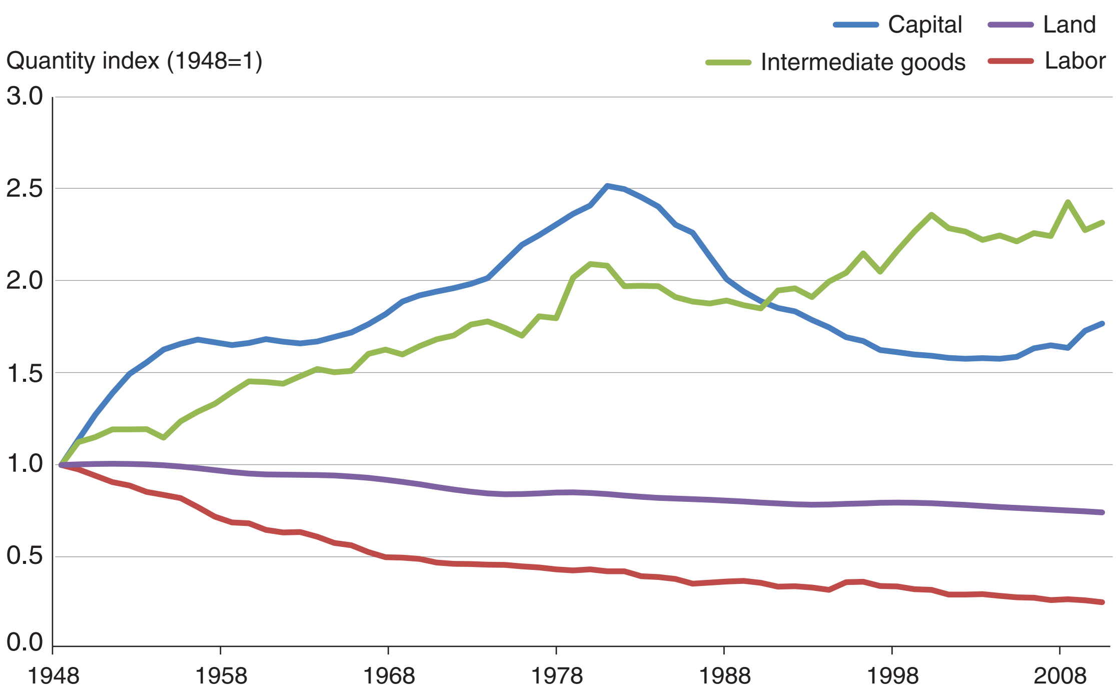
Source: USDA, Economic Research Service productivity accounts.

Trends and compositional shift in agricultural inputs: 1948-2011

In contrast to the fast growth in agricultural output, the implicit quantity of inputs—obtained by deflating input expenditures with input price indices—grew slightly, at an average annual rate of 0.07 percent during 1948-2011. Among the four major input categories—labor, capital, intermediate goods, and land—only capital and intermediate goods showed long-term positive growth, with average annual growth rates of 0.8 percent and 1.27 percent, respectively (fig. 8). During the same period, land input dropped by 26 percent, or 0.5 percent per year, while labor use declined much more sharply by 78 percent, or 2.41 percent per year. In addition to being replaced by machinery and agricultural chemicals, over the last two decades, farm labor input has also been replaced by purchased contract labor services, which are included as part of purchased services in intermediate goods.[7]

Since the longrun growth rates among inputs are different, the composition of inputs changed markedly over the past 60 years. In 1948, intermediate goods accounted for 40 percent of total input cost, but the cost share rose to almost 60 percent by 2011. Capital's cost share also increased from 4 percent of total production costs in 1948 to 8 percent in 2011. Along with the decline in land use, land's cost share decreased from one-third to less than one-fourth, and labor's share of input costs contracted from nearly 25 percent in 1948 to 13 percent in 2011 (table 2).

Figure 8
Since 1948, labor and land inputs have fallen in U.S. agriculture while use of intermediate inputs has risen



Source: USDA, Economic Research Service productivity accounts.

[7]In ERS's productivity accounts, contract labor service is included in the intermediate goods category as purchased service. In addition to hired labor and self-employed and unpaid farmworkers, farmers sometimes need to contract with labor brokers to assemble crews, especially during the harvest season when extra labor is needed. We call this farm expenditure "purchased contract labor service." Since farmers contract with labor brokers for a certain service of farm work, such as fruit picking, only total expenses information is collected in USDA's Agricultural Resource Management Survey (ARMS). Contracted workers are mostly paid by pieces, and no "hours worked" information for contract labor is available. The nominal expenditures of contract labor service are converted into implicit quantities using a "piece rate" price index as deflator.

Table 2
Input growth and changes in cost shares

	Total changes	Annual growth rate	Total cost shares	
	1948-2011	1948-2011	1948	2011
		Percent		
Total farm input	4	0.1	100	100
Capital	65	0.8	4	8
Durable equipment	76	0.9	3	5
Service buildings	16	0.2	1	2
Inventories	75	0.9	0	1
Land	-26	-0.5	33	23
Labor	-78	-2.4	24	13
Hired labor	-69	-1.9	7	6
Self-employed	-82	-2.7	17	8
Intermediate goods	122	1.3	40	56
Farm origin	98	1.1	30	29
Energy	32	0.5	2	5
Fertilizer and lime	190	1.7	2	6
Pesticides	3,022	5.5	0	3
Purchased services	112	1.2	5	11

Source: USDA, Economic Research Service productivity accounts.

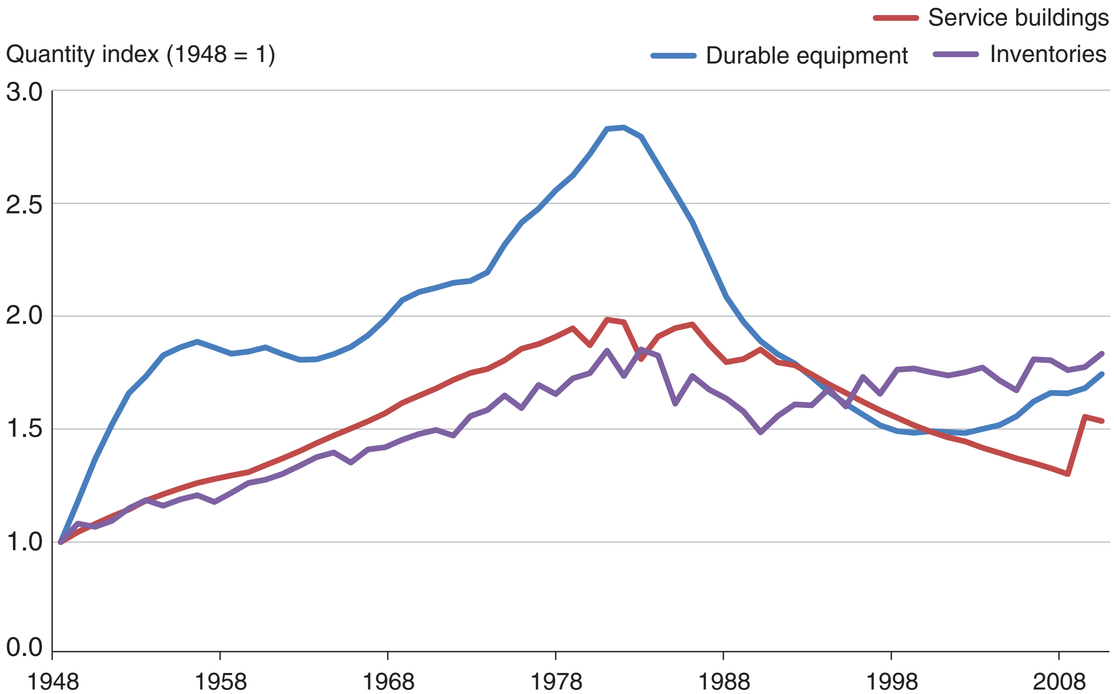
Capital (excluding land)

Capital goods include durable equipment and farm buildings. Capital investment increased dramatically in the immediate postwar period. In the productivity accounts, capital inputs are measured as the service flows provided by capital stocks, which are the net accumulation of capital investment from the past (USDA-ERS, 2013b). Service flows from durable equipment rose at an average annual rate of 11.1 percent between 1948 and 1953, reflecting rapid mechanization of agriculture (fig. 9). Growth slowed between the late 1950s and late 1960s and accelerated again after 1973, coincident with expansion in U.S. agriculture exports, fueled by growth in global liquidity and production shortages abroad (Ball and Wang, 2012). Agricultural exports continued to grow until 1981. Since interest rates did not rise as fast as inflation, real interest rates (nominal interest rates minus inflation) fell or remained very low between 1975 and 1980, and the cost of investment fell accordingly. As a result, farmers increased borrowing to purchase more machinery. Other capital inputs, including service building and inventories, also grew steadily until 1980.

The three capital series—durable equipment, service buildings, and inventories—peaked in 1980-81 and then declined. Monetary policy pushed nominal interest rates up sharply in 1981-83. Since nominal rates rose above the inflation rate during that period, real interest rates rose and made it costly to finance purchases of additional farm machinery. In addition, high real interest rates attracted capital inflows from abroad and pushed up the value of the U.S. dollar (see box “The Real Interest Rate and the Value of the U.S. Dollar (Exchange Rate)"). Appreciation of the U.S. dollar slowed agricultural exports. Real agricultural exports fell by 25 percent between 1980 and 1986,

Figure 9

Trends of capital input components exhibit a similar inverted-V pattern, with turning points in the early 1980s



Source: USDA, Economic Research Service productivity accounts.

with nominal agricultural exports falling much more, by nearly 40 percent over the same period. Declining demand for U.S. agricultural commodity exports and rising borrowing costs reduced farmers' incentives for further capital investment. Capital investment declined between 1979 and 1986 and remained stable until the mid-1990s (see box "Capital Service Flow Versus Capital Investment and Capital Stock").

Capital investment in farm structures and machinery started to grow in the late 1990s as real borrowing costs fell and agricultural commodity prices rose. While machinery service flows declined in the 1980s, combined expenses[8] on custom machine work (such as tilling, plowing, field cultivation, mowing, planting, and fertilizer spreading) and capital equipment leasing (part of purchased service inputs) started to rise. Machinery service flows rebounded in the 2000s. On the other hand, purchased custom machine work and capital equipment leasing peaked in 1998 and declined thereafter. As expected, these two opposing trends imply a substitution relationship between onfarm machinery uses and purchased custom machinery work (fig. 10).

Although the patterns of growth look similar for individual capital components, their cost shares have varied over time. From 1948 to 2011, durable equipment's share of total capital costs dropped from 72 to 65 percent, inventories' share increased from 5 to 12 percent, and service buildings' share remained roughly unchanged at almost 25 percent of total capital costs. Durable equipment service flows still dominated capital composition in 2011.

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[8]The data were drawn from USDA's Agricultural Resource Management Survey where the two elements of custom machine work and capital equipment leasing were combined into one category. The category is included in the productivity accounts as part of purchased service inputs.

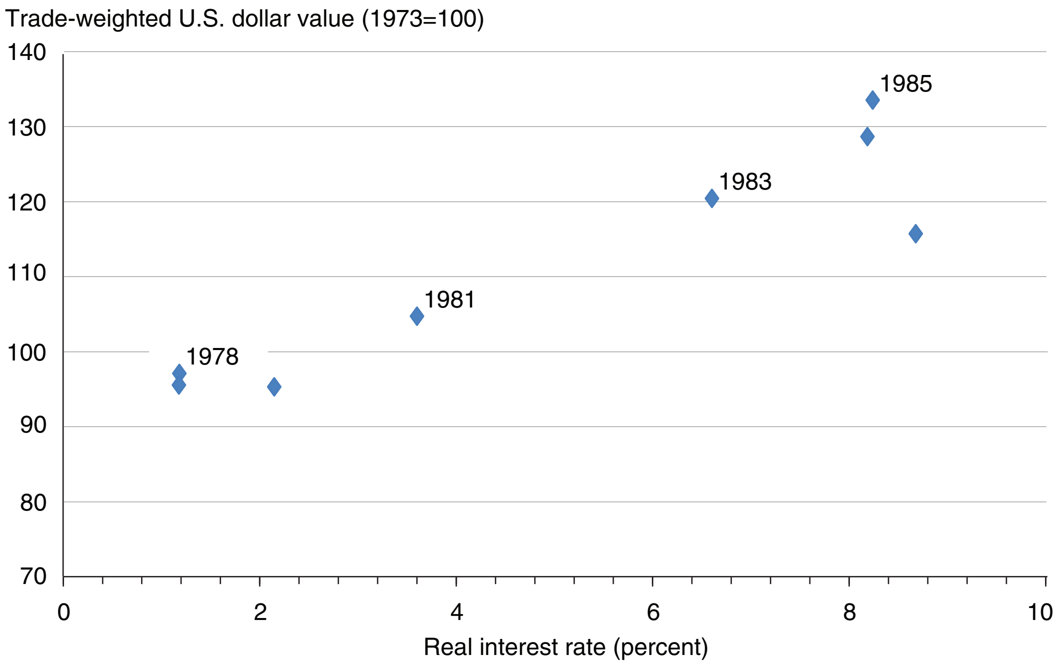
The Real Interest Rate and the Value of the U.S. Dollar (Exchange Rate)

According to the Fisher equation (Fisher, 1930), the real interest rate can be calculated as the nominal interest rate minus the inflation rate.[1] For example, 10-year Treasury bond rates (interest rate) were 9.10 percent, 12.57 percent, 10.46 percent, and 11.38 percent in January of 1979, 1981, 1983, and 1985, respectively. Given that Gross Domestic Product deflators increased by 7.93 percent, 8.93 percent, 3.87 percent, and 3.15 percent in each of those respective years, real interest rates were 1.17 percent, 3.64 percent, 6.59 percent, and 8.23 percent for 1979, 1981, 1983, and 1985, respectively.

Higher real interest rates tend to attract capital inflows from abroad and lead to U.S. currency appreciation. Box figure 2.1 shows the relationship between the real interest rate and the trade-weighted value of the U.S. dollar. During the early 1980s, real interest rates were high. Based on 10-year Treasury bond rates, real interest rates ranged from 1.2 percent to 8.7 percent between 1978 and 1985. The figure shows that a higher real interest rate was usually accompanied with a higher value of the U.S. dollar during that period.

Box figure 2.1

The increase in the real interest rate pushed up the U.S. dollar value in the early 1980s



Sources: USDA, Economic Research Service calculations based on data from Bureau of Economic Analysis, Federal Reserve Board, and Board of Governors of the Federal Reserve System.

[1] A more formal expression of the relationship between real interest rate and nominal interest rate is $1+r=\frac{1+i}{1+\pi}$ where r denotes the real interest rate, i denotes the nominal interest rate, and π denotes the inflation rate. The equation can be rearranged as $(1+r)*(1+\pi)=1+i$, or $1+r+\pi+r\pi=1+i$. When both the real interest rate and the inflation rate are small, the equation can be expressed as $r \approx i-\pi$, *i.e.*; the real interest rate is approximately the nominal interest rate minus the inflation rate. However, the Fisher equation is usually written as an equality that $r=i-\pi$.

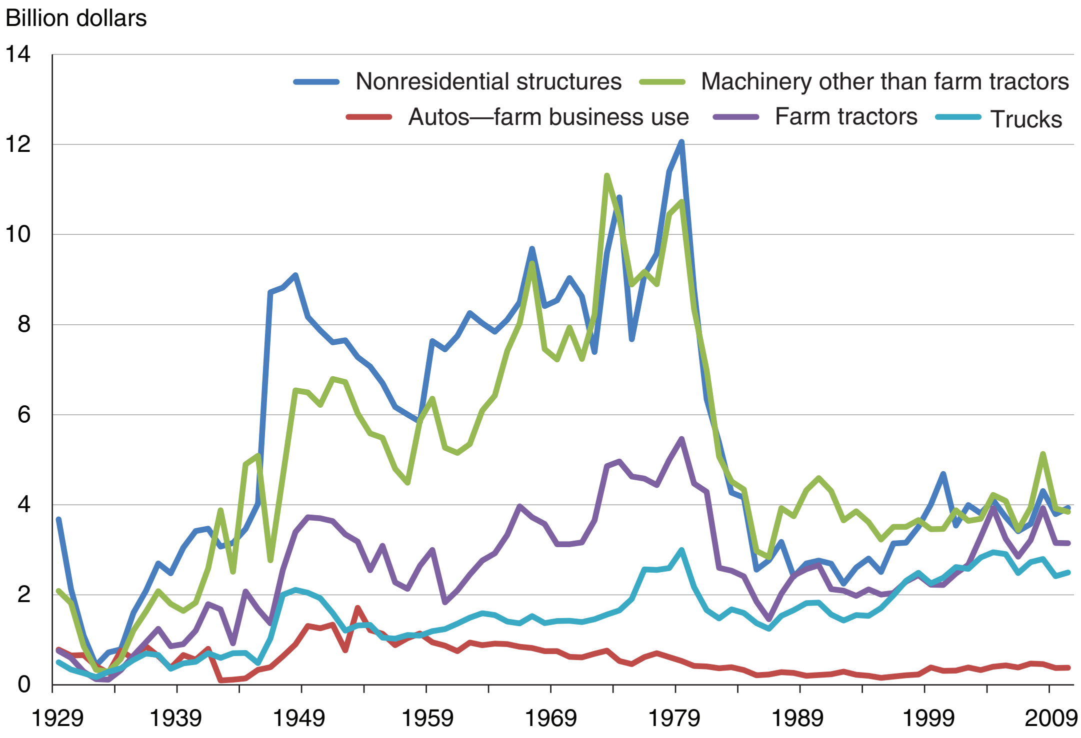
Capital Service Flow Versus Capital Investment and Capital Stock

In USDA's productivity accounts, capital input is measured as capital service flows instead of capital investment or capital stock. This is because the service life for each capital component is longer than 1 year and varies from one capital component to another. For example, a service building can last for more than 35 years, while a tractor may last for less than 10 years. Farmers use the services generated by different kinds of machinery or structures in their annual production of farm commodities.

The capital service flow is an annual aggregation of the services provided by each of the capital input components each year and is calculated as the rental rate multiplied by the capital stock, which is an accumulation of capital investment from the past. Since the efficiency of each piece of equipment decays over time, ERS applies a hyperbolic efficiency pattern to account for the depreciation of machinery and structures. The hyperbolic efficiency pattern assumes that buildings and equipment depreciate slowly in the beginning and then wear out faster near the end of their lifespans.

Because capital inputs are long lived, we need a long investment series prior to the first year of the estimates to construct a capital stock series. Box figure 3.1 presents data on investment in each capital component, while box figure 3.2 presents data on different capital stocks. The two figures show that although the investment amounts are similar for "other machinery" and "farm

Box figure 3.1
Agricultural capital investment trends (constant 2005 dollars)

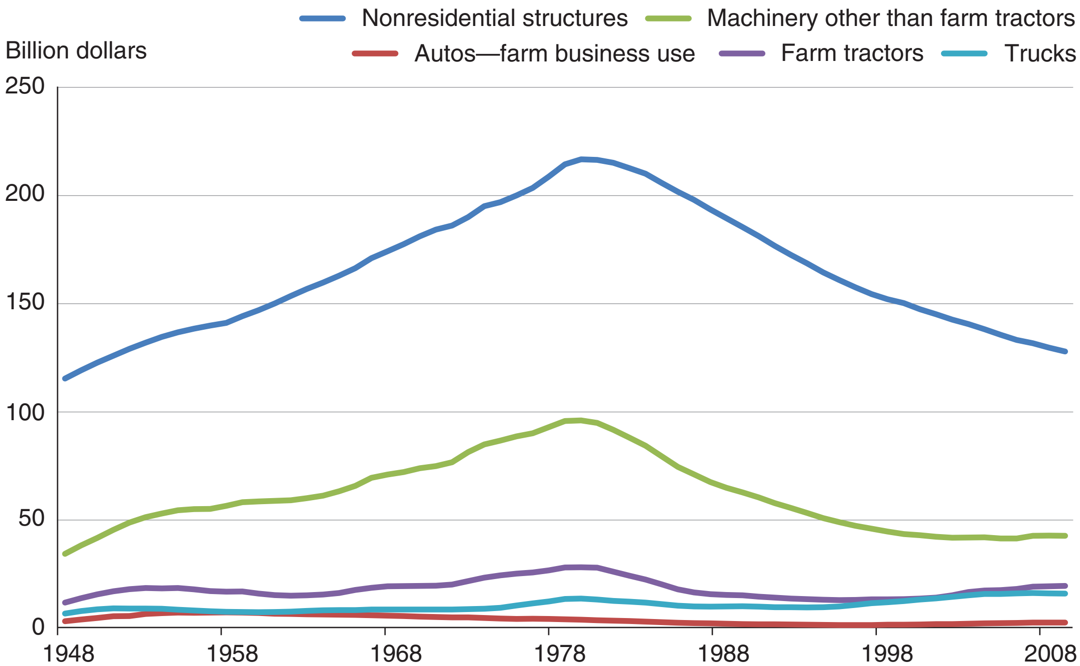


Source: USDA, Economic Research Service productivity accounts.

Continued—

Box figure 3.2

Agricultural capital stocks in the United States have declined since the early 1980s along with capital investment (2005 constant dollars)



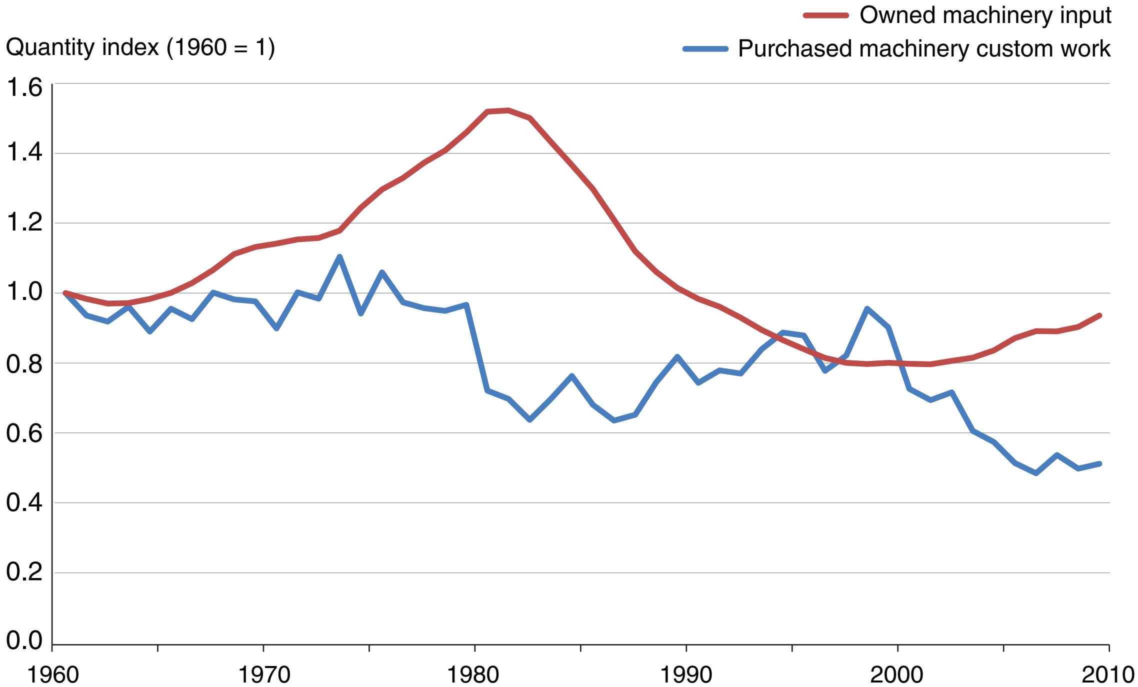
Source: USDA, Economic Research Service productivity accounts.

structures," the capital stock for farm structures is much higher than for other machinery. The gap is due to the different lifespans used in the calculations for these two capital stocks. For example, a $1 dollar investment in farm structure will still be accounted for as part of capital stock for the next 38 years or so. Yet, a $1 dollar investment in a tractor may only be incorporated as part of capital stock for the next 9 years or so.

The decline in investment in the early 1980s, with only limited subsequent recovery, resulted in substantial decline in capital stock estimates, especially for farm structures and other machinery. It was not until the 2000s that all capital stocks started to rise in response to the increased levels of capital investment that started in the 1990s.

Figure 10

Aggregate trends in owned machinery and purchased services in machinery custom work suggest these two inputs may be substitutes



Source: USDA, Economic Research Service productivity accounts.

Land

Agricultural land (farmland) consists primarily of land used for crops, pasture, or grazing but also includes acres of idled cropland and woodland.[9] In the ERS productivity accounts, land stock is measured as the real value of total farmland, which is nominal land value[10] deflated by a land price index from ERS's productivity accounts (USDA-ERS, 2013a). Agriculture land stock decreased consistently over time at an average rate of 0.52 percent per year, and by 2011 was about three-quarters of its 1948 level (fig. 11).

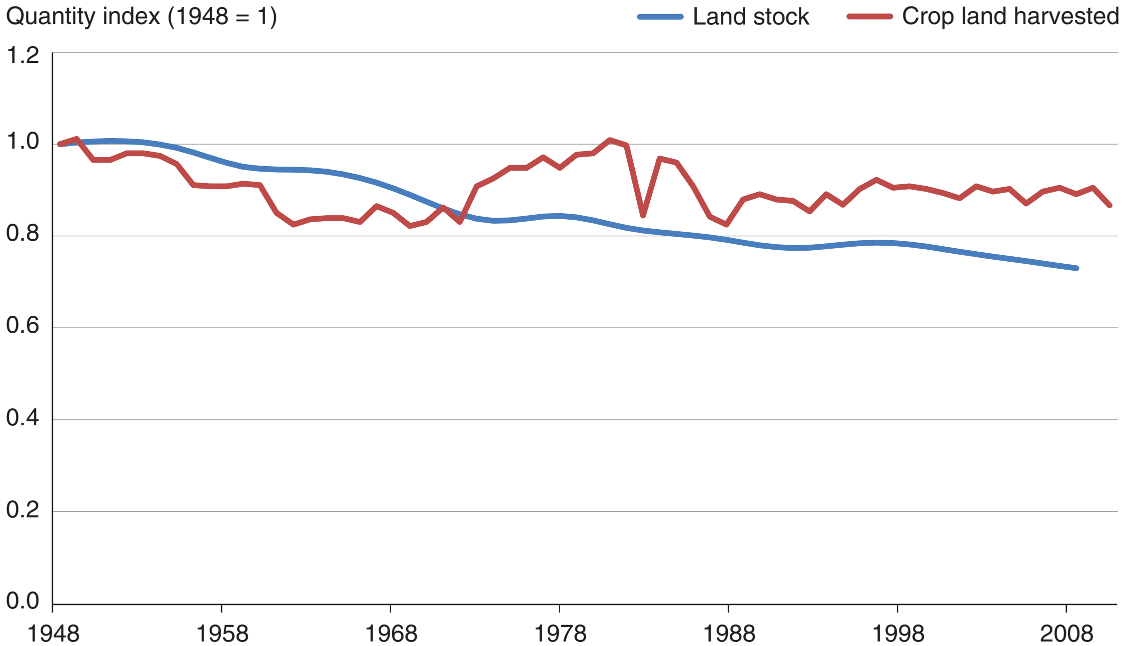
In general, grazed woodland has declined more rapidly than other land classes (Nickerson et al., 2011). According to ERS's major land use data (USDA-ERS, 2014), between 1949 and 2007, total U.S. cropland used for crops dropped from 383 million to 335 million acres, or 12.5 percent; cropland used for pasture dropped from 69 million to 36 million acres, or 48 percent; and grassland and pasture dropped from 632 million to 614 million acres, or 3 percent. On the other hand, idle cropland, which includes cropland enrolled in USDA's CRP, Wetlands Reserve Program (WRP), and other land retirement programs, increased from 26 million to 37 million acres between 1949 and 2007.

[9]According to the Census of Agriculture definition, woodland includes woodland used for pasture or grazing as well as some land that is not under cultivation or used for pasture or grazing (see www.ers.usda.gov/data/majorlanduses for data and more information).

[10]Farm real estate (including land and building) value from the census has been adjusted to exclude the value of farm structures in ERS's U.S. agricultural productivity accounts.

Figure 11

Although total U.S. land stock has declined steadily, crop land has stabilized since the 1990s



Source: USDA, Economic Research Service productivity accounts.

While total agricultural land stock continues to decline, the trend of harvested cropland area diverged from that of land stock after 1973 and has been far more stable since the 1990s. Changes in harvested cropland acres reflect smaller annual fluctuations in crop failure but also have an inverse relationship with idle land. Between 1948 and 1969, 51 million acres of U.S. cropland was diverted from crop production, mainly through Government acreage-reduction programs. The area under Federal cropland acreage reduction programs totaled 61 million acres in 1972 but declined to less than 3 million acres in 1974 (Nickerson et al., 2011).[11] Harvested cropland acres climbed to 351 million acres in 1981, when Federal programs did not idle any cropland, and dropped to 294 million acres in 1983, when Federal program set-aside acres reached their historic peak of 78 million acres. The CRP has been the largest driver of cropland changes since 1985 (Sullivan et al., 2004, Lubowski et al., 2006), although total acres of CRP enrollment have fallen since 2008 (Hellerstein, 2012; USDA-FSA, 2015). Harvested cropland area has been rather stable since the 1990s.

Labor

The labor estimate in the productivity accounts has been adjusted to reflect quality changes over time.[12] The quality-adjusted labor input fell by an average 2.41 percent per year between 1948

[11]Under the acreage reduction programs, the Government paid producers to voluntarily set aside a certain number of acres normally used for production.

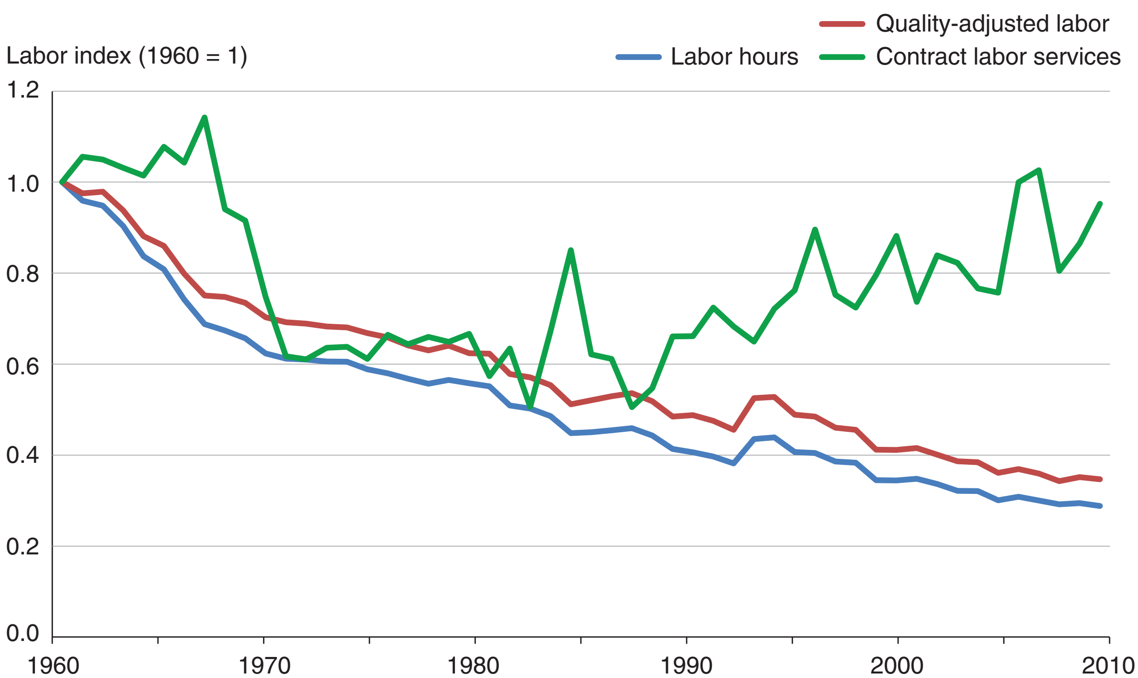
[12]ERS adjusts the labor series to account for changes in the composition of the farm labor force. ERS uses a cross-classification of 192 elements to account for changes in composition—two sexes, eight age classes, six educational classes (five before 1980), and two employment classes. In turn, skill differences are represented by differences in average earnings, economy-wide, across the 192 elements.

and 2011. In 2011, the total labor input was less than one-quarter of its 1948 level (see table 2). In comparison, total labor hours (without quality adjustment) dropped faster than the quality-adjusted labor series, at an average rate of 2.82 percent per year (fig. 12). This reflects increasing labor quality through higher educational attainment, which effectively slowed the decline in quality-adjusted labor input.

With the decline of farm labor, farmers have implemented labor-saving technology, such as the increased use of agricultural chemicals and farm machinery. Through time, machinery and materials substituted for labor use, and part of the labor input was also replaced by purchased contract labor services, especially in recent years (fig. 12). Farmers usually contract with labor brokers to assemble crews, especially during the harvest season when some work may rely more on hand picking instead of machinery. Contract labor services used to be a complement to total labor use and moved closely to the labor series in early years. However, starting in 1990, it seems that labor services have become a substitute for the labor input. Contract labor service is included in the purchased service series as part of the intermediate goods estimate in ERS's productivity accounts. It accounts for a much smaller share of the total production cost than self-employed and hired labor.

The rate of decline in labor input appears to have slowed since the 1970s (fig. 12). Between 1948 and 1970, total labor input declined by an average rate of 3.8 percent per year, whereas between 1970 and 2011, labor declined at an average rate of 1.8 percent per year. This may be due to the decreasing size of the gap between agricultural and nonagricultural labor wages. For example, the relative wage of agricultural to nonagricultural labor was 0.35, 0.51, and 0.69 in 1940, 1960, and 1980, respectively (Caselli and Coleman, 2001). In addition, average household incomes in the farm and nonfarm sectors converged in the 1980s, reducing the incentive for farm households to abandon farming

Figure 12
Labor input continues to decline, while purchased contract labor services have risen since the 1990s



Source: USDA, Economic Research Service productivity accounts.

(Hoppe and Banker, 2010). For instance, the ratio of average farm household income to average U.S. household income was 0.65 in 1960. This ratio increased to 0.95 in 1970 and was 1.25 by 2011 (USDA-ERS, 2013b).

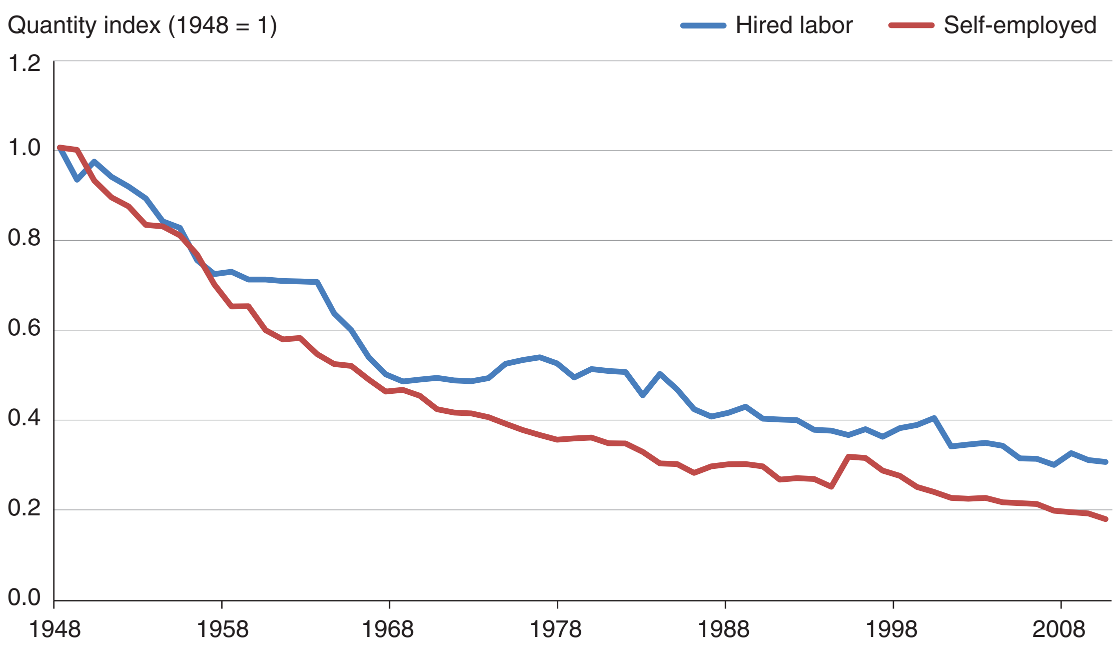
Although both "self-employed and unpaid family labor" and "hired labor" decreased over time, given that self-employed and unpaid family labor declined faster than hired labor, hired labor's share in total labor cost[13] increased from 29 to 42 percent between 1948 and 2011 (fig. 13 and table 2). Nevertheless, farm owners and their family labor still accounted for the majority of labor input in 2011.

In ERS's productivity accounts, contract labor service is included in the purchased services under the intermediate goods category.

Intermediate goods

Intermediate goods consist of farm origin,[14] fertilizer, pesticides, energy, and purchased services and were adjusted for quality changes when relevant data were available, such as changes in the characteristics of fertilizers, pesticides, and purchased contract labor services. Between 1948 and 2011, the average annual growth rate of intermediate goods was 1.27 percent, which was much higher than the growth rates of other inputs (see table 2). Over the past six decades, the combined growth of capital input (excluding land) and intermediate goods has more than offset the negative impact of declines

Figure 13
Use of both hired labor and self-employed labor in agriculture declined over time



Source: USDA, Economic Research Service productivity accounts.

[13]The cost of self-employed and unpaid family labor is imputed using the compensation information of hired labor with similar demographic details (see documentation in USDA-ERS, 2013a).

[14]Farm origin includes seed, feed, and purchased livestock in farm production.

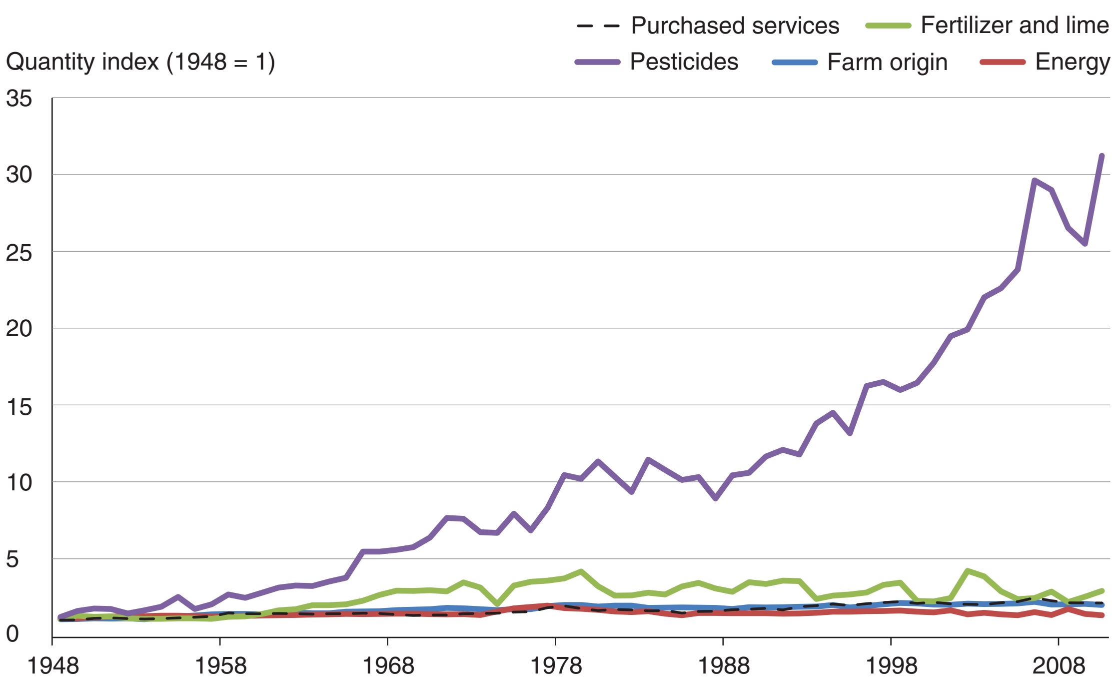
in the amount of labor and land used in agricultural production, turning the contribution of aggregate inputs to output growth positive.

Among the five intermediate goods, agricultural chemical uses—fertilizer and pesticides—grew the fastest, especially pesticides. Fertilizer use more than tripled between 1948 and 1980 (fig. 14). It then remained stable through the 1980s and fluctuated annually after 1995, with no clear long-term trend. On the other hand, pesticide use grew more than tenfold between 1948 and 1980, mainly due to herbicide adoption for major crops as farmers began switching from cultivation or other weed control methods. For example, in 1952, only 10 percent of U.S. planted corn acres were treated with herbicides, but by 1976, the share had increased to 90 percent (Fernandez-Cornejo et al., 2014a). The use of pesticides continued to grow, however, at a slower rate in the post-1980 period. The transition of agricultural chemical uses shifted the shares of pesticides and fertilizers in total input spending. In 1948, pesticides and fertilizers accounted for only 2 percent of total cost. By 2011, the shares had risen to 9 percent (see table 2).

As for other intermediate goods, between 1948 and 2011, energy use increased at an average rate of 0.45 percent per year, and inputs of farm origin and purchased services increased at average rates of 1.1 percent and 1.2 percent per year, respectively. All intermediate inputs expanded between 1973 and 1980 when U.S. agricultural export expansion was fueled by petrodollar circulation,[15] despite a threefold increase in the price of petroleum fuels following the 1973 oil embargo (fig. 14). The trends for all intermediate inputs except pesticides were interrupted after 1980, first declining and

Figure 14

Use of pesticides has risen more rapidly than use of other intermediate inputs since 1948



Source: USDA, Economic Research Service productivity accounts.

[15]Stallings et al. (1990) showed that higher oil prices have been associated with higher U.S. agricultural exports based on the effects of recessions in 1974/75 and 1981/82 following previous oil price shocks. They asserted that recycled “petrodollars” can boost world demand for U.S. farm products. The strength of this linkage depends, to a large degree, on the monetary policies adopted by the industrialized countries.

then leveling off through the early 1990s. With rapid growth that was exceeded only by agricultural chemicals, purchased services accounted for 11 percent of total cost by 2011 and was the second largest component in the intermediate goods category.

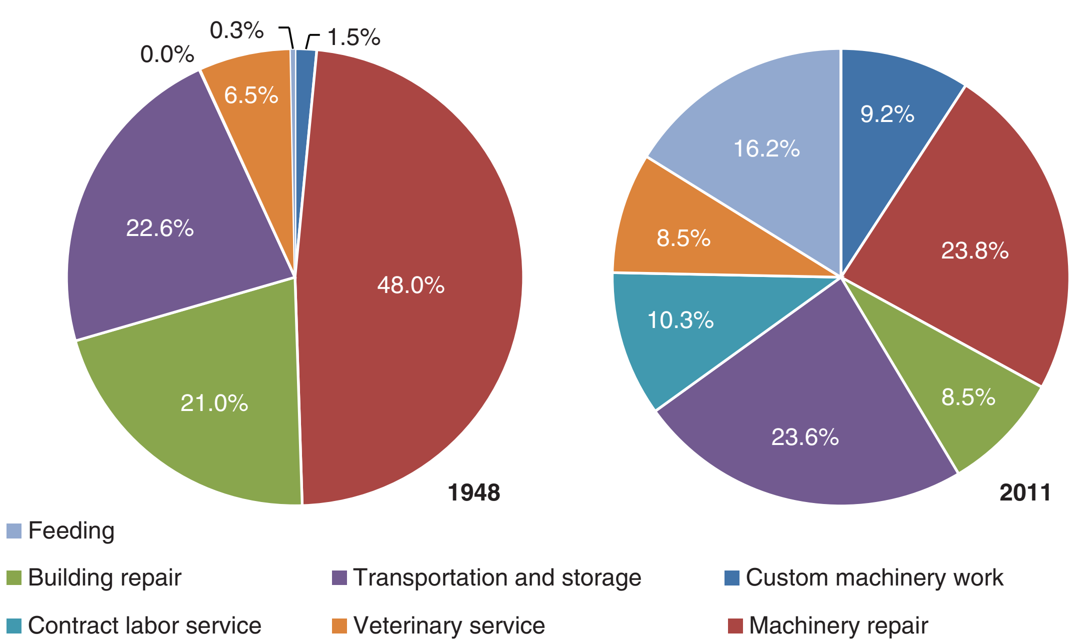
Purchased services can be further disaggregated into custom machinery work (including leasing), machinery repair, building repair, transportation and storage, contract labor services, veterinary services, and feeding. In 1948, repair expenses for machinery and buildings accounted for almost 70 percent of purchased services, while contract labor and custom machinery work accounted for less than 3 percent (fig. 15). By 2011, custom machinery work and contract labor services accounted for about 20 percent of total purchased services. Feeding service increased from essentially nothing in 1948 to 16 percent of purchased services in 2011. Over the long term, farmers have come to rely far more on purchased services as a substitute for farm labor or capital investment. Service providers may provide specific expertise that the farm operator lacks, and purchased services provide farmers with flexibility in capital and labor decisions that they may value in times of sharply fluctuating input and output prices.

Relative changes in input prices

Except for some short periods, the prices of machinery, energy, chemicals, and purchased service inputs all fell relative to the price for labor between 1948 and 2011 (fig. 16). The declines were large; between 1948 and 2011, the relative price of agricultural chemicals to labor fell in aggregate by 75 percent, while the relative prices of machinery, purchased services, and energy fell by about two-thirds. The changes in relative input prices are most likely due to increasing demand in labor from the nonfarm sector and technical advancement in other inputs. These relative price changes

Figure 15

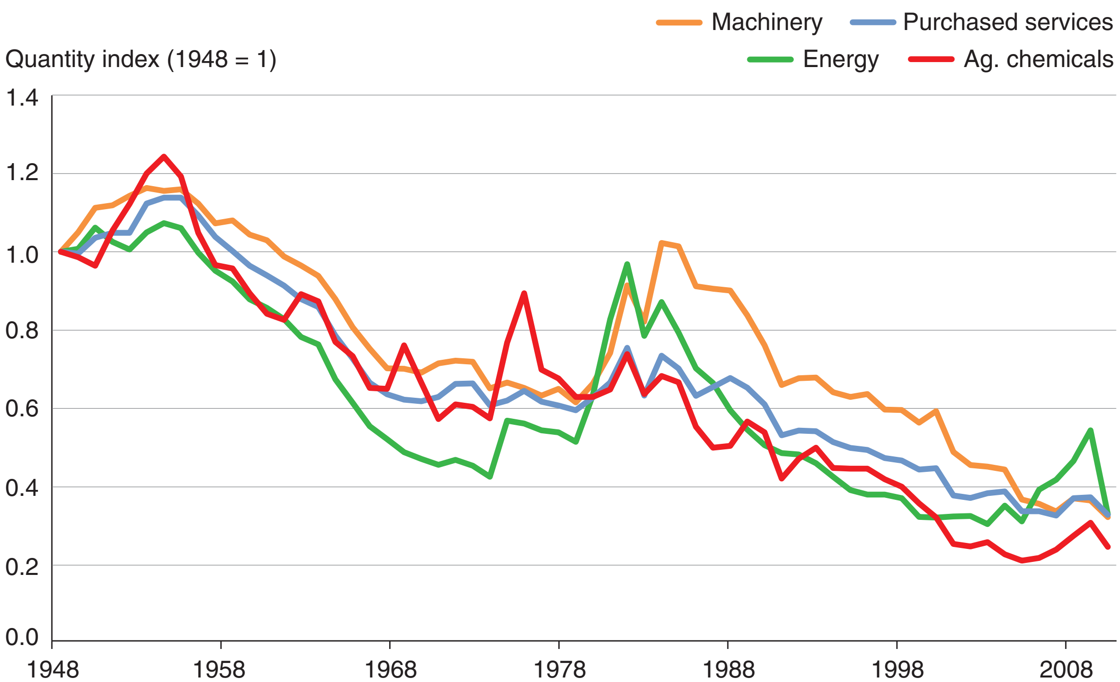
Cost share dropped for machinery repairs but grew faster for contract labor services, feeding, and custom machinery than for all other purchased services from 1948 to 2011



Source: USDA, Economic Research Service productivity accounts.

have caused substitution effects among input uses and resulted in input composition shifts. Over time, farmers substituted labor with chemicals, purchased services, energy, and capital due to the combined effects of both labor-saving technical change and a rise in the relative price of labor (Huffman, 1976; Olmstead and Rhode, 2008; Huffman and Evenson, 2001).

Figure 16
Prices of most major inputs fell relative to the price of labor over time



Source: USDA, Economic Research Service productivity accounts.

Yield, Land Productivity, Labor Productivity, and Total Factor Productivity

Over time, as use of labor and land has declined and use of other inputs has increased, average outputs per unit of labor or land have increased. Given their simplicity, these two measures (labor productivity and land productivity, or yield) are often used to examine changes in agricultural productivity. But labor and land productivity may both be affected by intensified use of other inputs and, thus, are inappropriate measures of overall productivity change. A more appropriate measure is total factor productivity, which takes into account the contributions of all inputs. Still, labor productivity and land productivity are widely used, and we compare these two partial factor productivity indicators with TFP as part of this analysis.

Single factor productivity (partial factor productivity) versus total factor productivity

The advantages of using single factor, or partial factor, productivity measures are that the calculations are relatively simple and the concept is straightforward, which communicates well to stakeholders. For example, yield is used to analyze and communicate the impacts of drought and climate change. An increase in a single factor measure of productivity, such as yield (land productivity), may not necessarily be caused by technical change (see fig. 1 and the discussion in "Introduction and Objectives" on page 1) but could be attributed to the increased use of other inputs. As indicated in "Trends and Compositional Shifts in U.S. Agricultural Outputs and Inputs" on page 5, the composition of input use has shifted over the last six decades. Farmers now use machinery and agricultural chemicals more intensively than in the past in response to rising costs of labor and land. Therefore, an increase in crop yield may result from substitution among inputs. On the other hand, TFP measures the contribution from all inputs in production and, therefore, can be a more informative measurement in understanding changes in overall agricultural productivity over time.

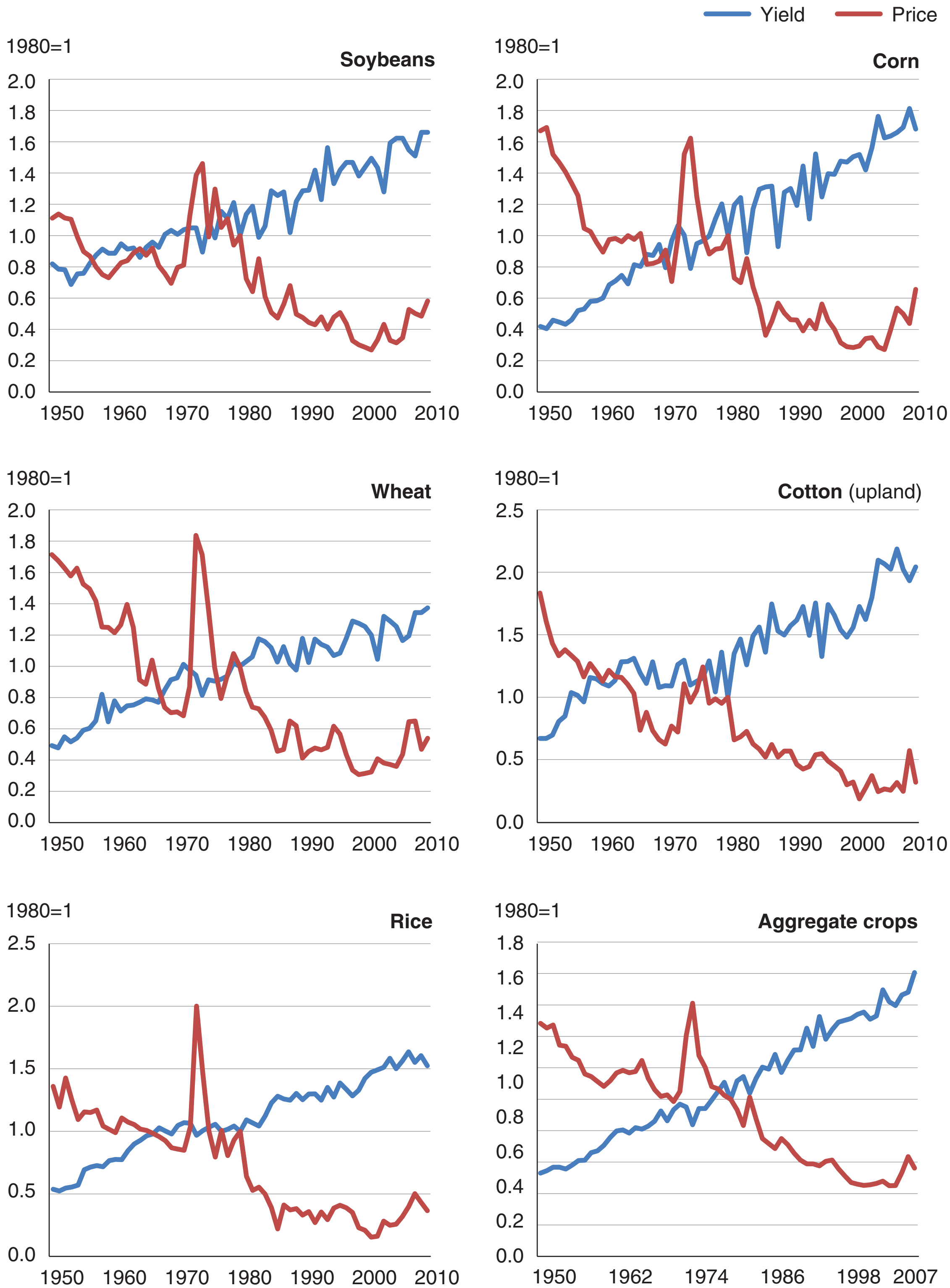
Trends of yield growth among major crops

In the literature, crop yield is commonly used to address agricultural productivity growth. This study uses data from USDA's National Agricultural Statistics Service (NASS) to calculate U.S. yields and real prices for five major crops—corn, cotton, rice, soybeans, and wheat—from 1950 through 2010. Real price is measured as the nominal crop price deflated by the Consumer Price Index to show changes in crop prices relative to overall price changes in a representative basket of consumer goods. This analysis also includes yield and real price for aggregate crops from the ERS productivity accounts in figure 17, panel F. All indices are normalized using 1980 as the base year (1980=1).

Between 1950 and 2010, U.S. crop yields grew, with soybean yields doubling and corn yields growing more than fourfold (fig. 17). Over this 60-year period, soybean yields increased by 22 bushels per acre and corn yield increased by 115 bushels per acre. The trend in yield growth appears to be linear for four of the five major crops analyzed, with cotton being the exception. U.S. crop yields are affected by short-term shocks periodically, mainly weather related, but continue to grow in the long run.

While yields increased, real commodity prices generally fell over time (see fig. 17). In the 2000s, they were less than half their value in the 1950s, although the long-term trends were interrupted by a

Figure 17
U.S. crop yields have risen and real crop prices have fallen over the last six decades



Source: USDA, Economic Research Service (ERS) calculations based on data from USDA's National Agricultural Statistics Service, ERS, and the Bureau of Labor Statistics.

spike due to energy shocks in the 1970s and a surge in the mid-to-late 2000s. Dramatic increases in demand for U.S. agricultural exports during the 1970s pushed commodity prices to record highs.[16] The real value of agricultural exports (in 2005 constant dollars (BEA, 2013)) increased by 46 percent between 1971 and 1973 and reached a new high in 1980—2.2 times its 1971 level. The crop price index also more than doubled between 1971 and 1980, mainly due to strong global demand for U.S. agricultural exports. The declining trend for major crop prices since the 1980s was interrupted in the 2000s due to tightening world balances in grains and oilseeds and increased global demand for biofuels feedstock. Adverse weather events in 2006 and 2007 in some major grain- and oilseed-producing areas also contributed to higher crop prices (Trostle, 2008).

Among the five crops examined here, corn had the fastest yield growth over the last six decades, with an average annual rate of 2.31 percent, followed by cotton (1.86 percent), rice (1.74 percent), and wheat (1.71 percent) (table 3). In general, growth in crop yields was due partly to increases in use of intermediate goods, such as fertilizer and pesticides. For example, average annual growth rates for both fertilizer and pesticides were 8.5 percent between 1960 and 1970 (table 4). Between 1948 and 1971, the use of fertilizers and pesticides increased by about 200 percent and 537 percent, respectively. Therefore, while the yields of many major crops grew rapidly during the early decades of the period—corn (3.6 percent), wheat (4.6 percent), and cotton (5.1 percent) in 1950-60, and corn (2.8 percent), rice (3 percent), and barley (3.2 percent) in 1960-70, average annual TFP growth was far less than that of crop yield growth (tables 3 and 4). On the other hand, even though the use of most inputs decreased or slowed in the 1980s, crop yield growth was sustained via improved genetics and other technical changes, when TFP also continued to grow.

Labor productivity

Labor productivity is measured as output per unit of labor. Figure 18 presents three labor productivity series—with labor measured as total hours worked on the farm (output per hour), total number of farm workers (output per person), and quality-adjusted labor. Quality-adjusted labor is drawn from the ERS productivity accounts, where labor hours have been adjusted for demographic composition shifts, which account for changes in gender, age, education, and occupational (hired or self-employed and family member) composition of farm labor.

Table 3
Crop yield, annual growth rate per harvested acre

Period	Corn	Cotton	Rice	Barley	Wheat	Soybeans
			Percent			
1950-60	3.6	5.1	3.7	1.3	4.6	0.8
1960-70	2.8	-0.2	3.0	3.2	1.7	1.3
1970-80	2.3	-0.9	-0.5	1.5	0.8	-0.1
1980-90	2.6	4.5	2.3	1.2	1.7	2.5
1990-2000	1.4	-0.1	1.3	0.9	0.6	1.1
2000-2010	1.1	2.7	0.7	1.7	0.9	1.4
1950-2010	2.31	1.86	1.74	1.63	1.71	1.18

Source: USDA, Economic Research Service using agricultural yield survey data from USDA, National Agricultural Statistics Service.

[16] Stallings et al. (1990), among others, have suggested that the large buildup of petroleum dollars increased demand for U.S. agricultural commodity exports during the 1970s, pushing agricultural commodity prices to record highs.

Table 4
Average annual growth of inputs and TFP

Decade	Input growth: All	Capital: Durable equipment	Capital: Service buildings	Capital: Inventories	Land	Labor	Intermediate Inputs: Farm origin	Intermediate Inputs: Energy	Intermediate Inputs: Fertilizer and lime	Intermediate Inputs: Pesticides	Intermediate Inputs: Purchased services	TFP growth
	Percent											
1950-1960	0.37	3.1	1.9	1.8	-0.6	-4.0	2.6	1.1	-0.3	4.3	3.4	1.9
1960-1970	0.24	1.3	2.1	1.6	-0.8	-3.5	1.8	1.1	8.5	8.5	-0.8	1.0
1970-1980	1.16	2.9	1.5	2.1	-0.5	-1.2	1.6	2.0	3.6	5.7	2.9	1.0
1980-1990	-1.53	-4.3	-1.0	-1.7	-0.7	-2.5	-0.7	-1.8	-1.8	0.4	-0.3	3.1
1990-2000	0.04	-2.1	-2.0	1.1	0.0	-1.6	1.2	0.7	-4.3	4.4	2.0	1.8
2000-2010	-0.18	1.6	-1.6	0.5	-0.5	-1.6	-0.1	-1.0	1.1	4.4	0.1	0.7
1950-2010	0.02	0.4	0.1	0.9	-0.5	-2.4	1.3	0.4	1.1	4.6	1.2	1.6

Note: Farm origin consists of seed, feed, and purchased livestock. TFP = total factor productivity.
Sources: USDA, Economic Research Service's productivity accounts.

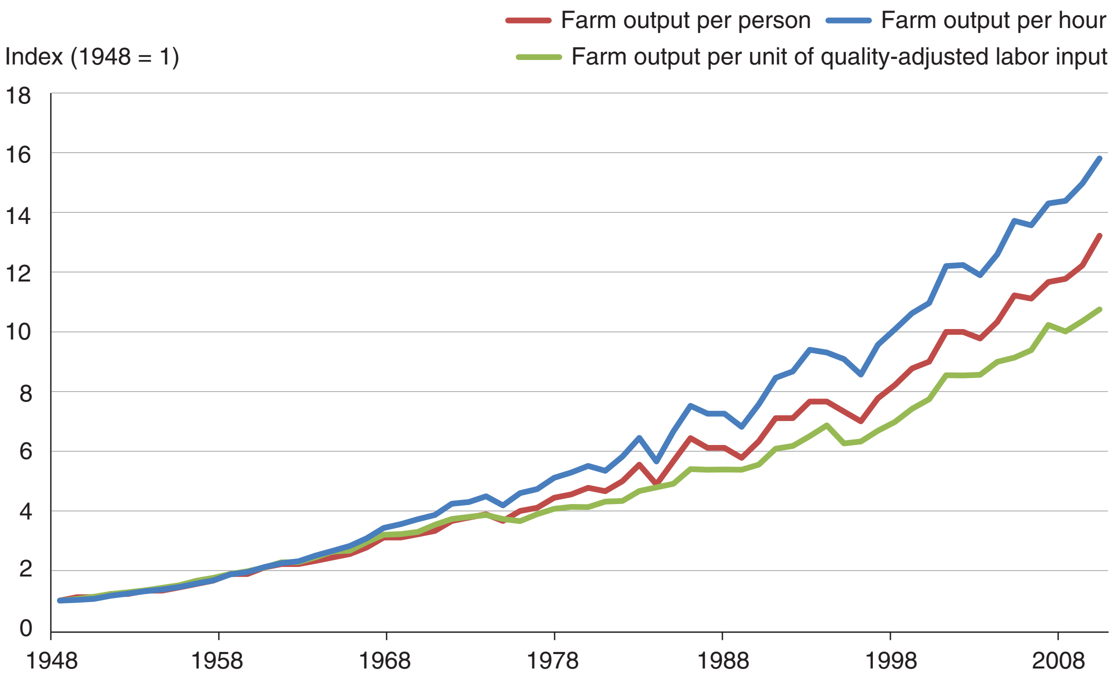
Overall, labor productivity growth in the U.S. farm sector was extraordinary from 1948-2011, no matter which labor measure is used. In 2011, farm output per labor hour was nearly 16 times its 1948 level. Given that the reported total number of hours worked declined faster than the reported number of farmworkers, the labor productivity index (1948=1) based on hours worked increased faster than that based on number of workers. Output per quality-adjusted labor hour was nearly 11 times its 1948 level in 2011 (see fig. 18). The growth of labor productivity (output per hour) in the U.S. farm sector surpassed that in the U.S. manufacturing sector during the post-WWII period, with average annual growth rates at 4.3 percent and 2.4 percent, respectively, between 1948 and 2011.

Labor productivity versus land productivity

Following the framework used by Hayami and Ruttan (1985), we plot trends in labor productivity (horizontal axis) against land productivity (vertical axis) to show the relationship between factor endowments (land, labor) and agricultural output (fig. 19). Labor productivity is measured as farm output per unit of quality-adjusted labor input,[17] and land productivity is measured as farm output

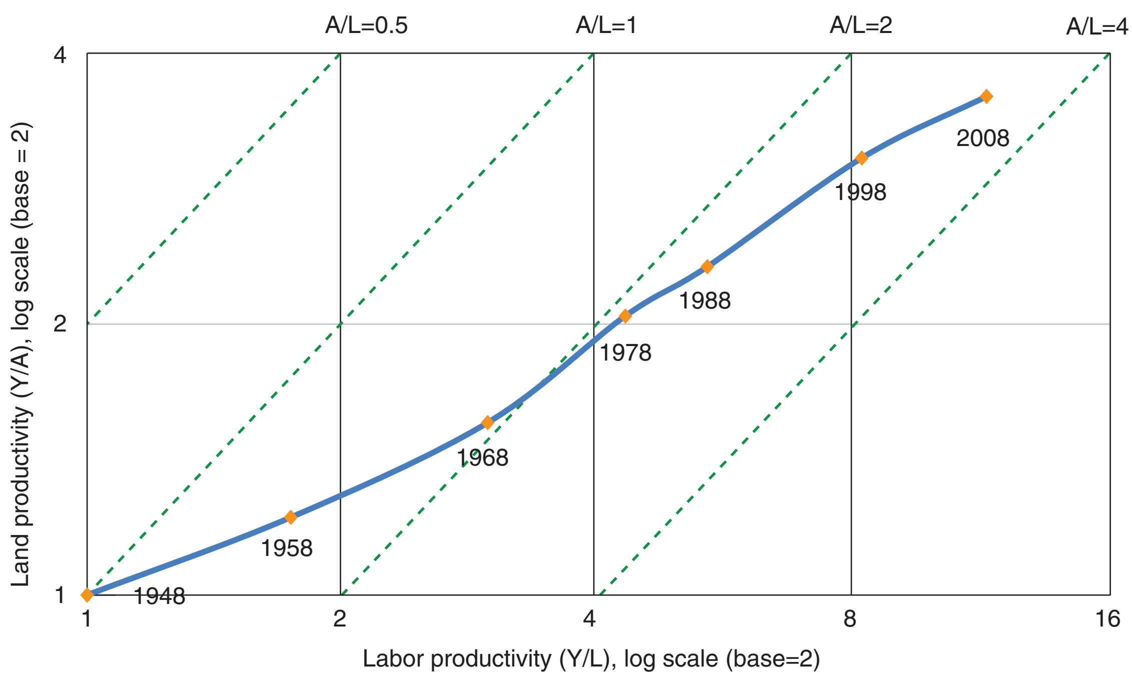
[17]Using alternative measures of labor or land input could result in slightly different results presented in the figure. Since the number of labor hours or workers declined much faster than the quality adjusted labor estimate, labor productivity based on the unadjusted labor series could result in a greater labor productivity than that charted in figure 19.

Figure 18
U.S. agricultural labor productivity has risen over the past 60 years



Source: USDA, Economic Research Service productivity accounts.

Figure 19
Labor productivity grew faster than land productivity over time



Note: A/L represents land/labor ratio based on normalized labor and land quantities data where the numbers in 1948 are set to equal 100.
Source: USDA, Economic Research Service productivity accounts.

per unit of land.[18] Note that figure 19 uses a logarithmic scale, capturing percentage increases in labor and land productivity. Each of the 45-degree dashed lines indicates a uni-land/labor ratio line corresponding to a certain land area (A) per unit of labor (L) as indicated on the top of each dashed 45-degree line, such as A/L=1, 2, or 4.

Each of the dashed 45-degree lines also represents a path in which labor and land productivity growth rates are equal, while the solid line represents the actual path of labor and land productivity. Since labor input decreased faster than land input, the land/labor ratio (A/L) increased over time and, therefore, the solid line (actual path of agricultural growth) is flatter than the 45-degree lines. It shows that growth in labor productivity exceeded the growth in land productivity throughout the period, except for 1968-78. While new technology and increased use of intermediate inputs and equipment have enabled U.S. agriculture to expand output per unit of land and labor, the rate of growth of labor productivity has exceeded that of land productivity.

While this figure allows one to see the evolution of productivity changes in these two factor endowments—land and labor—it does not show the contribution from intermediate inputs to output growth. Therefore, it cannot provide information on overall productivity changes that separate technical changes from input contributions.

Patterns of total factor productivity growth

While land and labor productivity can increase by adding other inputs, TFP accounts for the growth in all inputs. Therefore, TFP measures the output growth that cannot be explained by input growth alone (see box "How Does ERS Measure Agricultural Output, Input, and Total Factor Productivity in U.S. Agricultural Productivity Accounts" on page 4). We attribute output growth to either input growth or TFP growth. Input growth is further disaggregated into four sources—labor, capital, land, and intermediate goods. Table 5 presents the sources of agricultural output growth. Since agricultural output growth (and thus TFP growth) can sometimes be affected by factors that also influence macroeconomic performance, such as energy shocks or recession (Jorgenson, 1981; Maddison, 1987; Wang and McPhail, 2014), we report average annual rates of TFP growth for the 1948-2011 period and for 12 subperiods measured from cyclical peak to peak in aggregate economic activity (or the business cycle)[19] to provide background information over time.

Between 1948 and 2011, total farm output growth averaged 1.49 percent per year. With aggregate inputs growing at an average annual rate of 0.07 percent, TFP growth averaged 1.42 percent per year, which was substantially higher than the 1.12 percent annual growth rate in the manufacturing sector over the same period (DOL-BLS, 2014). TFP growth has been the major driver of U.S. farm output growth during the post-WWII period (see table 5). Over the 12 cyclical subperiods examined, the lowest TFP annual growth rate was 0.3 percent in 1948-53. During this period, total farm input grew at the second highest rate, next to the energy shocks period, among all 12 subperiods. Farm operators largely increased investment in capital goods, use of land, and materials, with labor being the only input not increasing, in an effort to recover and catch up in the immediate post-WWII period. While total output grew at an average annual rate of 1.08 percent in the period, most of this

[18] Land is a measure of land stock, as indicated.

[19] This convention and these subperiods have been adopted by the major productivity studies. See, for example, Jorgenson et al. (1987).

Table 5
Sources of U.S. agricultural output growth (average annual growth rates)

	1948-2011	1948-1953	1953-1957	1957-1960	1960-1966	1966-1969	1969-1973	1973-1979	1979-1981	1981-1990	1990-2000	2000-2007	2007-2011
							Percent						
Output growth	1.49	1.08	0.94	3.87	1.20	2.27	2.68	2.26	1.54	0.99	1.86	0.78	-0.27
Sources of output growth													
Input growth	0.07	0.78	0.27	0.67	0.17	0.73	0.39	1.63	-2.52	-1.20	0.04	0.47	-1.30
Labor	-0.50	-0.80	-1.10	-0.80	-0.80	-0.60	-0.40	-0.20	-0.20	-0.40	-0.30	-0.30	-0.30
Capital	0.01	0.60	0.20	0.030	0.10	0.30	0.10	0.30	0.20	-0.60	-0.20	0.10	0.05
Land	-0.10	0.020	-0.20	-0.20	-0.10	-0.20	-0.30	0.004	-0.10	-0.10	-0.003	-0.10	-0.02
Materials	0.60	1.00	1.30	1.60	1.00	1.20	0.90	1.50	-2.40	-0.10	0.60	0.80	-1.10
TFP growth	1.42	0.30	0.66	3.21	1.03	1.54	2.29	0.63	4.06	2.19	1.82	0.31	1.03

TFP = total factor productivity.
Note: Subperiods are measured from cyclical peak to peak in aggregate economic activity.
Source: USDA, Economic Research Service productivity accounts.

increased production stemmed from input growth (see table 5). TFP growth only accounted for 0.3 percentage points of total output growth.

Annual TFP growth fell below 1 percent in only four subperiods—1948-53, 1953-57, 1973-79, and 2000-07. In the first two subperiods, the capacity[20] for development of new technology was just re-emerging after WWII. The rapidly increasing use of materials, such as agricultural chemicals, played an important role in the early stages of these subperiods, when overall productivity growth (TFP) was still slow. The last two subperiods were associated with high energy prices and soaring commodity prices. However, while high energy prices may have partially contributed to the slower TFP growth, soaring commodity prices are more likely the result of high energy prices and low TFP growth (see Sands et al. (2011) and Wang and McPhail (2014) for more discussion).

Annual rates of growth in materials use averaged well over 2.0 percent per year between 1948 and 1960 (see table 5) and accounted for high shares of output growth. Still, since labor and land were being pulled out of agriculture into nonfarm sectors, the contribution from total inputs only contributed 0.27 and 0.67 percentage points to total output growth during the 1953-57 and 1957-60 periods, respectively. In those periods, TFP growth contributed to output growth at annual rates of 0.66 and 3.21 percentage points, respectively.

In addition to materials, capital service flows—including service flows from durable equipment and farm buildings—also contributed to output growth in most subperiods (table 5). Capital input growth persisted until 1981. Capital input declined and contributed negatively to output growth in 1981-90 and 1991-2000. The rapid increase in capital goods investment during 1973-1980 was stimulated by high agricultural commodity prices, expanded agricultural exports, and low real interest rates. The decline in capital investment and stocks during 1981-90 and 1991-2000 generated concern regarding potential capital obsolescence and possible slower productivity growth (Ball et al., 2013a).

[20]In the nonfarm sector, while the multifactor productivity growth rate for the manufacturing sector was above 1 percent per year during 1948-53, it dropped to about 0.5 percent per year during 1953-57 (DOL-BLS, 1983, 2014), which was slightly lower than 0.7 percent per year in the farm sector over the same period.

The labor input in agriculture contracted over the post-WWII period and contributed negatively to output growth at a rate of -0.5 percent annually. Negative contributions to output growth from declining labor were sustained during all 12 subperiods. Land is the other input that fairly consistently contributed negatively to annual output growth, at an overall average rate of -0.08 percent per year (table 5). On the other hand, average annual TFP growth contributed positively to output growth in all subperiods. The TFP growth rate also exceeded 1.5 percent per year—higher than its overall average annual growth rate—in six subperiods. However, slower growth during 2000-07 raised concerns over the sustainability of U.S. agricultural output growth. Although productivity growth rebounded after 2007, it is uncertain whether growth has slowed from a longrun perspective.

In summary, given the increasing use of intermediate goods and the declining use of labor and land inputs over time, the growth of labor productivity and land productivity in U.S. agriculture reflected not only technical changes but also contributions from the increased use of other inputs. TFP, on the other hand, accounts for output growth that cannot be explained by all input changes combined. Since 1981, there has been much less rapid growth in intermediate input use and a steady decline in capital inputs. Along with a continuing decline in the use of labor and land, the importance of TFP growth to output growth substantially increased after 1981.

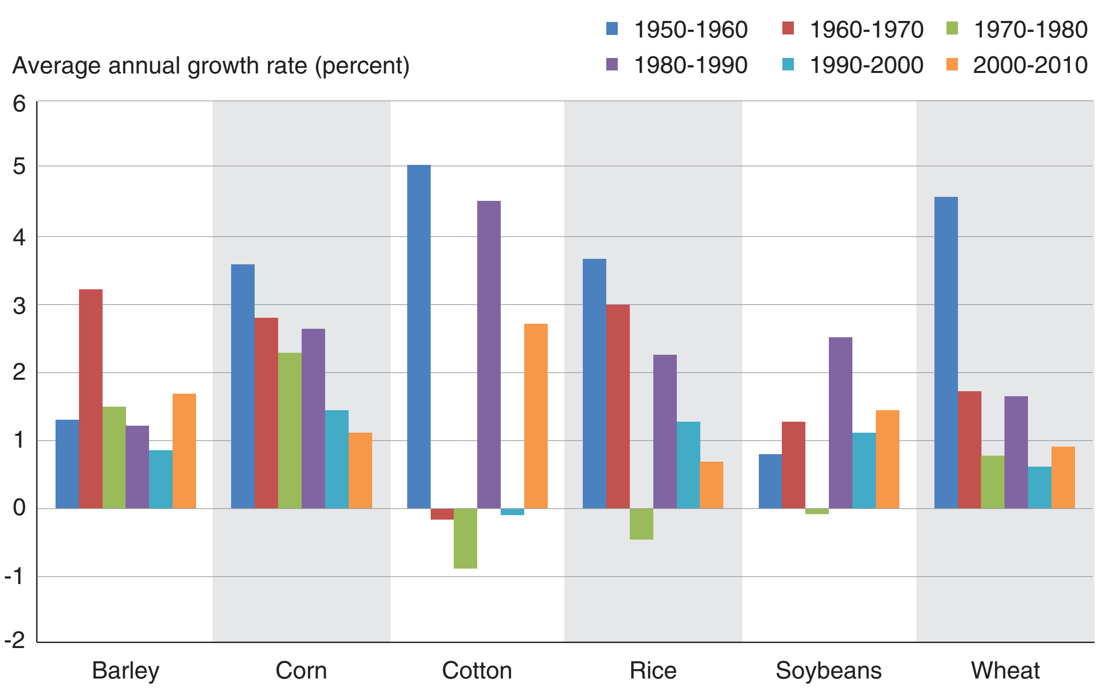
Is U.S. Agricultural Productivity Growth Slowing?

Background

Growth in crop yields slowed in the 1990-2000 period (fig. 20), and real crop prices increased in the late 2000s after a long decline (see fig. 17). These changes raise concerns about whether or not U.S. agriculture can maintain persistent productivity growth and sustainable production practices in the future. The United States is one of the world's biggest consumers and producers of agricultural commodities. With global population and food demand both expected to grow,[21] the ability of the United States to maintain sustainable agricultural productivity growth in the long run may affect not only U.S. food markets but also global food security.

Some studies (Alston et al., 2009) link recent crop yield growth rate declines relative to trends in the 1960s and 1970s to a slowdown in U.S. agricultural productivity. These decadal growth rates (see fig. 20) fluctuate substantially and do appear to have slowed until the most recent period, 2000-10, when yield rates for cotton, barley, wheat, and soybeans all increased. Yet, as shown in figure 17, yield levels (not growth rates) actually appear to have increased linearly since the 1950s. Although constant linear growth will manifest a slowing percentage growth rate as base yield levels increase, crop yield growth should not have declined as much as shown in figure 20 based on decadal mean calculations. Since our analysis concerns the entire U.S. agricultural sector, including both livestock production and crop production, we use TFP statistics for the U.S. farm sector to examine the productivity slowdown.

Figure 20
Average annual crop yield growth rates rebounded in 2000-2010 for most major U.S. field crops



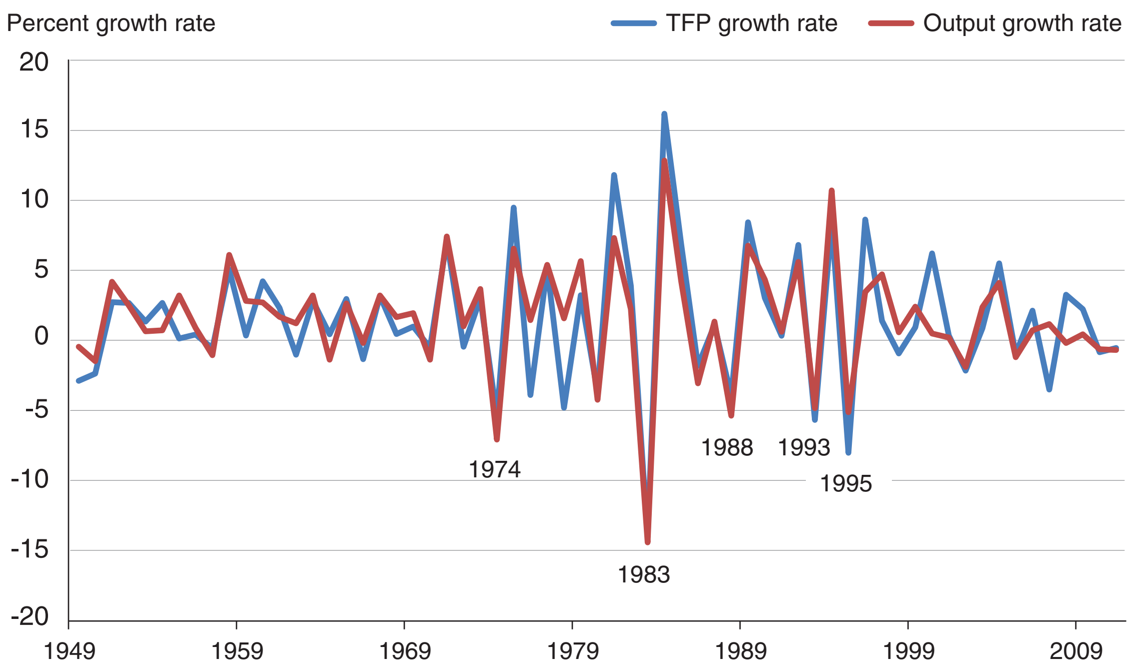
Source: USDA, Economic Research Service calculations based on data from USDA's National Agricultural Statistics Service.

[21]The world population is projected to be 34 percent higher in 2050 than it was in 2010 (World Bank, 2014).

Long-term TFP growth is driven mainly by technological innovation that occurs with a time lag. However, in the short term, TFP growth can fluctuate considerably from year to year, largely in response to weather events, energy shocks, macroeconomic impacts, and other international factors. These wide short-term fluctuations can make it difficult to identify changes in longrun trends. In general, growth in output and TFP are highly correlated, and both have varied dramatically over time (fig. 21). Variation in input growth, on the other hand, is much less pronounced than variation in either output or TFP. Input growth is more closely controlled by farm operators, who often make cropping decisions months before planting dates, while short-term changes in output and, hence, TFP may be affected more by random events.

Because TFP is a residual that captures unexplained factors affecting output growth that are not accounted for by observed input growth, it is reasonable to expect the TFP series to move concurrently with output growth, given that input growth is relatively stable. For example, in 1983, severe weather events and the Federal Government's Payment-In-Kind (PIK) program[22] caused output to drop by 14.4 percent. In the same year, TFP declined by 13.6 percent, with only a minor reduction in input growth. Figure 21 also shows that when high temperatures affected much of the Nation in 1988, 1993, and 1995, output growth dropped.[23] The associated drought (and flooding in the Midwest in 1993) caused output to drop by 4.9 to 5.1 percent and caused TFP to decrease by 4 to 8

Figure 21
TFP growth moved closely with output growth, and both were affected by adverse weather events



Source: USDA, Economic Research Service productivity accounts.

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[22]To lower accumulated Government-held commodity surpluses, farmers were encouraged to reduce crop production through participating in the Payment-in-Kind program (USDA, 1983).

[23]Schlenker and Roberts (2009) show that yields increase gradually for temperatures up to 29-32°C for corn, soybeans, and cotton. They also estimate that yields drop sharply for all three crops at higher temperatures; cotton, which is highly irrigated, is the only crop not sensitive to temperature and soil moisture variations.

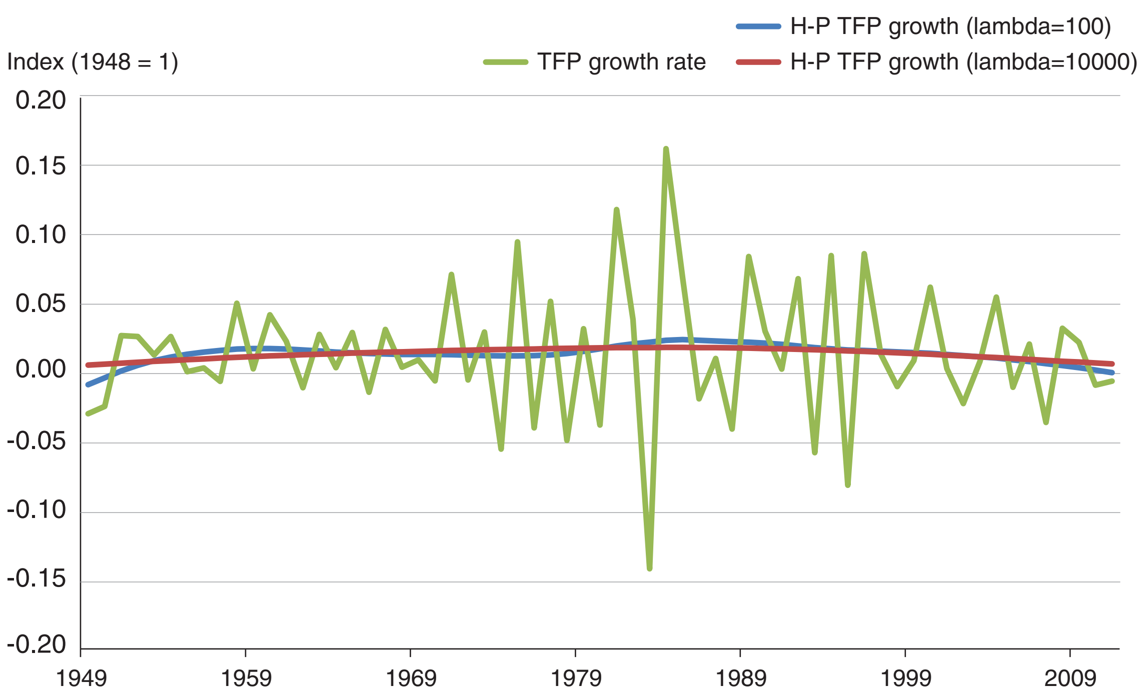
percent. Most of these events cannot be accurately predicted in the early stage of the planting season, so TFP declines can indicate "wasted" inputs that do not produce output but could not have been saved by farmers. Since conventional TFP measurement does not incorporate weather as an input, the decline in TFP is not due to deteriorated technology but is a reflection of bad weather. In the long run, TFP usually returns to its potential level.

Short-term fluctuations in weather events and macroeconomic movements (business cycles) may significantly affect TFP estimates; thus, growth rates can be sensitive to the selection of dates chosen for the beginning and end of time periods being examined. While it is convenient to use arbitrary dates (such as by decade) to break down the sample and make comparisons, the results using this approach could give misleading information regarding the productivity slowdown.

Slowdown tests, results, and implications

One approach to analyzing fluctuations and trends that does not depend on selecting pre-determined break dates is to apply the Hodrick-Prescott filter (H-P filter, Hodrick and Prescott (1997)) to smooth the variation in the TFP series.[24] We show two versions of "H-P modified TFP" using alternative smoothing coefficients (Lambda, λ) along with actual TFP growth rates in figure 22.

Figure 22
TFP growth versus H-P smoothed TFP growth



H-P = Hodrick-Prescott filter. TFP = total factor productivity.
Source: USDA, Economic Research Service productivity accounts.

[24]The Hodrick-Prescott filter (H-P filter) is an algorithm that "smooths" the original time series by choosing a smoothing value to remove its variations. A positive parameter λ is applied by the procedure to reduce fluctuations. A larger value of λ can make the time series look smoother without much high-frequency noise. Hodrick and Prescott suggest that λ = 1,600 is a reasonable choice for quarterly data, and their suggestion is usually followed in applied work. Since the greater the frequency of the data, the larger the value of λ, for annual data a value in the range from 5-15 for less smoothing up to 100 has been suggested in various studies (see, for example, Backus and Kehoe (1992) and Ravn and Uhlig (2002)).

Both estimated H-P series show that bumps in actual TFP growth are nearly counterbalanced, on average, by sudden drops.

There are two periods, one around 1958 and the other around 1984, when a smaller smoothing parameter (λ) shows higher bumps in the smoothed trend growth. This implies that TFP growth accelerated in the post-WWII period and then slowed after 1958 until the late 1970s, when the pace of growth picked up and reached another high point in 1984. TFP growth slowed again after 1985. These periods of TFP growth may require further analysis in light of some limitations in the H-P filter approach. While avoiding the choice of arbitrary break dates for subperiods of analysis, the H-P filter uses an arbitrary smoothing parameter λ that could affect the estimated trend growth. The H-P filter technique also has an end point bias problem in that the data it uses are often truncated at a point that is not at the end of a cycle, leading to the detection of spurious cycles and correlations with unimportant events (Harvey and Jaeger, 1993).

Another way to examine the statistical properties of these data and address longrun productivity trends is to conduct tests that partition the sample into many subperiods and test for differences in the resulting subperiod mean rates of growth. A more formal way to implement this approach, Chow's structural break test (Chow, 1960), involves estimating regression parameters for each subperiod and testing the equality of the two sets of parameters using an F-test.

For example, James et al. (2009) employ the InSTePP[25] TFP dataset to look at U.S. agricultural productivity trends using State-level estimates of TFP growth rates for 1949-2002. They select various breakpoints and test for differences in average TFP growth rates in pre-break point and post-break point periods. They found that, using 1990 as the break point, TFP grew more slowly in the post-1990 period. Wang et al. (2012b) also applied this method to test for productivity slowdowns in the farm sectors of several Western European countries over the last few decades. They found that when using 1983 as the break point, the TFP growth rate significantly increased after 1983 for Belgium, Denmark, Italy, and the Netherlands but decreased for Germany, Spain, Sweden, and the UK. With 1993 as the breakpoint, most of the tests show lower productivity growth in the post-period, but most of the differences are insignificant, except for those of France and Sweden. On the other hand, Italy is the only country demonstrating significantly higher TFP growth in the post-period no matter which breakpoint is used.

An important limitation of the Chow structural break test is that the break date must be specified in advance. Researchers pick candidate break dates based on either arbitrary points in time covering possibly equal length periods, or some other known feature of the data. As Hansen (2001) points out, these test results can be "uninformative" because this nonstatistical approach can miss a true break date, or can be "misleading" because the break date is endogenous, determined by the data, and a test on an arbitrary period can indicate a break when none in fact exists.

Some statistical methods allow for unknown structural breaks in a time series—that is, structural breaks are identified statistically. Ball et al. (2013a) use such an approach with the ERS TFP series for 1948-2009. They identify a productivity slowdown beginning in 1974, a year identified by researchers examining structural changes in other industries and often associated with economic slowdowns, along with 1985, the year of a shift in the mean TFP. Factors discussed by other researchers as contributing to structural changes between 1974 and 1985 include capital obsoles-

[25]InStePP is an abbreviation for the University of Minnesota's "International Science & Technology Practice & Policy."

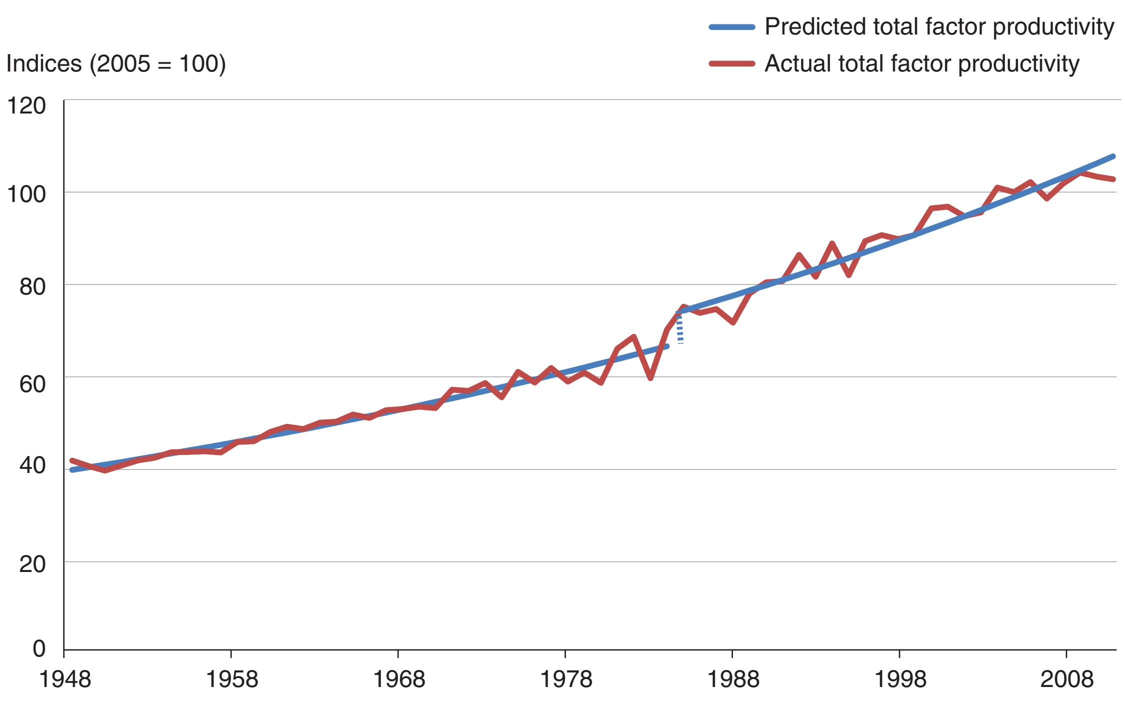
cence as capital investment declined due to higher interest rates and energy shocks that made equipment more expensive to operate. Farmers benefited from soaring commodity prices at that time, but rapidly changing economic conditions made many longrun investment decisions difficult to evaluate.

Since ERS's TFP series has been revised to incorporate new estimates of quality-adjusted chemicals and contract labor services, the slowdown results from Ball et al. (2013a) may have changed. Therefore, we follow the same procedure and redo the test to examine the productivity slowdown issue incorporating the revised and updated 1948-2011 ERS TFP series.

To develop tests for the slowdown hypothesis, we suggest a simple trend model and test the null hypothesis of a stable linear model against the alternative of "breaks" in the parameters in the trend regression. We use statistical procedures to identify possible break points in either TFP level (intercept) or TFP-trend growth (see appendix for details). The tests place an optimal break point in 1985 for an intercept shift to a higher level as found in Ball et al. (2013a), but the slowdown results indicated in the earlier study are no longer statistically significant (fig. 23). This implies a lack of evidence for a slowdown in the longrun trend of U.S. agricultural productivity in the revised and updated TFP series.[26]

The upward shift in the intercept in 1985 could be the result of several factors. For example, U.S. economic activity recovered as energy prices retreated from what were record levels in 1974 and

Figure 23
Predicted productivity growth is closely aligned with actual growth



Source: USDA, Economic Research Service estimates.

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[26]The TFP series used in this report is different from that used by Ball et al. (2013a) in two ways: first, the revised TFP series has incorporated a new estimate for quality-adjusted fertilizer series, as well as quality-adjusted contract labor services series; second, the updated TFP series has incorporated some data revision done by USDA's National Agricultural Statistics Service. It has also been extended to 2011.

1979. Agricultural production also rebounded after a serious drought in 1983 and an agricultural policy intervention in 1983 where farmers were encouraged to reduce crop production through the PIK program. In addition, changes to the price-support program in the Food Security Act of 1985 (Farm Act) were part of a more market-oriented farm policy that continued into the future. The Farm Act reduced Government farm supports, promoted exports, and set up USDA's Conservation Reserve Program. Since 1985, commodity prices have largely been based on market supply and demand, with reduced influence of Government price supports.

If there is no slowdown in U.S. agricultural productivity based on the latest data, how does one explain the lack of a productivity effect from the widely discussed stagnation in public R&D investments over the last two decades? One possible explanation is that although there is a strong link between public R&D and productivity growth, the rapid growth in private-sector R&D over this period may have compensated for stagnant public R&D spending (King et al., 2012; Wang et al., 2013). While the overall size of the public R&D portfolio may not have grown and some of the portfolio may have shifted away from productivity improvements and toward environmental protection and food safety (Schimmelpfennig and Heisey 2009), private-sector research investments have continued to grow. R&D from private industry is often directed toward developing marketable improvements in factors of production or seeds that will become available to farmers as improved inputs or seeds that tend to raise productivity directly.

Based on the metric of publications and cited references, there is evidence to suggest that the growth of science is being generated at an increasing rate (Bornmann and Mutz, 2015).[27] If this is the case for agricultural research, complementarities between faster public and private research could offset the decline in public research spending. In addition, technology spillovers from other industries, such as biogenetics, could have contributed to agricultural innovation. Nevertheless, the overall impact of slower public-sector investment in R&D is still unclear, and evidence of changes in productivity growth trends will continue to be monitored in the future.

In sum, as long as the United States remains a primary producer of some of the world's basic agricultural commodities, the potential for a slowdown in U.S. agricultural productivity will be a concern. Slower U.S. productivity growth could be a contributing factor in increases in global food prices if production cannot keep pace with increasing global demand. It could also result in environmental problems if farmers intensify their use of land and chemicals in attempts to produce more output. While crop yields might seem to be the most direct link to agricultural production, TFP needs to be examined as it takes into account all input uses. Identifying trend breaks and a slowdown in the long-term growth trend in TFP is challenging because TFP fluctuates annually due to extreme weather and other developments. The statistical approach taken here reliably deals with these issues, and the most recent data do not show a statistically significant slowdown in long-term TFP growth.

[27]Bornmann and Mutz (2014) show that growth rates in the development of science output tripled when compared to the 2 to 3 percent rates between the two World Wars and the 8 to 9 percent growth rates in the period up to 2012.

Drivers of U.S. Agricultural Productivity Growth

TFP growth is the major source of U.S. agricultural output growth. Since aggregate input growth averaged only 0.07 percent per year, the average annual rate of output growth (1.49 percent) was almost entirely attributable to TFP growth, which increased at an average annual rate of 1.42 percent between 1948 and 2011. The major driver of longrun TFP growth—including both embodied and disembodied technical changes—is innovation. Although agricultural and trade policies and the regulatory environment can influence output changes, input uses and, thus, TFP estimates, they are short-term factors instead of TFP drivers.

While both public and private agricultural research investments help spur technological innovation, extension activities and public infrastructure help promote the use of the technology. For example, agricultural R&D may lead to new technologies, but these technologies must be adopted by farmers before they affect TFP growth. Therefore, factors that affect the speed of adoption, such as extension services or infrastructural development, will also affect TFP growth.

Agricultural research policy and the research environment

Both private firms and public-sector institutions finance and conduct food and agricultural research. The most broadly defined measures of public and private research include far more than research directly affecting farm productivity. Empirical measures, particularly for the private sector, may include food research as well as agricultural research, and research expenditures in other resource-based industries, such as forestry and fisheries, are often combined with agricultural research expenditures.

Although the geographical nature of farm production means conditions on specific farms are likely to vary considerably, the decentralized nature of agricultural production means individual farmers are extremely unlikely to have the market share and industry dominance necessary to recover R&D costs (Alston and Pardey, 1996). Thus, agricultural research by profit-seeking private firms is conducted primarily by the sectors that supply inputs to agriculture. Scientific knowledge derived from research has two defining characteristics of public goods. First, information produced by scientific R&D is *nonrival in consumption*, meaning one individual's use of that information does not diminish the amount available to others. Second, the cost of duplicating information is low relative to the costs of creating it, meaning it is relatively difficult to *exclude* other individuals from using information once it is created. The second characteristic will often lead private firms to underinvest in research (Nelson, 1959; Arrow, 1962; for agricultural research in particular, see, for example, Fuglie et al., 1996). As Arrow (1962) indicated, "In the absence of special legal protection, the owner cannot, however, simply sell information on the open market. Any one purchaser can destroy the monopoly, since he can reproduce the information at little or no cost." This reduces incentives for the provision of information.

In agriculture, farmers innovate constantly in small-scale ways, especially in farm practices—adapting equipment, experimenting with crop rotations, or trying out new feed mixes, for example. The expense of large-scale R&D, combined with the ease of copying many innovations, however, makes many R&D investments a losing proposition for farmers.

Even large firms face many of the same challenges. For example, it is easy for farmers to replant seed of self-pollinated crops such as wheat or soybeans without much of a yield penalty. Thus, firms producing such seed may capture some of the benefits in years that farmers purchase new seed, but they may not be able to extract the benefits farmers gain from replanting in subsequent years without seed purchase—in other words, unless legal limits exist and are honored, firms cannot exclude farmers from planting in years after they buy seed. If the firm can only capture a fraction of the benefits from their research investments, they have fewer incentives to innovate. This kind of market failure may lead to insufficient private investment in agricultural research, especially in the field of fundamental research that tends to have little or no profit potential.

Most broadly, agricultural research policy is directed at creating and sustaining the institutions that develop and transmit scientific and technical knowledge as well as the complementary institutions (that, for example, educate the farm population, promote efficient markets, or enhance the effectiveness of political institutions) that support technology development consistent with a nation's "physical and cultural endowments" (Ruttan, 1982). More specifically, governments attempt to influence the *quantity* of research investment. They may respond to insufficient private incentives by funding intramural research agencies,[28] by sponsoring research in universities or industry, or by changing the incentives for private firms to invest in research. This latter group of policy instruments includes the establishment of intellectual property rights, and, less frequently, tax and subsidy policy. Intellectual property rights are aimed at increasing research incentives by increasing the proportion of benefits that innovators can retain. However, intellectual property regimes may differ in their coverage and in the strength of the protection they confer. Taxes and subsidies attempt to increase R&D investments by reducing the costs of doing research. Governments may also attempt to influence the *composition* of research spending. This is harder to do, although allocation of resources within intramural research agencies is one tool. Grant programs may have some limited influence on research composition, but intellectual property rights are usually quite general in their impact.[29]

Technological opportunity, conditioned by spillovers from basic sciences, may also help direct the course of agricultural research (Huffman and Evenson, 2006, chapter 2). Over time, science not originally aimed at agricultural applications may come to have important uses in agriculture. For example, basic biological science research findings often "spill over" into agriculture, such as recombinant DNA technology used in genetically engineered crops, and these spillovers may be changing in nature with general advances in life sciences (Shoemaker et al., 2001; Wang et al., 2009). New firms have entered agricultural input industries where considerable consolidation has taken place and firms often operate globally (Fuglie et al., 2011). Thus, firms may respond to different signals in different markets than they did when they were smaller and active primarily in U.S. markets. Consumer demand, particularly in affluent societies, may also play an important role in the direction of agricultural research (Ruttan and Hayami, 1995; Fuglie et al., 1996).

[28]Other motivations for public investment in agricultural research might include support for agency mission or attempts to reduce economy-wide waste, for example, by coordinating efforts by many diverse research actors (Bozeman, 2000).

[29]One seldom-used mechanism, awarding research prizes, has much stronger influence on the nature of research pursued.

Public and private agricultural R&D in the United States

The current U.S. food and agricultural research system is complex, with diverse sources of research funding, both in the public and private sectors, and a number of research performers, also in both public and private sectors.[30] The long-term Federal-State partnership in public agricultural research has been a key factor driving agricultural productivity growth (Fuglie et al., 1996; Huffman and Evenson, 2006; Alston et al., 2010; and Heisey et al., 2010). Fuglie et al. and Huffman and Evenson surveyed the means by which the Federal-State partnership has fostered complementary research by the private sector. Wang et al. (2013) use disaggregated data on research programs in the United States to evaluate dynamic and longrun relationships among public R&D, private R&D, and agricultural productivity growth. They find econometric evidence of complementarity as well as asymmetric substitution effects between public and private agricultural research investments. Their findings suggest spending on public fundamental (basic) or applied crop research programs appears to stimulate an increase in private research on crops and, at the same time, public crop research appears to decline following an exogenous increase in private crop research. Wang et al. hypothesize that new technological opportunities for commercialization may have been opened up to the private sector by public research, and the public sector may withdraw from areas it sees private companies pursuing. In addition, Fuglie and Toole (2014) review the limited number of studies concerning interaction between public and private-sector agricultural research and conclude that the bulk of the evidence supports a complementary relationship rather than the substitution of public for private research.

Although investments in agricultural research often have a high payoff, long time periods often elapse between the investment and the economic impacts from that investment. This means current research expenditures alone are likely to have little impact on contemporaneous agricultural productivity. Instead, research capital, which takes into account many years of research investment, is expected to have a significant impact on productivity.[31] Furthermore, at the time research investments are made, it is not always clear which research projects will ultimately have the most significant economic impact.

For example, in the early 1980s, economists at the University of Minnesota assessed technology use in commercial corn production in the United States (Sundquist et al., 1982). They also looked at potential applications of emerging biotechnologies in corn production, based on reference to the USDA competitive grants program for 1980, literature review, and discussions with agricultural scientists. The five technologies selected were photosynthetic enhancement, plant growth regulators, cell and tissue culture, gene transfer at the cellular level, and biological nitrogen fixation. Through interviews with scientists, the study tried to measure expected gross benefits from four of these five technologies from about 1980 to the year 2000. Interestingly enough, Sundquist et al. state “no quantification of benefits was attempted for gene transfer because of its early stage of development.” Arguably, by 2000, the technology that actually had the most observable commercial impact was gene transfer. Even in this case, observations of the rapid adoption of genetically engineered corn, and other crops, in the late 1990s and early 2000s obscures the fact that some of the underlying research was being performed as early as 1980.

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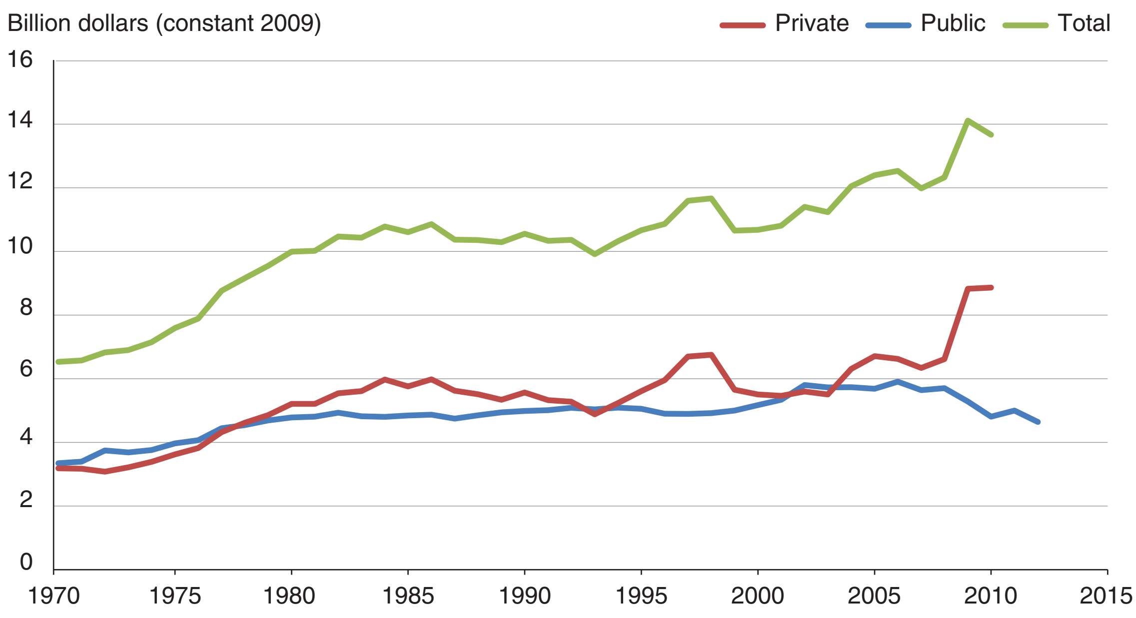
[30]For more information, see Agricultural Science Policy on the ERS Web site, www.ers.usda.gov/topics/farm-economy/agricultural-science-policy.aspx.

[31]Formal treatment of lag lengths can be found in some of the references listed in the box “How the Projections Were Derived" on page 59. In particular, Huffman and Evenson (2006) estimate public agricultural R&D has impacts with lags up to 35 years, and Alston et al. (2010) estimate lags of up to 50 years.

These long lags between research investment and associated research impact mean that long time series are necessary to analyze thoroughly the impact of agricultural research on productivity. Older historical data are more difficult to obtain. Furthermore, the complexity of the system means it is often difficult to get exact estimates of research investments by various institutions, particularly in the private sector, for which data are not regularly collected. Over the past 40 years, the real value of agricultural research funding in the United States has increased, and total funding since 2004 has ranged between $12 billion and 14 billion per year in 2009 dollars.[32] Private R&D investment has been growing more rapidly although more variably than public-sector investment for much of the past 40 years (fig. 24).

Although there is some overlap between broad public and private R&D themes, in many ways public and private research are complementary rather than competitive. Little incentive exists for private firms to pursue research areas where the results are more likely to benefit society as a whole rather than the specific innovator. As a result, the private sector focuses more on R&D related to marketable goods (fig. 25). The private sector dominates food manufacturing research, where very few of the investments directly affect farm-level productivity. On the other hand, research on agriculture's relationship to the environment and on human nutrition and food safety, where it is much more difficult for private firms to capture any benefits from research results, is done primarily by public-sector institutions. Over time, real private-sector investment has increased most markedly in food manufacturing and crops.

Figure 24
U.S. real food and agricultural R&D funding



Note: Data for 2010-12 are preliminary. R&D = research and development.
Source: USDA, Economic Research Service (ERS) based on data from National Science Foundation, USDA's Current Research Information System (CRIS), and various private-sector data sources as reported by Fuglie et al. (2011). Data are adjusted for inflation using an index for agricultural research spending developed by ERS.

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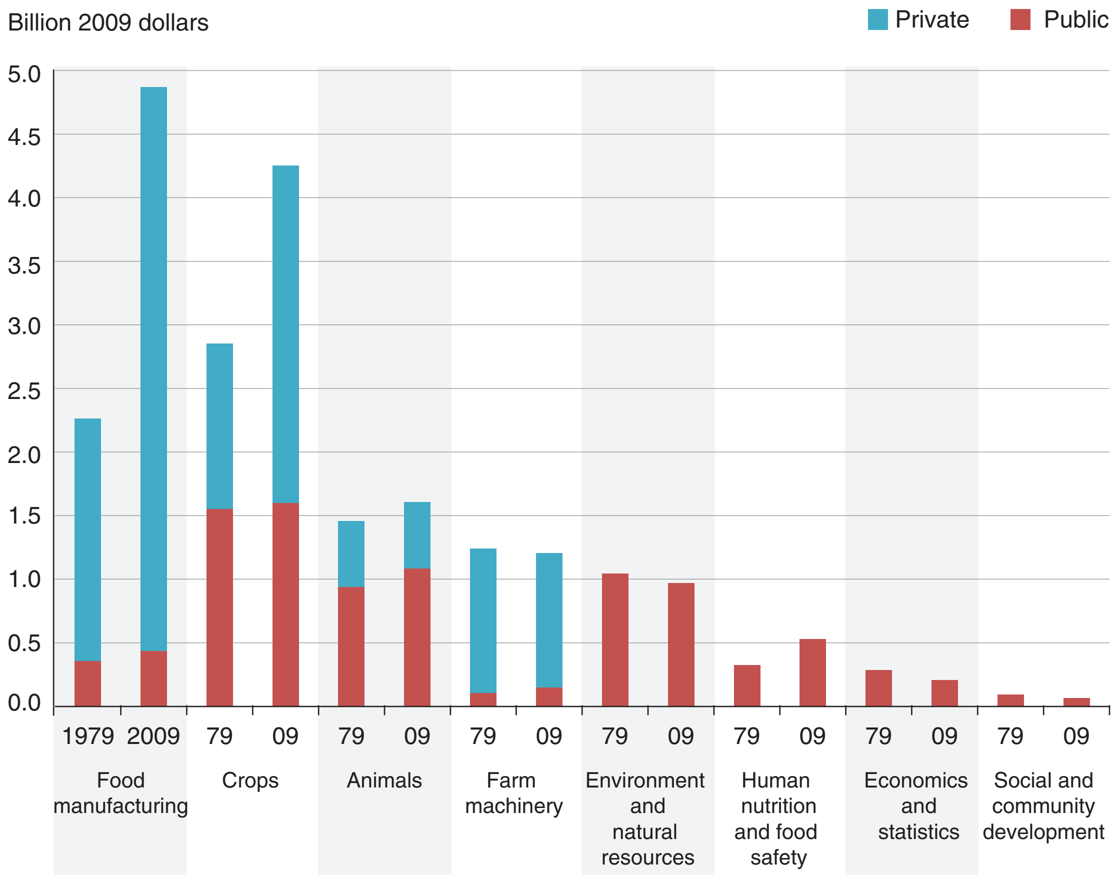
[32]The real value is nominal total agricultural research funding, deflated by a price index that accounts for changes in the costs of doing research. Our "research deflator" measures changes in the costs of doing research, in particular changes in scientists' salaries but also changes in the costs of building construction and supplies.

Figure 25
Allocation of research expenditures by topic area in 1979 and 2009



Source: USDA, Economic Research Service (ERS) based on data from National Science Foundation, USDA's Current Research Information System (CRIS), and various private sector data sources as reported by Fuglie et al. (2011). Data are adjusted for inflation using an index for agricultural research spending developed by ERS.

Public-sector agricultural research investment

Total U.S. public agricultural R&D expenditures were 39 percent higher in 2012 than they were in 1970 in real terms, with growth averaging 0.87 percent per year (see fig. 24). The increase in real research expenditures conceals considerable variability in the annual rate of growth for public agricultural research, which has slowed for notable periods since the early 1980s. From 1970 to 1982, real public R&D expenditures rose at an annual rate of over 3 percent (see box "Data on Public Agricultural Research in the United States." for information on how these data are compiled).

These rapid increases in real public R&D expenditures during the 1970s are consistent with increases in real public R&D expenditures from WWII to 1970 as reported by Huffman and Evenson (2006) and Alston and Pardey (1996), which are based on the archival work of these authors. Taking the nominal figures they report and applying the ERS research deflator,[33] we find

[33]We used the ERS research deflator as opposed to alternative research deflators proposed by Huffman and Evenson (2006) or Alston et al. (2010) to maintain consistency with the later data series discussed here. The three series of R&D deflators are very close, and they are also similar to the Biomedical Research and Development Price Index maintained by the National Institutes of Health (NIH). The major differences among them are how they weight the individual components. The ERS research deflator is explained further at www.ers.usda.gov/data-products/agricultural-research-funding-in-the-public-and-private-sectors/documentation.aspx.

Data on Public Agricultural Research in the United States

In 1966, the Secretary of Agriculture authorized the creation of a Current Research Information System (CRIS) to "document the publicly funded activities of the USDA/State agricultural and forestry research system" (see http://cris.nifa.usda.gov/aboutus.html). This system, now maintained by USDA's National Institute of Food and Agriculture (NIFA), previously provided national summaries of gross expenditures of funds by source as well as scientist years for each fiscal year. The data can also be broken down by State, as well as by other categories, such as commodity/subject of investigation, research problem area or knowledge area, and field of science. These data are compiled from reports submitted by research performers at USDA's research agencies, State agricultural experiment stations, forestry schools, colleges of veterinary medicine, 1890 universities, and other cooperating institutions. CRIS data are still the core of NIFA's research documentation system, but they have been supplemented by the Leadership Management Dashboard (LMD) and the Research, Education, and Economics Research System (REEIS), which also add information from multistate research projects, plans of work, accomplishment reports, and NIFA's grants management system to CRIS data.

In design, CRIS has been a comprehensive data system, reflecting all research funders and research performers in the U.S. public agricultural research system starting in 1966. However, at times, there may be omissions or inaccuracies in reporting by research performers. An alternative approach calculates expenditures reported by research funders. Such data are generally not available for all funders of public agricultural research, most notably for funding from the States, a major source. In addition to NIFA-maintained data, the National Science Foundation reports research funding stemming from USDA agencies from 1967 onward in terms of annual outlays and from 1951 onward in terms of annual obligations (NSF, various years). Public agricultural research expenditures for years before the CRIS system was instituted have been compiled through detailed archival work and reported by Huffman and Evenson (2006), Alston and Pardey (1996), and Alston et al. (2010).

that real public research expenditures also rose at a rapid rate between 1946 and 1970. Depending on the source, real U.S. agricultural R&D expenditures grew by at least 2.6 percent annually in the early postwar period and, possibly, at a rate of over 4 percent. Calculated rates of growth for this period do vary more than for subsequent periods, since data sources are more fragmented and researchers piece together their time series estimates in different ways. But it is likely that from WWII through the early 1980s, real public R&D expenditures in the United States grew much more rapidly than they have at any time since.

Starting in the early 1980s, public agricultural R&D investment in the United States grew more slowly and with more variability than in previous years. With the exception of a brief period of relatively rapid growth from 1998 to 2002, real public research expenditures have been essentially flat since 1982 (fig. 24). Real expenditures in 2012 were nearly 6 percent lower than they were in 1982.

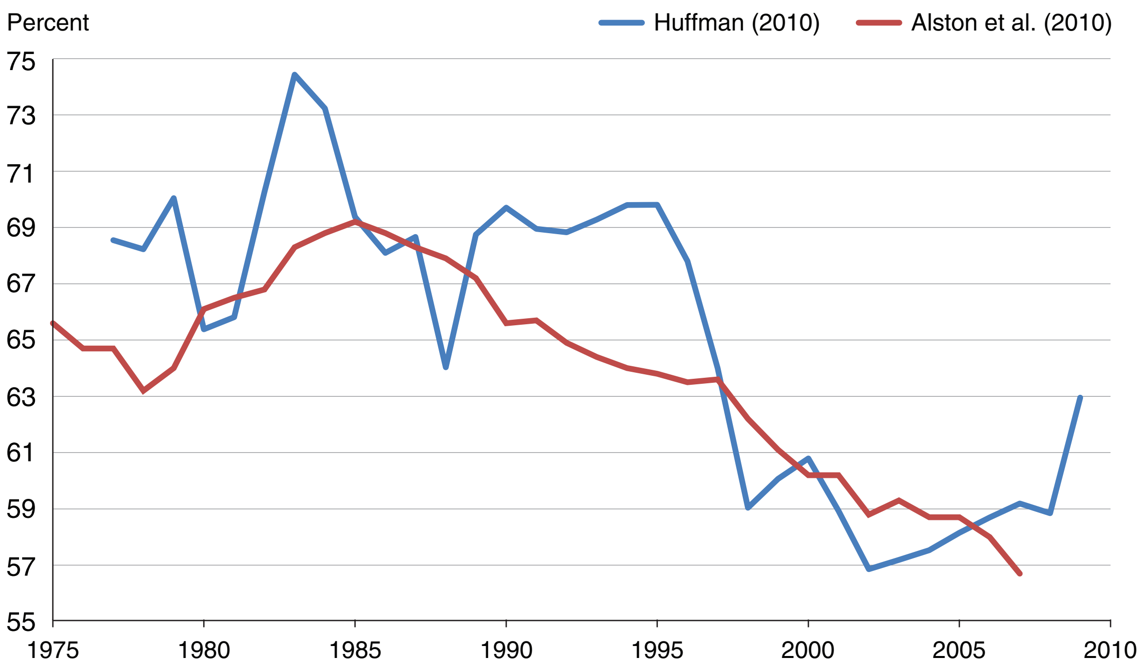
Slower rates of growth and greater fluctuation in U.S. public agricultural R&D expenditures have been accompanied by relative reductions in the share of those expenditures that might be expected to affect farm-level agricultural productivity directly. While it is possible to use different categories of research as defined by the Current Research Information System (CRIS) in different ways to determine the amount of public research that is "productivity-oriented," the research in the broad areas of crops, animals, and farm machinery/engineering as indicated in figure 25 could generally be considered "productivity oriented."[34]

Using similar data from CRIS, but with criteria that may be overlapping but not completely congruent, Huffman (2015) and Alston et al. (2010) have estimated how much U.S. public-sector agricultural research is directly oriented toward agricultural productivity. Alston et al. present results in percentage terms. We have taken Huffman's estimates of productivity-oriented research expenditures and combined them with estimates for total U.S. agricultural research from Huffman and Evenson (2006), supplemented by more recent CRIS data, to also calculate the productivity-oriented research percentage (fig. 26). Both estimates suggest productivity-oriented research has been declining as a share of the public-sector total for 20 years or more, from about 70 percent to perhaps under 60 percent.

The net effect on the real level of productivity-oriented public research depends in part on which series for total public research is used as the basis for the comparison. After combining the data from ERS's total public research series (fig. 24) with the data in figure 26 on productivity-oriented public research, no trend is evident from the mid-1980s through the mid-2000s in total public research investment, with drops in the share of research devoted directly to productivity

Figure 26

The share of U.S. public agricultural research aimed at agricultural productivity[1] has fallen since the 1980s



[1]See main text. Broadly speaking, "research directly aimed at agricultural productivity" includes topics like crop, livestock, and farm machinery research but does not include topics such as more general environmental research or food, nutrition, and food safety research.

Source: USDA, Economic Research Service using data from Huffman and Evenson (2006), Huffman (2010), and Alston et al. (2010).

[34]Depending on the criteria used for definition, some of the research categories sometimes summarized under Environment and Natural Resources (e.g., "Soil, Plant, Water, and Nutrient Relationships") might be considered "productivity oriented" as well.

enhancement offset by increases in other public research investment. Since the mid-2000s, total public research has begun to fall in real terms, which suggests productivity-oriented public research may have also fallen.[35] Falling investment in productivity-oriented research would suggest potential negative impacts on the growth rate of agricultural productivity, although given the long lag lengths over which research influences productivity, these negative impacts might not yet be observable.

Private-sector agricultural research investment

Total private food and agricultural research expenditures in the United States were 2.75 times as large in real terms in 2010 than they were in 1970, having grown by an average 2.01 percent per year over that period (see fig. 24). A sizable portion of this research, however, was made by the food industry, directed at food products, and is therefore not directly relevant to farm-level productivity.[36] The rest of the private-sector total—agricultural-input research—is generally directed at raising farm-level output. Over 1970-2010, private agricultural-input research varied as a share of total private R&D. In general, this share fell as real agricultural-input research grew at an annual rate of 1.4 percent, more slowly than food research (fig. 27).[37] The productivity impacts of private agricultural research have been less studied than those of public research. Private research lags, while still lengthy, are likely shorter than those for public research.[38]

The most striking change in private agricultural input research has been a shift in the composition of that research. Private-sector research investment in crop seed or crop biotechnology research has grown rapidly. Although other sectors, such as agricultural chemicals and farm machinery, remain important components of private agricultural input research, crop seed research, once a relatively small share, now accounts for the largest part of private research on agricultural inputs (fig. 28).[39] In fact, between 1970 and 2010, crop seed/biotechnology research grew at an average annual rate of well over 8 percent per year, even though expenditures in this area remained essentially flat between 1998 and 2005 before resuming growth.

Several factors account for the rapid growth in private crop seed/biotechnology research. These include increased opportunities related to new biotechnologies, such as tissue cell culture, genetic engineering, and molecular mapping. Changes in intellectual property rights (IPRs), such as the Plant Varietal Protection Act in 1970, a Supreme Court decision authorizing the use of standard utility patents for microorganisms in 1980, and Patent Office rulings authorizing utility patents for plants and animals in 1985 and 1987, respectively, increased the ability of private-sector firms to appropriate more of the value associated with biotechnology innovations. In other words, stronger

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[35]A somewhat contrasting picture of the trend in productivity-oriented research is provided by Huffman (2015), who indicates a sharp drop in the late 1990s and then no trend through 2009.

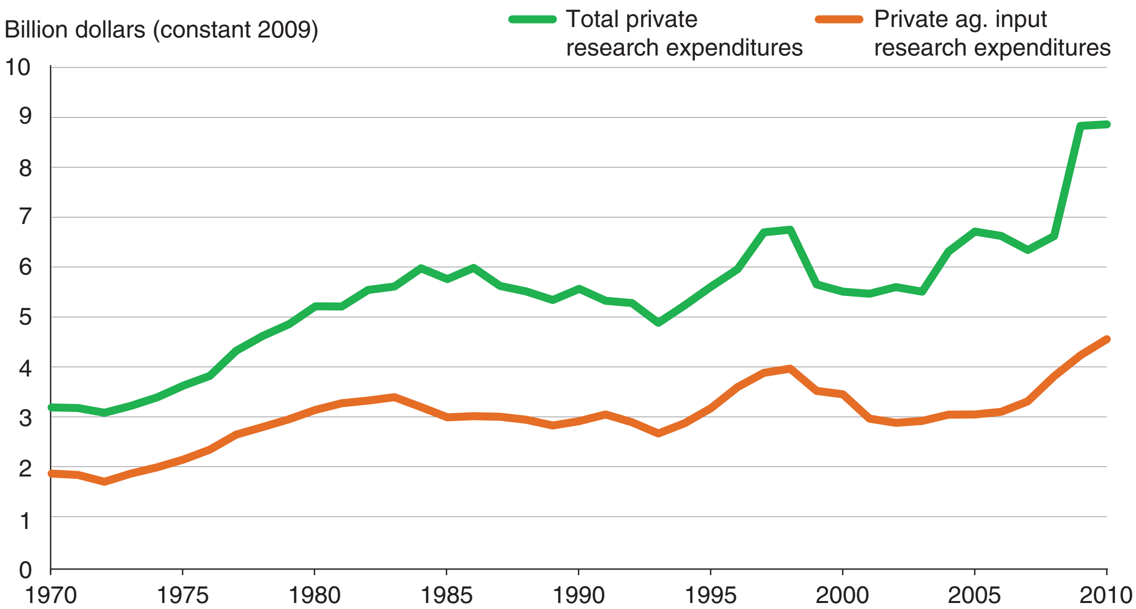
[36]Research is classified by the sector of use rather than the sector of origin. In other words, research from a company like Bayer Crop Sciences is considered agricultural research, from the sector to which it is targeted, rather than pharmaceutical research, which is the sector in which the parent company would be classified by an industrial classification system.

[37]The recent increase in real private agricultural-input research in the United States means that if we consider the period 1970-2010, agricultural input research has grown at an annual rate of 1.46 percent.

[38]See, for example, Wang et al. (2013) for a discussion of lag lengths for private agricultural research.

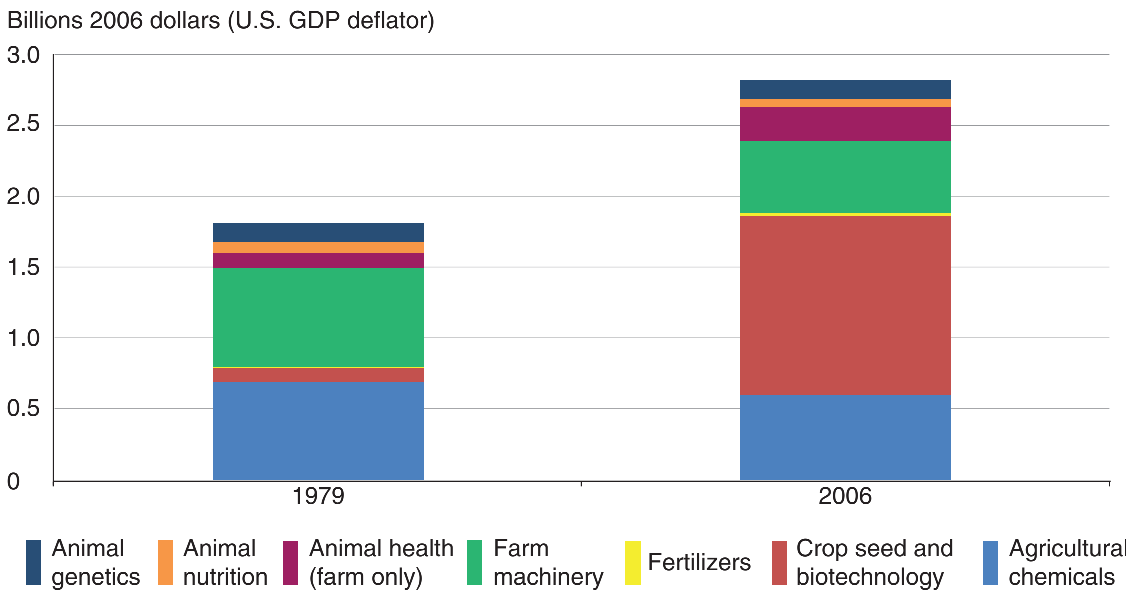
[39]Figure 28 is based on the years 1979 and 2006 because we have some of the most complete data for private agricultural research for those years, in particular for private research on animal genetics. Many of the estimates for animal genetics, a relatively small component of private agricultural-input research (3-5 percent of the total), are based on interpolation or extrapolation, but the 1979 and 2006 estimates are two out of a handful based on survey results.

Figure 27
Total private-sector food and agricultural research and agricultural-input research expenditures in the United States



Source: USDA, Economic Research Service (ERS) based on various private sector data sources compiled by Fuglie et al. (2011).
Data are adjusted for inflation using an index for agricultural research spending developed by ERS.

Figure 28
Since 1979, the most dramatic change in private agricultural-input research in the United States has been a rapid increase in crop seed and biotechnology research



GDP = Gross Domestic Product.
Source: USDA, Economic Research Service (ERS) based on Fuglie et al. (2011).

IPRs made it possible for firms to appropriate more of the economic value from their innovations, addressing somewhat the difficulty of excluding nonpaying users of research results for seed. Expansion of global markets for seed, combined with the location-specificity of much seed technology, meant that multinational firms expanded their research investments not only at home but also in other countries. Over the same period, there was essentially no growth in real private-sector investment for all other agricultural inputs.

Implications

The overall growth in real public and private agricultural research in the United States as represented in figure 24 obscures some important shifts that have occurred over the past 40 years:

- A slowing in the rate of growth of real public-sector agricultural research investment.
- Some decline in the proportion of public-sector agricultural research that has a direct impact on agricultural productivity.
- An uneven but notable shift in the composition of private-sector food and agricultural research, with a greater proportion being devoted to food.
- A marked shift in the composition of agricultural inputs research, with a very rapid rise in the amount invested in crop seed/biotechnology research.

Together, the first three factors suggest that real research investment aimed directly at agricultural productivity by public and private sectors combined probably peaked in the late 1990s, fell somewhat afterward, and has increased at less than 1 percent per year since 2001. However, the final factor has received a great deal of attention and led some observers to hypothesize that private-sector research may now be substituting for public-sector research. There have been relatively few empirical attempts to test this hypothesis, however, and the information we do have suggests that, in fact, public and private research may be complements, not substitutes, even for crop seed/biotechnology (Wang et al., 2009; Fuglie and Toole, 2014).

Extension and infrastructure

While innovation is the major force driving U.S. agricultural productivity growth in the long run, new techniques cannot have impacts on productivity growth if farmers do not have access to them or do not incorporate new farm practices in their production processes. Figure 1 introduced extension and infrastructure as factors affecting the speed of technology diffusion, input quality, and thus productivity growth.[40] The literature has also linked declining productivity in many developed countries in the 1970s to reductions in public capital investment (Aschauer, 1989; 1990).

Extension

The United States has a unique national agricultural cooperative extension system (extension), which was created by the Smith-Lever Act in 1914. The system consists of three parties—a Federal

[40]Extension, roads, electricity, and telecommunications facilities may affect the speed of technology diffusion; irrigation may particularly influence input quality.

partner (USDA); State partners (land-grant colleges and universities (LGU),[41] including the 1890 universities,[42] and State governments); and local partners (local, city, or county governments).

The publicly funded national extension system links professionals from educational institutions to farmers and rural communities. It helps USDA achieve its goals in developing the rural economy (through its home economics and community development programs), training tomorrow's leaders (through the 4-H program[43]), disseminating knowledge, and pursuing sustainable agriculture and environmental protection. Agricultural extension can influence productivity by providing information that bridges the gap between research discoveries and changes in individual farmer's fields. Agricultural extension specialists and agents can provide information that helps farmers improve managerial skills, thus promoting production efficiency and productivity. Through cooperative funding arrangements, the extension system has established a working relationship between land-grant institutions and local communities and has enhanced knowledge, attitudes, skills, and practices in the farm sector and rural areas for decades.

However, given its relatively smaller budget compared to public R&D and its unique role as educator and communicator, it is not easy to quantify extension's economic benefit separately or disentangle its impact on productivity growth from that of public R&D. In recent years, some researchers have used a combined extension-R&D knowledge stock to estimate their economic benefit as a package. According to the literature, the reported rates of return for extension-R&D knowledge stock are high, ranging from 7 to 110 percent.[44] The estimated benefit-cost (B-C) ratios are also high, ranging between 13 and 69 to 1, depending on the measures and data used (Wang, 2014). However, using an independent measure of extension, some researchers have shown that extension by itself could have accounted for 7.3 percent of annual agricultural productivity growth between 1949 and 2002 (Alston et al., 2011), contributed 0.12 percent to productivity growth for each 1-percent increase in extension stock in the Southeast region (Yee et al., 2002), or saved 0.25 percent in total production costs for each 1-percent increase in extension density, measured as full-time-equivalent (FTE) staff per farm (Wang et al., 2012), during 1980-2004.

Extension is jointly funded by Federal, State, and local governments. The State's role in funding extension has continued to grow since 1936 and has accounted for about 80 percent of total extension

[41]A land-grant college or university is an institution that has been designated by its State legislature or Congress to receive unique Federal support. There are more than 100 colleges and universities that make up the Nation's Land-Grant University System, which was created by the Morrill Acts of 1862 and 1890 and expanded by the Hatch Act of 1887, the Smith-Lever Act of 1914, and subsequent legislation (Graham, 1994). Each U.S. State and territory has a State office at its land-grant university and a network of local or regional offices (see USDA's Web site at www.csrees.usda.gov/Extension/index.html for more details).

[42]The 1890 Universities include 18 historically Black land-grant institutions in 16 Southern States and 2 universities in the District of Columbia and the U.S. Virgin Islands. While most of these Black land-grant universities were created by the Morrill Act of 1890, University of the District of Columbia and University of the Virgin Islands were established under the 1862 Morrill Act and are recognized as associate members of the Council of 1890 Universities.

[43]4-H is a national youth development program and organization administered by USDA's National Institute of Food and Agriculture. Its name represents four personal development areas—head, heart, hands, and health.

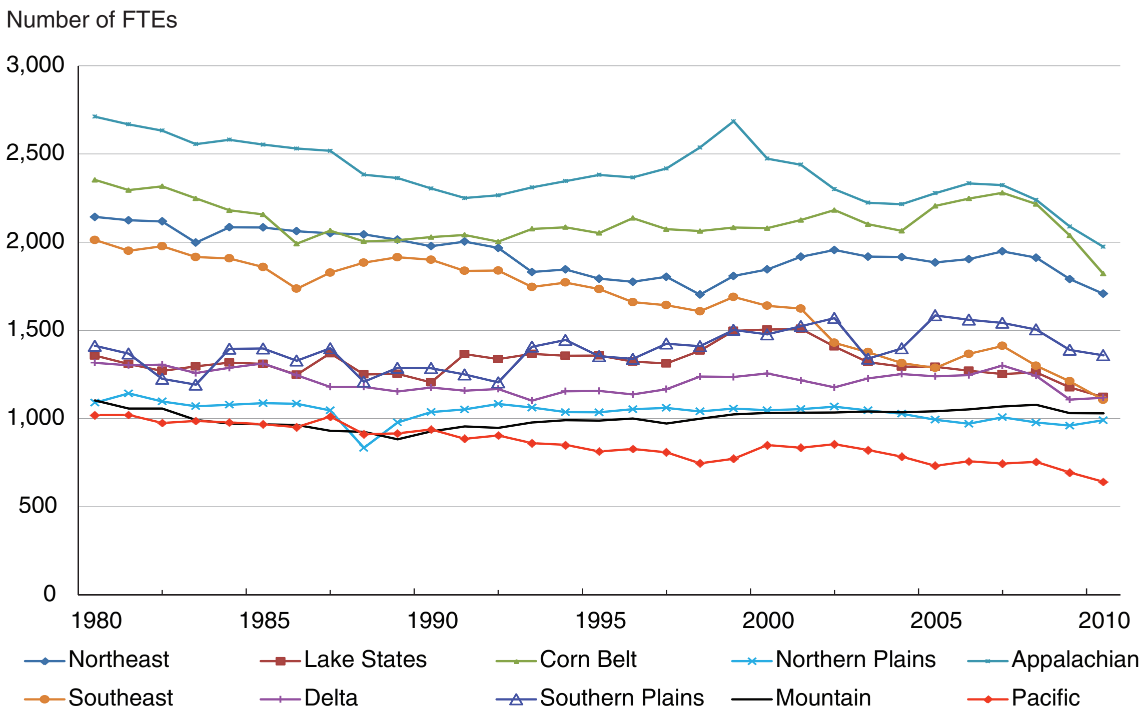
[44]A rate of return of, say, 10 percent, would be equivalent to the return of an investment of 1 dollar today that then returns 10 cents each year in perpetuity. The return to a public investment in agricultural extension or R&D is the return to society in general, rather than to only one group, such as innovators. The rate of return to public agricultural research or extension funding is usually measured in terms of productivity growth, production increase, or cost reduction from each 1 dollar of investment. The beneficiaries can include producers, when the increased production and/or reduced cost bring in more profit, and consumers, when food price decrease due to productivity growth.

funding in recent years (Wang, 2014). As a result, extension budgets, the number of FTE staff,[45] and extension program focuses are quite diverse across regions and, therefore, may have different impacts on regional development and productivity growth. Extension FTEs in all regions declined during the 1980s and then stabilized or rebounded slightly in the 1990s and 2000s, except for the Southeast and Pacific regions, which experienced persistent decline over time (fig. 29). The number of extension FTEs in most regions began dropping once again in 2007 due to Government budgetary pressure. From 1980 to 2010, total extension FTEs dropped by more than 20 percent nationally; however, the Southeast region experienced a 45-percent decline (see table 6). Program diversity and differential rates of extension FTE growth/decline across regions could have different impacts on productivity growth in the local farm sector.

U.S. agricultural production has continued to shift to larger farms with greater specialization over the last few decades (MacDonald et al., 2013), and farmers have relied more heavily on contracting (O'Donoghue et al., 2011) to market their output. Along with these changes, the role of private firms in providing information on farm practices, such as pest management or fertilizer usage, also grew (Padgitt et al., 2000). While the private sector has played an increasing role in disseminating

Figure 29

Although trends differ by region, public extension personnel in the U.S. have declined since 1980



FTEs: Full-time equivalent staff.

Sources: USDA, Economic Research Service (ERS) calculations based on data from Current Research Information Systems and ERS.

[45]Extension personnel are usually involved in other activities, such as teaching or research, in addition to extension activities. Full-time equivalent (FTE) staff is a unit used to measure the size of the staff's annual involvement in extension projects. For example, 1 FTE means that a total of 2,096 employee hours were spent on an extension project during the year, either by 1 employee working full-time or by 2 or more employees working part-time on the project.

knowledge, public extension has an irreplaceable role to play, particularly in nonprofit activities such as providing technical guidance to beginning or socially disadvantaged farmers and ranchers.[46]

Table 6

Changes in cooperative extension (USDA, district, and county) full-time equivalent staff

Regions	1980	2010	Total changes	Average annual changes
	Number		*Percent*	
Appalachian	2,712	1,974	-27	-1.1
Corn Belt	2,353	1,820	-23	-0.9
Northeast	2,143	1,708	-20	-0.8
Southeast	2,012	1,106	-45	-2.0
Southern Plains	1,412	1,359	-4	-0.1
Lake States	1,357	1,122	-17	-0.6
Delta	1,316	1,118	-15	-0.5
Mountain	1,102	1,030	-7	-0.2
Northern Plains	1,090	990	-9	-0.3
Pacific	1,019	642	-37	-1.5
Total	16,516	12,868	-22	-0.8

Source: USDA, Economic Research Service using data from USDA, National Institute of Food and Agriculture, "Salary Analyses of Cooperative Extension Service Positions" report, various years.

[46]According to USDA's definition, a family farm is considered a beginning farm when a farmer or rancher has not operated a farm or ranch for more than 10 years. A family farm is considered "socially disadvantaged" when the principal farmer or rancher is a member of a group whose members may have been subjected to gender, racial, or ethnic prejudices because of their identity as members of a group, without regard to their individual qualities. USDA operates a number of programs that include provisions aimed at helping beginning and socially disadvantaged farmers and ranchers develop their skills and knowledge of farming practices. Depending on the farm program, socially disadvantaged groups may include women, African Americans, Native Americans, Alaskan Natives, Hispanics, Asians, and Pacific Islanders. See www.ers.usda.gov/topics/farm-economy/beginning-disadvantaged-farmers/glossary.aspx for details.

Roads

Roads facilitate growth in agricultural productivity by making inputs, new technology, and extension staff more accessible to farmers, and by making delivery of farm commodities to markets easier and less costly. In an international study of 66 countries representing the full range of economic development, Antle (1983) finds that transportation and communications infrastructure (measured per square kilometer of land area) contribute positively to agricultural productivity growth, since farmers' use of new technologies depends on the costs and benefits of acquiring and using them. Based on U.S. data, Gopinath and Roe (1997) and Yee et al. (2002) found significant positive relationships between infrastructure and U.S. agricultural productivity at the national and State level, respectively. Using highway stocks as one input, Paul et al. (2001) also found that public infrastructure capital investment had a significant positive effect on U.S. agricultural productivity. Their results show that the impact is especially significant for animal products—including meat and dairy—for which transportation networks may have a major influence on production costs.

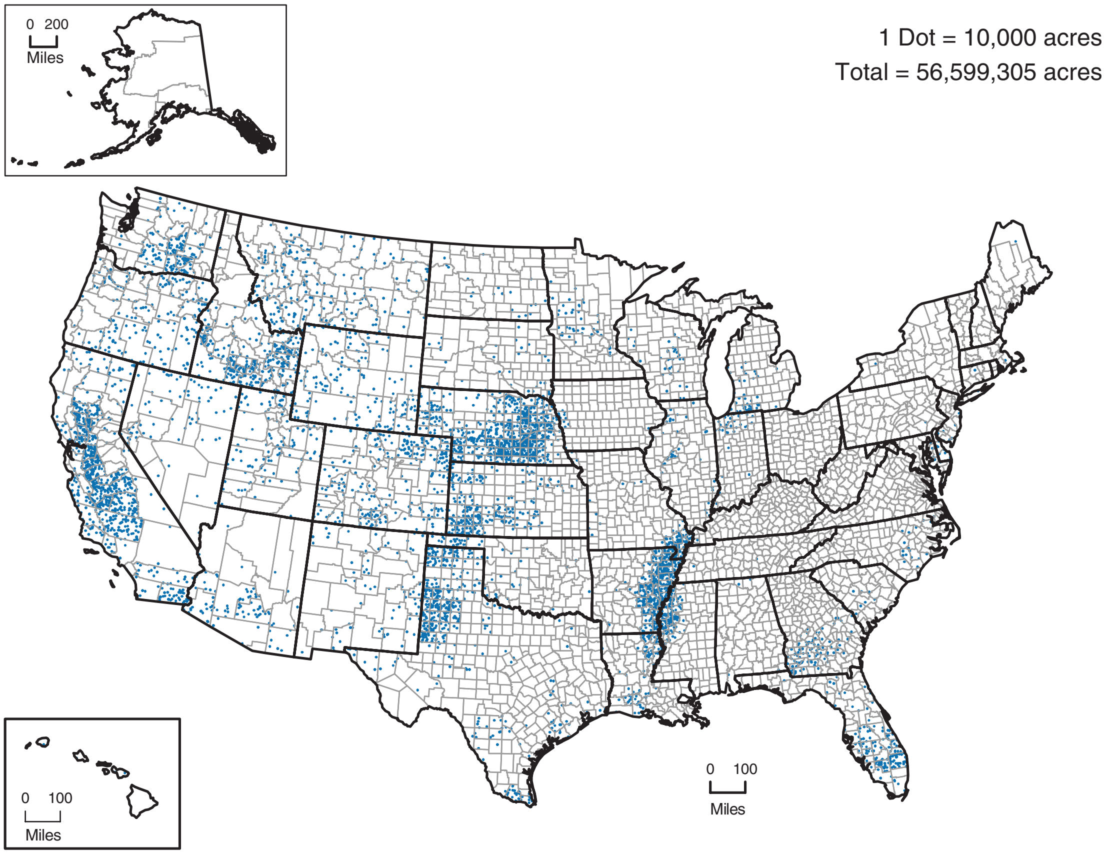
Using road density (including both highways and local roads, measured per square mile of land area) as one of the factors in a U.S. study, Wang et al. (2012a) showed that a more dense transportation network could enhance the benefits of public R&D investment and reduce production cost at the State level. They found that a 1-percent increase in road density reduced production cost by 0.04 percent and increased the elasticity of R&D cost (in absolute value) by 1.6 percent, from 0.1287 to 0.1307. That is, with higher road density, R&D investment has a larger impact on productivity growth in terms of cost reduction. Wang et al.'s findings imply that a more dense transportation network can help reduce transportation time and cost and, thus, make new technology more accessible and affordable to farmers. An increase in road density also helps to reduce production cost directly by lowering transportation costs for delivery of inputs and outputs and, therefore, enhances productivity growth.

Irrigation systems

As mentioned earlier in this study, random weather events, such as drought or flooding, can have a dramatic effect on agricultural production. New technologies are designed to help farmers maximize the biological performance of seeds and plants using appropriate combinations of soil, water, chemicals, and other inputs and reduce adverse effects from unexpected weather events. Irrigation systems have been widely adopted in areas with variable weather conditions to help growers adjust and control water usage during the growing season. Irrigation is also prominent where summers are consistently and uniformly dry. Agriculture is the largest user of fresh water, and irrigated acreage continued to expand in most regions through 2007. In 1959, total irrigated U.S. land area was 33.2 million acres; by 2007, it had increased by 70 percent to 56.6 million acres. In addition, more efficient irrigation systems have been installed, with automatic water usage adjustment functions that result in reduced average applied water rates per acre (Schaible and Aillery, 2012). In 2007, about 7.5 percent of all agricultural cropland and pastureland in the United States was irrigated; adoption is especially high in the Western States and the Mountain and Plains regions (fig. 30). According to the Census of Agriculture, the average crop yield per irrigated acre of barley, corn, cotton, and wheat ranged from 1.2 to 2.2 times the corresponding nonirrigated crop yield (table 7). In general, irrigation can help to create higher and more reliable agricultural production and, thus, result in greater productivity.

Figure 30

Much of U.S. irrigated acreage in 2007 was concentrated in the Delta States, the Plains States, and the Mountain and Pacific regions



Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, 2007 Agricultural Census.

Table 7

Crop yield per acre—irrigated and nonirrigated

	Average crop yield (per acre)					
	2002			2007		
Crops	Irrigated (A)	Nonirri-gated (B)	Ratio A/B	Irrigated (A)	Nonirri-gated (B)	Ratio A/B
Barley for grain (bushels)	88.9	44.6	2.0	100.0	49.9	2.0
Corn for grain (bushels)	158.9	122.5	1.3	180.0	144.3	1.2
Cotton, all (bales)	2.1	1.1	1.9	2.5	1.5	1.7
Wheat for grain, all (bushels)	80.3	37.0	2.2	80.3	37.0	2.2

Source: USDA, Economic Research Service using data from USDA's Census of Agriculture.

Projections of 2050 U.S. Agricultural Productivity: Alternative Scenarios of Public Research Funding

The most important factor determining longrun productivity growth is innovation, which, in turn, is driven by research investment. Previous sections of this study have demonstrated a slowing in the rate of growth of public agricultural R&D investment in the United States, particularly in productivity-oriented public research. In this section, we make some projections of the effect of slowing public R&D investments on future TFP growth.

There is a rich body of literature attempting to quantify linkages between public R&D investment and productivity growth. Evenson (2001), Alston et al. (2000), Huffman and Evenson (2006), and Fuglie and Heisey (2007) draw findings from the literature and conclude that returns to public research funding are high. In general, the mean rates of return to public investments in agricultural research—in other words, returns to society in general—range from 20 to 60 percent, depending on the methodology and data used (Fuglie and Heisey, 2007).[47] The rates of return of public R&D can be higher when considering the spillover contributions from research in a particular State to other States' productivity growth (Huffman et al., 2001; Alston et al., 2010; Plastina and Fulginiti, 2011; among others). These rates of return are consistent with benefit cost ratios of 10:1, 20:1, or more (Fuglie and Heisey, 2007; Alston et al., 2010). They are also comparable to estimated rates of return on public research investments in other areas. For example, Cockburn and Henderson (2001) reported that the rate of return on public-sector biomedical research may be as high as 30 percent. For private research investments, other analysts using Bureau of Economic Analysis national income and product accounts (NIPA) data estimate a pre-tax rate of return to investment in the U.S. nonfinancial corporate sector of 8.5 percent (Burgess and Zerbe, 2011). Thus, estimated rates of return to public agricultural research compare favorably to other public research investments as well as to private corporate investments.

Wang et al. (2012a) found the benefit from U.S. public agricultural research is also affected by the capacity of the State's extension service, public infrastructure, and neighboring States' research funding. According to the study, extension has the highest impact on the contribution of local R&D, followed by the R&D investment in neighboring States, and road density within the State. A larger number of extension FTEs, higher road density, and higher R&D investment in neighboring States all help to increase the impact of R&D investment within a State. Wang et al. refer to extension, roads, and R&D spill-ins from neighboring States as "efficiency variables" because they act as catalysts to enhance the outcome of local public R&D investment. Wang et al.'s results show that the return to U.S. public agricultural research funding varied from State to State and averaged about 13 percent when only the contribution of the "home" State's public R&D investment was estimated.[48] The return to public R&D investment averaged about 45 percent when the contribution to neighboring States' productivity growth was also included.[49] Since Wang et al.'s estimated return rates to public R&D are smaller than those of many other studies, the authors suggest that the rates of return

[47]The most contentious part of analyzing public investments usually revolves around how discount rates are chosen and incorporated into the analysis.

[48]This kind of rate of return to public research investment has usually been termed the "local rate of return" in the literature.

[49]This kind of rate of return to public research investment has usually been termed the "social rate of return" in the literature.

for local public research investments may be exaggerated if contributions from other efficiency variables are neglected.

Based on the model developed in Wang et al. (2012a), Heisey et al. (2011) projected that if public agricultural research spending continues to level off, or fall, U.S. agricultural production may not be able to keep pace with growing global demand for food. The study made different assumptions about future trajectories for U.S. public agricultural R&D spending and applied R&D stocks constructed on the basis of alternative R&D investments to project future trends in U.S. TFP.[50]

We extend the study of Heisey et al. (2011) by adding one more scenario to the two scenarios that were previously explored. The three scenarios all assume the research deflator will rise by 3.73 percent per year over the projection period, consistent with historical trends from 1983 to 2009 (see box "How the Projections Were Derived"). The scenarios were developed to reflect three basic situations. Scenario 1 is optimistic, assuming research spending grows in real terms. Scenario 2 assumes nominal expenditures remain constant, which means real spending falls as research costs rise. In light of concerns that stringent across-the-board reductions in the Federal budget could further reduce research spending, Scenario 3 reflects a sharp drop in research spending in a single year, 2014, to test whether this would have a significant long-term impact on productivity growth, or whether the effect would essentially dissipate over the next 40 years. Results are as follows (see fig. 31):

- Scenario 1: If U.S. public agricultural research spending through 2050 grows at an average annual rate of 1 percent in real terms from the 2005-09 average level of expenditures, the annual rate of agricultural TFP growth will increase to 1.46 percent during 2010-50, compared with 1.42 percent during 1948-2011.

- Scenario 2: If annual U.S. public agricultural research spending through 2050 remains unchanged in nominal dollars at its average 2005-09 level of $2.5 billion per year, real research expenditures will decline at a rate of 3.73 percent per year. The annual rate of agricultural TFP growth will fall to 0.86 percent during 2010-50, much lower than the 1.42-percent historical average annual rate.

- Scenario 3: If there is a one-time 25-percent spending reduction in 2014 followed by no additional changes in nominal spending,[51] the annual rate of agricultural TFP growth will fall to 0.63 percent during 2010-50, less than half its historical average growth rate.

Although the estimates of annual productivity growth between 2010 and 2050 differ considerably under these three scenarios, their impacts during early stages are rather small as it takes time for research investment to affect TFP growth. Projected output increases by 13 percent, 12 percent, and 12 percent, respectively, under these three scenarios by 2020. However, between 2010 and 2050, agricultural output grows differently—by about 80 percent, 40 percent, and 30 percent under scenarios 1, 2, and 3, respectively. In general, raising R&D spending by 1 percent in real terms would enable the U.S. farm sector to keep pace with increasing domestic and global food

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[50]The projections were focused on analyzing the impacts of different patterns of public R&D investment, and, thus, they do not take into account additional factors, such as climate change, that might have large impacts on future U.S. agricultural productivity. A working hypothesis might be that climate change may reduce projected productivity growth for all three scenarios considered here. However, the impacts of climate change are difficult to project as they are likely to vary by the severity of the climate change; by region; by crop; and by the degree to which farmers are assumed to adapt through such factors as crop choice (Malcolm et al., 2010).

[51]In other words, from 2015 through 2050, nominal spending remains constant at the new, lower amount.

demand with its current level of resource use.[52] On the other hand, increasing agricultural output to keep pace with demand under scenarios 2 and 3 would require bringing more land, labor, capital, materials, and other resources into production. Not only would this increase the cost of food, but

How the Projections Were Derived

We use an econometric model developed by Wang et al. (2012a) along with data on productivity-oriented research expenditures data from Wallace Huffman at Iowa State University (see Huffman and Evenson (2006) and Huffman (2015) for details). The projection model also accounts for the contribution of neighboring States' public R&D investment (R&D spill-ins), extension activities, and road infrastructure, in addition to local public R&D investment (for more details regarding the model setup, see Wang et al., 2012a). Research investment usually has a time lag before actually affecting productivity growth. It also continues to have an impact for a long time (even decades) after investments are made. Therefore, researchers tend to construct a measure of R&D "stock," similar to the measure of physical capital stock to evaluate the relationship between research and productivity growth.

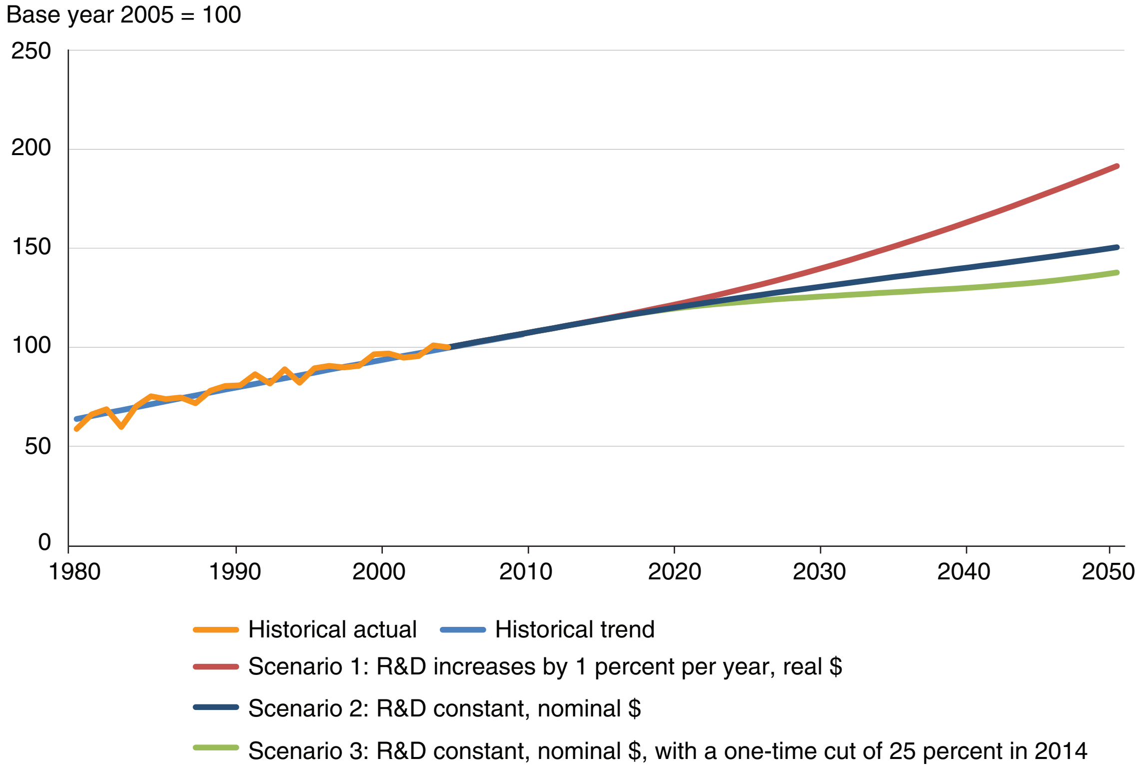
There are several ways to construct R&D stocks based on alternative hypotheses on the lag structure—including assumptions on lag time between when research is done and when productivity is likely to be affected, and research's impacts (weight) to each period of time in the future. There are three popular lag structures assumed in the literature. The first is a trapezoidal lag specification developed by Huffman and Evenson (2006) with a total lag length of 35 years for public research. The second is based on a gamma distribution from Alston et al. (2010). They suggest a lag length of 50 years. The third specification is an inverted-V lag structure from Chavas and Cox (1992) with a lag length of 31 years. However, those alternative lag structures all represent arbitrary assumptions, and no agreement exists on the best model to use in constructing R&D stocks (Griliches, 1998). Wang et al. (2013) find similar econometric results when using three different R&D stock estimates based on alternative lag structure assumptions. Therefore, in our projections, we simply adopt a trapezoidal lag structure to construct R&D stock to be consistent with Wang et al. (2012a).

We assume alternative scenarios for future public R&D funding to simulate future growth in U.S. agricultural TFP to 2050.[1] We use statistical relationships based on different productivity and investment patterns across States for 1980-2004 to estimate the effects of public R&D stocks on productivity growth. These estimated relationships are used to project future TFP growth patterns given alternative assumptions about future public R&D spending. Changes in current levels of public R&D spending affect future TFP growth only gradually since most of today's "knowledge capital stock" is the result of past accumulated investment in R&D. To model the effects of different scenarios for R&D spending on future TFP growth, we hold the contributions to agricultural productivity from other sources—such as agricultural extension, farmer education, infrastructure, economies of scale, private R&D, and technology transfer—constant and allow only the effects from public agricultural R&D to change.

[1]The only thing that changes in each scenario is the level of public R&D investment. In other words, we do not attempt to simultaneously project other variables, such as climate change, that could affect TFP growth.

[52]FAO (2012) suggested that global food demand will increase between 70 and 100 percent by 2050.

Figure 31
Projected agricultural TFP growth based on alternative research investment scenarios moved closely in the first decade before diverging at an accelerating rate



R&D = Research and development. TFP = Total factor productivity.
Source: USDA, Economic Research Service based on Heisey et al. (2011) and Wang et al. (2012).

more intensive use of agricultural chemicals and land could also cause environmental problems, such as impaired water and soil quality, through nutrient and chemical runoff or erosion, or the loss of wildlife habitat or wetlands through conversion to cropland. Even if future growth in U.S. agricultural production would meet U.S. needs, U.S. production would be unable to keep pace with growing global demand.

In the long run, lower rates of TFP growth could mean lower rates of growth in agricultural output, which in turn could stimulate higher food prices if output does not keep pace with demand. Consumer benefits for low-income households, whose spending is more likely concentrated on food consumption, would be reduced disproportionately. Higher rates of TFP growth would reduce the likelihood of these outcomes. Since Government budgets have been under pressure in recent years, the private sector may find it advantageous to take a larger role in developing the new technologies needed to spur future agricultural productivity growth. However, Tokgoz (2006) and Wang et al. (2013) found that certain categories of public R&D spending appear to stimulate private R&D spending, making it unlikely that private agricultural R&D could ever substitute completely for public R&D in supporting longrun growth in TFP. Therefore, determining the appropriate set of research policies may be critical to sustained agricultural productivity growth in the long run.

Conclusion

Historical trends suggest that U.S. agricultural output has more than doubled since 1948 at an average growth rate of 1.49 percent per year through 2011. With little growth in aggregate input use, the impressive performance in U.S. farm production has been driven mainly by TFP growth. Over this period, TFP grew at an average annual rate of 1.42 percent.

At the same time, agricultural input composition has shifted significantly, with increasing use of intermediate goods and less use of labor and land. The nonfarm sector has benefited as the agricultural sector has reduced its use of these production inputs, particularly labor. Intermediate goods, whose growth was the most rapid among agricultural inputs, have taken on a more important role. The output mix changed as well, with crop production growing faster than livestock production, and the share of farm revenue resulting from crop production increased from 52 percent in 1948 to 56 percent in 2011. In addition, production of fruits and nuts as well as vegetables and melons grew faster than production of food grains and feed grains, while production of poultry and eggs grew faster than that of other meat animals and dairy products. The shifts of input composition and output mix reflect the combined effects of changes in technology, factor endowments, and consumer preference.

Until the early 1980s, the growth of labor and land productivity reflected the increasing use of intermediate goods and capital inputs in addition to technical change, while labor and land inputs declined. Since 1981, intermediate input use has grown more slowly, and capital inputs have declined, increasing the importance of TFP growth to output growth.

We found no statistical evidence of a recent productivity slowdown. However, Government budgetary pressures in recent years have restricted investment in public agricultural science research, extension, and infrastructure, which may limit TFP growth in the future. In addition, FAO (2012) projects that by 2050, global agricultural demand will rise by 70-100 percent due to population growth and rising incomes in developing countries. Meeting this demand from existing or declining agricultural resources, such as rural labor and land, will require raising global agricultural TFP by a similar or larger level. Maintaining the U.S. contribution to global food supply would require a similar rise in U.S. agricultural TFP.

Based on a scenario analysis, projections show that TFP growth will not be affected much by slowing or declining public R&D investment in the short term (within 10 years). However, in the long run, TFP growth is projected to slow significantly in response to reduced public R&D investments. Furthermore, it will become increasingly difficult to increase the rate of TFP growth even if public R&D investment should increase again because of the long time periods between research investment and the effect of the research on TFP. Encouraging private-sector investment in productivity-related science may help leverage an even more complementary partnership between public and private sectors to pursue the objective of continued advances in agricultural productivity.

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Appendix—Tests for a U.S. Agricultural Productivity Slowdown

To develop tests for the slowdown hypothesis, we suggest a simple trend model and test the null hypothesis of a stable linear model against the alternative of "breaks" in the parameters in the trend regression:

$$\ln TFP = c0 \ + \tau_0 t + \varepsilon_t, \tag{1}$$

where *lnTFP* is TFP in natural logarithmic form, c_0 is an intercept and τ_0 is the trend coefficient to be estimated, t is a time trend, and ε is the disturbance term. The simple comparative static of (1) with respect to time yields

$$\frac{d \ln TFP}{d\,t} = \tau_0$$

where τ_0 is the estimated trend rate of productivity growth. Therefore, by testing whether τ changes over time or if there is a break in the structure of (1) that changes the estimated trend rate of growth, we can see if the productivity growth rate changes over a long time period. We first conduct the Elliott and Müller (2006) "quasi-local level" (qLL) test[53] to determine if there are structural breaks. The qLL test accomplishes this by assessing the general persistence of the time variation in the regression coefficients (i.e., if c_0 and τ_0 in (1) stay close to the estimated relationship over the sample period. If the hypothesis of persistence of the coefficient estimate is rejected, it suggests a possible structural break for that parameter, such as the TFP growth rate (τ).

Each of the first three rows of table A.1 reports a separate qLL test result. The first row of table appendix table 1 reports the qLL test result when no break is included in the test. We reject the null hypothesis of fixed coefficients at the usual confidence level. However, this qLL test does not provide information on the timing of the structural breaks. Additional break tests are required to determine the number of breaks and their form over time.

Appendix table 1
Elliott-Muller qLL test results

Break characterization	qLL statistics[1]
No break	-53.9***
With intercept break at 1985 only	-10.7
With trend break at 1985 only	-18.94***
With intercept break at 1985 and trend break at 1974	-10.3
With intercept break at 1985 and trend break at 1978	-10.1
With intercept and trend break at 1985	-10.7

* indicates significant at 5-percent level; ** indicates significant at 10-percent level; *** indicates significant at 1-percent level. Significant statistics indicate possible structural break or breaks in either intercept or trend growth rate.
[1] Null hypothesis is fixed coefficients over the sample period.
Source: USDA, Economic Research Service.

[53]The qLL test allows for a large class of breaking trends, including many or relatively few breaks, breaks that occur close to one another, breaks that occur at regular intervals, and smooth transitions in τ_0 that statistically indicate a break in trend. This enables us to determine if the time series has been free of structural breaks over the study period.

The simple trend model makes an appealing basis for this first round of productivity slowdown tests because it uses a time trend that has been used for analysis of economic data for decades. The limitations of exclusive reliance on a deterministic trend have more recently motivated development of an expanded toolbox of statistical techniques for analyzing trends. The main tools that have been developed are called stochastic trends, structural breaks in stochastic trends, and nonstationary time series tests used to classify stochastic trends into types of unit roots. Recent time series econometrics provides practitioners of trend analysis with the necessary machinery to cope with trend processes that are inherently random or subject to random shifts, or as is often the case, both.

Having determined in the first set of tests above that structural breaks are an issue, the next step is to try to identify the type and timing of breaks. As previous work has shown, we first have to determine if there is also a stochastic component to the time series and if this result is sensitive to the structural breaks specified. After conducting three fundamentally different unit root tests (Enders, 2009) without structural breaks—the augmented Dickey and Fuller (1979, 1981) unit root test (ADF test), the autocorrelation robust Phillips and Perron (1988) test (PP test), and the Kwiatkowski et al. (1992) test (KPSS test) that posits a different null of no unit root, the results show that the log TFP series is trend stationary when a deterministic trend is included in the test. Otherwise, it is not stationary and the identification of breaks could be spurious, depending on misspecified unit root characteristics.

Since the result of the qLL tests indicate the presence of one or more structural breaks in TFP we employ the Zivot and Andrews (1992) test (Z-Andrews test) to test for a unit root that also allows for possible structural breaks. The form of the Z-Andrews test is helpful because it has an alternative hypothesis that the time series is trend stationary with either a break in the level (intercept) or trend or both occurring at an unknown point in time. This unit root test can then be used to validate the qLL results that were obtained without including unit root characteristics. The results of the Z-Andrews test suggest that the TFP series is trend stationary when an intercept shift, or both an intercept shift and a trend break, are included. The Z-Andrews test places an optimal breakpoint at 1985. This evidence suggests that the TFP series is trend stationary with possible intercept and trend structural breaks. We conclude from the unit root tests and Z-Andrews tests that it is necessary to include a deterministic trend in a regression model with lnTFP as the dependent variable to ensure stationarity, but additional tests may be required to fully characterize the nature and timing of the structural change.

The next step we take is to refine our estimate of the break date or break dates that will best depict the trend rate of growth of TFP over the study period. The Z-Andrews test results showed possible intercept and trend breaks at one break date, which confirmed the qLL test that intercept and trend breaks were possible, but we would like to check if a combination of trend and intercept shifts are necessary to fully characterize the breaks in TFP. The break in the trend of TFP could take the form of a change in the slope of the trend line or a discontinuous jump up or down (an intercept shift) that could also be accompanied by a change in slope. For the purpose of determining the precise form of the trend break or possibly multiple breaks if there is more than one, we rewrite equation (1) to allow for multiple breaks in intercept and trend as follows:

$$\text{(2)} \quad \ln TFP = c_0 + c_1 D_{B_1} + \tau_0 t + \varepsilon_t$$

$$\text{(3)} \quad \ln TFP = c_0 + c_1 D_{B_1} + \tau_0 t + \tau_1 D_{B_2} t + \varepsilon_t$$

where D_{B_1}=1 if $t > B_1$ if and zero otherwise, D_{B_2}=1 if $t>B_2$ and zero otherwise, and B_i, i =1,2, represent possibly different breakdates for the timing of change in the intercept (B_1) and for the timing of the change in the trend growth (B_2). We are curious if two break dates may more fully characterize the breaking activity. We note that in this more exhaustive set of tests using (2) and (3), breaks in trend and intercept need not be contemporaneous.

After incorporating 1985 as a break date as detected with a deterministic trend by the Z-Andrews test, we conduct qLL tests to determine if further breaks may exist. Rows two and three in table A.1 show that the qLL tests reject the hypothesis of only one trend break in 1985. Yet, we cannot reject the hypothesis of no further breaks after the 1985 intercept break is considered in the model. Although there is no need to test for further trend break date, we still conduct additional tests by incorporating 1974 trend break (from Ball et al., 2013a) and 1978 trend break (which was decided based on the minimum residual variance criteria suggested by Hansen and used by others to identify an optimal trend break date) to make comparisons. The qLL test in rows four through six of table A.1 indicates no additional breaks are detected. Appendix table 2 presents regression results of combinations of alternative trend breaks and 1985 intercept break. The t-statistics are insignificant for all trend break estimates, suggesting there is no statistical evidence of a productivity slowdown. The estimated annual rate of productivity growth is 1.43 percent for the period 1948-2011 (when 1985 intercept shift is incorporated in the estimation), which is slightly higher than ERS's 1.42-percent estimate over the same period.

Appendix table 2

Productivity slowdown test results

	Annual productivity growth rate *(Percent)*					
Models with alternative breaks	First period	Second period	Difference	t-statistics	Residual variance	adj R^2
(A) With intercept break at 1985 and trend break at 1974	1.492	1.432	-0.059	-0.98	0.0621	0.9891
(B) With intercept break at 1985 and trend break at 1978	1.484	1.421	-0.063	-1.17	0.0616	0.9892
(C) With both intercept and trend breaks at 1985	1.427	1.428	0.001	0.02	0.0630	0.9895
(D) With intercept break at 1985 only	1.428			33.97***		0.9892

Note: t-statistics are from the difference tests in row A-C, and is for the trend growth rate in row D.
*** indicates significant at 1-percent level.
Source: USDA, Economic Research Service.