Agricultural Research Investment and Policy Reform in High-Income Countries

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Abstract

Investment in research is a primary driver of productivity growth in agriculture. However, in high-income countries, as agriculture's contribution to national economies declines, many public agricultural research systems face stagnant or falling financial support while research costs continue to rise. Public spending on agricultural research and development in high-income member countries of the Organisation for Economic Co-operation and Development as a whole has fallen in real (inflation-adjusted) terms since at least 2009. At the same time, society's expectations of food and agricultural systems have evolved to include a broader set of issues. These forces have induced pressure to reform agricultural research policies. Lessons from research policy reforms include accommodating a larger role for private firms in conducting agricultural research, diversifying funding sources to broaden the public research agenda, and providing stronger incentives for producer-levy funding of research.

Keywords: agricultural research and development (R&D); agricultural research policy; agricultural productivity; research costs; public and private R&D; farmer-funded research; plant breeding royalties

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What Is the Issue?

In recent years, public agricultural research systems in many high-income countries have faced new challenges. As agriculture's share of national economies in these countries has declined, public research and development (R&D) systems have faced stagnant or falling financial support while research costs have risen. At the same time, society's expectations of food and agricultural systems have evolved to include a broader set of issues. These forces have created pressure to reform agricultural research policies, and some countries have introduced reforms to broaden sources of financial support and refocus priorities of public agricultural R&D and accommodate a larger role for private-sector research and innovation. Comprehensive information on these developments is generally unavailable, however. This study aims to provide a more complete and up-to-date assessment of agricultural research funding trends in high-income countries that belong to the Organisation for Economic Co-operation and Development (OECD). It also provides a synthesis of selected research policy reforms with lessons for the United States.

What Did the Study Find?

Public and private investments in agricultural R&D have been the primary drivers of long-term agricultural productivity growth in high-income countries. Productivity growth in agriculture has raised the competitiveness of the sector and enabled countries to expand output and with-draw resources such as labor and capital from the sector for use elsewhere in the economy. The economic value of productivity improvement has been high relative to R&D spending in these countries, leading to high economic returns to public agricultural research.

Aggregate public spending on agricultural R&D in high-income OECD countries has fallen in real (inflation-adjusted) terms since at least 2009. Converting national spending into inflation-adjusted dollars (using general price indices and consumer purchasing power exchange rates), the study finds that public agricultural R&D spending peaked in 2009 and fell by an average of 1.5 percent per year between 2009 and 2013 (see figure). The United States continues to spend the most of any high-income country on public agricultural R&D, although the U.S. share of the total fell from 35 percent in 1960 to less than 25 percent by 2013.

However, these figures likely understate the decline in the value of inflation-adjusted public agri-cultural research investment because the costs of research tend to rise *faster* than the general rate of inflation. Moreover, the U.S. share of total public R&D spending by high-income countries could actually be lower than indicated in the figure because the United States has relatively high research costs: that is, another country spending the same amount as the United States might get more research output because that country could hire more scientists than the United States for the same amount of money. Although lack of data precludes comparisons for all countries in all

years, data that are available indicate the costs of scientific labor are higher in the United States and Canada compared with other high-income countries.

In response to financial and other pressures, several high-income countries have implemented reforms to their public agricultural research systems, with mixed results. Some lessons from these reforms are:

- Public agricultural research systems broadened the scope of their research investment to give more emphasis to social objectives such as environmental and food safety concerns.

- Public agricultural research systems have diversified their sources of funding, which in turn has affected their research priorities.

- Efforts to increase producer funding of research through levies on commodity production ("check-offs") have generated very little funding for production-oriented research without significant matching grants from governments.

- Growth in agricultural R&D spending by private firms has partially compensated for the stagnation in public R&D investment. However, public and private roles in agricultural R&D have generally evolved to be complementary, implying greater public investment can lead to increased private R&D. Premature withdrawal of public R&D in some applied areas can lead to productivity stagnation, as exemplified by the UK experience with wheat in the mid-1990s.

How Was the Study Conducted?

The study focused on public agricultural R&D spending trends by 31 high-income countries that are members of the OECD. It drew upon OECD, national, and other statistical sources to construct comprehensive R&D investment spending trends for food and agriculture. It examined alternative ways of constructing internationally comparable measures of R&D spending—using purchasing power parity ratios and cost-of-science indicators. It measured growth in R&D spending over time, R&D spending relative to agricultural GDP, and public agricultural R&D spending relative to total public R&D spending. It also reviewed case studies of the impact of R&D policy reforms in the United Kingdom, the Netherlands, and Australia, and suggests possible lessons of these reforms for the United States.

After many years of increase, real public agricultural R&D investment in high-income countries has fallen since 2009

Constant 2011 international dollars, billion

Legend:
- United States
- Central Europe
- S. Europe/Mediterranean
- Northwest Europe
- Japan & South Korea
- Canada, Australia, and New Zealand

| Annual growth rate in spending: | 1960-1990: 4.0%/year | 1990-2009: 1.3%/year | 2009-2013: -1.5%/year |
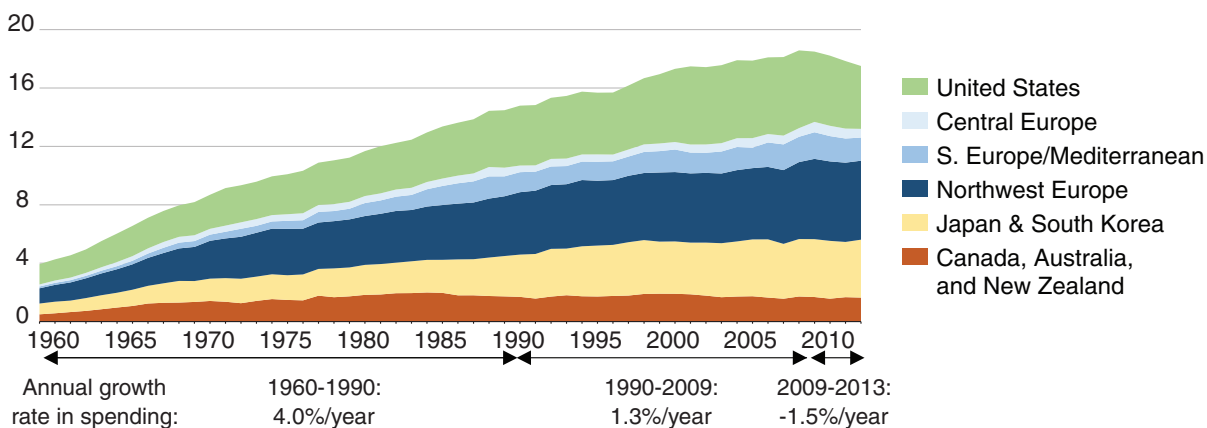
Note: Central Europe: Czech Republic, Estonia, Hungary, Poland, Slovakia, and Slovenia; Mediterranean: Greece, Israel, Italy, Portugal, and Spain; Northwest Europe: Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Iceland, Luxembourg, Netherlands, Norway, Sweden, Switzerland, and the United Kingdom. R&D = research and development.

Source: USDA, ERS analysis of data from the Organisation for Economic Co-operation and Development, Pardey and Roseboom (1989), World Bank, and numerous supplementary sources. See appendix B.

Introduction

In today's high-income countries, agriculture accounts for only a small share of economic output and employment. Yet it remains a focus of government policy. One dimension of this policy is public investment in agricultural research and development (R&D). R&D spending has had a large impact on the rate and direction of technical change in agriculture and has led to vast improvements in agricultural productivity. Higher agricultural productivity has made food more abundant at a lower cost, strengthened farm income and competitiveness, and reduced the resources needed for agricultural production. In recent years, however, agricultural research policy in many high-income countries has faced new challenges. Total spending by these countries on agricultural R&D has not kept up with inflation, while research priorities have evolved to give greater emphasis to a broader set of objectives. Public R&D has also needed to adjust to accommodate a larger role for the private sector in agricultural innovation.

The primary economic justification for a government to invest in agricultural research is that it provides a public good. *Public goods* are goods that are nonrival (many persons can consume or use them without diminishing their availability to others) and nonexcludable (once available to one person it is difficult to exclude others from using it). Because of these characteristics, it is difficult for a supplier to charge users of such goods a price sufficient to cover the cost of supply. Examples of public goods include fresh air, knowledge, national security, and lighthouses. Government support or some other form of collective action is usually necessary to provide public goods. In the case of knowledge creation, governments finance research directly as well as provide exclusion mechanisms (such as patents and copyrights) to incentivize the private sector to invest in R&D. Government-financed research tends to be concentrated in areas where the private sector, even with exclusion mechanisms, is likely to underinvest. This includes areas where new knowledge is likely to have potentially wide uses beyond local or specific applications intended by an inventor. Such knowledge is said to create large "spillovers" (potential benefits to society above and beyond the benefits to the inventor).

This study reviews long-term trends in public agricultural R&D investment by high-income countries, examines how these investments have contributed to economic growth, and assesses some important policy reforms that some countries have undertaken. It presents a framework for understanding the complementary roles of public and private R&D and the degree to which public R&D investments can continue to provide significant public goods in affluent countries. The focus of the analysis is 31 high-income countries that are also members of the Organisation for Economic Co-operation and Development (OECD)[1]. These countries all operate market-based economies,

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[1] The Organisation for Economic Co-operation and Development (OECD) is a Paris-based intergovernmental organization that includes most of the world's industrialized and democratic nations. Through the OECD, member countries share and compare information and experiences with economic policy and performance.
    This study covers 31 of the 35 OECD member countries:
- North America: Canada and the United States;
- Asia-Pacific: Australia, New Zealand, Japan, and South Korea;
- Northwest Europe: Austria, Belgium and Luxembourg (combined), Denmark, Finland, France, Germany, Ireland, Iceland, Netherlands, Norway, Sweden, Switzerland, and the United Kingdom;
- Southern Europe and the Mediterranean: Greece, Israel, Italy, Portugal, and Spain;
- Central Europe: the Czech Republic, Estonia, Hungary, Poland, Slovakia, and Slovenia.

    The OECD countries not covered in the study are Chile (because of its unique location in South America), Latvia (which only became a member of the OECD in 2016), and Turkey and Mexico (which as of 2017 had not yet reached "high-income" status). A country's income status is based on the World Bank's classification.

have significant agricultural sectors, are located in primarily temperate zones, and share other features that make their experiences in agricultural research policy relevant for the United States.

Together, these 31 countries account for a significant but declining share of the total global investments in agricultural R&D. As recently as 1990, public agricultural R&D spending by high-income countries accounted for about 36 percent of total public and private spending on food and agricultural research worldwide, but that share had fallen to under 25 percent by 2011 (fig. 1.1).[2] Even though public agricultural R&D spending by high-income countries rose during most of this period, it rose faster in developing countries and the private sector. The most recent evidence, which will be detailed later in this study, shows that aggregate public agricultural R&D spending by high-income countries peaked in real (adjusted for inflation) terms in 2009 and subsequently declined.

Figure 1.1

Global spending on food and agricultural R&D, 1990 and 2011

(constant 2011 purchasing power parity (PPP) $, billion)

1990
$40.2 billion

Public R&D by high-income countries, $14.5

Public R&D by other countries, $10.7

R&D by ag input companies, $7.6

R&D by food manufacturing companies, $7.4

2011
$75.9 billion

Public R&D by high-income countries, $18.2

Public R&D by other countries, $24.1

R&D by ag input companies, $14.3

R&D by food manufacturing companies, $19.3
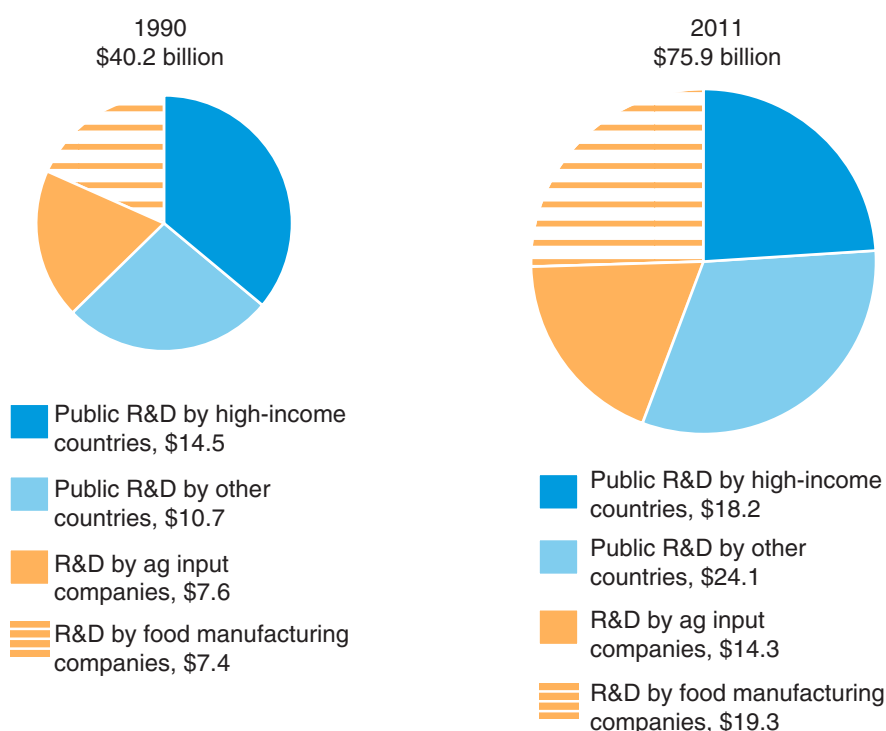
Sources: USDA, Economic Research Service using data on public agricultural research and development (R&D) in high-income countries from this study (see appendix B); data on public agricultural R&D in other countries from Agricultural Science and Technology Indicators (ASTI); and data on private food and agricultural R&D from Fuglie (2016).

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[2] In accordance with standard international scientific reporting, for the most part, "agricultural R&D" is a *gross* measure that includes, for example, forestry and fisheries research as well as research for primary agriculture. In this study, we will note the impact of using gross measures when it is useful for understanding the data and analysis. Also in this context, "food research" refers primarily to research on improving food manufacturing processes and developing new food products. By strict Frascati Manual standards (see page 5 for a discussion of the Frascati Manual and further information on definitional issues), this would be research focused on "industrial production and technology." Another research area, nutrition research, would have as its objective "health." In principle, it would be desirable to identify public expenditures in these categories separately; in practice, it is difficult to separate them in much of the available data.

According to estimates by the Food and Agriculture Organization of the United Nations, global food demand will rise by about 60 percent between 2006 and 2050, and at least 90 percent of this increase will be met by raising agricultural yield and cropping intensity on existing farmland rather than from expanding farmland (Alexandratos and Bruinsma, 2012). The decline in public R&D investment could place future agricultural growth at risk if this spending shortfall is not offset by increases in R&D expenditures elsewhere, such as the private sector or developing countries.

However, increases in agricultural R&D by the private sector or developing countries are likely to be an imperfect substitute for public R&D in high-income countries for two principal reasons. First, private companies are unwilling to invest in the types of research that yield insufficient financial returns. Private agricultural R&D, which is conducted mainly by firms that manufacture farm inputs (e.g., farm machines, agricultural chemicals, seeds, animal pharmaceuticals), significantly underinvests in many vital areas, such as precommercial science and technology platforms, environmental protection, and food safety and nutrition (Fuglie and Toole, 2014). Market returns for these types of investments are much lower than their social returns because this research generates large spillover benefits that are hard for the provider to appropriate; furthermore, in some cases, such as environmental protection, markets do not always directly value the social benefits (Pray and Fuglie, 2015). Second, agricultural technology is sensitive to environmental conditions and therefore tends to be location-specific. Agricultural research in tropical environments, for example, is likely to focus on different crops and different production constraints than agricultural research in temperate environments. Thus, high-income countries, which are almost entirely located in temperate zones, are likely to only benefit marginally from technological advances from research conducted in developing countries, which are mostly located in tropical and subtropical environments.[3]

The technological advances that emerge from research raise productivity in agriculture. This productivity growth not only expands output but also saves resources. Figure 1.2 decomposes agricultural growth by decade into growth due to increasing inputs in agriculture and growth due to raising the productivity of those resources. Productivity is measured as the ratio of total crop and livestock outputs to total land, labor, capital, and material inputs used in production, or total factor productivity (TFP). For the world as a whole, raising agricultural output became much more dependent on improving TFP after 1990. Since then, about three-fourths of output growth has come from increasing TFP and only about one-fourth has come from expanding the use of inputs in production. For high-income countries, increases in agricultural output are almost entirely dependent on raising TFP. While growth in agricultural output has slowed in recent decades (to less than 1 percent per year on average since 1980), continued growth in TFP has allowed for a reduction in agricultural inputs, freeing up resources like land and labor for use elsewhere in the economy. Total inputs used in agriculture in high-income countries have been falling since at least 1980. Yet, agricultural output has continued to expand because the total productivity of the resources remaining in the sector has increased at a faster pace than the decline in inputs.

It should also be noted that agricultural research and innovation may have significant social and economic benefits even if measured TFP is not growing at all. If the environment degrades—say, because of the emergence of new pests and diseases, depletion of groundwater resources for irrigation, or potentially negative impacts of a changing climate—the reduction in agricultural productivity that may result could cause TFP to decline. Ongoing research investment helps to

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[3] A recent review notes some international research spillovers from public agricultural research in high-income countries but, to date, little or no observable cross-country spillovers from public agricultural research in developing countries (Fuglie, 2018).

offset stresses from environmental changes through the development of new technologies to cope with such changes. Research to keep TFP from falling is sometimes referred to as "maintenance research," which is thought to have been especially important in the development of U.S. agriculture (Olmstead and Rhode, 2008). One study estimates that as much as 40 percent of U.S. public agricultural R&D is devoted to maintenance research (Sparger et al., 2013). In addition to economic benefits that raise or maintain productivity, research that leads to technologies that conserve environmental resources or improve the nutritional quality of food[4] can confer significant nonmarket benefits to society.

Figure 1.2
Contributions of inputs and total factor productivity (TFP) to agricultural growth

a. World average

Average annual growth (%)
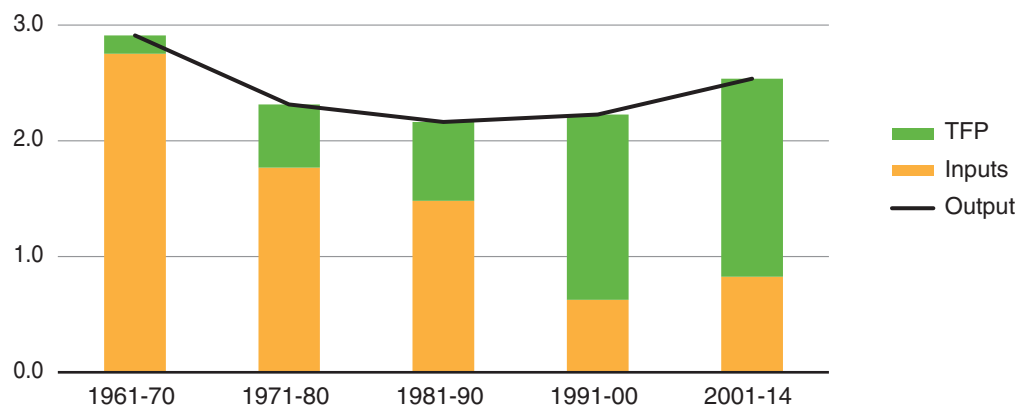
b. High-income countries

Average annual growth (%)
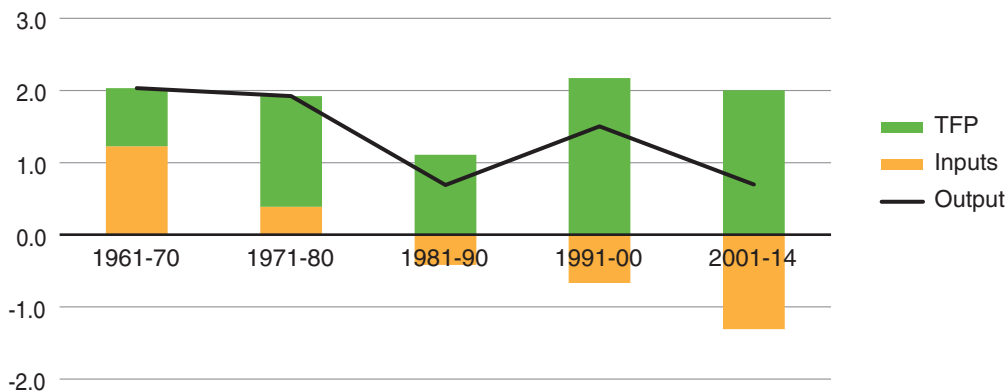
In figures 1.2 and 3.1, total factor productivity (TFP) growth is estimated as the difference between real output growth and real input growth. Agricultural output growth is based on the Food and Agriculture Organization of the United Nations Gross Agricultural Output measure, an aggregation of about 190 crop and livestock commodities based on a fixed set of average world farm-level commodity prices from the 2004-2006 period. Real input growth is the weighted-average growth rate of agricultural labor, quality-adjusted agricultural land, agricultural capital, and fertilizer and feed variable inputs, where the weights are average cost shares. See Fuglie (2015) for further details.
Source: USDA, Economic Research Service, International Agricultural Productivity Data Product.

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[4] Although private firms have some incentives to produce food with healthy attributes, both inadequate nutrition, particularly among consumers with limited resources, and improper nutrition, related to overconsumption, suggest that private firms underinvest in nutrition research (Day Rubenstein, 2003).

Basic Concepts and Data Sources

The focus of this study is on agricultural R&D policy and investment in today's high-income OECD countries. In these countries, agriculture's share of national Gross Domestic Product (GDP) has declined. While most of these countries continue to invest resources in agricultural R&D, for the OECD countries as a whole, this investment has fallen in recent years. It has also become a smaller part of overall spending on science and technology. As national priorities for R&D have shifted over time, some countries have implemented research policy reforms to reflect these new priorities.

This study covers 31 of the 33 OECD members that are classified by the World Bank as "high-income" (see footnote 1 for a list of countries covered in this report). For 29 of these countries, we construct a consistent annual time series of public agricultural R&D spending from 1960 to 2013; for 2 other countries (Estonia and Slovenia), spending data begin in the 1990s. For consistency, we define public agricultural R&D according to the principles and definitions laid out in the Frascati Manual (OECD, 2015b)[5]: Public R&D is R&D performed by government (central/Federal and provincial/State) institutes and universities.[6] To frame agricultural R&D investment in this multi-national context, we also collect data on total public R&D investments, the size of the agricultural sector, and the costs of R&D inputs (in this last case, the exercise is restricted to a subsample of these countries). We examine agricultural research policy changes using a framework for science policy developed by Stokes (1997) and Ruttan (2001). Together, these analyses may provide a basis for assessments of likely future trends in both the level and composition of public agricultural R&D funding, the potential impacts of these trends, the impacts of some of the agricultural policy reforms, and the degree to which interactions between different agricultural R&D performers and potential research spillovers might guide future research policy.

This study uses two principal sources of data on public R&D and agricultural R&D spending: (i) the OECD "Research and Development Statistics" database, especially for years after 1980, and (ii) for public agricultural R&D in the 1960s, 1970s, and early 1980s, the volumes compiled by the International Service for National Agricultural Research (ISNAR) (Pardey and Roseboom, 1989; Pardey et al., 1991).[7] These data are supplemented with other sources to fill gaps for some years and to assure a consistent institutional coverage for public R&D. The World Bank provides data

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[5] The Frascati Manual, first developed in 1963 and now in its seventh edition, is the international standard for science and technology reporting. Nonetheless, several features of available data mean there is often substantial room for judgment in the choice of indicators. The first is the large number of missing observations in available data sources. The second is that we follow Pardey and Roseboom (1989) in attempting to define research by purpose (agriculture; or, more generally, agriculture, forestry, and fisheries) rather than content. Increasingly, however, the "socioeconomic objective" of the research—the measure most consistent with purpose—is less likely to be defined outside of government budgets or government-performed research (appendix B). Finally, we note that some university or other publicly performed research may be privately financed, with some of the results restricted by the companies providing the funds. In the United States, for example, in 2013, around 22 percent of university agricultural research was funded from nongovernmental sources (OECD, 2016). About 9 percent of research came from grants and agreements with industry; the other 13 percent came from product sales, licensing agreements, commodity groups, foundations—which might be industry affiliated—and other sources.

[6] Research by the private nonprofit sector is also usually included with public R&D. For many countries, private nonprofit agricultural R&D is either small or not reported at all.

[7] ISNAR was incorporated into the International Food Policy Research Institute (IFPRI) in 2004. The ISNAR sources provide estimates for 24 of the 31 countries in our study, excluding only the Central European Countries and Luxembourg. In addition, Pardey et al. (1999) update estimates for 22 of these 24 countries to 1993. In most but not all countries, the Pardey et al. (1999) estimates are similar to those of Pardey and Roseboom (1989) in overlapping years. South Korea and Israel are the two countries included in the Pardey and Roseboom (1989) database but not in the Pardey et al. (1999) update.

on GDP, price indexes, and exchange rates. Additional sources are consulted for information on research costs for selected countries. Appendixes B and C contain a full description of sources for individual countries.

Organization and Structure of Public Agricultural Research Systems

Formal systems for public-sector agricultural research in some of today's high-income countries began in the 19th century. In a number of cases, including in the United States, agricultural research was one of the first scientific areas in which governments invested. Historically, agricultural innovation had been the province of individual farmers, but with advances in science, there was growing recognition that farms were unlikely to reach the size of industrial firms that would enable them to recover R&D costs (Alston and Pardey, 1996). At the same time, in many countries, initial public-sector efforts were inspired by the desire to link science-based research with practical information relevant to farmers.

Over time, a number of common themes emerged across these countries. The emphasis on linking scientific research with practical farming information meant that much initial public investment was in areas of applied research that affected agricultural productivity and other societal goals. Yet in many of these areas, commercial returns were low due to the difficulty for private innovators to appropriate, or capture, the benefits from R&D. A new scientific discovery may have many applications that increase the profitability of many producers or lower the cost of food for many consumers. Funding the research that leads to the discovery of such a technique would cost substantially less than the sum of the benefits it generates but would be much too expensive for any one producer or consumer to fund. An early example of international research collaboration that illustrates this point was the grafting of French vines onto American rootstock in the 19th century in response to the *phylloxera* pandemic.[8] "Spillover gaps"—the extent to which social returns to research exceed private returns—were large, even in the development of many farm-level technologies, such as new crop varieties. (The section "Agricultural R&D Policy Reforms" elaborates on the distinctions between more fundamental and more applied research, as well as the commercial potential of research.)

Over the first hundred years or so of "modern" public agricultural R&D systems, roughly spanning the time from the origin of these systems to the period analyzed here, at least two major questions shaped the design and structure of these systems. The first concerned whether or how to integrate agricultural research and higher education; the second, particularly for larger countries, concerned the degree of decentralization of research management (Alston and Pardey, 1996; Fuglie et al., 1996). Answers to these questions are conditioned, in turn, by the size of the agricultural sector, the relative proportions of land and labor used in agriculture, the political organization of each country, and the level of general scientific development (see appendix A).

One measure relevant to both the degree of integration between agricultural research and the educational system and the degree of research decentralization is a comparison of the amounts of research performed by government agencies and by higher education institutions. Relative proportions have varied widely over time and from country to country. Estimates of the share of higher education in total public spending on agricultural research is sometimes directly available and sometimes must

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[8] *Phylloxera* is an aphidlike insect native to eastern North America that often kills the highly susceptible Vitis vinifera grape essential to French wine production. *Phylloxera* probably first arrived in France in the late 1850s and was first recorded in 1863. French grape growers initially responded by ripping up and burning their vines, roots and all, in an unsuccessful attempt to control the pest. A number of scientific solutions were proposed, but eventually the use of American rootstock proved essential. See Mudge et al. (2009).

be inferred, but there is enough current information about this share to examine it as a potential measure of the decentralization of the system. It might also indicate the level of integration between research and training in agriculturally related science. To some extent, it could also suggest the balance between more applied and more fundamental research, under the assumption that more fundamental research is more often performed by universities, although this assumption has not been widely tested.[9] Research conducted by regional institutes may be another indicator of decentralization. In several countries with larger annual research expenditures, some of the research by government research institutes may be partially performed as well as funded by regional, State, or provincial rather than central governments (table 2.1).

Table 2.1
Public research expenditures and some features of public research organization, by country

	Annual public research expenditure[1]			
	Small < $100 million	Intermediate $100–$499 million	Large $500 million–$999 million	Very large ≥ $1 billion
Government-oriented < 1/3 public research performed by higher education institutions	Israel Slovak Republic[2] *Greece* Luxembourg	Norway Finland New Zealand Ireland	Spain[6] United Kingdom[7]	Japan[6] *France*
Mixed 1/3 to 2/3 public research performed by higher education institutions	Iceland[2]	Poland[3] Switzerland Austria Portugal Czech Republic[2] Hungary	Korea *Canada*[3, 6] Australia[2, 6] Italy[6] Netherlands	Germany[6]
University-oriented > 2/3 public research performed by higher education institutions	Slovenia Estonia	Belgium[4] Denmark[5] Sweden		United States

No Organisation for Economic Co-operation and Development data or other data on higher education percentage for countries in italics (France, Canada, and Greece). Likely government and higher education percentages inferred from other information.

[1]Based on 5-year averages, 2009-2013.

[2]These countries may be increasing higher education's share of public agricultural research significantly.

[3]Higher education institutions perform almost one-third of public agricultural research in Poland and Canada (Canada estimate from Carew, 2001).

[4]Belgium's research system comprises discrete systems in Flanders and Wallonia (Chartier et al., 2014a).

[5]After a period of slow increase in higher education's share of agricultural research in Denmark, the share was changed from about 40 percent to about 100 percent between 2006 and 2007.

[6]A notable portion of nonhigher education (i.e., government) performed research in these countries is performed below the level of the central government, although the structure of research differs by country.

[7]In addition to research funded and performed by the UK central government, the Governments of Scotland and Northern Ireland also support agricultural research activities.

Source: USDA, Economic Research Service.

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[9] For example, structural changes in the UK research system over the past 40 years may have moved it toward more fundamental research. Nonetheless, even today, only 25–30 percent of public agricultural research in the UK appears to be performed by higher education institutions.

With a few exceptions, most currently large systems (in terms of investment levels) in geographically larger countries were partially decentralized to address location-specific agricultural issues. Following the lead of first Germany and then the United States, a number of countries also attempted to integrate higher education with agricultural research, with varying degrees of success. Out of 10 countries in which 80 percent or more of public research is performed either in government institutes or primarily in universities—i.e., countries where public research is concentrated in one kind of institution rather than two—8 are relatively small, with annual research expenditures of $200 million international dollars or less.[10] One country, Denmark, has markedly shifted public agricultural research performance from government institutes to universities, and several other countries (Czech Republic, Slovak Republic, and Iceland) may be making similar changes. All of these countries have relatively small systems.[11] The U.S. system, in which currently over two-thirds of all public research is performed by universities/State Agricultural Experiment Stations, is unique in this respect among larger public agricultural research systems (see table 2.1).

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[10] The exceptions are France, which has the most highly centralized large public agricultural research system, and Spain, for which decentralization has taken place more by research devolution to regional governments than to universities.

[11] At least one larger system, that of the Netherlands, has integrated government research institutes with university research. The agricultural research performance data reported to OECD still show a roughly 55–45 percent split however. We note that the Netherlands, which has a larger research system in terms of expenditure, is relatively small geographically, which may have some impact on research centralization.

Agricultural R&D Investments and Productivity

Government priorities for agricultural research in high-income countries have been generally directed toward improving the productivity and sustainability of the sector. In the early part of the 20th century, this was motivated by the goals of providing stable, low-cost food for consumers and higher income for producers. Over time, these goals have grown to give greater weight to environmental protection; food quality, safety, and nutrition; animal welfare; international competitiveness, and other priorities.

Public Agricultural R&D Spending and Its Relationship to Agricultural Policy Goals Since 1960

Public spending on agricultural R&D in today's high-income countries grew rapidly in the latter half of the 20th century but recently declined in real terms. Between 1960 and 2010, aggregate annual spending on agricultural R&D[12] by these countries increased from $3.93 billion to $18.49 billion but then fell to $17.51 billion in 2013, in constant 2011 purchasing power parity (PPP) dollars. Research spending in individual countries followed varied patterns, but the aggregate increased consistently until recent years (table 3.1). In 2013, the United States, Japan, France, Germany, and South Korea had the largest public (government and university) agricultural R&D systems, each spending at least $1 billion.

Government expenditures on agricultural R&D are designed to support the various goals of food and agricultural policies of these countries. Following World War II, Europe and East Asia experienced severe food shortages, and governments intervened heavily in their agricultural sectors to further national food security. To expand food production, Western European countries used trade policy (import tariffs and export subsidies) and other measures to support farm prices and stepped up spending on agricultural research and extension (Fennel, 1997), while Japan and South Korea implemented land reform, enacted food price controls and barriers to agricultural imports, and increased government investments in agricultural R&D and rural infrastructure (Hayami, 1988; Kim and Lee, 2004). For traditional food exporting countries in North America (United States and Canada) and Oceania (Australia and New Zealand), greater spending on agricultural R&D was a means to lower costs, raise farm incomes, and strengthen competitiveness in international markets (Gardner, 2002). Centrally planned economies in Central Europe followed a markedly different development path. They initially taxed agriculture in favor of industrial development, and most (Poland and Yugoslavia excepted) forced farms to join collectives (Pryor, 1992; Wong and Ruttan, 1986). By the 1960s, they began to subsidize agriculture to increase food supply, especially of meat and animal products, for their populations (Anderson and Swinnen, 2008). The principal means for agricultural growth in centrally planned economies was to expand the use of inputs in production; less emphasis was given to R&D and raising productivity.

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[12] In keeping with the most common accounting for international R&D and sectoral data, "agriculture" generally refers to "agriculture, forestry, and fisheries." In general, we will refer to "agriculture" and "agricultural research" for simplicity but make note of other primary industry research where it is important. In many cases, primary agriculture is the dominant category in "agriculture, forestry, and fisheries."

Table 3.1
Public R&D spending for agriculture, forestry, and fisheries

High-income, OECD countries	Region	1960	1970	1980	1990	2000	2010	2011	2012	2013
		Constant 2011 purchasing power parity (PPP) $, million								
Canada	North America	218	690	823	841	785	777	699	744	777
United States	North America	1,389	2,269	3,024	3,934	4,743	4,813	4,803	4,622	4,305
Japan	Asia-Oceania	721	1,381	1,919	2,469	2,953	2,972	2,979	2,834	2,948
South Korea	Asia-Oceania	17	49	60	295	613	991	979	950	1,017
Australia	Asia-Oceania	229	532	696	698	973	747	720	777	724
New Zealand	Asia-Oceania	53	126	213	189	155	160	153	152	146
Austria	Europe, NW	16	61	64	83	137	169	170	158	146
Belgium-Luxembourg	Europe, NW	61	79	123	167	226	307	297	327	329
Denmark	Europe, NW	84	80	76	141	183	201	183	184	162
Finland	Europe, NW	22	48	74	124	121	194	198	182	169
France	Europe, NW	94	443	865	1,048	1,255	1,549	1,562	1,548	1,578
Germany	Europe, NW	244	605	651	880	1,041	1,329	1,251	1,305	1,235
Iceland	Europe, NW	4	7	11	16	30	16	5	7	8
Ireland	Europe, NW	38	59	58	51	88	98	111	111	110
Netherlands	Europe, NW	109	208	409	461	483	547	649	593	604
Norway	Europe, NW	34	64	96	181	193	188	181	173	172
Sweden	Europe, NW	48	117	131	225	142	156	159	155	152
Switzerland	Europe, NW	40	101	81	85	96	121	138	157	154
United Kingdom	Europe, NW	249	466	651	629	739	623	536	529	589
Greece	Mediterranean	4	26	41	71	50	42	45	39	41
Israel	Mediterranean	21	51	107	87	88	86	94	88	86
Italy	Mediterranean	31	198	282	632	594	702	750	739	713
Portugal	Mediterranean	22	60	69	104	176	120	133	109	90
Spain	Mediterranean	46	67	230	469	555	873	711	678	654
Czech-Slovakia	Europe, Central	63	78	95	129	92	164	184	197	127
Czech Republic	Europe, Central			63	76	73	101	119	125	93
Slovakia	Europe, Central			32	53	19	63	65	72	34
Estonia	Europe, Central				5	11	16	23	17	23
Hungary	Europe, Central	14	147	158	129	118	102	98	96	90
Poland	Europe, Central	63	174	222	293	283	415	372	341	330
Slovenia	Europe, Central				39	21	12	29	30	26
North America		1,607	2,959	3,847	4,775	5,528	5,590	5,502	5,366	5,082
Asia-Oceania		1,020	2,088	2,888	3,651	4,694	4,870	4,831	4,713	4,835
Europe, NW		1,043	2,338	3,290	4,091	4,734	5,498	5,440	5,429	5,408
Mediterranean		124	402	729	1,363	1,463	1,823	1,733	1,653	1,584
Europe, Central		140	399	475	595	525	709	706	681	596
Total, high-income OECD countries		3,934	8,186	11,229	14,475	16,944	18,490	18,212	17,842	17,505

OECD = Organisation for Economic Co-operation and Development. National research and development (R&D) adjusted to constant 2011 expenditures using the national Gross Domestic Product (GDP) price index, and then converted to purchasing power parity (PPP) using the 2011 PPP exchange rate. GDP price index and PPP exchange rates from the World Bank. See appendix for sources of data on national R&D spending.

Source: USDA, Economic Research Service. See appendix B.

In the 1980s, significant disequilibria emerged in world agricultural markets. Under the Common Agricultural Policy (CAP) of the European Union (EU), high price supports, external trade protection, and rising productivity led to significant agricultural surpluses (Gardner, 1996). Production surpluses also emerged in the United States and other traditional food exporters as growth in international food demand slowed (Gardner, 2002). In centrally planned economies of Central and Eastern Europe, the high subsidies for farms and low food prices for consumers exacted a heavy price in terms of national economic wealth (Anderson and Swinnen, 2008).

In response to these pressures, many countries implemented agricultural policy reforms. The Food Security Act of 1985 (U.S. farm bill) and the 1992 MacSharry reforms to the EU CAP introduced programs to retire farmland from production. Australia and New Zealand also implemented reforms, reducing or ending price-support schemes and input subsidies to make their agricultural sectors more economically competitive and market responsive (Gray et al., 2014). The most extensive reforms took place in Central Europe, where, following the breakup of the Soviet Union in 1991, countries began a transition from centrally planned to market-based economies (Macours and Swinnen, 2002).

As part of these new circumstances, the objectives for agricultural policy in many high-income countries were broadened. U.S. and EU farm policies included cross-compliance provisions that required farmers to follow certain environmental and other guidelines to receive farm subsidies. Other reforms sought to decouple farm subsidies from commodity prices. At the same time, environmental, food safety, animal welfare, and other social objectives became important components of agricultural research policy. Public R&D devoted more attention to developing technologies and farming systems that would move agriculture toward these goals. In the United States, for example, the share of public agricultural R&D oriented toward "farm production" declined from 66 percent in 1975 to 57 percent in 2007 as the focus shifted to broader research concerns (Alston et al., 2010). Although data are unavailable, the composition of public agricultural research in other countries may be similar to that of the United States.[13]

Despite these changing policy goals, raising farm productivity remained an important objective for public agricultural research. In an increasingly open international trading environment for agricultural products, higher productivity enhances competitiveness by lowering the unit costs of production and may contribute to lower consumer food prices. Higher productivity could also save on natural resources in agricultural production, giving rise to potential net benefits to the environment. Besides these economic and environmental objectives, the "public good" nature of research continued to provide an important justification for government support for agricultural R&D.

The Growing Role of the Private Sector in Agricultural R&D

In recent decades, the private sector has played an increasingly important role in food and agricultural innovation. Pardey et al. (2016) estimate that food and agricultural R&D spending by the private sector worldwide increased from $9.7 billion in 1980 to $31.2 billion in 2011 in constant dollars, a threefold increase. Factors contributing to the growth in private agricultural R&D include (i) expanding consumer demand for new and diverse food products, (ii) liberalization of food and agricultural input markets, particularly in developing countries, which expanded private-sector market shares, (iii) technological opportunities opened up by scientific advances in nutrition,

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[13] Some support for this contention can be found in information from non-OECD sources consulted for this study, including data from government statistical agencies or other sources, in countries such as Australia, Canada, France, and New Zealand.

biotechnology, and information sciences, and (iv) stronger intellectual property rights, especially for biological inventions (Pray and Fuglie, 2015).

Public policies in high-income countries have generally supported the growth in private food and agricultural R&D. But despite the increase in private R&D spending, several recent studies find evidence that total spending on agricultural research remains low: estimates of social returns to public agricultural R&D continue to be high—*prima facie* evidence of underinvestment.[14] One reason why the growth of private R&D has not closed the underinvestment gap is that private R&D is an imperfect substitute for public R&D. The downstream, relatively narrow focus and applied nature of much private R&D suggests that there continues to be a significant role for governments to directly finance much agricultural research. Nonetheless, greater private-sector spending on food and agriculture R&D can help to at least partially reduce public underinvestment. Policy options include stronger intellectual property rights (IPR) for new crop varieties and biotechnology inventions for use in agriculture. Policies have also sought to move public R&D away from areas that would compete directly with private R&D and focus more on pre-commercial sciences. This can open up new technological opportunities for private-sector commercialization.

While stronger IPRs can help firms to capture (or "appropriate") more of the economic benefits of R&D and therefore encourage more R&D investment by these firms, this incentive comes at a social cost. By enabling a firm to exclude others from using its intellectual property, except perhaps for a fee, IPRs raise the cost and reduce the use of new technology. IPRs, like patents, thus entail a tradeoff between the long-term benefit from greater research and innovation and the short-term cost to society of the temporary monopoly afforded by the IPR. Moreover, IPRs rarely offer perfect protection for an inventor. Even patented technologies may generate significant spillovers—economic benefits that accrue to other users that the inventor is not able to appropriate (Clancy and Moschini, 2017).

Privatization of the downstream products of R&D and charging technology fees for their use means that all users (domestic and foreign) contribute to the costs of the research and technology development. In an increasingly global marketplace for food and agricultural innovations, IPRs can help reduce free-rider problems arising from international technology transfer. However, IPRs do not necessarily inhibit such transfers. In fact, IPRs may accelerate international technology transfer by encouraging investments in foreign markets by domestic firms. Many large food and agricultural companies have established international R&D networks to facilitate adaptation of their technologies to conditions and needs of producers in other countries (Fuglie et al., 2011). IPRs have also become widely used by public institutions when new scientific advances are thought to have significant commercial applications.

It is difficult to compare the amounts of public and private spending on agricultural R&D by individual countries or even by global regions. Large multinational companies may make R&D investments in several countries but report these expenditures only as a global total. If R&D expenditures in 2011 were assigned to the countries in which firms have their corporate headquarters, then 86 percent of global private agricultural R&D occurred in high-income countries that year (table 3.2). However, if R&D expenditures by the largest 23 companies during the same period were allocated in proportion to the regional sales of these companies, then the share of private R&D in high-income countries would fall to 67 percent of the world total (Fuglie, 2016).

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[14] Social rates of return above the cost of government borrowing imply the marginal benefits from spending exceed the marginal costs of funds. Social returns may be significantly greater than private returns due to spillover benefits of R&D. These studies on returns to public agricultural R&D are reviewed later in this section—see table 3.3.

Table 3.2

Public and private agricultural R&D spending by region, 2011 (constant 2011 purchasing power parity (PPP) \$, million)

| Sector[1] | High-income countries | Other countries | World | North America | Europe, Middle East, Africa | | Asia-Oceania | | Latin America |
					High-income	Other countries	High-income	Other countries	
Public agricultural R&D	18,212	24,116	42,328	5,501	7,879	2,999	4,832	14,215	6,901
Private agricultural R&D, allocated to country of company incorporation	12,326	1,933	14,260	6,458	5,023	110	845	1,788	36
Private agricultural R&D, allocated to location of company product sales[2]	9,510	4,750	14,260	5,106	3,696		3,489		1,968

[1] Private agricultural research and development (R&D) includes R&D by agricultural input companies. R&D by food companies is excluded from the table.

[2] For 23 companies with over \$100 million in agricultural R&D (which accounted for about 70 percent of total private agricultural R&D), R&D was prorated to regions according to the share of company sales in that region. For other companies, R&D was assigned to the country of incorporation.

Source: USDA, Economic Research Service using Fuglie (2016) for private agricultural R&D, ASTI for public agricultural R&D in other countries, and this report for public R&D in high-income countries.

Assessing the Impact of R&D on Agricultural Productivity

The successful transition from resource-dependent to productivity-led agricultural growth during the latter half of the 20th century largely stemmed from investments in agricultural R&D and the application of industrial inputs in agriculture (Hayami and Ruttan, 1985; Federico, 2005). Figure 1.2 illustrated the importance of productivity for agricultural growth by showing the rising share of growth due to improvements in TFP. Figure 3.1 presents this information another way. It shows the accumulated change in total agricultural output and inputs over time. Thus, between 1961 and 2014, real agricultural output in high-income countries increased from an index value of 100 to 198, or 98 percent, while total inputs declined from an index value of 100 to 86, or 14 percent (the mix of inputs also changed, with capital and material inputs substituting for labor and land) (fig. 3.1a). This growth in output and the decline in inputs implies that TFP (i.e., the total productivity of the land, labor, capital, and material inputs employed in agricultural production) more than doubled over this 54-year period.

These growth patterns vary somewhat across high-income countries. In North America and Oceania, productivity growth primarily raised agricultural output rather than reduced total inputs (fig 3.1b and 3.1c). In Northwest Europe, output growth stagnated in the 1980s, and TFP improvement led to substantially fewer inputs used in agriculture (fig. 3.1d). Southern European/Mediterranean and East Asian countries followed a similar pattern to Northwest Europe, except that output continued to grow until the 1990s before leveling off (fig. 3.1e and 3.1f). In all these countries, agricultural TFP grew rapidly. Central European transition economies, which showed little improvement in agricultural TFP during the Communist era, are a notable exception. In these countries, output closely paralleled input use. Only in the last decade has agricultural TFP in Central European countries begun to rise significantly (fig. 3.1g).

Figure 3.1

Indexes of agricultural output and total input, 1961-2014[1]

a: All high-income countries

Index, 1961=100
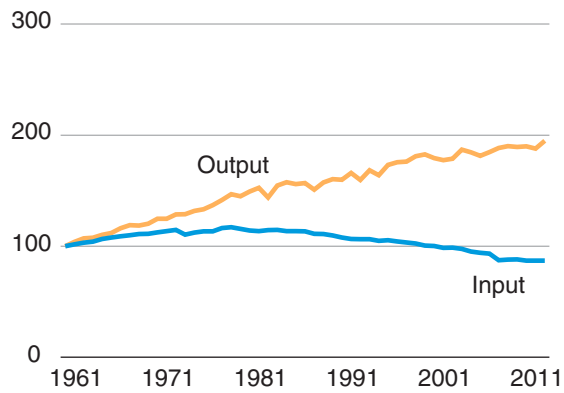
b: North America (Canada and U.S.)

Index, 1961=100
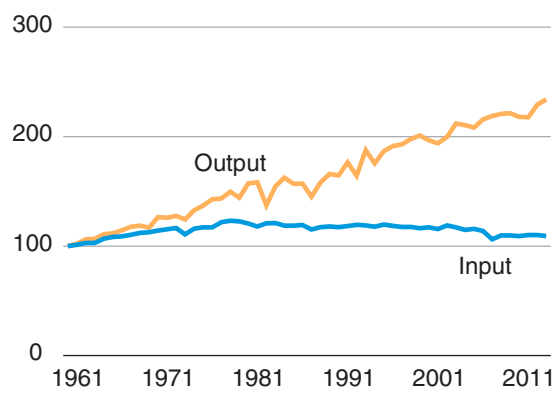
c: Oceania (Australia and New Zealand)

Index, 1961=100
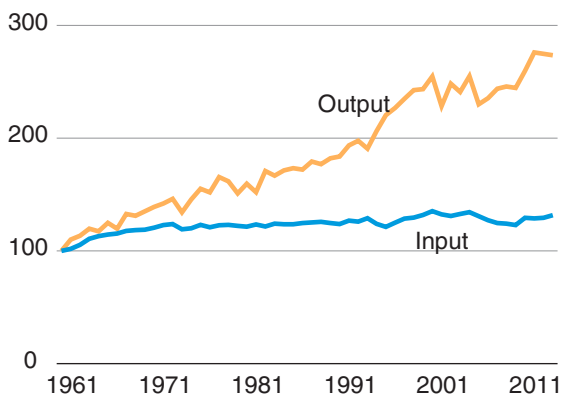
d: Northwest Europe

Index, 1961=100
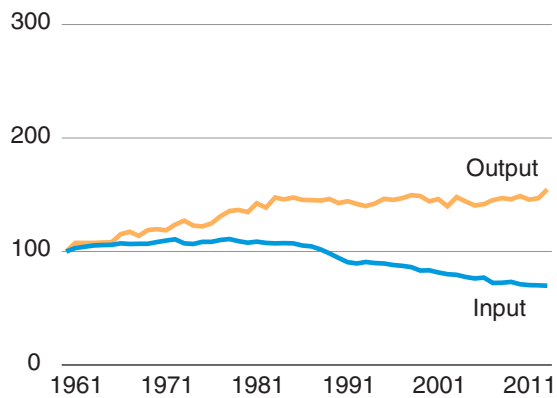
—continued

Figure 3.1

Indexes of agricultural output and total input, 1961-2014[1]—continued

e. Southern Europe/Mediterranean

Index, 1961=100
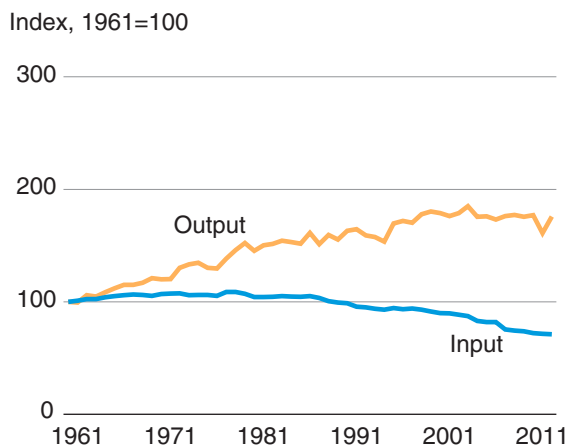
f. East Asia (Japan and South Korea)

Index, 1961=100
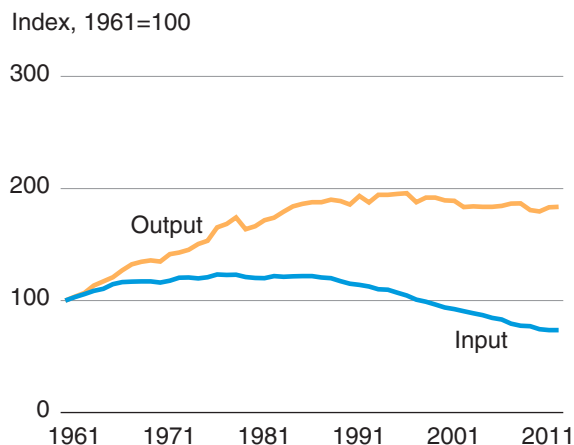
g. Central Europe (transition economies)

Index, 1961=100
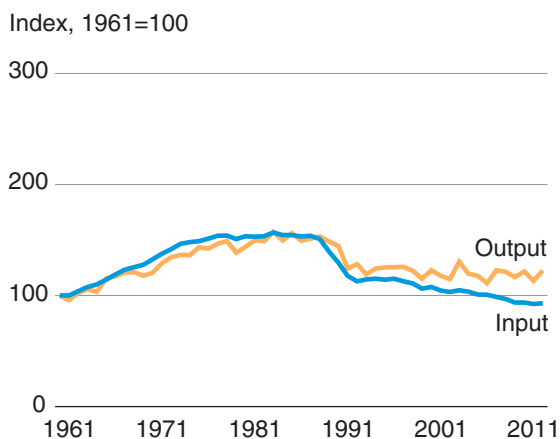
Notes: Output = index of total crop and animal commodities produced on farms. Input = index of total labor, land, capital, and intermediate inputs used in farm production. See the footnote to figure 1.2 and Fuglie (2015) for further details.

[1]All series end in 2014. The x-axis is marked in 10-year intervals, starting from the beginning year, 1961.

Source: USDA, Economic Research Service, International Agricultural Productivity Data Product.

The agricultural growth experiences of high-income countries shown in figure 3.1 illustrate how improvements to agricultural productivity affected economic welfare, whether agricultural output was growing or not. Even in countries where agricultural output stagnated, TFP growth freed up resources for use elsewhere in the economy. Not only did agricultural employment decline but so, too, did the amount of land in agricultural production.

The economic value of the gains in agricultural productivity has exceeded the public investment in agricultural R&D by several fold. Figure 3.2 plots a simple correlation between the value of TFP improvements on the y-axis and the cost of public R&D investment on the x-axis. Both benefits and costs are the cumulative total over 40 years measured in constant 2005 dollars.[15] Research costs are summed over 1960-1999 and productivity improvements over 1974–2013 to account for the lag between the time that research is initiated and the time that it is likely to affect farm productivity. The graph illustrates that first, the value of productivity improvements exceeded the cost of R&D by at least a factor of 10, and that second, countries that invested more in R&D generally achieved greater productivity growth. The latter point is illustrated by the upward sloping line, which is the average relation between R&D spending and the value of TFP growth from a log-log regression. Partly this reflects country size—larger countries tend to invest more in R&D and get greater impact from TFP growth. But it also helps explain why countries like the Netherlands achieved substantially more productivity growth than other midsized producers like New Zealand and Ireland: the Netherlands invested significantly more in agricultural R&D over this period.

National investment in agricultural R&D is only one factor that may account for the growth in agricultural TFP. Other important sources of new farm technologies are likely to be R&D spillovers (i.e., science and technology borrowed from other countries or other research areas) and private-sector investments. Improvements in farmer education, greater openness to trade, and farm structural adjustment can also contribute to greater overall efficiency and productivity. Table 3.3 summarizes findings from recent studies that used econometric models to try to quantify the contribution of public R&D and other factors to long-term agricultural TFP growth in high-income countries.[16] All the studies found that public R&D had a major impact on agricultural TFP growth. In nearly all cases, the economic benefits of TFP growth were substantially greater than the costs of the R&D:

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[15] See note under figure 3.2 for explanation of how these estimates were derived.

[16] The studies in table 3.3 all assessed the contribution of total agricultural R&D spending to aggregate agricultural TFP growth. Numerous other studies have examined returns to R&D on particular commodities or particular projects, but these could be biased if they focused only on success stories. For more comprehensive reviews of returns to agricultural research, see Alston et al. (2000) and Hurley et al. (2014).

Figure 3.2

Investment in public R&D and value of agricultural productivity growth

Total value of agricultural TFP growth over 1974-2013,
at constant 2005 prices, million 2005$, log scale

Total public agricultural R&D spending over
1960-1999, million 2005$, log scale
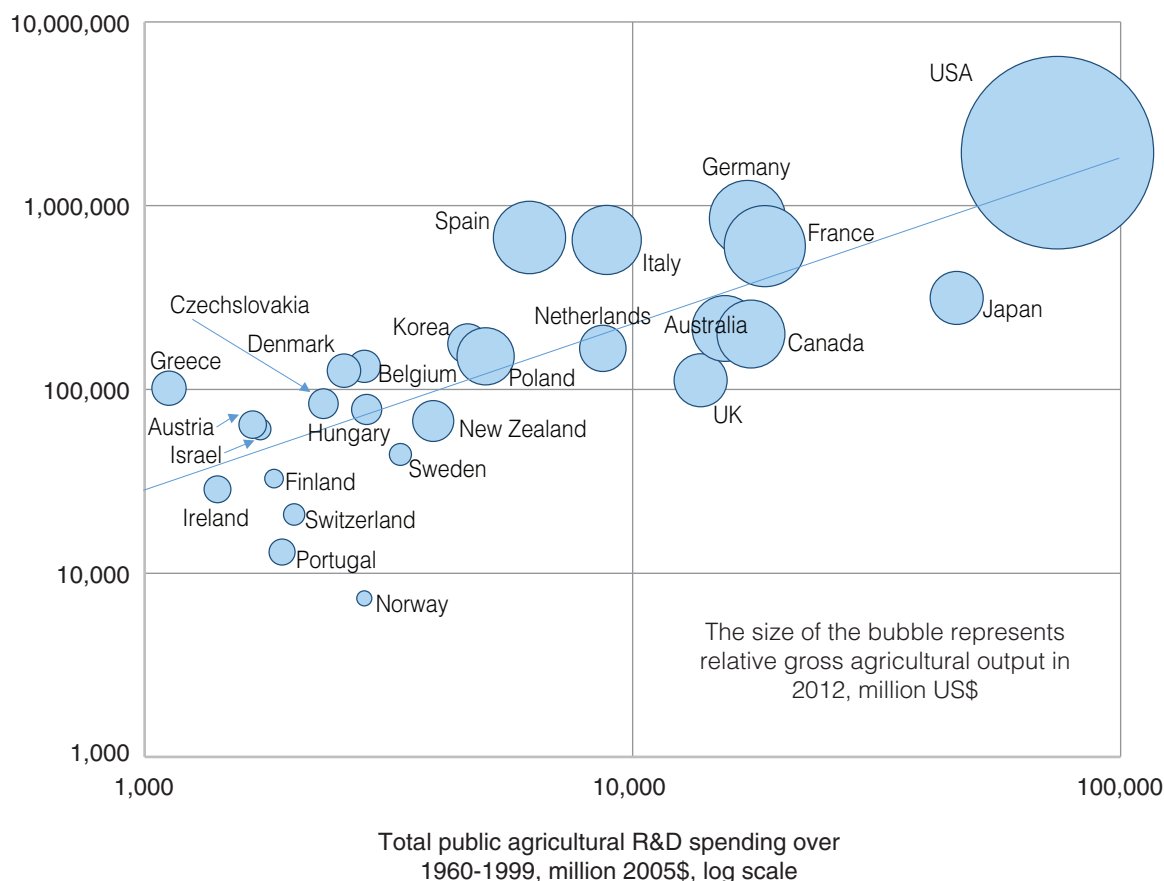
The y axis measures the value of the additional agricultural output over 1974-2013 due to total factor productivity (TFP) growth, using constant 2004-06 international commodity prices in international dollars. It is measured by first estimating the value of TFP growth for each year as the difference in actual output and what output would have been using that year's inputs with 1974 technology (i.e., what output would have been in the absence of TFP growth; thus, this value is zero in 1974 and grows over time as TFP rises). Then, these annual values are summed over 1974-2013 to get the total value of TFP growth over this period. The x axis measures the cumulative investment in public agricultural R&D over 1960-1999, measured in constant 2005 international dollars. Both the value of TFP growth and research and development (R&D) investment are cumulative over 40 years, with the difference in periods (1974-2013 for the value of TFP growth and 1960-1999 for R&D investment) reflecting a time lag between R&D investment and productivity growth. This valuation of TFP growth likely represents a lower bound since commodity prices during 2004-06 were lower than average real (inflation-adjusted) prices over 1974-2013. Furthermore, to avoid overstating the value of productivity growth if domestic prices are artificially high due to commodity price supports, international average commodity prices are used.
Source: USDA, Economic Research Service (ERS). Estimates of the value of productivity growth are derived from the ERS International Agricultural Productivity Data Product; estimates of public agricultural R&D spending from this report.

The social internal rate of return (IRR)[17] estimated for public agricultural R&D in these studies ranged from 4 percent for Italy to 67 percent for the United States and 83 percent for Ontario, Canada.

Table 3.3
Social internal rates of return (IRR) to public agricultural research in high-income countries

Study	Country	Period	Social IRR to public R&D (%)[1]	Other sources of innovation[2]	R&D time path [3]
Baldos et al. (forthcoming)	U.S.	1949-2011	17	n.e.	50 years
Andersen & Song (2013)	U.S.	1949-2002	21	n.e.	50 years
Alston et al. (2010)	U.S.	1949-2002	23	n.e.	50 years
Wang et al. (2012)	U.S.	1980-2004	45	n.e.	35 years
Jin & Huffman (2016)	U.S.	1970-2004	67	n.e.	35 years
Huffman & Evenson (2006)	U.S.	1970-1999	56	Private R&D	35 years
Prentice & Brinkman (1982)	Canada (Ontario only)	1950-1972	83	n.e.	20 years
Schimmelpfennig & Thirtle (1999)	EU (11 countries)	1973-2002	11	Foreign R&D	PIM (5%)
Butault et al. (2015)	France	1959-2012	30	Foreign R&D	50 years
Thirtle et al. (2008)	UK	1953-2005	26	Private R&D	25 years
Esposti & Pierani (2003)	Italy	1961-1991	4	n.e.	PIM (5%)
Rutten (1992)	Netherlands	1949-1987	40	n.e.	5 years
Sheng et al. (2011)	Australia	1953-2007	28	Foreign R&D	35 years
Hall & Scobie (2006)	New Zealand	1927-2001	29	Foreign R&D	PIM (5%)
Ito (1992)	Japan	1960-1987	46	n.e.	PIM (10%)

All of the studies in the table evaluated the impact of research and development (R&D) at the systems level (i.e., of total public agricultural R&D spending on productivity growth of the entire agricultural sector or, in the case of Australia, the impact of R&D on rainfed agriculture).

[1] The social IRR to public R&D is the internal rate of return to research taking into account benefits to farmers and consumers. An IRR of 17 percent, say, can be interpreted as providing an annual payoff of $0.17 over the lifetime of an investment from an initial investment of $1.00.

[2] Other sources of innovation refers to sources other than national public agricultural R&D. "Foreign" refers to public agricultural R&D in other countries; "Private" refers to private R&D; "n.e." means that spillovers were not explicitly included in the model but usually represented by a time trend in these models.

[3] The R&D time path is the length of time that R&D is assumed to contribute to productivity growth after some gestation period and before technology obsolescence sets in. Studies using a longer R&D stock profile assume a longer life for R&D capital but also a longer gestation period. Thus, longer R&D profiles tend to give lower rates of return (Alston, 2010).

Source: USDA, Economic Research Service. See references.

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[17] The social internal rates of return include benefits to producers (profits) and consumers (from more abundant food at lower prices) and are all adjusted for inflation. The IRR can be interpreted as an annual stream of benefits resulting from an initial one-time investment. For example, an IRR of 12 percent implies that an R&D investment of $1.00 generates an annual stream of benefits worth $0.12 per year for the life of the investment. The ratio of total benefits to total cost can be approximated by dividing the IRR by a real interest rate. Assuming the cost of government borrowing is 4 percent, for example, would mean that an IRR of 12 percent would give a benefit/cost ratio of 3, or $3.00 in total benefits per $1.00 in public R&D spending.

One reason for the wide dispersion in estimates of the IRR to agricultural research is that the estimates are sensitive to assumptions made about the time it takes R&D spending to affect productivity. Studies that assume a longer gestation period for R&D to result in new technologies that are widely adopted by farmers tend to produce lower IRRs, since benefits that are further in the future are worth less in today's dollars. The econometric models have generally not been able to clearly identify a preferred R&D time path, but even the studies that have used more conservative assumptions find large benefits relative to R&D costs.

Several of the studies in table 3.3 find that R&D spillovers among high-income countries were a significant source of national agricultural TFP growth. These spillovers may arise from public or private agricultural R&D conducted in other countries, as well as domestic or foreign R&D in other industries (like computing, medicine, or aeronautics). The ability to borrow technology developed elsewhere may explain why some countries in figure 3.2 appeared to have achieved agricultural TFP growth above what their national R&D investments alone would seem to warrant (i.e., they lie above the regression line in figure 3.2). Spain and Italy, for example, obtained similar productivity growth during 1974–2013 as Germany and France but with less cumulative investment in agricultural R&D. Ball et al. (2010) find that in the 1970s and 1980s, countries in southern Europe had agricultural productivity levels far below the "frontier" countries of Northwest Europe, but faster agricultural TFP growth enabled them to close this productivity gap by the 1990s. Schimmelpfennig and Thirtle (1999) find direct evidence to this effect: among 11 EU countries, cross-country R&D spillovers were just as important as national R&D investments to domestic agricultural TFP growth.

These models provide less evidence on the impact of private R&D on agricultural productivity, due to both conceptual and data challenges. Conceptually, private R&D is focused on developing improved inputs, which are then sold to farmers; thus, R&D costs are reflected in prices paid for farm inputs and are not part of TFP. The contribution of private R&D to agricultural TFP growth would represent economic benefits from the adoption of improved inputs above what input suppliers are able to capture through the prices they charge for them. Studies find that adoption of genetically modified crops—a technology developed with significant input from private R&D—improved farm profits and benefited consumers by lowering commodity prices (Klümper and Qaim, 2014). This suggests that only a portion of the productivity benefits of this new technology were captured by its private-sector developers. However, private R&D often complements public R&D in developing innovations. Some studies find that private R&D responds positively to public R&D investment when public R&D opens up new technological opportunities for the private sector to commercialize (Schimmelpfennig and Thirtle, 1999; Wang et al., 2013). Thus, it may be inappropriate to attribute productivity gains from new technology solely to public or private R&D. And, as described above, another limitation faced by the studies in table 3.3 is that data on private R&D spending are not well defined at the country level.

The studies in table 3.3 estimate returns to research by comparing farm productivity gains against all research classified as "agricultural" by public institutions. But productivity is only one goal of public R&D, and as noted earlier, a significant share of this research is devoted to other objectives. This may explain why Scandinavian countries, which devote a considerable share of their "agricultural" research to forestry and fisheries, appear in figure 3.2 to have obtained relatively low benefits from productivity growth in crops and livestock compared to their agricultural R&D spending. Norway, in particular, has committed considerable resources to fisheries research, which helped give rise to a highly competitive marine aquaculture industry. Omitting the impacts of public R&D on these other objectives would understate the returns to R&D. Some studies attempt to address

this issue by only considering R&D spending that is oriented toward farm productivity. This was the approach taken by three U.S. studies that find exceptionally high IRRs (ranging between 45 and 67 percent) (see table 3.3). This has also been the approach used by studies that estimate returns to research on specific commodities (see Alston et al. (2000) for a comprehensive compilation of rate-of-return estimates and Hurley et al. (2014) for a more recent survey).

More generally, the exclusive focus on the economic benefits of agricultural TFP growth may bias the estimated social IRR to public agricultural R&D. Not only is public R&D focused on other objectives, but TFP growth may not be the only outcome from the use of new technologies in agriculture. Since TFP measures are based on outputs and inputs that are valued in the market, they generally ignore nonmarket (but socially valuable) environmental services used in agriculture and the effects of technical change on the demand for these services. Extending the focus to include environmental impacts could lower or raise the estimated returns to agricultural research. For example, the reduction in agricultural land that has accompanied agricultural TFP growth in many high-income countries has made environmental services from land available for other uses, such as forests, grasslands, parks, or urban development. However, land remaining in agriculture has been used more intensively, which could degrade natural resources like soil, water, and air quality. Agricultural TFP growth in high-income countries may have been associated with the use of fewer environmental services per unit of agricultural output (OECD, 2014), but the causation and economic significance of these changes has not been comprehensively assessed.

Some Economic Fundamentals of Public Investment in Agricultural R&D

In the preceding sections, we outlined similarities and differences in agricultural output, productivity, and R&D investment among high-income countries. In this section, we provide more detailed comparisons of government spending on agricultural R&D. In all high-income countries examined here, agriculture's share of total economic output declined from 1960 to 2014. The share now represents less than 2 percent of GDP in all high-income countries taken together and less than 4 percent in 29 of 31 countries in this study. Nonetheless, agriculture retains an important position in most countries' R&D systems. Five features of public investment in agricultural R&D tend to be common among high-income countries:

1. Agriculture commands a relatively high share of total public R&D spending.

2. However, agriculture's share of public R&D has fallen over time.

3. In the aggregate, public agricultural R&D spending tends to rise faster than agricultural GDP.

4. The cost of agricultural R&D rises faster than the general rate of inflation.

5. R&D costs more in the United States than in most other high-income countries.

Agriculture Commands a Relatively Large but Declining Share of Public R&D

Governments play a leading role in generating and disseminating new technologies for agriculture. As a consequence, agriculture commands a relatively large share of total government spending on R&D: the share of public R&D devoted to agriculture is high relative to the size of agriculture in the whole economy. For the 31 high-income countries included in this study, agricultural R&D accounts for about 5.5 percent of total public R&D expenditures during the 2009–13 period.[18] This share ranged from 1.7 percent for Luxembourg to 15.9 percent for New Zealand. In the United States, agriculture accounted for 3.6 percent of total public R&D (fig. 4.1). The agricultural share of total public R&D spending in the United States is smaller than the average for all high-income countries, despite the United States having the highest total expenditures on public agricultural research. In fact, Government-sponsored research as a whole in the U.S. total is nearly four times greater than Japan and Germany, the high-income countries with the next highest R&D spending. The high U.S. total R&D investment helps explain its relatively small share for agricultural R&D.

The ratio of R&D to value-added GDP of an economy or sector is sometimes referred to as the "research intensity" ratio. Figure 4.2 compares research intensities for all R&D spending, public and private; for all public R&D; and for all public agricultural R&D (averaged over 2009–13) for the 31 countries covered in this study. The first research intensity, for *all R&D*, compares all research investment, public and private, to each country's GDP. The second research intensity, for *all public R&D*, compares total public research investment to GDP. The final measure is *public agricultural*

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[18] OECD data on total Government Expenditure on R&D (GOVERD), total Higher Education Expenditure on R&D (HERD), and total Private Non-Profit Expenditure on R&D (PNPERD) are more complete than data for more detailed breakdowns, such as field of science (e.g., agricultural sciences) or socioeconomic objective (e.g., agriculture, forestry, and fisheries). Note that these categories, which together comprise "public-sector research," reflect research performance by the sectors in question; they are not the same thing as GBARD, or Government Budget Allocations for R&D. See appendix B.

research intensity, which compares public R&D to agricultural GDP in each country. Here, we are particularly interested in public agricultural research intensity, but the other measures for the entire economy help place this last measure in context.

Figure 4.1

Agriculture's share of total public R&D spending, 2009-13 average
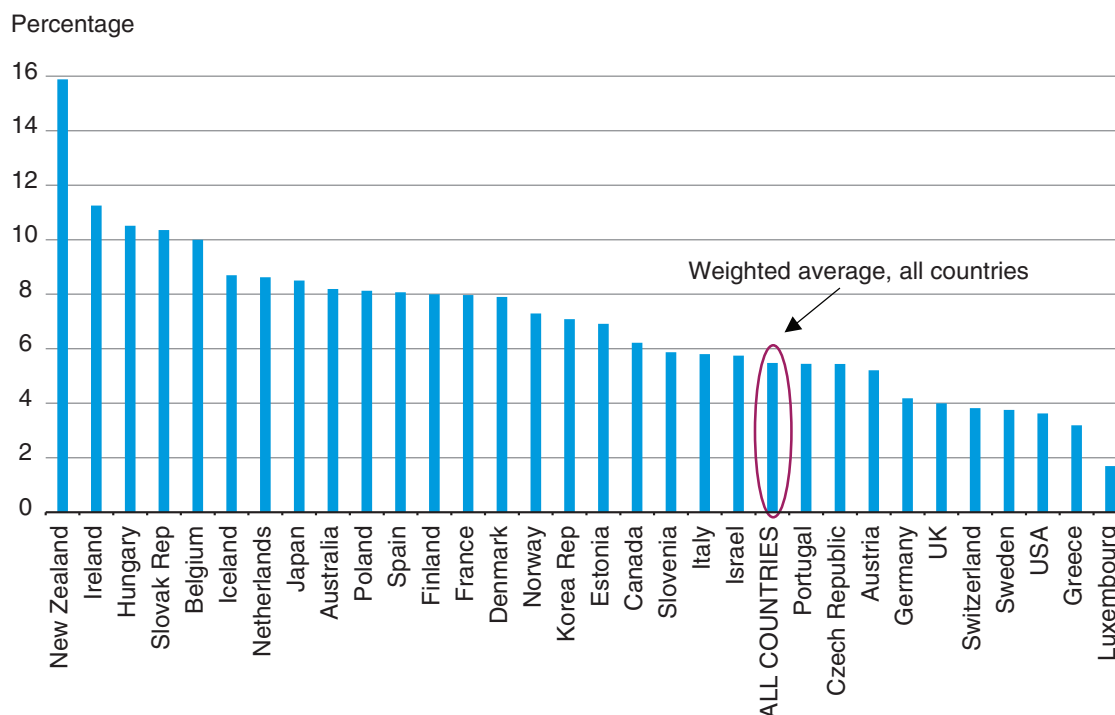
Percentage

Source: USDA, Economic Research Service using the Organisation for Economic Co-Operation and Development's Main Science and Technology Indicators and data from this study (see appendix B). Additional information from U.S. National Science Foundation, Survey of Federal Funds for Research and Development, various years; Israel Central Bureau of Statistics; and Chung (2011).

The first measure, R&D (public and private)/GDP, is larger than the second (Public R&D/GDP), which it encompasses. Across all countries, the amount of all private R&D averages more than twice the amount of all public R&D—as reflected in the comparison of the weighted mean research intensity for all public and private R&D, 2.47 percent, with the weighted mean research intensity for all public R&D of 0.79 percent. The R&D (public and private)/GDP intensity is also more variable than the Public R&D/GDP intensity, as countries differ more in the relative amounts of private R&D than they do for public R&D.

The weighted mean research intensity ratio for public agricultural R&D over 2009–13 is 3.12 percent, which is considerably higher than the research intensity for all public R&D but only somewhat higher than the weighted mean research intensity for all public and private R&D. The public agricultural R&D intensity is the most variable of the three measures. Agricultural research intensities among these countries range from a low of 0.47 percent for Greece to a high of 10.0 percent for Belgium. For the United States, the research intensity for public agricultural R&D (2.68 percent) is slightly lower than the total research intensity, public and private, of the economy (2.75 percent).

Figure 4.2

Research and Development (R&D)/Gross Domestic Product (GDP) intensity ratios for agricultural and nonagricultural research

Percentage

Source: USDA, Economic Research Service using the Organisation for Economic Co-operation and Development's Main Science and Technology Indicators; World Bank; and data from this study. See notes to tables 4.1, 4.2, and figure 4.1.

Several factors help explain the relatively high research intensity of public agricultural R&D. First, public R&D compensates for relatively low private R&D in this sector, even in production agriculture.[19] Because farms are relatively small and dispersed enterprises, few conduct any formal R&D themselves. Private agricultural R&D is concentrated in industries that supply manufactured inputs to agriculture, such as the chemical, machinery, and biotechnology industries. In the last few decades, private agricultural R&D has increased substantially, especially for agricultural seed and biotechnology, but it is still less than total public agricultural R&D across all high-income countries.[20] This contrasts with R&D for the entire economy, where private expenditures are more than double public expenditures. Second, agriculture is a technology-dependent sector. A much larger share of output growth for agriculture comes from increases in TFP than for the economy as a whole. For high-income countries, virtually all agricultural growth comes from raising TFP, compared with about one-third of total growth economy-wide. Technology-dependent sectors typically have a larger research intensity than other sectors. Third, governments invest in agricultural R&D to address a range of public goods other than food production or food security. Increasingly, what is classified as agricultural R&D by governments is oriented toward addressing environmental concerns, food safety and nutrition, and other social issues.

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[19] As noted, data availability and definitional ambiguity generally preclude strict separation of production agriculture research from research in related areas such as environmental or food research. In any case, relatively little public-sector research is directed toward food processing, where the private sector takes a much larger role. See Clancy et al. (2016) for the United States.

[20] See table 3.2.

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As Countries Get Richer, Agriculture's Share of Public R&D Declines

Despite the heavy emphasis given to agriculture in government R&D spending, agriculture's share of total public R&D has fallen over time as countries have gotten richer. Although real public agricultural R&D has risen over most of the time period in our analysis, total public R&D has risen at a faster rate. For all the high-income countries combined, the share of public R&D devoted to agriculture fell from just over 9.0 percent in 1981 to 5.2 percent in 2013 (fig. 4.3).[21] Among high-income countries, the agricultural share of public R&D tends to fall more rapidly in countries where it was initially the highest, such as New Zealand, Australia, Canada, and Central Europe.

Figure 4.3

Public agricultural research expenditures as a percentage of total public research expenditures, 1981-2013
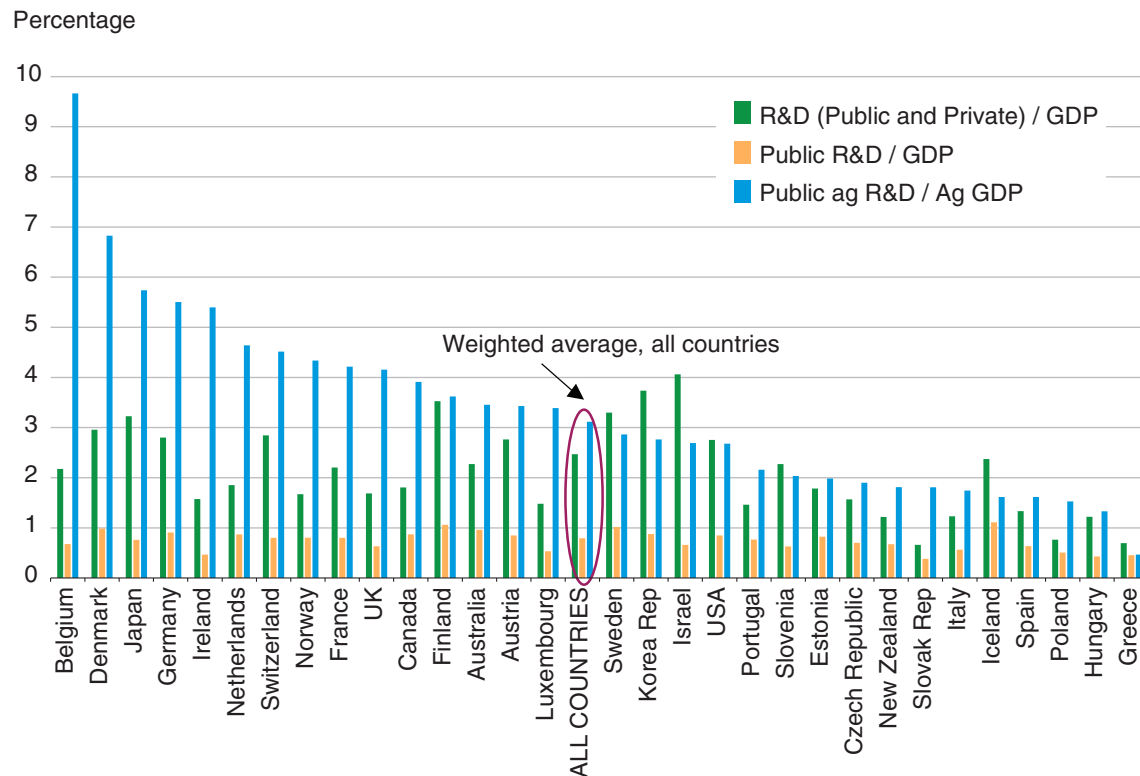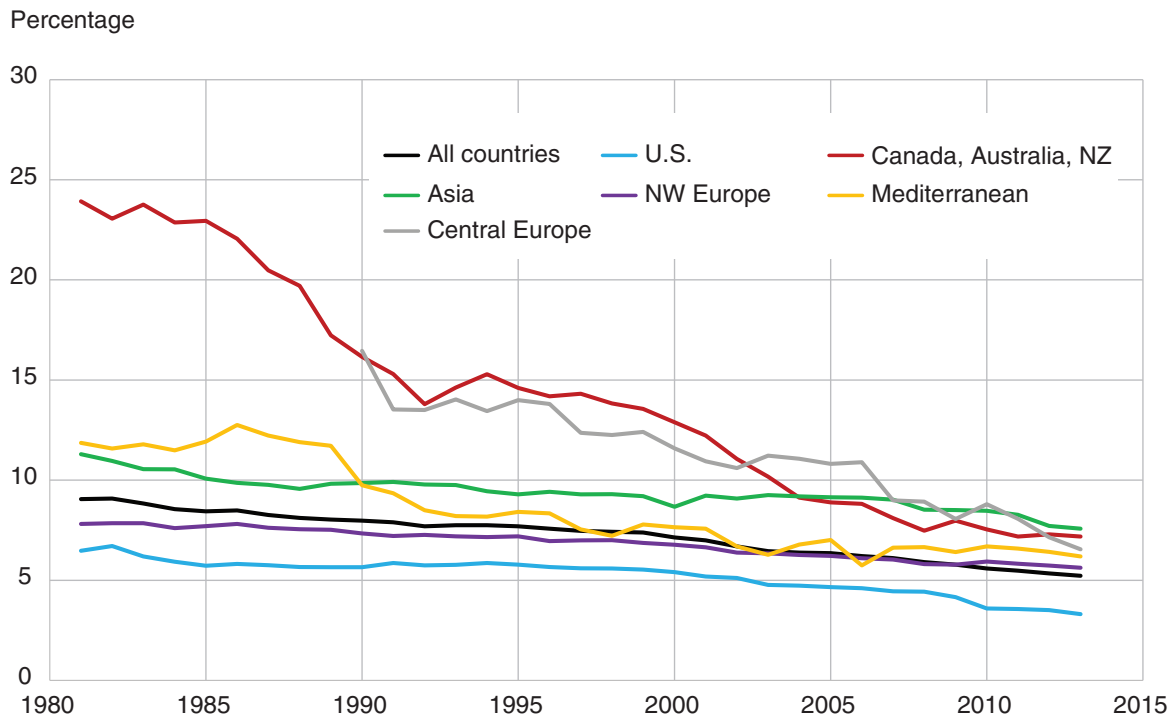

Source: USDA, Economic Research Service using the Organisation for Economic Co-operation and Development's Main Science and Technology Indicators and data from this study. See notes to figure 4.1.

Table 3.1 demonstrates a decrease in real total public agricultural R&D in high-income countries in recent years, the first sustained decrease in the period of our analysis. Trends in total public R&D (and total civilian, or nondefense, public R&D), along with the secular decline in the percentage of public R&D going to agriculture, provide another way of looking at this decline. Total public R&D in these countries began growing at a slower rate, or even fell in some cases, following the global recession of 2008–09. As agriculture's share of total public R&D continued to fall, the combined effect was to further suppress public agricultural R&D spending in the aggregate.

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[21] In the United States and a few other countries (e.g., the UK, France, and Israel), a notable portion of publicly performed research is for defense. Although the levels of the agricultural research/all public research ratios for these countries would differ if publicly performed research is restricted only to civilian expenditures, the trends do not change.

A major reason for agriculture's declining share in public R&D is agriculture's decreased contribution to national economies. One of the major markers of the process of industrialization and economic development is a secular decline in the relative size of the agricultural sector. Taking a long view of economic development, Johnston and Mellor (1961) state that "in virtually all under-developed economies, agriculture is an existing industry of major proportions, frequently the only existing industry of any consequence. Typically, some 40 to 60 percent of the national income is produced in agriculture and from 50 to 80 percent of the labor force is engaged in agricultural production." In later stages of development, "the long-term decline in agriculture's share reflects slow growth in domestic food consumption, combined with high growth in agricultural productivity, which reduces the amount of land, capital, and labor required per unit of agricultural production" (OECD, 2016). In many high-income countries, primary agriculture[22] currently contributes only 1–2 percent of national GDP. As agriculture's share of national GDP has declined, national research policies have shifted to other priorities.

Some of these trends can be observed even in the current high-income countries covered by this study over the period 1960–2014. Although agricultural output continued to rise in some countries, and flattened or fell in others, agriculture's share of total GDP fell in all of them. From 1960–64 to 2010–14, the median percentage of GDP contributed by agriculture for these countries fell from 10.4 to 1.7 percent. In 1960-64, agriculture accounted for over 40 percent of South Korea's GDP (South Korea at that time, of course, would have been classified as a low- or lower-middle-income country), and Greece, Portugal, Ireland, Spain, New Zealand, Finland, and Iceland all had agricultural GDPs of between 15 and 25 percent of total GDP. At the other end of the scale, Canada, Germany, the United States, and the United Kingdom had the lowest ratios in this early period, ranging from 3.4 percent (UK) to 5.5 percent (Canada) (table 4.1). By 2010-14, only two countries, Iceland and New Zealand, had agricultural shares of total GDP at 6 percent or higher.[23] Six countries had ratios of agricultural GDP to total GDP of under 1 percent.

Public Agricultural R&D Investment Has Tended To Rise Faster Than Agricultural GDP, but for Several High-Income Countries, This Trend Has Reversed

Research intensities for agriculture (here defined as public agricultural R&D as a percent of agricultural GDP) have tended to increase over time, although this trend reversed in 2009. The average public agricultural research intensity in today's high-income countries rose from under 1 percent in the early 1960s to about 3 percent in 2009–13. However, in parallel with a downturn in aggregate real public agricultural research in 2009, aggregate research intensity as well as research intensity for many individual countries turned down around 2009 (fig. 4.4; table 4.2). This is the first time over the last half century that average agricultural research intensity in high-income countries declined over more than 2 years in a row. The magnitude of the decline is also quite significant.

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[22] As we have indicated, although primary (crop and livestock) agriculture is often the dominant category in "agriculture, forestry, and fisheries," research for forestry and fisheries is usually included in the analysis.

[23] Note that "agriculture" refers to crops, livestock, forestry, and fisheries. For Iceland, fisheries are the most important component of agriculture. Fisheries and forestry also make up at least a one-third of agricultural GDP in Norway, where fisheries and aquaculture are particularly important, and in Sweden, Finland, and Estonia, where forestry is a major component. Fisheries and forestry also account for 20-25 percent of agricultural GDP in Canada and New Zealand.

Table 4.1
Agricultural GDP as a percentage of total gross domestic product (GDP)

High-income OECD countries	Region	1960–64	1970–74	1980–84	1990–94	2000–04	2010–14
				Percentage			
Canada	North America	*5.5*	*4.0*	*3.6*	*2.6*	*2.0*	*1.7*
United States	North America	*3.7*	*3.2*	2.3	1.5	1.1	1.3
Japan	Asia-Oceania	*10.7*	4.7	2.9	1.9	1.4	1.2
South Korea	Asia-Oceania	*41.0*	24.4	12.8	6.4	3.5	2.2
Australia	Asia-Oceania	*11.5*	*6.9*	5.6	3.4	3.3	2.3
New Zealand	Asia-Oceania	*19.5*	*11.3*	8.3	6.7	6.5	*6.0*
Austria	Europe, NW	*10.3*	*6.0*	3.8	2.6	1.6	1.3
Belgium	Europe, NW	*6.1*	*3.6*	2.3	*1.7*	1.1	0.7
Denmark	Europe, NW	*10.4*	*5.7*	4.5	2.9	1.9	1.3
Finland	Europe, NW	*17.0*	*10.2*	7.8	4.6	2.7	2.4
France	Europe, NW	*9.2*	*6.3*	*3.6*	2.6	2.0	1.6
Germany[1]	Europe, NW	*5.1*	*3.0*	2.1	*1.2*	0.9	0.7
Iceland	Europe, NW	*16.4*	*11.2*	*9.0*	*9.8*	6.8	*6.3*
Ireland	Europe, NW	*20.3*	*13.1*	10.4	7.5	*1.9*	1.2
Luxembourg	Europe, NW		*3.5*	2.4	1.3	0.6	0.3
Netherlands	Europe, NW	*8.5*	4.6	3.7	3.5	2.0	1.6
Norway	Europe, NW	*8.2*	4.7	3.3	2.7	1.5	1.4
Sweden	Europe, NW	*6.3*	*4.7*	4.0	2.6	1.6	1.3
Switzerland[2]	Europe, NW			2.6	1.9	1.0	0.7
United Kingdom	Europe, NW	*3.4*	*2.5*	*1.8*	1.3	0.8	0.6
Greece	Mediterranean	*22.4*	*18.5*	*12.5*	*8.3*	*5.0*	3.2
Israel	Mediterranean	*8.2*	*5.3*	*3.6*	*2.1*	1.4	1.3
Italy	Mediterranean	*12.9*	*7.3*	*5.2*	*3.1*	2.4	1.9
Portugal	Mediterranean	*21.1*	*17.6*	*14.0*	*6.4*	2.8	2.0
Spain	Mediterranean	*20.3*	*10.4*	*6.2*	*4.6*	3.5	2.4
Czech-Slovakia	Europe, Central						
Czech Republic	Europe, Central			*5.2*	4.4	2.7	2.2
Slovakia	Europe, Central			*6.8*	6.0	4.1	3.3
Estonia	Europe, Central				*5.8*	3.9	3.2
Hungary	Europe, Central			*17.2*	*8.4*	4.4	3.7
Poland	Europe, Central			*10.6*	*7.2*	2.9	2.9
Slovenia	Europe, Central				*4.5*	2.5	1.8

OECD = Organisation for Economic Co-operation and Development. Figures in italics are calculated from earlier editions of the World Development Indicators or World Tables or other sources. In most cases, the ratio of agricultural Gross Domestic Product (GDP) to total GDP is calculated using the same source for the numerator (agricultural GDP) and the denominator (total GDP).

[1]Estimates for Germany prior to 1990 refer only to the former West Germany.

[2]Estimates were made for Switzerland for the 1960s and 1970s for purposes of aggregation, but the ratios are not included here as the data sources were particularly limited and inconsistent.

Source: USDA, Economic Research Service using primarily World Bank, World Development Indicators or World Tables. Other sources consulted include the Bureau of Economic Analysis, U.S. Department of Commerce; Statistics Canada; Petmezas (2009); and Wolf (2009).

Figure 4.4

Public agricultural research intensities (public agricultural research/agricultural GDP) in high-income countries, 1960-2013

Percentage

Legend: All countries, U.S., Canada, Australia, NZ, Asia, NW Europe, Mediterranean, Central Europe
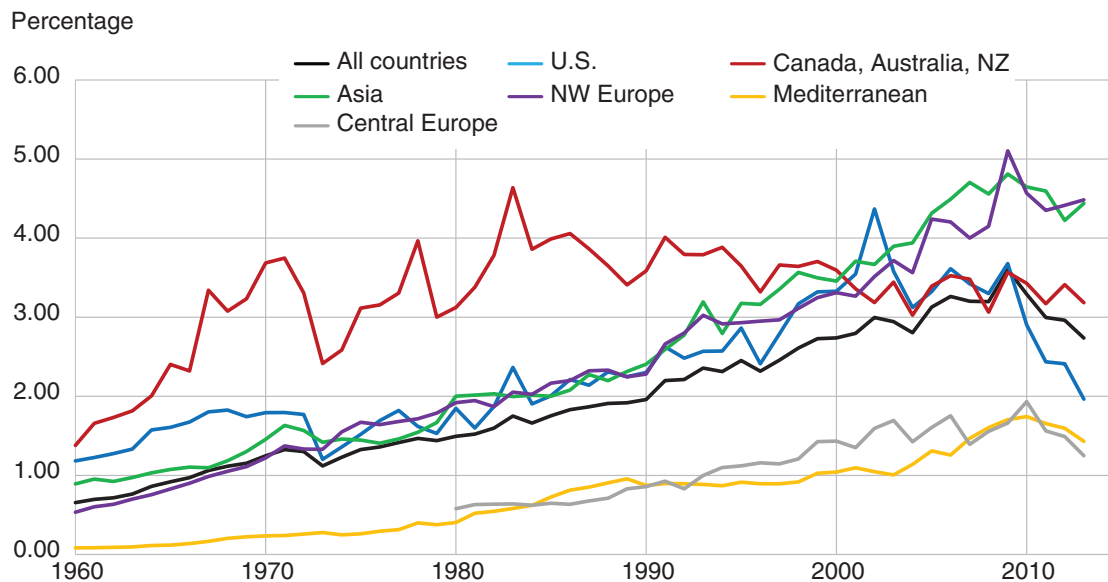
GDP = Gross Domestic Product.
Source: USDA, Economic Research Service using data from World Bank and this study. See notes to tables 4.1 and 4.2.

In the 1960s and 1970s, real agricultural research investments in most high-income countries grew rapidly, boosting research intensity whether real agricultural GDP rose, fell, or displayed a more varied pattern. Growth rates in real agricultural R&D spending were high, averaging over 3 percent annually in 25 of 28 countries for which some data are available for these early years. Greater relative investment in developing a modern agricultural research system by countries that did not have as much initial research infrastructure helped raise research intensities during these two decades. Growth rates in agricultural R&D were particularly high (averaging over 6 percent annually) in all seven countries with larger agricultural GDP, over $10 billion annually in 2011 PPP dollars, but lower research intensities, under 1 percent in the early 1960s. In the other five countries with larger agricultural GDP but higher initial research intensities, only one saw agricultural R&D growth surpass 6 percent annually from 1960 to 1979.

Several reasons help explain the tendency for a country's agricultural research intensity to rise over time. One reason is an expanding research agenda for public agricultural R&D, to include greater emphasis on environmental and other concerns. A second factor is the heavy reliance on productivity as a source of agricultural growth. Rates of TFP growth in agriculture have been more rapid than TFP growth for economies as a whole, and, in this regard, agriculture resembles other high-technology sectors like computer and information technology (IT) sectors. However, unlike the IT sector, agriculture also requires "maintenance research"—research just to keep productivity from falling. The co-evolution of biological pests and the degradation of natural resources like soil, water, and climate imply an ongoing need to develop new technologies to counteract these forces. Sparger et al. (2013) estimate that in 2008, about 40 percent of public agricultural R&D in the United States was devoted to productivity maintenance and that this share increased over time. Lastly, the rising research intensity in agriculture is partly attributed to technological change that has driven agricultural prices down relative to the general price level. Thus, the real value of agricultural GDP tends to fall even if the quantity of production remains the same.

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Table 4.2
Public agricultural research intensity (public agricultural R&D/agricultural GDP) by country, 1960-2013

High-income OECD countries	Region	1960–64	1970–74	1980–8	1990–94	2000–04	2009–13	2009	2013
					Percentage				
Canada	North America	1.98	3.35	3.81	3.88	3.18	3.91	4.21	3.82
United States	North America	1.32	1.58	1.92	2.51	3.59	2.68	3.68	1.96
Japan	Asia	1.17	1.93	2.77	3.66	5.08	5.74	6.35	5.43
South Korea	Asia	0.11	0.20	0.26	1.05	1.59	2.76	2.55	2.91
Australia	Oceania	1.69	3.22	3.72	3.92	3.91	3.46	3.54	3.15
New Zealand	Oceania	1.10	2.52	3.81	3.30	2.07	1.81	2.01	1.73
Austria	Europe, NW	0.22	0.67	0.96	1.47	2.74	3.43	4.09	3.07
Belgium	Europe, NW	0.83	1.32	2.14	3.10	5.85	9.66	10.2	10.2
Denmark	Europe, NW	1.09	1.19	1.39	2.89	4.42	6.83	10.7	5.78
Finland	Europe, NW	0.32	0.61	0.81	2.22	2.70	3.62	3.69	3.11
France	Europe, NW	0.30	0.90	1.79	2.38	2.87	4.21	4.81	4.47
Germany	Europe, NW	0.64	1.68	1.85	3.69	3.81	5.50	5.99	5.01
Iceland	Europe, NW	1.10	1.77	2.10	2.61	4.30	1.62	3.73	1.04
Ireland	Europe, NW	1.00	1.31	1.10	0.84	3.22	5.40	9.30	3.95
Luxembourg[1]	Europe, NW		0.00	0.00	0.15	0.51	3.39	0.00	2.75
Netherlands	Europe, NW	0.99	1.96	2.88	2.72	3.67	4.64	4.00	4.58
Norway	Europe, NW	0.89	1.53	2.26	3.52	5.06	4.34	4.88	3.77
Sweden	Europe, NW	0.73	1.38	1.63	3.09	2.57	2.86	3.08	2.96
Switzerland	Europe, NW	1.19	1.61	1.46	1.39	2.86	4.51	3.50	5.03
United Kingdom	Europe, NW	1.12	2.23	3.50	3.43	4.13	4.16	5.15	3.98
Greece	Mediterranean	0.05	0.19	0.31	0.28	0.33	0.47	0.47	0.47
Israel	Mediterranean	1.59	2.80	4.15	4.58	3.91	2.69	2.40	2.85
Italy	Mediterranean	0.06	0.27	0.62	1.10	1.20	1.74	1.49	1.68
Portugal	Mediterranean	0.23	0.31	0.31	0.92	2.09	2.16	2.37	1.61
Spain	Mediterranean	0.08	0.16	0.45	0.77	0.90	1.61	2.01	1.28
Czech-Slovakia	Europe, Central			0.83	1.03	1.27	1.86	1.96	1.17
Czech Republic	Europe, Central			0.71	0.89	1.45	1.90	2.33	1.30
Slovakia	Europe, Central			1.27	1.44	0.87	1.81	1.33	1.92
Estonia	Europe, Central				0.97	1.42	1.98	2.22	2.24
Hungary	Europe, Central			0.54	0.80	1.64	1.33	1.85	1.04
Poland	Europe, Central			0.62	0.91	1.54	1.53	1.50	1.26
Slovenia	Europe, Central				2.41	1.87	2.03	1.01	2.56
North America		1.40	1.78	2.16	2.67	3.53	2.79	3.74	2.12
Asia only		0.96	1.51	2.01	2.75	3.73	4.54	4.81	4.44
Oceania only		1.54	3.00	3.73	3.75	3.44	2.99	3.12	2.77
Europe, NW		0.65	1.36	1.96	2.74	3.47	4.58	5.10	4.48
Mediterranean		0.09	0.25	0.54	0.88	1.07	1.63	1.70	1.13
Europe, Central				0.62	0.95	1.50	1.58	1.66	1.25
Total, high-income OECD countries		0.77	1.31	1.61	2.21	2.86	3.12	3.60	2.74

[1]Luxembourg had no observable public research expenditures of any kind before the mid-1980s (see appendix B). In the Organisation for Economic Co-operation and Development (OECD) database, reported total agricultural research for 2009 was zero; the 2010 amount was considerably higher than trend. This suggests accounting or reporting anomalies for those 2 years. Such anomalies are likely to be accentuated for a very small country like Luxembourg.

Source: USDA, Economic Research Service. Research data—see appendix B. Agricultural Gross Domestic Product (GDP) data primarily from the World Bank. See table 4.1.

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While the overall trend has been for the agricultural research intensity to rise over time, at a regional and country level, research intensities have displayed a more varied pattern. In high-income countries of Oceania and North America, research intensities leveled off or even fell following an initial period of growth. In Australia, New Zealand, and Canada, growth rates in agricultural research spending since the 1980s have been close to or even below growth rates in agricultural GDP. In the United States, public agricultural research intensity rose until the early 2000s, after which it began to fall even before the global financial downturn at the end of the decade. Thus, several empirical observations—recent downturns in public agricultural research intensities in many countries, earlier flattening or declines in intensities in the agricultural exporting countries of North America and Oceania, and intensities in some regions (Mediterranean, Central Europe) that remain well below the high-income country average—suggest there may be countervailing forces that reduce the tendency for investment in public agricultural R&D to rise faster than agricultural GDP (table 4.2). These might include general public budgetary constraints, specific factors in the political economy of public science funding, or perhaps differences in the reliance on research spill-ins from other countries or the private sector.

Research Costs Rise Faster Than the General Rate of Inflation

The international comparisons in agricultural R&D spending in this report are based on first adjusting each country's spending (in national currency units) for inflation by the implicit GDP price deflator of that country (using 2011 as the base year), and then converting to (constant) dollars using the purchasing power parity (PPP) exchange rate. This procedure is the standard in international reporting of agricultural R&D data (Craig et al., 1991; Beintema et al., 2012; and Pardey et al., 2016). These "constant dollar" series are intended to make comparisons across countries and over time in the amount of real R&D resources devoted to agriculture. However, these estimates could be systematically biased if price inflation of R&D inputs differs from general price inflation (Jaffe, 1972; Griliches, 1984) or if the relative prices of R&D inputs across countries deviate from the relative prices of a common basket of consumer goods used to estimate PPP exchange rates (Dougherty et al., 2007).

To examine these potential biases in measures of agricultural R&D spending, we constructed internationally comparable Griliches-Jaffe price indexes for agricultural research for seven high-income countries over 1992-2012 (see box "Estimating Internationally Comparable R&D Price Indexes"). These include the United States, Canada, Australia, Japan, Germany, France, and the UK, which together account for between two-thirds and three-fourths of the total public agricultural R&D spending by all high-income countries. The Griliches-Jaffe R&D price index assumes R&D inputs are composed of scientific labor and capital and constructs a cost-share weighted price index for these inputs. Our index uses university faculty salaries for the price of scientific labor and assumes that labor costs account for approximately 70 percent of total agricultural R&D expenses. Nonlabor costs are assumed to rise at the level of the implicit GDP price index, and their cross-country relative values are assumed to be the same as given by the PPP exchange rate. Cross-country relative values for faculty salaries are combined with the PPP exchange rate using the same factor proportions (roughly 70 percent scientific labor, 30 percent other expenses) to create an alternative PPP exchange rate that specifically takes into account the cost of scientific labor.

Estimating Internationally Comparable R&D Price Indexes

Adjusting an expenditure series in nominal currency by a price index corrects for the effects of price inflation and gives us a measure of real (inflation-adjusted) expenditure. However, if the prices of inputs used in research (e.g., scientists' salaries, laboratory equipment and materials, etc.) are rising at a faster rate than the average price level, then a research and development (R&D) expenditure series that has been deflated by a general price index overstates the rate of growth in R&D—it overstates the amount of research that the expenditure is actually buying. Similarly, comparing R&D spending across countries is usually done using a purchasing power parity (PPP) exchange rate, which is based on the cost of a common basket of consumer goods purchased in local currency. However, if the relative prices of research inputs in two countries vary systematically from the relative prices of consumer goods, using the PPP exchange rate could bias the comparison of real R&D spending.

A better way to compare R&D spending over time and across countries is to use price indexes and exchange rates based on the actual cost of R&D inputs. The most important cost item in R&D is compensation paid to scientists and technicians. Labor costs typically account for 60–70 percent of total research costs. The Griliches-Jaffe R&D price index—a simplified version of an R&D price index—assumes R&D costs are composed of two inputs: scientific labor and capital. A price index is created by taking the cost-share weighted average of the growth rate in the price of each input relative to some base year. University faculty salaries are typically used to measure the price of scientific labor and the Gross Domestic Product (GDP) price index for the price of capital inputs. For agricultural R&D in the United States, Pardey et al. (1989) develop an R&D price index composed of labor, capital, and material inputs. They also use faculty salaries for R&D labor prices and find that because average faculty salaries rose at a faster rate than general inflation, R&D prices rose faster than the GDP price index.

To compare research costs across countries, Dougherty et al. (2007) estimate prices for four different R&D inputs in manufacturing industries in the United States, Japan, and four Western European countries. For each country, they estimate the price of R&D inputs relative to R&D inputs in the United States (in local currency units per dollar) and compare these against market and PPP exchange rates. They find that using market or PPP exchange rates biased the estimates of relative amounts of R&D spending among these countries, especially due to differences in the price of research labor. They also find that a Griliches-Jaffe type R&D price index (with country-specific labor prices and general PPP prices for other inputs) provides a reasonably good approximation of their four-input R&D price indexes across countries and industries.

We have constructed Griliches-Jaffe R&D price indexes with dollar conversions for the United States, Canada, Australia, Japan, Germany, France, and the United Kingdom over 1992–2012. For scientific labor costs, we use university faculty salaries, or an approximation of the rate of change in these salaries, for each country (see appendix C for data sources); for nonlabor R&D inputs, we use the GDP price index and the PPP exchange rate. We also assume that the labor share of R&D costs is approximately 70 percent for all countries, which is similar to the estimated share for the United States (Pardey et al., 1989).

The first step is to construct an R&D price index $P_{c,t}^{R\&D}$ for each country c. Letting 2011 be the base year ($P_{c,2011}^{R\&D} =1.00$), then the rate of change in the index between 2011 and year t is:

$$ln\left(P_{c,t}^{R\&D}\right)=\theta^s ln\left(\frac{W_{c,t}^S}{W_{c,2011}^S}\right)+\left(1-\theta^s\right)ln\left[\frac{I_{i,t}^{GDP}}{I_{i,2011}^{GDP}}\right]$$

where θ^s is the share of labor in R&D costs, $W_{c,t}^S$ is the average faculty salary, and $I_{c,t}^{GDP}$ is implicit GDP price index for country c in year t. We use this index to put each country's agricultural R&D spending in constant 2011 local currency units. We then estimate an R&D-input cost parity ratio for each country relative to the United States and use this ratio to convert these expenditures into constant 2011 dollars. The R&D input-cost parity ratio, $R\&D_c^{cost\ parity}$, for country c is given by:

$$R\&D_c^{cost\ parity}=\theta^s\left(\frac{W_{c,2011}^S}{W_{USA,2011}^S}\right)+\left(1-\theta^s\right)PPP_{c,2011}$$

where $PPP_{c,2011}$ is general 2011 purchasing power parity ratio for country c for a common basket of goods. In other words, the R&D input-cost parity ratio is a weighted combination of a simple price comparison of scientific labor and the GDP conversion factor used as a proxy for other research inputs.

Some simplifying assumptions of this procedure include (i) scientists are the same quality, (ii) the cost shares of R&D inputs are constant and the same across countries, and (iii) the GDP price indexes and PPP exchange rates provide reasonable approximations of movements in prices of nonlabor R&D inputs. While it would be preferable to have more detailed estimates of R&D costs for each country, our method captures differences in the cost of R&D labor over time and space, the factor that previous work on this topic has identified as being the most significant source of bias in developing comparisons of R&D spending. A more difficult challenge is likely to be accounting for differences in the quality of scientific labor. One potential measure is per capita scientific publications, which Messinis (2004) used in a price index developed for life sciences research, although this measure requires information on the number of scientists employed in agricultural research. Improving the comparability of R&D inputs and expenditures over time and across countries is an important area for further inquiry.

These R&D price indexes show that for each of these countries, the cost of conducting agricultural R&D rose faster in 1992-2012 than the general rate of inflation (table 4.3). On average, R&D costs were rising by about 0.7 percent higher than the implicit GDP price indexes. This implies that even if R&D spending were to keep up with the general rate of inflation, the amount of R&D would fall in real terms by about 0.7 percent per year. Since scientific labor constitutes the bulk of R&D costs, this essentially means that the number of scientists employed in agricultural research would fall by about 0.7 percent per year. What these price indexes imply is that the real rate of growth in public agricultural R&D investment in high-income countries has been lower than that reported in the section "Agricultural R&D Investments and Productivity," at least since 1992. Using the GDP price index, total R&D spending for these seven countries showed a modest increase in real

terms between 1992 and 2012. Using the R&D price index, total R&D spending by these countries showed no growth at all over this 20-year period.

Table 4.3
Average annual growth rates of alternative price indexes in seven countries

Country	Average annual growth rate in the GDP deflator, 1992-2012 (%)	Average annual growth rate in the Griliches-Jaffe R&D deflator, 1992-2012 (%)	Average annual growth rate in the ERS R&D deflator, 1992-2012 (U.S. only) (%)
Canada	2.18	3.04	n.a.
U.S.	2.04	2.78	3.57
Japan	-1.03	-0.05	n.a.
Australia	3.03	3.48	n.a.
France	1.51	1.82	n.a.
Germany	0.94	1.01	n.a.
United Kingdom	2.29	3.43	n.a.

n.a. = not available. R&D = research and development. GDP = Gross Domestic Product.

Source: USDA, Economic Research Service.

For the United States, ERS has constructed a more detailed agricultural R&D cost index that has specific price components for scientific labor, capital (laboratory equipment, buildings and land), and materials (research services and supplies) (table 4.3). This index shows even more rapid inflation in the cost of R&D inputs than the Griliches-Jaffe R&D price index. While all three price indexes (the implicit GDP price index, Griliches-Jaffe R&D price index, and the ERS R&D price index) show that public agricultural R&D spending by the United States peaked in real terms in 2002, the ERS R&D price index indicates that R&D spending declined even more rapidly than when changes are calculated using one of the other price indexes.

Historically, R&D costs have been rising faster than the rate of inflation not only for agricultural research but for all types of R&D, in both the public and private sectors (Jaffe, 1972; Mansfield et al., 1983; Griliches, 1984). This disparity in growth rates is triggered by salaries of scientists rising faster than the general price level, which Acemoglu (2002) attributed to "skills-biased technical change" in the overall economy. In other words, modern technologies require increasing amounts of highly skilled scientific and technical labor to develop and utilize. This causes wages of highly skilled labor to rise faster than wages of less skilled labor or other goods in the economy.

Whether this additional inflation in the cost of conducting research reduces the amount of new knowledge produced, however, is not entirely clear. Although it does imply that for a given research budget, fewer scientists could be employed, this loss could be offset if the productivity of the remaining scientists (research output per scientist) increased. It is possible that availability of information technologies and new computational tools together with advances in basic life sciences have raised the productivity of agricultural scientists. One recent study of productivity of agricultural scientists in the United States finds significant improvements in their productivity (measured by the number of scientific publications) per unit of time between 1975 and 2005, but that these gains were largely offset by increased administrative duties, such as grant seeking and project management by scientists (Prager et al., 2014).

Research in the United States Costs More Than Research in Most Other Countries

Applying an R&D-based measure rather than a consumer goods-based PPP measure for international comparisons shows that R&D costs in the United States are relatively high. In PPP dollars, scientific labor costs (agricultural faculty salaries) in the United States are higher than those in five of the other six countries for which we have comparable data (Canada is the exception). Since other countries' R&D costs are lower relative to those of the United States, this implies they are actually spending somewhat more, in comparable dollars, on agricultural R&D than reported earlier. Figure 4.5 compares total spending on public agricultural R&D by the other six countries relative to spending in the United States using both the GDP price index with consumer goods-based PPP exchange rates and the R&D price index with R&D cost-based exchange rates calculated for this study. In the aggregate, using the standard GDP-PPP price indexes and exchange rates, total R&D spending in these seven countries increased from $11.0 billion to $12.4 billion over 1992–2012. However, using the Griliches-Jaffe R&D-based price indexes and exchange rates, aggregate R&D spending is estimated to have changed from $13.9 billion in 1992 to $13.6 billion in 2012 (the fact that it is higher overall reflects the larger R&D effort in Europe and Japan relative to the United States, due to their lower R&D costs). But instead of increasing by $1.4 billion when using standard methods, as it does when adjusted by changes in the general price level, R&D investment by these countries declined by $0.3 billion when adjusted by the Griliches-Jaffe research price index. Growth of total R&D declined between 1992 and 2012, when Griliches-Jaffe deflators are used rather than GDP deflators, because R&D costs in all countries grew more rapidly than the general rate of inflation. These findings on how choice of price indexes affects the relative cost of research across countries and over time are similar to results of Dougherty et al. (2007) and Messinis (2004) in comparing R&D spending between U.S. and European R&D manufacturing and pharmaceutical industries, respectively.[24]

Figure 4.5

Agricultural R&D in six countries relative to the U.S. level using alternative deflators and R&D input cost parity comparisons, 2008-2012 average

Public research total as a percentage of U.S. public research
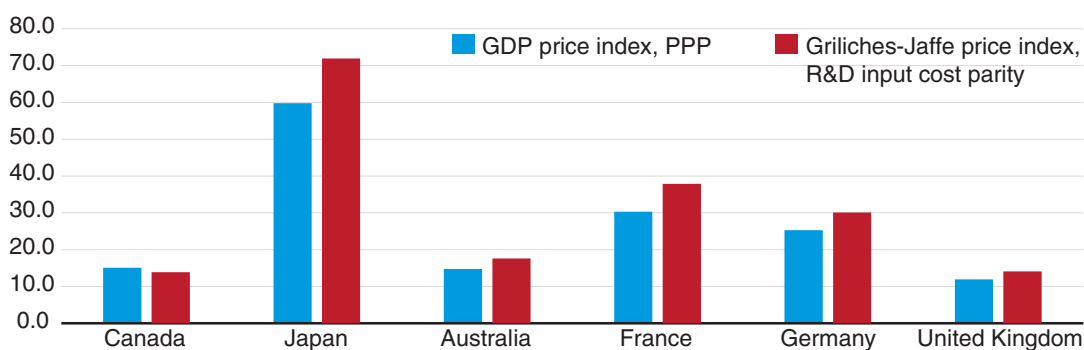
R&D = research and development. GDP = Gross Domestic Product. PPP = purchasing power parity.
Source: USDA, Economic Research Service, based on multiple sources. See Appendix C, in particular, for data used in calculating scientific labor costs.

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[24] The Dougherty et al. study of manufacturing also included Japan.

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Agricultural R&D Policy Reforms

Over the past few decades, several high-income countries adapted their agricultural R&D systems to accommodate new priorities and attract new funding sources. Systems that had originally been constructed to serve large numbers of small and diverse farms sought to reorient themselves to a new agricultural structure: farms had become fewer, larger, and more specialized; farmers were better educated and acquiring information and new technologies from diverse sources; corporate agribusiness was playing a larger role in developing new technologies and providing services for agriculture; and consumer expectations had changed. With the goal of secure and affordable food supplies largely achieved, consumers and society at large placed relatively greater weight on other sources of utility and welfare, such as the environment; the quality, safety and nutritional value of food products; the treatment of farm animals; the livelihoods of farmworkers; and the resilience of rural communities.

Perhaps the first two major documents signaling a change in thinking in agricultural research policy in high-income countries were a parliamentary review of all public research in the UK led by Lord Rothschild in 1971, and a review of the U.S. system of agricultural research by the National Academy of Sciences (NAS) in 1972 (HMSO, 1971; NAS, 1972). On the surface, these two reviews provided rather different recommendations. The Rothschild report argued that the UK Agricultural Research Council had become divorced from the needs of its clientele of farmers, agricultural input suppliers, and food processors, and recommended it adopt a "customer-contractor" principle for public agricultural R&D (Thirtle et al., 1999). The NAS report contended, on the other hand, that U.S. agricultural research had become too focused on applied research, it had moved too far from the cutting edge of biological research, and changes in the mechanisms of research funding were necessary to make the requisite adjustments in research emphases (Day Rubenstein et al., 2003). The Rothschild and NAS reports were significant not so much because of their content or the degree to which their recommendations were implemented but because they represent early attempts to redefine the role and priorities of public agricultural research.

Pressures to reform public agricultural research were not limited to the United States and the UK. In a number of countries, the responses to changes in the economic and policy environments included the diversification of funding sources, the broadening of research themes addressed, and a shift toward more fundamental biological sciences. These reforms diverted resources away from the direct provision of productivity-enhancing new technologies to farmers (which was increasingly to be left to the private sector) and into more fundamental, long-term research, as well as applied research to find practical solutions to social issues that the private sector was unlikely to pursue, like farming practices that conserve environmental resources.

Important components of these reforms included changing the way public agricultural R&D was financed and allocated. Some countries sought to increase the role of farmers in funding research through greater use of commodity levies (assessments on commodity sales), technology royalties (assessments on input purchases), or other user fees. An important reform to research funds allocation was a movement away from block grants to research institutes to greater reliance on competitive grants to scientists. Competitively awarded grants aimed to fund the highest quality science, avoid duplication, and allow funding agencies greater control over research portfolios. This also encouraged grant seeking from more diverse funding sources, including industry, nonprofit foundations, and government departments other than agriculture, which had the effect of directing more

public research to issues of particular interest to these organizations. Some countries also privatized, closed, or amalgamated components of their public research systems they deemed redundant or no longer essential.

The growing agricultural research capacities in the private sector—usually by input-manufacturing firms—posed both a challenge and an opportunity for public agricultural research systems. Public research systems may seek to avoid direct competition with private research so as not to duplicate what could adequately be performed by for-profit firms. As private research expanded, this meant divesting of some public research and redefining the public role in a more complex public-private research system.

The Stokes-Ruttan Paradigm for Public and Private Roles in R&D Systems

The 20th century paradigm for U.S. science policy was expressed by Franklin Roosevelt's science advisor Vannevar Bush in *Science: The Endless Frontier* (1945).[25] As WWII came to a close, Roosevelt asked Bush for his recommendations in turning the scientific and technological achievements of the war to support peacetime economic growth. In Bush's depiction, science and technology proceeded in a *linear or assembly line model* in which advances in basic scientific knowledge lead to new technological applications. He argued for a strong government commitment to support curiosity-driven basic science, which would subsequently feed into private-sector-led technological and commercial applications. However, over time, more complex interpretations have emerged regarding the relationship between scientific research and technology development. "It is no longer believed that a heavy investment in pure, curiosity-driven basic science will itself guarantee the technology required to compete in the world and meet a full spectrum of other societal needs" (Stokes, 1997, p. 58). Critics of the linear model emphasized that advances in science and technology are often closely interrelated, with the distinction between who "does science" and who "does technology" becoming increasingly blurred (Ruttan, 2001, p. 536).

In 1997, Princeton political scientist Donald Stokes proposed a new science policy paradigm that draws a distinction between (i) basic scientific research that is motivated solely by the quest for understanding without thought of practical use and (ii) research that seeks to extend frontiers of understanding but is also inspired by considerations of use (fig. 5.1). He labeled pure science endeavors as "Bohr's Quadrant," after the Danish physicist Niels Bohr's search for a model of atomic structure. Drawing on the example of 19th century French chemist Louis Pasteur, whose research to improve fermentation led to fundamental advances in microbiology, Stokes drew a distinction between the pure science of Bohr and the use-inspired science of Pasture, labeling the latter as research in "Pasteur's Quadrant." Research that is guided solely by applied goals without seeking more general scientific understanding Stokes placed in "Edison's Quadrant."

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[25] Important earlier events in the history of public agricultural science policy in the United States included the Morrill Act of 1862, which established the U.S. Department of Agriculture, and the Hatch Act of 1887, which established the State Agricultural Experiment Stations (Huffman and Evenson, 2006). Other early examples of U.S. public investment in research include civil engineering and research at the National Armory, in support of the military mission (Hounshell, 1984), and the founding of the Hygienic Laboratory at the Marine Hospital Service, later the Public Health Service, in 1891 (Terris, 1992). However, *Science: The Endless Frontier* was the first U.S. document to explicitly assess the role of the government in scientific research.

Later, Ruttan (2001) modified Stokes' paradigm by making a further distinction between applied R&D that offers sufficient commercial returns and applied R&D that fills other technological gaps or addresses other societal goals. Ruttan labeled this type of research as falling into "Rickover's Quadrant," in reference to the effort led by Admiral Hyman Rickover to develop the first practical nuclear power plant, not for commercial purposes but to power naval vessels. Ruttan placed much of Federal and State investment in agricultural research in Rickover's Quadrant, noting that it focused on developing technologies that significantly affected U.S. agricultural productivity and natural resource conservation, but in areas where commercial returns were low due to the difficulty for private innovators to appropriate returns. Besides defense and agriculture, much of the applied research in social sciences and policy, environment, and health, and research that supports government regulatory functions and program performance, also falls into Rickover's Quadrant. The Stokes-Ruttan framework suggests a significant role of the public sector in funding the basic and applied scientific research that falls into the Bohr, Pasteur, and Rickover quadrants. The private sector will concentrate its R&D spending on research that falls into Edison's Quadrant, where it can be expected to make sufficient commercial returns on that investment.

Figure 5.1

The Stokes-Ruttan paradigm for the roles of public and private research

The Stokes-Ruttan paradigm classifies research along two dimensions: (i) whether or not it involves a quest for fundamental understanding and (ii) whether there are explicit considerations for commercial use. The public sector will have primary responsibility for research falling into Bohr's, Pasteur's and Rickover's Quadrants, while the private sector will concentrate primarily on Edison's Quadrant, where it can earn sufficient commercial returns from its R&D investment.

Source: USDA, Economic Research Service using Ruttan (2001).

One implication of the Stokes-Ruttan research paradigm is that the boundaries between public and private R&D may shift over time as new commercial opportunities develop, the structure of an economy changes, or stakeholders respond to changes in other policies. For example, the emergence of potential applications of biotechnology to agriculture, and changes in intellectual property rights that made it possible for private companies to appropriate returns from them, induced significant private R&D in crop breeding and biotechnology, at least for some commodities (Fuglie and Toole, 2014). Besides new technological opportunities and stronger IPR over biological inventions, other factors that have affected private incentives to invest in agricultural R&D in the United States and other countries include changes to industry structure, liberalization of input markets, and new environmental and food safety regulations (Pray and Fuglie, 2015).

In terms of the Stokes-Ruttan framework, the expansion of private R&D could be viewed as an enlargement of Edison's Quadrant. Research areas that were previously unprofitable (because the R&D was too risky, intellectual property rights were too weak, markets too small, etc.) were now seen as generating sufficient private returns to attract private-sector interest. As private R&D expanded, public agricultural R&D could be reallocated to stay within the new boundaries of the Pasteur and Rickover Quadrants. Public R&D could move upstream to more fundamental or pre-commercial research that defines the Pasteur Quadrant, or to applied R&D in Rickover's Quadrant that addresses social issues that lack strong commercial interest.

Reforms To Accommodate Private-Led Food and Agricultural Innovation

The United Kingdom and the Netherlands are two countries that introduced major reforms to accommodate changing views on the appropriate roles of public and private sectors in agricultural research. Below, we summarize key elements of their reforms, their outcomes, and draw potential lessons for agricultural research policies in the United States and other high-income countries.

United Kingdom

Beginning in 1982, the UK took a number of steps to move public agricultural research away from areas that could directly compete with industry (Thirtle et al., 1999). As part of these reforms, the UK government:

- Privatized, closed, or amalgamated several agricultural research institutes.

- Reallocated research funding from applied, near-market research to more basic research.

- Reduced institutional support (block grants) for research institutes, requiring scientists to raise more of their research funding from competitive grants and by charging farmers and other users for technology services.

- Established a centralized authority to set research priorities, which included membership from the food industry and consumer groups.

- Gave producer associations authority to impose mandatory levies on commodity sales to fund research.

- Established programs to encourage joint public-private funding of research and technology transfer (Thirtle et al., 1999).

An unintended consequence of these reforms was that total public and private funding for agricultural research subsequently declined (Thirtle et al., 1999). By the 1990s, productivity in UK agriculture showed signs of stagnation. Average yields of wheat, the most important crop in the UK, plateaued at around 8 tons per hectare in the mid-1990s after having risen steadily from around 4 tons per hectare in the 1960s. Until the reforms, the UK's highly successful wheat-breeding program was dominated by the public-sector Plant Breeding Institute (PBI). In 1987, as part of the research system reforms, PBI's crop-breeding program was sold to the private sector.[26] However, private seed companies had difficulty recouping their research investments through seed sales, and investment in wheat breeding declined. One factor that constrained research revenues was relatively weak intellectual property rights over improved crop varieties. UK plant breeders' rights provided for a *farmers' exemption*—farmers could save a portion of their harvest for use as seed the following year. Although a royalty system assessed a technology fee on both certified seed and farmer-saved seed, it was not sufficient to fund a robust private-sector breeding program. Galushko and Gray (2012) estimated that by 2010, R&D spending on private wheat breeding amounted to $9 million, less than 0.3 percent of the $3.3 billion farm value of wheat production in the country. By comparison, in 2010 private corn and soybean breeding research in the United States amounted to about 1 percent of the value of crop production, or more than three times as much as private wheat breeding in the UK (Gray, 2010).

Another reform that failed to materialize was more levy-funded research from commodity producer groups. Although commodity organizations had legal authority to impose mandatory levies on their members, few were willing to impose fees for research, and the vast majority of funds raised through levies were used to support extension services for members instead (Fowler et al., 2014). Overall funding for public agricultural research in the UK peaked at an average of about $700 million per year during 1980-2000 and then declined to under $600 million per year by 2010 (constant 2011 PPP$).

More successful were efforts to shift the form of public funding away from block grants to institutions toward competitive grants to scientists. The increased reliance on competitive research grants diversified sources of funding to include other government ministries, the EU, and the private sector. UK agricultural scientists have been particularly successful in competing for EU research funds and have achieved relatively high ratings on indicators of research output and quality (OECD, 2015a). Greater centralization in setting research priorities also succeeded in shifting funds from farm-productivity research to other issues, animal product food safety in particular (Thirtle et al., 1999).

The Netherlands

For many of the same reasons as the UK, the Netherlands embarked on major reforms of its agricultural research, extension, and education system beginning around 1990. Key reforms included:[27]

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[26] Initially, the Plant Breeding Institute was sold to Unilever, an English-Dutch food company. Unilever was not able to make a profit from wheat breeding and sold its breeding assets to the U.S. agricultural biotechnology company Monsanto in 1998. Monsanto was unsuccessful in its efforts to develop genetically modified wheat varieties that were acceptable to consumers and, in 2004, sold its wheat-breeding assets to RAGT, a French seed company (Galushko and Gray, 2012). As part of the reforms, some horticultural and livestock research was also privatized in the 1980s (Thirtle et al., 1999).

[27] This summary of reforms draws from Roseboom and Rutten (1999), Poppe (2008), and OECD (2015a).

- *Privatization of agricultural extension services.* In 1990, extension was reoriented toward a fee-for-service system. In 1998, it was spun off completely into several private, for-profit consulting companies.

- *Amalgamation and merger of research institutes.* In 1998, government agricultural research institutes and the main agricultural university merged to form the Wageningen University and Research Center (WUR), and some regional experiment stations were closed.

- Shift in the government funding of agricultural research from institutional (block) grants to competitive grants.

- Diversification of funding sources to include greater reliance on grants from a wider set of government agencies, private companies, and foreign institutions.

- Reduced role for commodity boards and levy-funded research. Commodity boards were finally abolished in 2014.

- Greater emphasis on public-private research and development partnerships along the agriculture and food marketing chain, including the establishment of new R&D consortia (e.g., "Seed Valley" and "Food Valley" innovation clusters).

Figure 5.2 shows the changing levels and sources of support for agricultural research conducted by WUR agricultural research institutes between 1995 and 2013.[28] While total funding (in constant euros) remained roughly the same, the sources of funding greatly diversified. In 1995, more than three-fourths of research funds were provided as institutional support from the Dutch Ministry of Agriculture.[29] By 2013, this source made up only 40 percent of total funding. Competitively funded research grants and contracts, from government ministries, the EU, and the private sector, as well as own revenues generated from fees and product sales, made up the bulk of funds for agricultural research.

One factor favoring research system reform in the Netherlands was its well-established system of plant breeders' rights (PBR). The Netherlands was the second country in the world (after the United States) to adopt formal PBR legislation in 1941. PBRs have been particularly important for encouraging private plant breeding in vegetables, floriculture, and potatoes, sectors important to Dutch agriculture. In the Netherlands, PBRs give breeders the exclusive right to commercialize their varieties and restrict the breeders' exemption commonly associated with PBR: other breeders are free to use protected varieties as parent material but must obtain a license if they wish to commercialize varieties containing any protected pedigree. In 2013, the Netherlands amended its patent law so that patented varieties are also afforded this exemption. Obtaining a license ex post (after a new variety has been bred) is generally thought to favor the owner of the PBR or patent in negotiating licensing fees (OECD, 2015a). At the time of the reforms to the public research system, the Netherlands already had a vibrant private seed industry with significant capacity in plant breeding.

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[28] Figure 5.2 is based on information pertaining directly to WUR; the data sources overlap with but are not completely the same as those (e.g., OECD, Eurostat) this report uses to estimate public agricultural research for the Netherlands.

[29] In 2010, the Ministry of Agriculture was merged with the Ministry of Economic Affairs. In 2017, it was reinstated as the Ministry of Agriculture, Nature and Food Quality.

Figure 5.2

Funding sources for Wageningen University Agricultural Research Institutes

Million 2013 euros
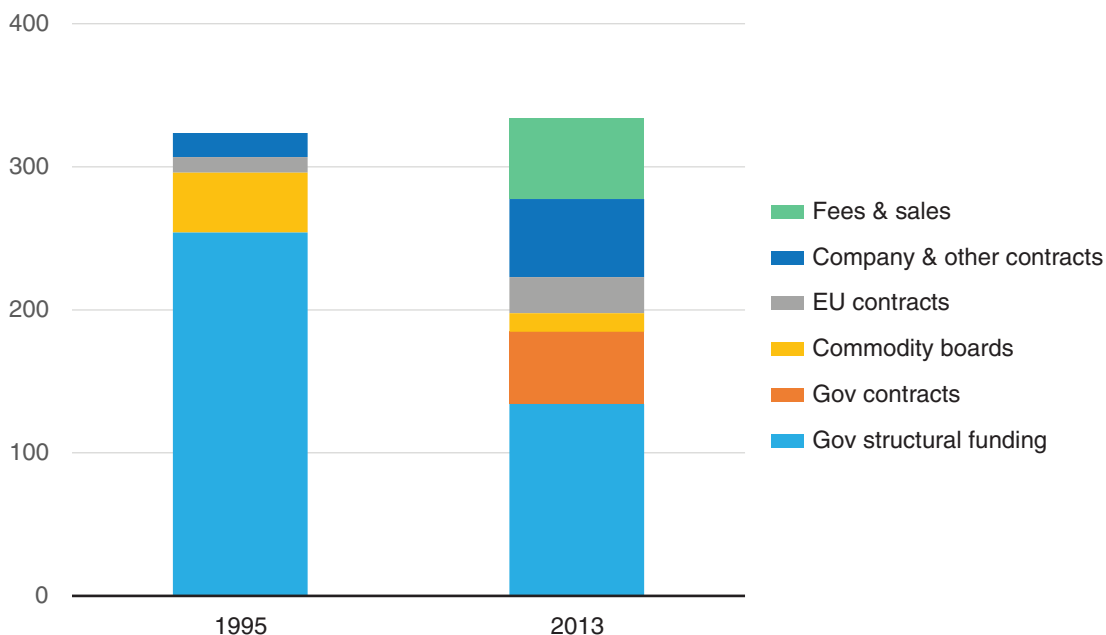
Figures include funding for former DLO (Dutch Agricultural Research Service) institutes and experiment stations that merged with Wageningen University & Research (WUR) in 1998.

Sources: USDA, Economic Research Service using 1995 data from Roseboom and Rutten (1999) and 2013 data from Wageningen UR (2014).

The reforms introduced considerable dynamism into the Dutch food and agricultural innovation system. The concentration of public research resources at Wageningen University created an attractive innovation environment for the private sector. More than 15,000 scientists and engineers are currently employed in food and agribusiness in the Wageningen innovation cluster (Geerling-Eiff et al., 2014). Public-private research consortia have been established to support Silicon Valley-type concentrations of innovation in food manufacturing ("Food Valley") and seed and planting materials ("Seed Valley"). It appears that both public and private R&D spending for food and agriculture rose in the past decade; by 2013, these R&D expenditures reached $600 million for public institutions and $530 million for private firms (Eurostat).

Assessment of research policy reforms in the UK and the Netherlands

The Stokes-Ruttan paradigm can help interpret the mixed experiences of the UK and the Netherlands. In both cases, a major objective of the reforms was to encourage a greater role for the private sector in commercially oriented technology development for food and agriculture. Relatively large parts of public R&D were thought to be located in Edison's Quadrant, with perceived commercial value. The reforms were designed to attract more private R&D to this domain and refocus public R&D toward more fundamental research (Pasteur's Quadrant) and applied R&D to address other social issues like environmental protection and food safety (Rickover's Quadrant). A challenge for public research policy in this new environment was to delineate the division between Pasteur-quadrant research and Edison-quadrant research, establish stronger linkages between public and

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private R&D to assure efficient transfer of knowledge discoveries from one sector to the other, and assure sufficient legal protection for intellectual property so that private innovators could recoup their R&D investments.

In the UK case, the abrupt departure of the public sector from applied crop breeding left a major gap in the UK agricultural innovation system. Due in part to royalty limits placed on what companies could charge farmers for seed, private returns to wheat breeding in particular were too low to stimulate sufficient R&D to maintain yield improvement. This suggests that the public-sector withdrawal from applied crop breeding was an attempted shift from Rickover's Quadrant to Edison's Quadrant without sufficient change in incentives that might have encouraged more investment in private-sector breeding. The Netherlands took a more gradualist approach. Sixteen years elapsed between the first introduction of "fee-for-service" agricultural extension and full privatization. The amalgamation and reorganization of the agricultural research system was also phased in over time. As experience was gained as to what functions were redundant with the private sector, some research institutes merged or closed. The Netherlands also had a stronger royalty system that encouraged seed companies to invest in crop-breeding research.

Both countries used greater reliance on competitive grants to shift public R&D upstream toward Pasteur's Quadrant. Competitive grants provided a means of allocating research resources to projects judged by scientist-peers to be most likely to advance the agricultural science and technology frontier. A reduction in block grants to institutions forced scientists in the public sector to compete for funds and diversify sources of funding. These diverse funding sources included not only the ministries of agriculture (the traditional main source of support for agricultural research) but other ministries, the private sector, and foreign and foundation support. This served to broaden the focus of public agricultural scientists to address the interests of these diverse funding sources.[30]

Reforms To Enhance Farmer Funding of R&D Through Levies on Commodity Production

Even though individual farmers may lack the means or incentive to invest in agricultural R&D, farmers as a whole benefit from the higher productivity brought about by new technologies. Many countries have developed systems to enable or encourage farmers to collectively fund agricultural research. However, despite evidence of high returns to investments in public agricultural research, success in organizing groups of farmers to fund it collectively has been mixed. Neither the UK nor the Netherlands was able to increase research funding using farmer levies. In both countries, public agricultural research funded by commodity boards declined following the reforms. What remains of UK levies is used almost entirely to support extension rather than research, and the Netherlands abolished its commodity boards entirely in 2014.

According to Alston et al. (2012), uncertainty about benefits makes farmers reluctant to fund production-oriented research. This is particularly so for producer groups that are heterogeneous—composed, for example, of small and large farms or irrigated and dryland farms. With such heterogeneity, new technologies derived through research may be suitable for some farmers but not others and may even benefit farmers in States or regions that did not contribute to the research. Moreover,

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[30] In the United States, the evidence that competitive grant funding supports more fundamental research in agriculture is mixed (Day Rubenstein et al., 2003; Schimmelpfennig and Heisey, 2009). In addition, U.S. evidence has not established the superiority of one funding mechanism over another for stimulating productivity growth (OECD, 2016).

the inelastic nature of demand for many farm commodities (where increased supply reduces total revenue) means the ultimate beneficiaries of agricultural research are often consumers and not producers. Even for farmers who benefit from early technology adoption, the long lag between the time that research is first funded and the time that a new technology is available may make it difficult for farmers to clearly link current benefits to past payments to support research.

United States' experience with producer-funded research

In the United States, Federal and State legislation has given producer groups authority to levy assessments (or "checkoffs") on their members to fund investments in collective goods that would benefit the industry, such as research, extension, and market promotion. Generally, a levy can be established when a majority of the commodity producers (and/or producers representing a majority of production) in a State or region are in favor. Assessments may be either voluntary (where a farmer can "check off" a box on a form to request a refund of the assessment) or mandatory. Voluntary assessments have been in use in the United States since the 1930s. Mandatory assessments were authorized by the U.S. Congress in the 1996 Commodity Promotion, Research, and Information Act. The levies are determined and voted on by State producer groups, which then provide the levied funds to commodity boards for use for market promotion and research.

In 2014, 19 national and dozens of State producer levies raised about $1 billion in assessments on farm commodity sales, or about 0.33 percent of the gross production value (GPV), to support market promotion and research (table 5.1). The majority of funds were used for market promotion. Only about 18 percent, or $180 million, of total levied funds were allocated to support research, which was mainly channeled to State agricultural universities. The research funding amounted to only 0.06 percent of commodity value (somewhat higher for crop than animal commodities). Moreover, most of the research funded by levies is directed to commodity utilization rather than farm production. A survey by the President's Council of Advisors for Science and Technology (2012) found that 55 percent of the research funded by producer levies was tied to market promotion (i.e., developing new uses for commodities or enhancing health and safety attributes of food products). The evidence shows that, in the United States, research is less popular than advertising as a use of producer levies, and research that is funded through producer levies is heavily slanted toward market development rather than farm productivity.

Table 5.1
Producer levies for market promotion and research in the United States

Commodity	Gross production value (GPV) (mil. US$)	Total producer levies (mil. US$)	Levy research spending (mil. US$)	Research / total levy (%)	Total levy / GPV (%)	Research / GPV (%)
National boards [1]						
Beef	78,229	72.000	3.19	4.42	0.09	0.00
Egg	13,500	22.386	1.50	6.70	0.17	0.01
Lamb	544	2.592	0.50	19.15	0.48	0.09
Dairy	35,739	102.600	19.05	19.00	0.29	0.05
Fluid milk	35,739	103.300	4.00	3.87	0.29	0.01
Pork	21,032	77.155	19.05	24.69	0.37	0.09
Honey	329	4.481	0.32	7.14	1.36	0.10
Cotton	5,026	78.443	24.19	30.84	1.56	0.48
Soybean	34,147	190.100	60.98	32.08	0.56	0.18
Potatoes	3,415	20.70	0.75	3.62	0.61	0.02
Peanuts	1,127	10.40	1.37	13.21	0.92	0.12
Sorghum	1,422	6.00	1.40	23.33	0.42	0.10
Mushrooms	959	5.10	0.73	14.22	0.53	0.08
Watermelon	483	3.40	0.00	0.00	0.70	0.00
Avocados	296	7.20	1.81	25.10	2.43	0.61
Blueberries	517	9.00	0.42	4.68	1.74	0.08
Mango	NA	6.70	1.20	17.93	NA	NA
Raspberries	38	2.70	0.00	0.00	7.10	0.00
Popcorn	NA	1.00	0.00	0.00	NA	NA
Softwood lumber	NA	15.40	1.20	7.79	NA	NA
Christmas trees	210	1.50	0.04	2.33	0.71	0.02
Paper & packaging	NA	28.70	0.00	0.00	NA	NA
State producer groups [2]						
Wheat	12,545	40.03	12.50	31.23	0.32	0.10
Corn	47,739	102.74	1.00	0.97	0.22	0.00
Sugar beets	1,374	NA	1.30	NA	NA	0.09
Horticulture (California)	13,638	141.06	24.32	17.24	1.03	0.18
Animal commodities	185,113	384.51	48.05	12.50	0.21	0.03
Field crops	106,794	448.42	103.49	23.08	0.42	0.10
Horticultural crops	15,931	176.16	28.47	16.16	1.11	0.18
Forestry products	NA	45.60	1.24	2.71	NA	NA
All animals & crops	307,837	1,009.09	180.02	17.84	0.33	0.06

Figures are for 2014 except for California horticultural crops (2004) and sugar beets (2009).

NA = not available.

[1]National boards are funded through levies raised by State producer groups. The figures show funding by the national boards and do not include levy funds retained by the State organizations.

[2]Twenty-three States have corn levies, and 22 States have wheat levies. Not shown in the table are State levies for small grains (barley, oats, and rye), rice, pulses, aquaculture, and other commodities.

Sources: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, for gross production values; 2014 annual reports for levy rates for national boards; and State organization annual reports for corn and wheat levy data. California horticultural levy data are from Carman (2007); and estimates of the sugar beet and soybean research levies are from PCAST (2012).

Australian reform: Government matching of producer R&D levies

In the 1980s, Australia established a policy whereby the Commonwealth Government agreed to match dollar-for-dollar producer levies raised for agricultural research. The combined funds would be managed by nongovernment bodies called Research and Development Corporations (RDCs) to support research at universities or other institutes, government or private. RDCs do not conduct research of their own but act as funding boards to prioritize and allocate research funds competitively among research performers (Alston et al., 1999). Representatives from producer groups, government agencies, universities, and other stakeholders sit on the RDC funding boards.

The matching provision significantly strengthened incentives for producers to assess levies on themselves to fund research (Alston et al., 1999). By the early 1990s, 16 RDCs had been established (with 15 operating in 2016), each covering a specific commodity or resource area (table 5.2). The Government capped its maximum matching contribution at 0.5 percent of the gross production value (GPV) of a commodity, and several commodity groups set levy assessments to obtain the maximum match. By 1993, producer levies accounted for 18 percent of total public agricultural research in Australia, and total funds allocated by the RDCs (including the Government match) accounted for 44 percent (Alston et al., 1999). However, between 1993 and 2009, the RDC share of funding for public agricultural R&D fell from 44 to 34 percent as other sources of funding grew more rapidly (Alston et al., 1999; Productivity Commission, 2011). Nonetheless, through funding arrangements with research performers (universities, State departments of agriculture, and Commonwealth research institutes like CSIRO), RDCs leverage significant additional funding to support their priorities (Alston et al., 2012).

One of the consequences of the creation of the RDCs was a move to a more centralized research system. Previous to the establishment of RDCs, agricultural research in Australia was dominated by State governments and the interests of their local constituencies. The RDCs gave a stronger voice to producer interests at the national level, and with the Commonwealth Government funding match came expectations that the funded research would give rise to significant "spillover" benefits beyond the producers themselves, to include consumers, rural nonfarm populations, and other industries or sectors (Productivity Commission, 2011). Lack of clear evidence of significant spillover benefits from RDC-funded research led an external evaluation of the RDCs to recommend reducing the Government match from 100 percent of producer levies to just 20 percent (Productivity Commission, 2011). However, Alston et al. (2012) argue that research remains significantly underfunded and that the matching rate should be raised. Even when benefits to producers as a whole are large, these benefits are unlikely to be equally shared among all farms, and, as a consequence, many producers will be reluctant to fund production-oriented research. This is particularly true when producers form a heterogeneous group, reflecting farms with different scales of production, located in different production regions, and possessing varying capacities to adopt new technologies. Moreover, the levy payments are not insignificant for producers. While, on average, levies are set below 1 percent of the gross value of commodity production, in some years, they have amounted to as much as 11 percent of the net farm income of a commodity group (Productivity Commission, 2011).

Table 5.2

Sources of income and R&D spending by Australian Research and Development Corporations (RDCs), 2008–09

Australian Rural Research and Development Corporations (RDC)	Commodities	Producer levy funding	Government contribution	R&D spending	Gross production value (GPV)	R&D / GPV	Levy / GPV
		------------------- (Million 2005 US$) -------------------				(%)	(%)
Grains RDC [1]	Grains & oilseeds	56.3	27.7	76.6	5,071	1.51	1.11
Horticulture Australia Ltd.	Vegetables & fruits	25.8	25.1	52.5	3,528	1.49	0.73
Cotton RDC	Cotton	1.5	1.5	5.9	1,373	0.43	0.11
Grape & Wine RDC	Grapes & wine	8.4	7.4	16.5	1,057	1.56	0.79
Sugar Research Australia	Sugarcane	2.7	3.2	6.5	673	0.97	0.40
Rural Industries RDC [2]	Misc. commodities	2.5	10.4	15.0	1,131	1.33	0.22
Meat & Livestock Australia	Cattle & sheep	16.4	19.8	38.6	7,484	0.52	0.22
Dairy Australia	Dairy	9.2	12.1	21.3	2,179	0.98	0.42
Australian Wool Innovation	Wool	14.3	7.2	24.1	1,439	1.68	0.99
Australian Pork Limited	Pig production	2.0	1.8	3.5	625	0.56	0.31
Australian Egg Corp. Ltd.	Eggs	0.7	0.6	1.3	292	0.43	0.24
LiveCorp	Animal health	0.5	0.0	0.5			
Australian Meat Proc. Corp.	Meat processing	7.9	0.0	4.8			
Fisheries RDS	Fisheries	6.0	10.3	17.6			
Forest & Wood Products Aust.	Forest products	2.3	2.3	4.9			
Land & Water Australia [3]	Natural resources	0.0	8.2	18.7			
	Crops	94.8	65.0	158.1	11,702	1.35	0.81
	Animals	42.4	41.5	88.7	12,019	0.74	0.35
	All RDCs	156.3	137.7	308.2	24,851	1.24	0.63

R&D = research and development. GDP = Gross Domestic Product. RDC revenue sources include producer levies, government matching and nonmatching contributions, and other income not shown in the table (e.g., patent licensing or other fees for services). Some RDCs also fund extension and market promotion activities in addition to research, although government and matching contributions are used only for research.

[1] The Grain RDC research portfolio covers 25 leviable crops, including cereals (wheat, barley, oats, sorghum, triticale, millets, and rye); grain legumes (beans, lupins, peas, chickpeas, vetch, peanuts, and lentils); and oilseeds (canola, sunflower, soybean, safflower, and linseed).

[2] Rural Industries RDC funds research on poultry meat, honey, horses, pasture seeds, rice, new plant and animal industries, biofuel, and rural issues. The estimate of GPV for this RDC only includes farm commodities.

[3] Land and Water Australia RDC was closed in 2009. Because its research was not commodity specific, no producer levies were used to fund this RDC.

Sources: USDA, Economic Research Service using Australian Rural Research and Development Corporations funding data from Productivity Commission (2011). Figures converted to 2005 U.S.$ using Australian GDP price deflator and 2005 market exchange rate from the World Bank. Gross value of production from the Food and Agriculture Organization of the United Nations. It is the 2005-09 annual average farm-gate production value of commodities covered by the RDC, measured in millions of constant 2005 U.S.$.

Reforms Establishing Royalty Systems To Encourage Investment in Crop Breeding

Genetic improvement of crops has been a cornerstone of agricultural productivity growth since the early 20th century. While many technologies and practices—mechanical, chemical, and agronomic—have contributed to the growth of crop yields, biological improvements to crops and livestock have made up a large, if not dominant, part of measured yield gains (Fischer et al., 2014). Achieving and maintaining growth in crop yields requires robust and sustained funding for plant breeding. In the United States, the private sector has invested significantly in plant breeding for crops for which hybrid seed systems are practicable (so that farmers must repurchase seed each year) and for crops that have patent-protected genetic modifications that add significantly to seed value. Private investment in crop breeding, however, has remained low for many species of economically important crops, especially for small grains (wheat, barley, and oats), grain legumes, root and tuber crops, some oilseeds, and many vegetable and fruit crops. One factor reducing private returns to breeding on these crops is the possibility for farmers to save a portion of the harvest for use as seed the following season, a practice generally permitted under plant breeders' rights, as the case of UK wheat exemplified. Even if seed is protected by a patent (which does not permit saving seed), in some cases, it may be prohibitively costly for breeders to monitor and litigate the illegal use of saved seed.

Many countries have developed royalty systems to help finance plant-breeding research. In a royalty system, a fee is assessed on seed used by farmers. The fee is sent to the breeder (either in the public or private sector) who holds the patent or plant breeders' right to the particular variety used. Royalty systems are most commonly used for certified seed sold by registered seed companies. The breeder sets the royalty rate, and the seed companies collect the royalty at the point of sale. Several countries, especially in Europe, have extended royalty collection to farmer-saved seed. The royalty rate for farmer-saved seed is usually some fraction of the royalty rate set for certified seed (about 50 percent, in the case of the UK). These royalties may be collected by companies that condition the seed (clean it of contaminants and perhaps treat it with pesticides) before planting by farmers. Farmers declare the variety they are using and pay the royalty for that variety to the seed conditioner, who then transmits the royalty (minus an administrative fee) to the owner of that variety. In the European Union, small farmers (defined by their annual level of production, around 92 metric tons in the case of small grains) are exempted from paying royalties on farmer-saved seed (in some countries like Poland, this exempts most farmers from the royalty obligation). The performance of these royalty systems has been mixed (for a review of these systems by country, see Curtis and Nilsson, 2012): success appears to require strong cooperation among institutions representing breeders, seed companies, and seed conditioners, as well as general support among farmers.

In the 1990s, Australia introduced a variant of the royalty system in which royalties are collected not on the seed but on the grain sold. In this "end-point royalty," farmers declare the variety at the elevator when selling their grain. The elevator assesses the royalty on the amount of grain sold and transmits the royalty to the breeder or breeder association. A feature of an end-point royalty is that it applies equally to all seed used (whether certified or farmer-saved) of a variety. Production risk (how well the seed yields in a particular year) is also shared between the farmer and the breeder. A further advantage is that this system encourages an optimal use of seed and thus higher yield, since high royalties assessed on seed sales can lead farmers to lower their seeding rate in an effort to save costs (Alston et al., 2012).

Responses to Increased Private-Sector Research Investment in the United States

Like other high-income countries, the United States has witnessed a significantly expanding role of the private sector in developing new innovations for food and agriculture. Private R&D spending to improve farm inputs (seeds, agrichemicals, farm machinery, veterinary pharmaceuticals, etc.) is estimated to have grown from $2.1 billion in 1970 to $6.1 billion by 2013 (in constant 2013 dollars), with similar growth recorded in private R&D in food manufacturing (Clancy et al., 2016). For crop improvement, seed companies are making large R&D investments in genetically modified (GM) crops (corn, soybeans, and cotton in particular) and crops grown from hybrid seed (corn, sorghum, sunflower, alfalfa, tomato, and some others). At the same time, investments in applied plant breeding at public institutions have dropped sharply (Guner and Wehner, 2003).[31] The substitution of private breeding for public breeding as private plant breeding becomes more profitable is an example of Edison's Quadrant expanding its boundaries; public research investments are then reduced or reallocated to make room for this expanding role of private-led innovation.

One of the critical elements incentivizing this shift was the strengthening of IPR for new crop varieties. Plant breeders' rights were first made available for ornamental plants in 1930 and for field crops and vegetables in 1970. Biotechnology innovations (for crops genetically modified to contain specific traits) have been patentable since 1980. Since 2001, patents have also been available for new non-GM crop varieties. Patents offer a stronger form of IPR because farmers and other researchers are not legally allowed to use patented seed except under license from the patent holder (OECD, 2016).

Despite the stronger IPR and the growth in private agricultural R&D, some evidence suggests there is a continued role for the public sector in fostering agricultural innovations. This has been demonstrated in a number of econometric studies that have examined how public and private R&D affect each other (see Fuglie and Toole, 2014). These studies test whether public R&D "crowds out" (reduces) or "crowds in" (increases) private R&D. Crowding out would imply that each sector's R&D efforts are close substitutes and competitive, while crowding in suggests they are complementary. Most of these studies have focused on the United States, and most have found that public and private research are complementary (see Fuglie and Toole, 2014, for a review). However, for Europe, the evidence is mixed: Alfranca and Huffman (2001) found significant crowding out between public and private agricultural research spending in seven European Union countries between 1984 and 1995, while Schimmelpfennig and Thirtle (1999), using data from 11 EU countries between 1973 and 1993, found evidence of crowding in. For the United States at least, the empirical evidence suggests that the U.S. public sector responded to changing market and institutional environments by reallocating its research portfolio to avoid direct competition with the private sector (Wang et al., 2013; Fuglie and Toole, 2014).

The Stokes-Ruttan framework suggests several areas where public R&D may be shifting its focus. One is more fundamental science that characterizes Pasteur's Quadrant. More basic or fundamental research is long-term, more uncertain, and difficult to patent but generates potentially large spillovers, such as widely applicable platform technologies. Another is the type of noncommercial, applied R&D found in Rickover's Quadrant. This includes research to reduce environmental impacts of agriculture, improve food quality and safety, and strengthen resilience of rural communities.

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[31] See also Carter et al. (2014), Sylak-Glassman et al. (2016), and Shelton and Tracy (2017) for more recent evidence.

There also remains a role for public R&D in applied, production-oriented agricultural research for certain technologies where incentives remain weak for private R&D—in other words, production research that still is not easy to move from Rickover's Quadrant to Edison's Quadrant under existing incentives. These include agronomic and animal husbandry practices and integrated pest management. The private sector also appears to continue to underinvest in breeding for several important crops like wheat and other small grains, roots and tubers, grain legumes and certain oilseeds like peanuts, tree crops, and many species of vegetables (Frey, 1996).[32] These are all areas where farmers have a vested interest in maintaining or strengthening R&D programs, and where new R&D financing instruments like matched levy-funding and royalties might have applications (Alston and Gray, 2013). The varying experiences of other countries with these instruments provide useful information about what may work and what may be less successful in the design of such instruments.

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[32] Although Frey's comprehensive study for the United States has not been replicated, more recent evidence supports some of Frey's findings. This includes work by Traxler et al. (2005), Carter et al. (2014), Sylak-Glassman et al. (2016), and Shelton and Tracy (2017).

Conclusions

Public investments in agricultural R&D have been a significant policy lever for supporting long-run productivity growth in the sector. For most high-income countries, agriculture accounts for a greater percentage of public research spending than agriculture's share of the economy, at both national and aggregate levels. But after several decades of spending growth, real public investment in agricultural R&D by these countries as a group has declined since at least 2009. At the same time, research costs have risen faster than general inflation, and accounting for rising research costs suggests that there has been no real growth in public agricultural R&D spending by high-income countries since at least 1992. At the same time, research by the private sector has assumed a larger role in food and agriculture innovation, and worldwide, the dominant share of public agricultural research has shifted from high-income to developing countries.

Economic studies find that investments made in agricultural R&D and the application of industrial inputs in agriculture have been major factors in the successful transition from resource-dependent to productivity-led agricultural growth during the latter half of the 20th century. National public investments in agricultural R&D, along with technology spillovers from other countries and the private sector, are significant sources of new technology driving growth in agricultural TFP. Farmer education, liberalized trade, and changes in agricultural structure also contribute to greater agricultural efficiency and productivity. Nonetheless, nearly all studies that attempt to quantify the impacts of multiple factors on long-term agricultural TFP growth in high-income countries find that public R&D had a major impact. There have been fewer studies of the impact of private R&D on agricultural TFP, although available evidence suggests that private firms are not able to capture all the benefits from their research through the prices they charge for improved inputs, and thus some benefits accrue to farmers and consumers. Furthermore, some evidence suggests that private R&D responds positively to public R&D spending. The decline in public spending on agricultural R&D, therefore, has led to concerns that agricultural productivity growth in these countries may slow down or stagnate, which could, in turn, lead to loss of competitiveness, rising food prices, and greater dependence on land and other agricultural inputs for growth.

The decline in support for public agricultural R&D in high-income countries is in part an outgrowth of structural change in national economies and changing societal expectations from food and agriculture. In most high-income countries, agricultural value added has shrunk to a small share of national economic output, and public agricultural R&D spending as a share of total R&D investment has followed suit. As farms have become larger and more specialized, and as farmers have become more educated and skilled, private agribusiness has expanded its role in developing innovations and providing technical services for agriculture. In addition to demanding cheap and abundant food, consumers have also placed greater weight on conserving environmental resources, the quality and safety of food products, and farm animal welfare. These forces have exerted pressure on public agricultural research systems to enact reforms and redefine their roles, especially vis-à-vis the private sector.

Our review of public agricultural science policy reforms in several high-income countries suggests that these reforms affected the composition of public agricultural science programs and altered the incentives for private agricultural research investment. None of the policy changes, however, resulted in notably increased levels of public funding. The Netherlands case indicates that agricultural science policy reforms can be consistent with at least maintenance of real funding levels, but,

in general, the introduction of new funding sources has not led to major increases in the amounts of real public-sector agricultural research expenditures.

A useful paradigm for assessing public and private roles in agricultural R&D is the Stokes-Ruttan "quadrant" model, which classifies research in terms of its quest for fundamental scientific understanding and considerations of its commercial use. Private R&D focuses on research where considerations of commercial use are paramount, while the quest for fundamental understanding may be relatively insignificant. The scope for public research goes beyond curiosity-inspired pure science to include use-inspired basic research as well as applied R&D to supply knowledge and technologies in areas not well served by commercial incentives.

National experiences with reform to plant-breeding research offer an apt illustration of this research policy paradigm. Increasingly, governments have reduced their support for applied plant-breeding research under the assumption that this is a role for the private sector, but the response of the private sector to fill this gap has varied. Innovations in plant breeders' rights, royalty schemes, or other institutional arrangements that allow breeders to capture a share of the gains from plant breeding are often necessary to establish incentives for private R&D. In the case of the UK, privatization of its public wheat-breeding program led to a shortfall in wheat-breeding investment and a stagnation in wheat yield. In the Netherlands and Australia, however, institutional innovations created greater incentives for self-financing of plant-breeding research. The varying experiences of different countries in instituting different types of royalties (e.g., on seed sales, or end-point royalties on commodities) and producer levies (e.g., with or without matching grants from governments) suggest that appropriate legal and institutional support is critical for establishing effective incentives for producer funding of agricultural research.

Finally, we conclude with some suggestions for future research on the economics of agricultural science policy in high-income countries. Understanding interactions between research systems is likely to be of increasing relevance to agricultural science policy. One set of interactions is between public and private research. Analysis of the joint impacts of public-private R&D, and how public and private R&D contribute to policy and societal goals under different rules for intellectual property, technology transfer, and allocation of research funds may be useful. Such analysis could be based in part on comparative studies of alternative models of public-private cooperative or collaborative research as implemented in different countries. Another set of interactions is between national research systems. Knowledge spillovers among countries suggest there may be significant "free-rider" problems as well as potential efficiency gains from greater research coordination across international boundaries. Future studies of agricultural science policy could explore the design of measures that enhance international research coordination.

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Appendix A. Some Historical Changes in Public Agricultural Research Organization in High-Income Countries

The historical paths to current forms of research organization, and relative levels of research central-ization or decentralization, have varied widely across countries. European countries were the first to develop modern agricultural experiment stations, in part because of advances in general sciences made in Europe. Initially, stations in France and England were privately supported. Germany was the first country with publicly supported agricultural experiment stations, starting in 1852. State-supported agricultural experiment stations were developed at the same time as university agricul-tural faculties. Federal research centers were established in the early 20th century in response to the evolution of German political structure. In Germany, there are also "Blue List" agricultural research institutes that are supported jointly by the German Central Government and by the States (von Braun and Qaim, 2000). The reconstitution of German agricultural research following World War II led to a considerably greater Federal role (Ruttan, 1982).

The private station established at Rothamsted, England, by Lawes in 1843, the longest continuously operating agricultural experiment station in the world, is now funded by the United Kingdom (UK) Biotechnology and Biological Sciences Research Council (BBSRC). Despite the long tradition of agricultural research in the UK, however, the legal framework for public agricultural research funding was not established in the UK until 1901, and the Agricultural Research Council (ARC, one predecessor of the BBSRC) was established in 1931 (Ruttan, 1982).

In the 19th century, the first Ph.D. agricultural scientists in the United States were trained in Europe. Marked by both a vast expanse of agricultural production areas and a Federal system of govern-ment, the U.S. agricultural research system was decentralized from the beginning. Both the U.S. Department of Agriculture (USDA) as a separate department and the land-grant university system date to 1862 legislation. In the United States, States have contributed substantial research funding, and much of the State-level agricultural research is performed at State Agricultural Experiment Stations (SAES) authorized by the Hatch Act of 1887. Most of the SAES are usually affiliated with land-grant universities (Huffman and Evenson, 2006; Fuglie et al., 1996). In the assessment of Ruttan (1982), the U.S. public research system was not fully institutionalized at both national and State levels until the 1920s, 60 years after the initiation of the USDA/land-grant university system. Today, the United States is unusual in that the higher education percentage of agricultural research is higher than the higher education research and development (HERD) percentage of public research across all research topics. In a number of other countries, when the percentages differ substantially, higher education performs less of the agricultural research portfolio than it does of the entire public research portfolio.

Australia and Canada, two other countries with high land-labor ratios, significant agricultural exports, and Federal systems of government, also developed agricultural research systems that featured research performed by both the Federal Government and by States or Provinces. Neither the Australian nor the Canadian system featured university research to the degree of the U.S. system, but both, particularly Australia, developed systems with significant research performance below the Federal level. In Australia, government involvement in public agricultural research began almost as early as it had in Germany, when the State of Victoria Board of Agriculture took over an experi-mental farm that had been established by a committee of farmers in the 1850s. The major Federal

research provider, the Commonweath Scientific and Research Organization (CSIRO), came into existence as the Advisory Council on Science and Technology in 1916. Although State agriculture departments did perform a notable amount of basic research, they tended to concentrate on more applied research while CSIRO focused on basic research (Alston et al., 1999).

Agricultural research in Canada has been a joint responsibility of Federal and provincial governments since the British North American Act of 1867. In 1886, the Canadian House of Commons passed a law establishing Federal agricultural experiment stations. A major expansion of experiment stations took place between 1905 and 1915. From 1913 to 1923, Ontario and Quebec initiated provincial experiment stations connected with agricultural colleges, in part through the use of Federal grants. For many years, there were provincial differences in the degree to which policymakers thought the provinces should perform agricultural research, and not simply extension, and how much they believed research should be left to the Federal Government (Smallman et al., 1970). Although the Federal Government has always played a major role, richer Canadian Provinces have expanded their role at least since the 1960s (Carew, 2001). A few Canadian Provinces also sponsor a notable level of forestry research.

Although the United States and other agricultural research systems had been particularly influenced by the German system (Ruttan, 1982), by the late 19th century (Japan) or early 20th century (France), some other countries began to look to the United States, rather than Germany, as a research system model, particularly because of the way higher education and research were integrated in the United States. In the end, neither Japan nor France adopted the U.S. agricultural research model, as in general, experiment stations and institutions of higher education were not closely linked in either country. Each country eventually arrived at a rather different form of public agricultural research organization. In both countries, government research has played a prominent role, but in Japan, it is divided between central and prefectural governments. In France, public agricultural research is highly centralized (Hayami and Yamada, 1975; Castonguay, 2005).

In Japan, the central government started a national agricultural experiment station in 1893, initially with six regional branches. At first, recognition of "variations in soil and climate" led to expansion of the number of branches, but by the first decade of the 20th century, prefectural research stations were established as the preferred approach to variability in agricultural conditions, with relatively substantial financial contributions from prefectural governments (Hayami and Yamada, 1975). Although World War II created a shortage of critical farm inputs such as fertilizer, after the war, a backlog of technological innovations allowed a rapid expansion of agricultural output. By the time we are able to compare public agricultural research investment in Japan with agricultural Gross Domestic Product (GDP), in the early 1960s, research intensity was higher than that in most European countries and only lower than that in Canada, Australia, and the United States (among larger countries) (See table 4.2).

In contrast, in France, the Ministry of Agriculture established an Institut des Recherches Agronomiques (IRA) in 1920, uniting more than 80 laboratories and research stations owned and operated by the Ministry and departments (the second level of government below the national level), in part because centralized administration was thought to be better suited to recruitment and training of staff.[33] IRA was disbanded in 1934, but it was a predecessor to today's French National Institute

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[33] Many of the debates in early French public policy for agricultural research focused on jurisdictional disputes between the Ministry of Public Instruction and the Ministry of Agriculture (Castonguay, 2005).

for Agricultural Research (INRA), initially formed by the French provisional postwar government in 1946 (Castonguay, 2005). Research on agriculture and related areas in France is still primarily centrally administered. Public agricultural research investment in France was still low in comparison to agricultural GDP in the 1960s, only catching up to the Western Europe average by the 1970s.

In a few other larger countries, decentralization has come much later than it has in the land-abundant countries with Federal political systems, such as the United States, Canada, and Australia. In Spain, some research establishments managed by the National Institute for Agricultural and Food Research and Technology (INIA) came under regional control with regional financing in the 1980s (Montero Aparicio, 2014). Regional agricultural research is also important in Italy, with some expansion of the regional role in recent years (Materia, 2012).

In other countries, another indicator of more recent organizational change in public agricultural research is the higher education percentage of all public agricultural research funding. To the extent that trends in this indicator can be discerned, they usually involve a gradual move away from research performed by government agencies toward research at higher education institutions, particularly in countries with smaller research systems. In addition to the current trends noted in table 2.1, the university share of agricultural research in the Netherlands increased to about 40 percent during a period of research system reforms (Roseboom and Rutten, 1998), after which it has leveled off, as measured in the Organisation for Economic Co-operation and Development (OECD) database. However, reforms also led to a merger of the Dutch Foundation for Agriculture Research and the Wageningen Agricultural University, including physical co-location.[34] Furthermore, most countries with small or intermediate-sized public agricultural research systems tend to center agricultural research in fewer institutions, particularly government research institutes. In contrast, in Sweden and Denmark, agricultural research is concentrated in one or a few universities.[35] In Sweden, public agricultural research has been primarily conducted at the Swedish University of Agricultural Sciences for decades (Pardey and Roseboom, 1989). In Denmark, a slow trend toward greater university performance was dramatically accelerated in 2007, when a merger between former government research institutions and universities resulted in 95 percent or more of all agricultural research being performed in three universities (Vendelbo-Larsen and Abildskov, 2014).[36]

Appendix A References

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[34] Agricultural research policy reforms in the Netherlands are also analyzed in the "Agricultural R&D Policy Reforms" section. Despite the DLO-Wageningen merger, OECD data still separate agricultural research into government and university components.

[35] Less information is available about the dominance of the higher education sector in agricultural research in Belgium, Slovenia, and Estonia. In Belgium, the two regions of Flanders and Wallonia are the dominant players in agricultural research (Chartier et al., 2014a). Both Slovenia and Estonia were part of larger political entities, namely Yugoslavia and the former Soviet Union. It is possible that more of the research infrastructure available to these smaller countries after the dissolution of those entities consisted of universities.

[36] These changes were part of a general reorganization of the Danish research system (Wright and Ørberg, 2008; Oddershede, 2009).

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Appendix B. Data Sources on Agricultural R&D Spending and the Agricultural Sector in High-Income Countries

In-country institutions, such as the U.S. National Science Foundation (NSF) and, more recently, international organizations such as the Organisation for Economic Co-operation and Development (OECD) and the United Nations Educational, Scientific, and Cultural Organization (UNESCO), have published data on research and development (R&D) investments within or across countries. The most comprehensive information, however, refers to general research and development. Considerably less long-term and consistent data on R&D investments for subsectors of the economy such as agriculture are publicly available. In this appendix, we characterize some of the data gaps, outline some of the reasons they exist, note some of the methods used to overcome them, and expand on the ways we estimated public agricultural research expenditures for individual countries. We also briefly note the general procedures to estimate other variables such as total public research expenditures and agricultural GDP for calculation of research intensities.

Compiling data on R&D investments for agriculture at the country level has often resulted from large-scale studies of research impacts such as those for the United States by Huffman and Evenson (2006) or Alston, et al. (2010). Across countries, the International Service for National Agricultural Research (ISNAR)[37] made a major effort to collect, publish, and analyze public agricultural R&D data from developing and high-income countries through the mid-1980s (Pardey and Roseboom, 1989; Pardey et al., 1991).[38] This effort has been followed by R&D data collection for developing countries at the International Food Policy Research Institute (IFPRI), now coordinated through the Agricultural Science and Technology Indicators (ASTI) program.[39] Pardey et al. (1999) provided data on public agricultural R&D investments in 22 high-income countries, and Alston et al. (1998; 1999) analyzed research policy shifts in more detail for 5 of them—the United States, United Kingdom, the Netherlands, Australia, and New Zealand. ERS has developed recent estimates of global and U.S. private-sector agricultural and food R&D (Fuglie et al., 2011; Fuglie, 2016). Pardey et al. (2016) published estimates of global agricultural R&D totals, with some estimates for certain years in particular countries available in a data appendix.

Taken together, this means that of all the major participants in global agricultural R&D, trends for public research investment in high-income countries have been less widely reported and analyzed than trends for developing countries or for the private sector. This high-income public-sector investment may have represented nearly 60 percent of the global public-sector total in 1990 and about 40 percent of the global public-sector total in 2013 (fig. 1.1, main text).

Concepts for Estimates of Agricultural R&D

Any attempt to define research directed toward a particular subsector of the economy is, in effect, focusing on the *purpose* rather than the *content* of the research (Pardey and Roseboom, 1989). One of the major constraints to compiling long-term data series on agricultural R&D expenditures is the desire that data collected and reported conform to international norms for reporting R&D data as summarized in the OECD Frascati Manual (OECD, 2015b). But increasingly, the research

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[37] ISNAR as an institution was folded into the International Food Policy Research Institute (IFPRI) in 2004.

[38] Former Eastern Bloc countries were not included in this effort.

[39] ASTI relies on solicitation of grants to conduct its data collection efforts.

breakdowns in the Frascati Manual classification system are applied with widely different levels of coverage to different sectors of performance (e.g., governments, higher education institutions, private nonprofit entities, and private firms).

The Frascati Manual classifies research expenditures in several ways; in addition to sector of performance, for example, another classification is by source of funds. Yet another classification is by type of research—basic, applied, and experimental development. Business enterprise R&D can be classified by industrial classification; in the OECD database, it is reported by the International Standard Industrial Classification (ISIC) of the United Nations Statistics Division. The two classifications most relevant to the objective of identifying agricultural R&D are field of science and socioeconomic objective. Field of science (or FOS—the latest Frascati Manual changes this category to field of research and development, or FORD, but the OECD database only changed from "field of science" to "field of research and development" very recently) includes the category "agricultural and veterinary sciences," which in turn has five subcategories: "agriculture, forestry, and fisheries;" "animal and dairy science;" "veterinary science;" "agricultural biotechnology;" and "other agricultural sciences." Socioeconomic objective, or SEO, contains the category "agriculture," which "covers all R&D aimed at the promotion of agriculture, forestry, fisheries and foodstuff production, or furthering knowledge on chemical fertilizers, biocides, biological pest control, and the mechanization of agriculture, as well as concerning the impact of agricultural and forestry activities on the environment" (OECD, 2015b). Eurostat, the statistical directorate of the European Commission, takes primary responsibility for the "Nomenclature for the Analysis and Comparison of Scientific Programmes and Budgets" (NABS) system that is used to define the socioeconomic objectives of research.

In theory, these classification categories should provide numerous opportunities for cross-cutting analysis, and "socioeconomic objective" would appear closest to defining the "purpose" of the research. In practice, however, these estimates are missing for a great many country-year combinations. For example, Chartier et al. (2015) calculate that for a selection of European countries between 2000 and 2012, only 51.5 percent of the possible year-country combinations have estimates for research in agricultural sciences, and only 30.8 percent of the possible combinations have estimates for research directed at agriculture as an objective. Outside Europe, OECD "agricultural research" data—whether defined by socioeconomic objective or field of science—are limited or nonexistent for countries such as the United States, Canada, and New Zealand.

Increasingly, the "socioeconomic objective" category is applied most frequently to GBARD (Government Budget Allocations for R&D),[40] which is *not* a research performance measure—it is instead a measure of research funding. The categories for socioeconomic objectives, including agriculture, are not defined until the chapter on GBARD in the latest Frascati manuals. Some countries have reported R&D spending for the socioeconomic objective "agriculture" by sector of performance, but this reporting has tended to be (a) more common in the earlier years of the OECD database, which currently starts with 1981; and (b) more common for research performed by government institutes than for research performed by higher education institutions.[41] For the latter, it is more common to have the field of science category "agricultural sciences" reported.

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[40] GBARD was formerly called GBAORD (Government Budget Appropriations or Outlays for R&D).

[41] Business-sector research is also much more likely to have reported breakdowns by the industrial classification of the industry than by either field of science or socioeconomic objective. The ISIC classification "agriculture" includes a relatively limited group of firms. Many of the firms doing research aimed at applications in production agriculture are classified instead as "chemical," "pharmaceutical," or "machinery" firms.

In general, we tend to rely on "agricultural sciences" field of science classification more than the "agriculture" socioeconomic objective classification for several reasons, although we do use both. First, the field of science classification is somewhat more widely available than the socioeconomic objective classification. Second, in some cases where R&D data are available from government statistical organizations, particularly in recent years, these data are more likely to be for field of science than for socioeconomic objectives. In other words, it is possible in these cases to check the OECD or Eurostat data against the government statistical agency data for field of sciences but not for socioeconomic objective. Third, there are some ambiguities in the definition of the socioeconomic objective "agriculture" with respect to overlaps with other categories, in particular "Environment," as well as with food processing and manufacturing, which falls under "Industrial production and technology." The intent in the latter case is to differentiate between agriculture as an "extractive" industry involving the use of land and water to produce food, and food processing as a "transformative" industry (J. Jankowski, NSF, personal communication). Where research breakdowns by "socioeconomic" objective are available for individual countries from government statistical agencies, they may differ from the categories specified by the Frascati Manual. The variability in country reporting of socioeconomic objective to OECD may be greater than the variability in reporting field of science. This may be one of the reasons for a final observation. Although there may be some reasons to believe that totals reported under the socioeconomic objective "agriculture" might be larger than under the field of sciences category "agricultural sciences," in practice when both estimates are available for a given country or given sector of performance within a country, there is no observable pattern to which measure will be the greater. In some country-sector combinations, socioeconomic objective measures are greater. In others, field of science measures are greater. In yet others, the relationship between the two measures, in years of overlap, varies from year to year.

Despite the fact that GBARD is a budget measure and, therefore, an indicator of research funding rather than research performance, some analysts use it for cross-country comparisons of "agricultural research" simply because it is more widely available and because it may have some relationship to agricultural research policy in a given country. This is problematic for several reasons, however, in addition to the fact that it is not a research performance measure. First, in many cases, reported data refer to central government budgets only and not to budgets of regional, State, provincial, or prefectural governments. These lower level government budgets are important parts of public agricultural research funding in a number of countries, as the "Organization and Structure of Public Agricultural Research Systems" section and appendix A have shown. Second, in a number of countries, GBARD estimates for "agricultural" research bear little obvious relationship to other things we know about agricultural research in those countries.[42] For example, in France's highly centralized system, the largest research performer is INRA, the French National Institute for Agricultural Research. From 1995 through 2014, INRA's annual research budget from government sources (not including contract research or funding from product sales), available from annual reports, increased by a significant annual rate of 3.06 percent in nominal terms. Over the same period, OECD's reported nominal GBARD for France fell 2.28 percent annually. For 2006, INRA's annual direct government funding was 0.58 billion euros. In the same year, the European agrifood mapping

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[42] This is not always the case—for example, in Canada, the OECD estimate of GBARD from 1995 through 2008 corresponds almost exactly to Statistics Canada's estimate of Federal intramural and extramural outlays for agricultural, forestry, and fisheries research. From 2009 onward, the OECD GBARD estimate corresponds to Canada's Federal intramural and extramural outlays for agriculture only, but Federal outlays for forestry and fisheries research are still available from Statistics Canada.

project reported a total French budget for heading 187, the one most closely associated with public "agrifood" research, of 1.14 billion euros (EU Agri-Mapping, 2007). But the reported OECD GBARD estimate for agriculture in France was only 0.22 billion euros in 2006. Similar anomalies can be documented for the UK, the United States, and other countries.

In sum, data from different sources can be inconsistent, and judgment is required in choosing which data to include in the estimations. Splicing earlier data from ISNAR-based estimates with more recent data from the OECD also requires some judgment. Even data that are reported to OECD and subsequently published by OECD, which supposedly conform to Frascati standards, are sometimes inconsistent or appear to have been reported by using various shortcut approaches to estimation.

Estimates of Public Agricultural R&D Expenditures for Individual Countries

In this subsection, we provide more information about how we estimated public investments in agricultural R&D, country by country. Since our primary data sources are Pardey and Roseboom (1989) for earlier years, Pardey et al. (1999) for an extension of those earlier data, and the OECD "Main Science and Technology Indicators" database (available on the OECD website), we begin with a brief consideration of what data are available from those sources.[43] We also indicate other sources consulted.

To the extent possible, the data cover agriculture, forestry, and fisheries research, in line with the broad category as defined for most international science and technology reporting efforts. In many countries, primary agriculture is easily the largest component of research in this category, although forestry or fisheries research can be significant in certain countries, as noted in the main text.

Canada (North America)

Pardey and Roseboom: 1963; average of 1967 and 1969; 1971–85—based primarily on OECD data.

Pardey et al. (1999): 1971–93, again based primarily on OECD data.

OECD current database: No available information on field of science or socioeconomic objective.

In addition to these sources, Carew (2001) estimates public agricultural research only—exclusive of forestry and fisheries research—for 1967, 1978, 1991, and 1995. To estimate public agricultural R&D expenditures for Canada in recent years, we use data primarily from Statistics Canada and Agriculture and Agri-food Canada (Ag Canada). These data are primarily funding rather than performance data, but they include funding by both Federal and provincial governments. Thus, it is possible that some publicly performed research funded from other sources (e.g., the private sector) may not be included. We note first that from 1995 to 2008, the GBARD total reported by OECD is equivalent to Federal extramural and intramural funding for agriculture, forestry, and fisheries research as reported by Statistics Canada. From 2009 to 2013, the OECD-reported GBARD total is equivalent to Federal agricultural funding only, but since Statistics Canada still reports Federal

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[43] The data in Pardey et al. (1999) are reported only in millions of 1985 international dollars. Since we prefer to begin with nominal annual estimates in local currency units (LCU), we converted these to nominal LCU measures using the World Bank deflators and the Penn World Tables version 5.6 conversions for purchasing power parity (PPP), the sources Pardey et al. reported for GDP and PPP information.

extramural and intramural funding for forestry and fisheries research, we can construct a consistent series for Federal funding from 1995 to 2013.

Thus, we are left with the task of estimating provincial funding of agricultural research in Canada for more recent years. Statistics Canada provides information on provincial funding of agricultural, forestry, and fisheries research for some provinces (primarily Ontario, Manitoba, Saskatchewan, Alberta, and British Columbia) for some years between 1995 and 2010. Statistics Canada also provides longer series (1992–2013) for all non-Federal funding of total research performed by provincial governments and research institutions as well as universities and private nonprofits, which can be used in conjunction with reported information on provincial funding of agricultural research to estimate provincial agricultural research funding for the major provinces over a longer period of time. Alternatively, each year Ag Canada publishes a *Farm Income, Financial Conditions and Government Assistance Data Book* with estimates of province-by-province agricultural research program expenditures—exclusive of forestry and fisheries—from both provincial and Federal sources.[44] These data books are available between 1993 and 2014. We combine the Statistics Canada and Ag Canada information to estimate provincial expenditures on agricultural research, preferring Statistics Canada data when available but using primarily the Ag Canada data for agricultural research in the smaller provinces and Quebec. Finally the Statistical Institute of the Government of Quebec provides limited but useful information, particularly on forestry and fisheries research, for Quebec.

For earlier years, we note that the Pardey and Roseboom (1989) and Pardey et al. (1999) total estimates appear to be the same for all years in which they overlap, with the exception of 1984 and 1985 where the Pardey-Roseboom estimates are greater. We use these estimates to construct a series for the years 1960-1980. To interpolate between 1980 and 1995, where our more recent estimates begin, we use the rates of change as suggested by the OECD GBARD estimates for the intervening years, since GBARD has a direct correspondence to Federal agricultural research spending in the Canadian case.[45]

Several other sources provide some cross-checks on our recent estimates. First, although it is very difficult to estimate agricultural research as performed by Canadian universities, we combined limited information (with the most actual data coming from the University of Guelph, the university with the greatest agricultural research expenditures in Canada) on agricultural research in Canadian universities with our best guesses of orders of magnitude for universities with no data. For the years 2000–10, we estimated approximately one-third of Canadian agricultural research was conducted in Canadian universities. This is consistent with Carew's (2001) estimates. Second, the recent OECD report on *Agricultural Innovation in Canada* (OECD, 2015c) estimates agricultural research only, exclusive of forestry and fisheries research, for the years 1990–2011. Where our estimates permit focusing on agricultural research alone, from 1995 to 2011, they average about 18 percent higher than the estimates in the OECD study but with a similar trend.

Canada is one of eight countries for which comparisons can be made between our estimates and recent estimates by Pardey et al. (2016).[46] It is only one of two for which the differences cannot be explained relatively simply by different choices about measurement. Pardey et al.'s (2016) estimates

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[44] These Data Books were one of the primary sources used by Carew (2001).

[45] Our estimates for the years 1981–93 average less than 2 percent higher than the Pardey et al. (1999) estimates.

[46] These countries are Canada, the United States, Japan, South Korea, France, Germany, Italy, and Spain.

for Canada in 1980 and 1990 are well below our estimates and thus well below the estimates of Pardey and Roseboom (1989) and Pardey et al. (1999). In 2000, Pardey et al.'s (2016) estimate is roughly the same as ours, but in 2005, 2010, and 2011, their estimates are considerably higher. Thus, Pardey et al.'s (2016) estimates for the years since 1990 suggest real public agricultural research expenditures in Canada have increased, while ours indicate they have been essentially flat. In this respect, the trend in our estimates is similar to the trend in the estimates in the recent OECD study.

United States (North America)

Pardey and Roseboom: 1960–64 average; 1965-69 average; 1970–83—based primarily on the Current Research Information System (CRIS) maintained by CSRS/CSREES/NIFA,[47] and *Funds for Research at the State Agricultural Experiment Stations*, published by CSRS.

Pardey et al. (1999): 1971–93 based on Alston and Pardey (1996), who in turn base their estimates on the same USDA sources and on Huffman and Evenson (1993).

OECD current database: No available information on field of science or socioeconomic objective.

In addition to these sources, Huffman and Evenson (2006), Alston et al. (2010), and ERS have developed a series of public agricultural research funding in the United States. Our series is based on the ERS series (Agricultural Research Funding in the Public and Private Sectors), which in turn is based on CRIS and the NSF's Survey of Federal Funds for Research and Development for the years 1968–2013. Estimates for 1960–67 are projected backward based on the rates of growth for those years in Alston and Pardey (1996).

The primary difference among these sources is the choice of institutions whose research is included. Our estimates include research by the Forest Service as well as by Schools of Forestry in the States. The Pardey and Roseboom (1989) estimates appear to do the same, but all of the others exclude forestry.

Compared for the available years with the public agricultural research estimates for the United States from Pardey et al. (2016), our estimates are, on average, over 5 percent higher. However, if we subtract forestry research from our estimates, the resulting figures average about 5 percent lower than the Pardey et al. (2016) estimates. Another factor involved in these differences may be that the ERS series now relies on the National Science Foundation for much of both the intramural and extramural agricultural research in the United States that is funded by USDA.

Japan (Asia-Oceania)

Pardey and Roseboom: Recorded or estimated for national government expenditures from 1960 to 1985; recorded or estimated for prefectural government expenditures from 1962 to 1985; recorded or estimated for university expenditures from 1963 to 1985. Primary source personal communication from the Agriculture, Forestry and Fisheries Research Council.

Pardey et al. (1999): 1971–93, same source plus OECD and Boyce and Evenson (1975).

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[47] Succeeding institutions—CSRS: Cooperative States Research Service; CSREES: Cooperative State Research, Education, and Extension Service; NIFA: National Institute for Food and Agriculture.

OECD current database: Field of science estimates for government 2001–14; field of science estimates for higher education 1981–87, 1989, 1993, 1995–2014. Socioeconomic objective estimates for government 1981–2014, with the exception of 1990.[48]

In addition, Statistics Japan reports a great deal of R&D data. Our estimates for 1981–2013 are largely based on OECD data, although for 1981–2000, our estimates for government expenditure are from Statistics Japan. From 1981 to 1985, these are identical to OECD's socioeconomic objective estimates, and they are close to the OECD socioeconomic objective estimates for 1986–2000.

The biggest difference between our estimates and the estimates from most other sources is based on the fact that between 1995 and 1996, the OECD Field of Sciences estimate for higher education, the basis for our higher education estimate, drops sharply. This is because the data reported to OECD up until 1995 were based on total agricultural sciences faculty, and not full-time equivalents (FTE), with all faculty evaluated at the same salary levels.[49] Most of the data directly from Statistics Japan still do not adjust for FTEs in higher education research. However, to keep our estimates consistent over time, we adjust 1995 and earlier higher education data by dividing the field of science research totals by 1.4.

For earlier years, we first adjust the higher education estimates from Pardey and Roseboom downward by the same factor to convert to an FTE basis, then extend our series backward based on the annual changes in the adjusted totals from Pardey and Roseboom. As expected, our estimates average roughly 13 percent lower than those from Pardey et al. (2016). Trend growth appears quite similar. Furthermore, despite this reduction, Japan's agricultural research intensity is still the third highest of all the countries in this study and the highest among countries with large agricultural research systems (over 500 million PPP dollars annually).

South Korea (Asia-Oceania)

Pardey and Roseboom: 1960, 1964, 1968, 1970–86. Based on Boyce and Evenson (1975), survey by ISNAR, and personal communication from the Rural Development Administration, Republic of Korea.

Pardey et al. (1999): no data.

OECD current database: Field of science, all sectors, 2005–14; socioeconomic objective, all sectors, 1995–2014.

Our estimates use the OECD field of science estimates for 2005-present; socioeconomic objective estimates for 1995–2004; and Pardey and Roseboom's estimates for 1960–86. Estimates for the years 1987–94 are based on interpolation between the Pardey-Roseboom and OECD endpoints.

In the OECD South Korea data, there is very little difference between the field of science estimates and socioeconomic objective estimates where they overlap. The Pardey et al. (2016) estimates for South Korea appear to be based on the socioeconomic objective series for recent years. In the

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[48] We also use OECD data for private nonprofit agricultural research in Japan, as in other countries, but do not discuss it in detail here. Private nonprofit research has been roughly 8 percent of the Japan public-sector total for many years but has declined to 5 percent or less in recent years.

[49] This is indicated by a note in the OECD database.

earliest year of data, 1980, the Pardey et al. (2016) estimate is three times as large as the estimate by Pardey and Roseboom, and, by extension, our estimate.

Australia (Asia-Oceania)

Pardey and Roseboom: 1961, 1965, 1968, 1969, 1972, 1973, 1974, 1977, 1982. Based on various Australian sources.

Pardey et al. (1999): 1971–93 based on Alston et al. (1999), other work by Mullen and colleagues.

OECD current database: Field of science data and socioeconomic objective data overlapping for 1981, 1984, 1986, 1988, 1989, 1992, 1994, 1996, 1998, 2000, 2002, 2004, 2006, and 2008. Partial data for 1995, 2010, 2011, and 2012. In most cases, both FOS and SEO data are reported, but in the years from 1981 to 1992, government performed research is characterized only by the socioeconomic objective classification.

There are several other useful sources of data on agricultural research in Australia. Data are available from the Australian Bureau of Statistics (ABS), roughly in alternate years from 1992 through 2014, mostly corresponding to the years reported to OECD. The categories used by the ABS differ slightly from those in the OECD, and the reporting to OECD may not always be consistent. For example, in some years "environmental sciences" are grouped with "agricultural sciences" in the ABS data, and some years, they are not, and the aggregations reported to OECD are not always consistent with the aggregations reported directly by ABS.

The most carefully constructed data on agricultural research in Australia are due to Mullen and colleagues. However, these research data are for broadacre agriculture only. In Australia, "broadacre" refers to large-scale crop farming (somewhat akin to "field crops" in the U.S. context) as well as livestock raising for meat and wool. Other types of agriculture such as dairy or horticultural production are not included under the "broadacre" heading, nor are forestry and fisheries research included. Thus, the various versions of the "broadacre" research series (e.g., as reported by Alston et al. (1999), Mullen (2010), and Sheng et al. (2011)) are somewhat smaller in magnitude than the OECD estimates or the Pardey and Roseboom estimates. They are the basis for the Pardey et al. (1999) estimates, however.

Our estimates for 1981 onward are based on data reported to OECD with some interpolation and extrapolation; for years before 1981, they are based on the levels reported in the later OECD data, but with annual rates of change based on Mullen (2010). Thus, our estimates, along with those by Pardey and Roseboom, are intended to represent investment in all areas of agriculture, as well as forestry and fisheries, and not only broadacre agriculture.

New Zealand (Asia-Oceania)

Pardey and Roseboom: 1960–83, based on personal communication from the Ministry of Agriculture and Fisheries and a report of the National Research Advisory Council.

Pardey et al. (1999): 1971–93, based on reports by the National Research Advisory Council and the Ministry of Research, Science, and Technology.

OECD current database: Only three observations, for government research 1981–83, using the socioeconomic objective categorization.

Data from New Zealand are relatively sparse, with different sources sometimes inconsistent. Data for various earlier years are also available from Jacobsen and Scobie (1999) and Hall and Scobie (2006).[50] Furthermore, a period of relatively rapid inflation during the 1980s hampers our ability to create consistent estimates over time.

For 1994–2014, we rely on surveys of R&D conducted every 2 years and published first by the Ministry of Research, Science, and Technology and later directly by Statistics New Zealand. However, data in these surveys are reported using different components and different aggregates in different years. For the government and higher education sectors, we used research reported with the socioeconomic objective of agriculture, forestry, and fisheries and attempted to adjust research reported using a different classification scheme (e.g., "primary industries") in other years to be consistent with the years for which agriculture, forestry, and fisheries research was reported separately. In particular, for the years from 2008 to 2013–14, given the importance of Crown Research Institutes in government-performed research, we base our government research estimates on their Annual Reports. For these years, we allocated Crown Research Institute research spending to "agriculture, forestry, and fisheries" research using the following proportions: AgResearch (animal agriculture), 100 percent; Plant and Food Research, 100 percent; Scion (forest and forest products), 51 percent; Landcare Research Institute (environment, biodiversity, and sustainability), 34 percent; and the National Institute of Water and Atmospheric Research (which includes fisheries and aquaculture research), 15 percent.

For earlier years in which they overlap, estimated totals from Pardey et al. (1999) are roughly 15 percent higher than the estimates from Pardey and Roseboom. Pardey et al.'s estimates for the early 1990s are also 15–20 percent higher than our estimated total for 1994 based on Ministry of Research, Science, and Technology data. Therefore, we use Pardey and Roseboom estimates for the years 1960–83 and interpolate to obtain estimates for 1984–93. Despite the fact that our estimates are lower than some estimates from other sources (e.g., Pardey et al., 1999, and Hall and Scobie, 2006, for recent years), they still indicate the proportion of the total public science budget allocated to agriculture is higher than for any other country in the world.

Austria (Europe, NW)

Pardey and Roseboom: 1964, 1966, 1967, and 1975–85. Based on OECD, Austrian government, and Boyce and Evenson (1975).

Pardey et al. (1999): 1971–93, based on OECD data.

OECD current database: Field of science and socioeconomic objective estimates for 1981, 1985, 1989, 1993, 1998, 2002, 2004, 2006, 2007, 2009, 2011, and 2013.

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[50] As an example of the somewhat problematic nature of some of the New Zealand data, from 1972 onward, the estimates of Hall and Scobie are based on another paper by Johnson (2000) and appear to be somewhat overestimated. Johnson based many of his R&D series for public research in different sectors by applying rules of thumb to general budget data.

Currently available information from Statistics Austria is identical to the field of science data reported to OECD for the years 2002 onward. Statistics Austria also has a longer series for government "research and research promotion" as a socioeconomic objective, which is considerably larger than the socioeconomic objective total reported to OECD. On the other hand, Austria is one country for which reported research expenditures to OECD using the "agricultural sciences" definition are generally larger than research expenditures using the "agriculture" socioeconomic objective.

We follow our usual procedure of basing our estimates on "agricultural sciences" research for the OECD data from 1981 onward, interpolating for years without data. For overlapping years, our estimates are almost 40 percent higher than the estimates from Pardey et al. (1999) and Pardey and Roseboom, which appear to be based on a socioeconomic objective measure. Thus, for the years 1960-80, we extend our estimates backward based on the annual changes in the Pardey et al. or Pardey and Roseboom data but anchored to the levels we estimate from 1981 onward. It is worth remembering that using either socioeconomic objective or field of science definitions can be justified—we tend to use field of science data first for reasons explained above. In the Austrian case, as for other countries, it is somewhat more straightforward to see the same definitions being applied for national reporting and reporting to OECD when the criteria are based on field of science rather than socioeconomic objective.

Belgium (Europe, NW)

Pardey and Roseboom: 1960, 1963, 1971, 1975, 1981. Compiled from OECD, FAO, UNESCO, and Belgian sources.

Pardey et al. (1999): 1971–93. Based on data from OECD and personal communication. From 1981 to 1993, the data from Pardey et al. are essentially equivalent to the current estimates from OECD of GBARD for those years. Furthermore, for 1971, 1975, and 1981 the Pardey and Roseboom estimates are essentially equivalent to the Pardey et al. (1999) estimates.

OECD current database: 1999–2013 field of science data only. (Higher education data for 1999 are available from Eurostat but not from OECD.)

Agricultural R&D data from Belgium are quite limited; in part, this may be because Flanders and Wallonia operate relatively distinct agricultural research systems. We concur with Pardey and Roseboom that "the indicators should be used with some caution." From 2000 onward, the Belgian Science Policy Office reports agricultural science expenditures by sector that are almost identical to the field of science expenditures, by sector, reported by OECD.

To construct our series for the years 1983–98, we first noted that data on total spending by sector (government, higher education, and private nonprofit) are available from OECD for all years except 1990 and 1992. For the government sector, from 1999 to 2013, when both total government research spending and agricultural science research spending were available, we noted that nominal government spending for all research rose at roughly twice the rate by which nominal government spending for agricultural research rose. Therefore, for earlier years, we assumed that the rate of change in government agricultural research from year to year was roughly half the rate of change in total government-performed research. For both the higher education and private nonprofit sectors, we noted that there was no trend in the ratio of agricultural to total research between 1999 and 2013. For earlier years, we assumed that higher education agricultural research was 10.2 percent of total

higher education research, the 1999–2013 average, and private nonprofit agricultural research was 1.2 percent of total private nonprofit research, the 1999–2013 average for that category.

For years before 1983, we extrapolated backward from our series using the annual rates of change in the data from Pardey et al. (1999) and Pardey and Roseboom. These procedures result in our estimates being approximately 18 percent higher than the estimates of Pardey et al. (1999) and Pardey and Roseboom up through 1988. In 1989, increases of 50 percent or more in both total nominal government research and total nominal university research mean that our estimates from 1989 to 1993 are considerably higher than Pardey et al.'s (1999) estimates.

Denmark (Europe, NW)

Pardey and Roseboom: 1967, 1970–82. 1967 from OECD, the rest from the Danish Research Secretariat.

Pardey et al. (1999): 1971–93, primarily from the Danish Research Secretariat, with some information from OECD. For 1971–82, the Pardey et al. (1999) estimates are almost identical to the Pardey and Roseboom estimates.

OECD current database: From 1997 to 2013, both field of science and socioeconomic objective data are available across sectors for all years except 1998 and 2008. For earlier years, field of science data are available for the higher education sector for the years 1981–87, 1989, 1991, 1993, 1995, and 1997; and socioeconomic objective data for the higher education sector are available for 1982, 1984, 1997-1993, 1995, and 1997. For the government sector, only socioeconomic objective data are available for the years 1982, 1985, 1987-1993, 1995, and 1997.

For 1981–2013, our estimates are based on the OECD FOS estimates, with interpolation, with the exception of the government sector for the years from 1981 to 1996, for which we use the data available for socioeconomic objective. For 1980 and before, we use the Pardey and Roseboom estimates with a backward exponential projection to fill out years before 1970. We note that up through 2000, estimates based on field of sciences are only slightly higher than estimates based on socioeconomic objective. Since 2001, field of sciences estimates have diverged more widely from socioeconomic objective estimates. Our estimates for 1981–93 are roughly 4–5 percent higher than the estimates for those years by Pardey et al. (1999).

Finland (Europe, NW)

Pardey and Roseboom: 1969, 1971–86. Based primarily on data from OECD, the Central Statistical Office of Finland; also data from Boyce and Evenson (1975).

Pardey et al. (1999): 1971–93 data from OECD and the Central Statistical Office of Finland. From 1971 to 1986 these estimates are close to the Pardey-Roseboom estimates, particularly through 1983.

OECD current database: Field of science data only for 1983, 1987, 1989, 1991, 1993, 1995, 1997–2013.

Our estimates are from OECD from 1983 to 2013, with interpolation; 1969 and 1971–80 data are from Pardey and Roseboom, with interpolation between the Pardey and Roseboom 1980 esti-

mate and the OECD 1983 estimate. Earlier years are backward extrapolation from the Pardey and Roseboom estimates.

France (Europe, NW)

Pardey and Roseboom: 1960–66, 1968, 1970–86. Research expenditures for Institut National de la Recherche Agronomique (INRA) only. Data primarily from INRA. In addition, Pardey and Roseboom have estimates for 2 years of expenditure by CEMAGREF (Centre National du Machinisme Agricole, du Génie Rural, des Eaux et Forêts—agricultural engineering, water engineering and management, forest engineering). They estimate 1 year of joint research expenditures for ACTA (Association de Coordination Technique Agricole—agricultural technical institutes) and ACTIA (Association de Coordination Technique des Industries Agro-alimentaires—agrifood technical institutes).

Pardey et al. (1999): 1971–93. Although the sources for these data are listed exclusively as INRA documents, the estimates from Pardey et al. (1999) are approximately 50 percent higher than those from Pardey and Roseboom for overlapping years. This could be the result of estimating other agricultural and related research outside of INRA.

OECD current database: No field of science or socioeconomic objective estimates for any research performers. GBARD estimates only.

Almost no agricultural research estimates for France are available in the standard format. In France's highly centralized system, INRA is the largest research institution; Pardey and Roseboom and Pardey et al. (1999) estimate INRA research expenditures or build from estimates of INRA expenditures. Our estimates are also based on research expenditures by a number of research institutes or research associations, as defined by Pardey and Roseboom, the European Union Agri-Mapping project (EU Agri-Mapping, 2007) and IMPRESA (Chartier et al., 2014b). Information for these research institutes is also incomplete; we explain in further detail below how we made our estimates. Table B.1 summarizes information on the primary institutions responsible for agricultural research in France.[51] In addition, the French National Institute of Statistical and Economic Studies, INSEE, has published online research estimates for 1996-2009, in which Government research expenditures are divided into fundamental civilian research, other civilian research, and defense. The category of other civilian research is further divided into areas of emphasis that are somewhat related to the socioeconomic objective characterization. Two objectives, "agriculture" as well as "land and sea," are relevant to our exercise.

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[51] We do not include information for CIRAD (Centre de Cooperation Internationale en Recherches Agronomique pour le Développement, or Agricultural Research for Development), and IRD (Institut de Recherche pour Développement, or Research for Development). The former is focused on agricultural research, and the latter conducts some research related to agriculture, but both have nondomestic mandates. With one exception, we also exclude research by ACTIA (Association de Coordination Technique des Industries Agro-alimentaires, or federation of agri-food technical institutes).

Table B.1

Research institutes and associations in France involved in agricultural research

Organization	Predecessor(s)	Earlier predecessor(s)	Topics/Activities
INRA (French National Institute for Agricultural Research), founded 1946			Agriculture, food, environment (includes some forestry research)
IRSTEA (National Research Institute of Science and Technology for Environment and Agriculture), 2011	CEMAGREF (agricultural and environmental engineering), formed by the merger of CNEEMA and CTGREF in 1981	CNEEMA (agricultural mechanization), formed in 1955; CTGREF (agricultural engineering for water and forests), formed in 1972, succeeding CERAFER, formed in 1965	Environment, agriculture, water management, waste, and environmental risks
IFREMER[1] (French Research Institute for Exploitation of the Sea), formed by a merger of ISTPM and CNEXO in 1984	ISTPM (marine fisheries), founded 1953; CNEXO (ocean exploration), founded 1967		Fisheries and aquaculture (only a portion of the IFREMER research portfolio)[1]
ANSES[2] (French Agency for Food, Environmental and Occupational Health and Safety), created 2010 through the merger of AFSSA and AFSSET	AFSSA (French Food Safety Agency), created 1998 from CNEVA/ANMV; AFSSET (French Environmental and Occupational Health and Safety), created 2001	Veterinary Medicines Laboratory (LMV) created 1975; CNEVA (Veterinary Studies and Feed) organized 1988; ANMV (agency for veterinary medicine products) created on CNEVA campus 1995	Food safety/animal health[2]
ACTA[3] (federation of agricultural technical centers), created 1956			User-driven applied research

[1] IFREMER was formed from the merger of a fisheries research institute with a marine sciences research institute. We found it difficult to separate out fisheries research and, therefore, incorporate the entire IFREMER research budget when data were available. This results in an overestimate. A substantial portion of the IFREMER budget is amortization, related in particular to ocean-going vessels. We exclude amortization to reduce the overestimation somewhat.

[2] ANSES is primarily a risk-evaluation agency. Where available, we only attribute a small proportion of the ANSES budget (about 3 percent) to research, based on a percentage found in ANSES annual reports. It is possible that this slightly underestimates veterinary research.

[3] ACTA consists of some 14 agricultural technical institutes that conduct some applied research and technology transfer.

Source: USDA, Economic Research Service using Pardey and Roseboom (1989); EU Agri-mapping (2007); Chartrier et al. (2014b); and institution websites.

Our estimates for France were developed as follows. First, for INRA we have almost complete research expenditure data for 1960 through 1986 from Pardey and Roseboom. INRA research expenditures for 1995 through 2014 were taken from annual reports. For 1987 through 1994, we interpolate. In this case in particular, the later data are on almost the same trend line as the earlier data.

For CEMAGREF/IRSTEA, we have the following data: estimates for CEMAGREF for 1969 and 1985 from Pardey and Roseboom; estimates for 1998–2000 and 2002–04 from budget votes; an estimate for 2006 from the EU Agri-mapping exercise; an estimate for 2009 from INSEE, and estimates for 2010–14 from annual reports.

We have an almost complete set of estimates for IFREMER from 1984 on from annual reports. Before 1983, a long series of estimates from CNEXO annual reports also exists, which we use, even though CNEXO is the marine science and not the fisheries predecessor of IFREMER. In both sets of annual reports, we net out the amortization component, which is high because of the CNEXO/IFREMER fleet of ocean-going vessels. Excluding IFREMER from the total estimate of agricultural research from France would reduce the total by about 15 percent in recent years; a more desirable exclusion of only marine science research, if it were possible, would not reduce the total by as much.

We have only three estimates for ACTA. The 1985 estimate from Pardey and Roseboom is for both ACTA and ACTIA, but they also report a much greater number of "researchers" in ACTA than for ACTIA, so we attribute all of that total to ACTA. We also have a 2007 estimate from the EU agri-mapping estimate and a 2014 estimate from the ACTA website. We simply interpolate for the rest and project ACTA expenditures before 1985 using the rate of change in INRA expenditures for those years. This suggests that ACTA expenditures were just under 30 percent of INRA's in 1985, the year for which Pardey and Roseboom estimate expenditures for both institutions, falling gradually to about 20 percent of INRA's in recent years.

We only include estimates for ANSES from 2008 to 2014, based on annual reports. As noted in table B-1, we assume research is only a small part of the ANSES budget, although this might result in a slight underestimate of veterinary research totals.

In addition to these research institutions, Chartier et al. (2014b) indicate that two other basic science research institutions conduct some agricultural research. The first is the large National Center for Scientific Research (CNRS), which does some relevant research in the fields of ecology, plant and animal physiology and development, and a few other areas with potential agricultural application. The second is the French Atomic Energy Commision (CEA), which does some research in plant physiology. We do not include any expenditures by the CNRS or CEA in our estimates.

We can make several useful comparisons of our estimates for France. First, for the years 1971–93, our estimates are roughly 8–9 percent higher than the estimates made by Pardey et al. (1999). Conceivably, some of this difference could be caused by our inclusion of some marine science research, which we would wish to exclude if it were possible to do so in a nonarbitrary manner. For the years 1996–-2009, we can make some interesting comparisons of our estimates with the "socioeconomic objective" data from INSEE. Our estimate of the total for INRA and ACTA—the two institutions most closely connected with the "agricultural" portion of "agriculture, forestry, and fisheries" research—is very close to the INSEE estimate of research with the objective of "agriculture." The difference averages no more than about 2 percent across those years. On the other hand, the total of our estimate for IRSTEA plus IFREMER, subtracting amortization expenses for the latter, averages only about two-thirds of the INSEE category "land and sea." Thus, INSEE must be including a considerable amount of natural resources research that is not related to agriculture in its total estimate. To repeat, we are still overestimating fisheries research by including all of IFREMER, but even with this overestimation, we do not approach the INSEE total for what we might consider "natural resources" research.

Finally, Pardey et al. (2016) provide data that allow the calculation of public-sector research in France for 1980, 1990, 2000, 2005, 2010, and 2011. These estimates are lower than our estimates, and they are lower than the estimates from Pardey et al. (1999) for 1980 and 1990; but they are higher than INRA's research expenditures in all years. In recent years, the estimates from Pardey

et al. (2016) are closest to the INSEE estimates for the objective "agriculture." In other words, they appear to be a "net" measure rather than one that also includes broader, agriculturally related natural resources research.

Germany (Europe, NW)

Pardey and Roseboom: Federal Republic of Germany (West Germany) only, 1964, all odd-numbered years from 1967 through 1985. Personal communication from the Ministry for Research and Technology.

Pardey et al. (1999): 1971–93, primarily based on the Ministry for Research and Technology and the OECD.

OECD current database: 1993–2013, field of science data for both government and higher education; field of science data for higher education only in 1981, 1983, 1985, 1987, 1989, and 1991. Only four observations of government spending using the socioeconomic objective criterion are available.

First, we note that building long-term series on many variables for Germany that are of interest to this study are constrained by the effects of German reunification in 1990. Pre-1990 data are, in almost every case, based on data for West Germany alone. We are unaware of any source that would allow us to estimate agricultural research expenditures for East Germany prior to 1990 with any degree of accuracy. Judd et al. (1983) and, before them, Boyce and Evenson (1975) have made some estimates for "Eastern Europe and the USSR." Despite the fact that these data are less comparable than any of our other sources, we do use them to estimate long-run agricultural research series for Hungary, Poland, and, to a lesser extent, the countries of the former Czechoslovakia (see below). However, the only evidence they present for East Germany is a total for Eastern Europe, out of which estimates for other individual countries could be subtracted to leave East Germany as a residual. We consider this approach too unreliable for estimating comparable information for East Germany prior to 1990, and so our series in effect grafts later data for a reunified Germany onto earlier data for West Germany alone.

Second, for overlapping years, the Pardey et al. (1999) estimates are nearly identical to the estimates from Pardey and Roseboom, except for 2 years when the Pardey-Roseboom estimates are higher. We note that Pardey and Roseboom do indicate separate estimates for university and nonuniversity research. We will assume nonuniversity research is equivalent to government research, and note further that for government agricultural research, Pardey and Roseboom's 1981, 1983, and 1985 estimates average roughly 5.9 percent of total government research. This is almost the same share as the OECD governmental agricultural science research share of total government research for 1993–2001. Therefore, we use the Pardey and Roseboom estimates for government research in 1981, 1983, and 1985, and for other nonavailable years between 1981 and 1993, we estimate government agricultural research as also equivalent to 5.9 percent of total government research.

However, for 1981, 1983, and 1985, the Pardey and Roseboom estimates for university agricultural research are higher than the OECD estimates. To keep our estimates more consistent with later OECD data, we use the OECD university estimates for all years from 1981 to 2013, interpolating for years without data. Prior to 1981, we reduce the Pardey-Roseboom university research estimates downward to keep rates of change equivalent but to keep levels consistent with the later OECD data.

Combined, this means our estimates average about 9 percent lower than the estimates from Pardey and Roseboom for overlapping years and lower than the Pardey et al. (1999) estimates up until 1985. From 1986 to 1993, however, our estimates become larger than the Pardey et al. (1999) estimates and diverge increasingly. This suggests that Pardey et al.'s (1999) data might represent an attempt to maintain a consistent series for West Germany alone, which would be quite reasonable since their data only cover the first few years following reunification. Finally, for all years for which comparisons can be made from 1980 to 2011, our estimates for Germany are very similar to the estimates from Pardey et al. (2016), averaging only 2–3 percent larger.

Iceland (Europe, NW)

Pardey and Roseboom: 1961–71, 1975, 1977, 1979, and 1983, based on data from OECD.

Pardey et al (1999): 1971–93, based on data from OECD.

OECD current database: Field of science estimates for all odd-numbered years from 1995 to 2013, as well as 2000; field of science estimates for higher education in 1981, 1983, and 1985. Socioeconomic objective estimates for 1983, 1984, 1987, and 1989–92.

We use field of science estimates from OECD for all available years between 1981 and 2013, substituting socioeconomic objective estimates when field of science estimates are unavailable, as well as interpolating. For 1983–93, this results in estimates very similar to the estimates by Pardey et al. (1999), which are slightly larger than the estimate from Pardey and Roseboom for 1983. For 1980 and earlier, the Pardey and Roseboom estimates are very similar to those from Pardey et al. (1999), so we use the combination of these two sources to extend our series backward.

Pardey and Roseboom indicate that fisheries research accounts for half or more of all agricultural research in Iceland, which reflects the large role that fisheries play in Iceland's "agricultural" GDP.

Ireland (Europe, NW)

Pardey and Roseboom: 1963, 1967, 1969, 1970–85, compiled from various OECD sources.

Pardey et al. (1999): 1971–93, compiled from OECD sources.

OECD current database: Field of science data, government, 2002–13; higher education only 1981–92, 1994, 2000–13. Socioeconomic objective data, 1981–90, 1992, 1994; government only 2002–13.

Field of science data and socioeconomic objective data are fairly similar where they overlap in the OECD database. We use field of science data for 2000–13, socioeconomic objective data for 1981–94, with interpolation for years with missing data. For 1981–93, this results in estimates very close to the estimates of Pardey et al. (1999). These are also close to the estimates of Pardey and Roseboom in 1981–84; the Pardey-Roseboom estimate for 1985 is higher than the Pardey et al. (1999) estimate or our estimate.

From 1971 to 1989, the Pardey et al. (1999) and Pardey and Roseboom estimates are also quite similar. We use these to extend our series backward before 1981.

Luxembourg (Europe, NW)

Pardey and Roseboom: No data.

Pardey et al. (1999): No data.

OECD current database: Field of science data for 2000–03, 2005, 2009–13. Socioeconomic objective data for government only, 2010–13.

Luxembourg, a prosperous but very small country, had no history of public investment in research of any kind until the early 1980s. In 1981, the government instituted some funding of research by private firms, and in 1984, Luxembourg established a National Agency for Innovation and Research. Two public research institutes were founded in 1987. One of them had a department called the Resource Center for Environmental Technologies, and the other a Department of Environment and Agro-biotechnologies. These two institutes merged to form the Luxembourg Institute of Science and Technology in 2015. Luxembourg did not have a single university before the establishment of the University of Luxembourg in 2003.

Our estimates for agricultural research in Luxembourg are based on the OECD field of science data, government only, for the available years from 2000 to 2013. For years without OECD estimates, we estimated agricultural research was just over 2 percent of all public research, based on the average percentage from years where agricultural sciences research was recorded by OECD. For years from 1987 to 1999, we estimated total government research expenditure by projecting backward based on the trend observed from 2000 onward. We then estimated agricultural research as just over 2 percent of total government research. This procedure results in an estimate of very small but increasing real expenditure for agricultural research from 1987 through the mid-2000s and widely fluctuating but still small amounts thereafter.

Netherlands (Europe, NW)

Pardey and Roseboom: 1961, 1967, 1971, 1974, 1977, 1979, 1981, 1984, primarily from personal communication from the Dutch Council for Agricultural Research.

Pardey et al. (1999): 1971–93 from Roseboom and Rutten (earlier working paper)

OECD current database: Field of science, government—2007, 2009, 2011–13; higher education 1981-85, 1987, 1989, 1994-2009, 2011–13. Socioeconomic objective, government—1981–91; higher education 1981–86, 1989. However, the socioeconomic estimates for higher education are nearly constant in nominal terms, and very low.

In addition to these sources, Roseboom and Rutten (1999) provide detailed estimates of public agricultural and food research in the Netherlands from 1970 through 1995, and an estimate for private research from 1981 through 1995. Pardey et al.'s (1999) series is, in fact, based largely on Roseboom and Rutten.

A major problem in constructing a long-run series of public agricultural research expenditures for the Netherlands is that different sources tend to estimate different levels of total expenditures. For overlapping years, Pardey and Roseboom's estimates average about 15 percent greater than the estimates from Pardey et al. (1999)/Roseboom and Rutten. In turn, the Pardey et al. (1999) estimates average over 40 percent higher than estimates constructed by combining OECD socioeconomic

objective measurement of government research with field of science measurement of higher education research between 1981 and 1991. We also note that the OECD estimates for 1981–91 imply about 17 percent of all government research and roughly 5 percent of all higher education research was directed to agriculture. Using the recent OECD field of science estimates for 2007–13 would imply over 19 percent of all government research and just under 5 percent of all higher education research would be directed to agriculture. This would make the Netherlands an outlier in this study, where the agricultural percentage of all public science investment was higher in recent years than in the 1980s. In the aggregate for all countries in this study (see the "Some Economic Fundamentals of Public Investment in Agricultural R&D" section, main text), the agricultural percentage of the total science budget was lower in recent years than in the 1980s, and in other individual countries, it was either lower or roughly the same in the most recent years compared with the early 1980s.

With these considerations in mind, we use Roseboom and Rutten's detailed estimates for the years 1970–95 to build our long-term estimate, with one important exception. Unlike for other countries (e.g., the United States or the UK), Roseboom and Rutten's data allow us to exclude food research cleanly from the total since it was concentrated in one institute. In our estimate, we do so, which results in estimates 11–12 percent lower than the Pardey et al. (1999) estimates. To connect this series with the recent estimates from OECD, we (1) use higher education field of science estimates for 1996–2013; (2) estimate a 1996 public-sector agricultural research total consistent with the 1995 estimate based on Roseboom and Rutten's data; (3) use this to determine an estimated government agricultural research expenditure for 1996; and (4) interpolate to estimate government agricultural research expenditures between 1997 and 2007, when we can begin to use OECD field of science estimates for government expenditures. For 1960-69, we base our estimates on our total but with annual growth rates implied by Pardey and Roseboom's estimates for 1961, 1967, and 1971. Despite the imperfections in this approach, the major fluctuations in the resulting series only appear after 2007, in other words, in the years covered by the most recent OECD data when information for both government and higher education expenditures are reported by OECD.

Norway (Europe, NW)

Pardey and Roseboom: 1963, 1966–85, based on personal communication from the Agricultural Research Council of Norway and the Norwegian Fisheries Research Council, as well as some data from the OECD for the 1960s.

Pardey et al. (1999): 1971–93, based on similar sources as Pardey and Roseboom—personal communication from the Agricultural Research Council of Norway and the Norwegian Fisheries Research Council, as well as OECD data.

OECD current database: Government field of science estimates for odd years from 1999 to 2005, all years 2007–13; higher education field of science estimates for odd years from 1981 to 2013. Government and higher education socioeconomic objective estimates for odd years from 1981 to 2003.

The Research Council of Norway provides some estimates for odd-numbered years from 2003 to 2013. The estimates for the higher education sector are similar to the estimates from OECD, but for the government sector, the Research Council estimates are somewhat larger. It appears the Research Council estimates for the government sector may also include some business-sector research.

For 1981–2013, our estimates are based on OECD government socioeconomic objective estimates for 1981–97, government field of science estimates for 1999–2013, and higher education field of science estimates for 1981–2013, with interpolation for years without data. For overlapping years, our estimates average over 20 percent lower than the estimates from Pardey et al. (1999), which, in turn, are very similar to the Pardey and Roseboom estimates. For 1981–85, our estimates are more similar to Pardey and Roseboom's estimates for the Agricultural Research Council of Norway alone, (i.e., not including research attributed to the Norwegian Fisheries Research Council). It is possible then, that the OECD series underestimates fisheries research for Norway. Nonetheless, since the OECD series for recent years is fairly complete, we use it as the basis for the level of research in the earlier years for 1960–80, with annual changes based on the annual changes for Pardey and Roseboom.

Sweden (Europe, NW)

Pardey and Roseboom: 1961–85, personal communication and draft manuscript from the Department of Economics and Statistics, Swedish University of Agricultural Sciences.

Pardey et al. (1999): 1971–93, same source as Pardey and Roseboom.

OECD current database: Government estimates for socioeconomic objective, odd-numbered years from 1983 to 2013; higher education estimates for field of science, odd-numbered years from 1981 to 2013.

The OECD data are quite similar to data reported by Statistics Sweden. Sweden is a good example of a case where government data have been reported almost exclusively by the socioeconomic objective criteria, while higher education data are reported almost exclusively by the field of science criteria. We base our estimates for 1981-2013 on the OECD data, with interpolation.

From 1981 to 1993, our estimates average approximately 16 percent lower than the estimates from Pardey et al. (1999), but, in general, our estimates are higher than the estimates from Pardey and Roseboom for overlapping years. We are not certain of any possible explanation for these differences, especially since the Pardey et al. (1999) data are generally greater than the Pardey and Roseboom data for the same year, even though they are attributed to the same source. However, we use the estimates from Pardey and Roseboom for the years 1980 and earlier, since estimated public-sector research for 1980 from Pardey and Roseboom is very similar to our estimate for 1981 based on OECD data.

Switzerland (Europe, NW)

Pardey and Roseboom: 1960, 1965, 1967–77, 1979, 1981, 1983, 1986, with information from the Swiss Federal Statistics Office, University of Fribourg, and OECD.

Pardey et al. (1999): 1971–93, primarily from Federal Statistics Office and OECD information.

OECD current database: Government estimates for socioeconomic objective, 1981, 1992, even-numbered years from 1996 through 2012; higher education estimates for field of science, 2000, 2004, 2008, and 2012.

Swiss agricultural research data are fairly thin. We were able to fill in information for government expenditure in 1994, consistent with the other observations for 1992–2012, from the Swiss Federal Statistics Office. Higher education R&D apparently is surveyed only every 4 years.

To construct our estimates, we use the more recent data from OECD with the earlier data from Pardey et al. (1999) and Pardey and Roseboom by first noting that the Pardey-Roseboom estimates through 1986 refer to government-performed research only, and the Pardey et al. (1999) estimates are larger. We assume that the difference between them can be attributed to research in the higher education sector. For government research, we then fill in the years between 1986 and 1992 by observing that in both years, the percentage of total government research devoted to agriculture was roughly similar, and applying similar percentages to total government research for the years in between. We ignore the single OECD observation for government agricultural research in 1981. For higher education research, we calculate higher education research for 1986 as the difference between the Pardey et al. (1999) estimate and the Pardey-Roseboom estimate for that year, and then interpolate between that estimate and the OECD estimate for 2000. We have to extrapolate an estimate forward to 2013 and backward from 1971. For the years 1970 and earlier, we assume the levels are consistent with the Pardey et al. (1999) levels from 1971 onward but annual changes are determined by annual changes implied by the Pardey-Roseboom estimates.

These procedures result in our estimates for 1987–93 being lower than the estimates from Pardey et al. (1999), even though we use their estimates for total public agricultural research expenditures from 1986 and earlier. Our first complete estimate from OECD data, for 2000, combined with the Pardey et al. (1999) estimate from 1986, implies that nominal public agricultural research expenditures grew very slowly between 1986 and 2000, 0.6 percent per year, whereas the nominal research investment calculated from Pardey et al.'s (1999) data grew 4.6 percent annually from 1986 to 1993. This, in turn, would imply a very rapid expansion of agricultural research in the higher education sector over that period and a following contraction to reach the level of higher education agricultural research reported by OECD in 2000. Our approach results in a somewhat smoother transition from the earlier data to the recent OECD estimates, but the Swiss totals still demonstrate considerable fluctuation.

United Kingdom (Europe, NW)

Pardey and Roseboom: 1960–84 based primarily on personal communication from the Department of Agricultural Economics, University of Reading, with additional information from the Central Statistical Office, the Ministry of Agriculture, the Department of Education and Science, and several journal articles.

Pardey et al. (1999): 1971–93 based on Thirtle et al. (1999).

OECD current database: Field of science data, government and higher education, 2008–13; socio-economic objective data, government only, 2002–05.

Agricultural R&D in the United Kingdom is marked by a variety of funders and performers, as well as different jurisdictions (Thirtle et al., 1997). One major funding source, the Agricultural and Food Research Council (AFRC), was replaced in 1994 by the Biotechnology and Biological Sciences Research Council (BBSRC), with a broader mandate than agriculture alone. Similarly, the Ministry of Agriculture, Forestry, and Fisheries (MAFF) was succeeded in 2001 by the Department for Environment, Food & Rural Affairs (DEFRA). Today, a considerable portion of the research

recorded for DEFRA is policy research. In addition, the governments of both Scotland and Northern Ireland support agricultural research.

OECD data are limited, and in terms of research performance data, as opposed to GBARD, confined to recent years. The present Department for Business, Energy and Industrial Strategy provides Science, Engineering and Technological Indicators from about 1986 onward, but these data, when presented using socioeconomic objective criteria, appear to be related to GBARD, or government budget outlays, rather than research performance. Thirtle and colleagues, however, building on earlier work by Harvey Beck at the University of Reading (the principal source for estimates by Pardey and Roseboom), have made detailed estimates of public agricultural R&D expenditures for the UK from 1940 through at least 1997. These estimates have been published in considerable detail for 1972–93 (Thirtle et al., 1997, 1999) and Thirtle (personal communication) has kindly supplied us with estimates of total public agricultural R&D for 1940–97. As do Pardey et al. (1999), we make extensive use of these estimates in constructing a time series for public agricultural R&D in the UK. There are at least two caveats concerning our use of the data provided by Thirtle and colleagues. First, they are presented in real terms, and it is uncertain what deflator was used to esti-mate real values from the original local currency unit (LCU) observations. We experimented with a variety of deflators, and relied primarily on the GDP deflator as it was recorded by the World Bank in 1995, but this could lead to small discrepancies—we estimate about 5 percent at the most—from the "true," original LCU observations. Second, the Thirtle et al. data definitely exclude fisheries research, although they do include food research. Based on estimates from a recent report by the UK Natural Environment Research Council (NERC), we believe in recent years the omission of fisheries research would result in a total a little less than 2 percent lower than would be the case were fish-eries included. It is possible this discrepancy might be higher during the years for which we rely on the data from Thirtle et al.

Our final estimates are constructed by using the OECD data for 2008-13. To link the Thirtle et al. data up to 1997 with the OECD data, we note that for both government and higher education performed research, the percentages of total government and total higher education research that is devoted to agriculture is slightly higher when calculated in 1997, using Thirtle et al. data for agricul-ture and OECD data for all research, than they are in 2008, using OECD data for both all research and agricultural research. We interpolate these percentages between 1997 and 2008 and apply the interpolated percentages to total government and total higher education research for the intervening years.

In earlier years, we note that the Pardey-Roseboom estimates average about 15 percent higher than the Pardey et al./Thirtle et al. estimates for overlapping years. To construct our estimates for years prior to 1972, we start with the endpoint determined by the Thirtle et al. estimate for 1972 and add the assumption that annual rates of change for earlier years are equivalent to the annual rates of change implied by the Pardey-Roseboom data.

Greece (Mediterranean)

Pardey and Roseboom: 1966, 1969, 1977, 1979–85, primarily from OECD sources, also Boyce and Evenson (1975).

Pardey et al. (1999): 1971–93, from OECD sources.

OECD current database: Field of science data for government and higher education, 2011 and 2013 only; socioeconomic objective data for government, 2011 and 2013 only.

Estimates of public-sector agricultural R&D expenditures are very limited for Greece. In the end, we rely completely on GBARD estimates for the years 1981–2013, despite the fact that GBARD is a highly imperfect proxy for public-sector research performance and is likely to be an underestimate. In the early 1980s, annual estimates based on GBARD tend to be similar to the estimates from Pardey and Roseboom; for overlapping years, our GBARD-based estimates average about 25–30 percent lower than Pardey et al.'s (1999) estimates. We extend our series backward to 1980 and earlier years by assuming annual rates of change equivalent to those implied by Pardey et al. (1999) and Pardey and Roseboom.

The underestimation caused by the reliance on GBARD is one reason public agricultural research intensity for Greece appears to be lower than that in any other country (fig. 4.2, main text). However, we note that total public research intensity (all public R&D/total GDP) as well as total research intensity (all public and private R&D/total GDP) are also very low in Greece.

Israel (Mediterranean)

Pardey and Roseboom: 1960, 1965, 1967-70, 1972, 1975, 1977, 1979–83, primarily from personal communication, National Council for Research and Development; also Boyce and Evenson (1975).

Pardey et al. (1999): No data.

OECD current database: Government, socioeconomic objective criteria, 1993–2012; higher education, field of science criteria, 2009–13.

Geographically and climatically, Israel is most conveniently grouped with the other Mediterranean countries of southern Europe. Despite its relatively small economy and relatively small agricultural sector, however, Israel contrasts with the other Mediterranean countries both in its public research intensity for agriculture and in the overall research intensity (all public and private R&D/GDP), which are much higher in Israel than in the other countries in the region (fig. 4.2, main text). In fact, Israel's economy-wide research intensity, public and private, vies with that of Korea as the highest in the world.

Data for agricultural research expenditures in Israel are relatively limited. Furthermore, constructing a long-term series is hampered by the effects of the hyperinflation in the late 1970s and early 1980s, and the introduction of the new Israeli shekel in 1985. Our government agricultural research estimates for later years are based on the OECD socioeconomic objective criteria. The Israeli Central Bureau of Statistics (CBS) is also a source of estimates for both intramural and extramural research expenditures for the Ministry of Agriculture and Rural Development from 1992 through 2012. For most overlapping years, the CBS intramural estimates are relatively close to the OECD SEO estimates we use.

We then use OECD GBARD figures as the estimate of total research expenditures for 1993-2013. Through 2009, the GBARD estimate and the CBS estimate of all intramural and extramural expenditures by the Ministry of Agriculture are quite similar; in 2010–12, the CBS estimate is larger. This procedure results in an implicit estimator of higher education (and, possibly, private nonprofit) agricultural research obtained by subtracting the SEO estimates from the GBARD estimates. This

implicit estimator can be compared with another measure from the CBS, called "separately funded" agricultural research. The "separately funded" measure averages about 20 percent higher than our implicit estimator of higher education research and also fluctuates less. However, neither the implicit estimator nor the CBS "separately funded" estimator is nearly as high as the OECD field of science estimator for higher education agricultural research in 2009–13. We conclude that we may be under-estimating higher education agricultural research in Israel, particularly in the latest years of the series, and, thus, the total as well. However, more years of observation and consultation with available local sources are probably necessary to resolve the likelihood of this trend.

We use the estimates from Pardey and Roseboom for most earlier years, interpolating to reflect an apparent slight decline in real agricultural research investment over the mid- to late 1980s and early 1990s. Given the overlap of this period with the hyperinflationary period, however, the reliability of the interpolation may be compromised somewhat.

Italy (Mediterranean)

Pardey and Roseboom: 1966–87, personal communication from the National Research Council (Italy).

Pardey et al. (1999): 1971–93, personal communication from the National Research Council (Italy).

OECD current database: Field of science data for government, 2003–13; for higher education, 1981, 1983, 1985, 1987, 2005–13. Socioeconomic objective data for government 1981, 1984–91, 1998–2000, 2003–13.

Our estimates for government research are based on OECD socioeconomic objective data for 1988–91, 1998–2000, and OECD field of science data for 2003–13, with interpolation. We note that from 2008 onward, socioeconomic objective estimates for government have been slightly lower than field of science estimates for government; from 2003 to 2006, the socioeconomic objective estimates were mostly, but not always, lower. However, the socioeconomic objective estimate for 2008 is a clear outlier, nearly three times as large as the field of science estimator and three to four times as large as most of the other socioeconomic objective estimators for years immediately before or after. For higher education estimates in recent years, we use the field of science estimator for 2005–13.

For earlier years, we note that in overlapping years, the Pardey-Roseboom estimates are virtually identical to the Pardey et al. (1999) estimates for all years except 1987, when the Pardey-Roseboom estimate is higher. We found that the best way to maintain a consistent series between the recent OECD estimates and earlier estimates was to use Pardey and Roseboom for all estimates up to 1987. We further adjusted the Pardey-Roseboom estimates slightly by excluding the small amounts of funding contributed to international agricultural research and apportioning total funding to government and higher education in proportion to the staff counts reported by Pardey and Roseboom. This procedure results in government estimates that are higher than the limited socioeconomic objective government estimates in OECD data for the early 1980s, and higher education estimates than are lower than the field of science estimates in OECD data in those years. However, totals—government plus higher education—are very close between the more recent OECD data for the early 1980s and the Pardey-Roseboom estimates for those years.

Finally, this leaves the years 1988-2004 for higher education agricultural research to be accounted for. We interpolate to estimate these years for higher education research.

This procedure results in estimates that are very similar to those of Pardey et al. (1999) up through 1989 but increasingly lower for 1990-93. Furthermore, Italy is another country for which we can compare our estimates to those in Pardey et al. (2016). We note that in 2000, the Pardey et al. (2016) estimate is 85 percent higher than ours, and in 2005, 2010, and 2011, about 36 percent higher. We note further that the Pardey et al. (2016) estimate for 1990 is over 40 percent higher than the Pardey et al. (1999) estimate for that year, and the Pardey et al. (2016) estimate for 1980 is over 140 percent greater than the Pardey et al. (1999) estimate for that year. It is unclear why the Pardey et al. (2016) estimates are higher than both recent OECD estimates and earlier estimates by Pardey et al. (1999), Pardey and Roseboom, and the OECD.

Portugal (Mediterranean)

Pardey and Roseboom: 1960, 1964, 1971–72, 1976, 1978, 1984, primarily from National Board of Scientific and Technological Investigation; also OECD.

Pardey et al. (1999): 1971–93, primarily from National Board of Scientific and Technological Investigation; also OECD.

OECD current database: Government and higher education, field of science criteria, 1982–2013; government and higher education, socioeconomic objective criteria, 1982–2013.

Over the past 30 or more years, Portugal has been one of the few countries reporting almost complete information by both field of science and socioeconomic objective criteria, for both government and higher education sectors (as well as the private nonprofit sector) to OECD. In many cases, particularly in more recent years and especially from 1997 to 2004, estimates reported using the socioeconomic objective criteria have tended to be larger than those using the field of science criteria. However, in keeping with our general practice of using field of science-based estimates, the field of science criteria are the ones we use for our estimates from 1982 onward.

Up through 1988, the OECD estimates are very similar to those of Pardey et al. (1999), and, in turn, the Pardey et al. (1999) estimates are very similar to the estimates made by Pardey and Roseboom. From 1989 to 1993, the Pardey et al. (1999) estimates are greater than the OECD estimates, and this would be the case regardless of whether field of science or socioeconomic objective based estimates are used. Given the similarity of the OECD estimates with those of Pardey et al. (1999) and Pardey and Roseboom for overlapping years, we use those publications as the basis of our estimates for 1960–81.

Spain (Mediterranean)

Pardey and Roseboom: 1963, 1967, 1969-74, 1982–83, primarily from the National Institute of Statistics; also from OECD and the Council of Scientific Investigation.

Pardey et al. (1999): 1971–93 primarily from the National Institute of Statistics; also from a journal article.

OECD current database: Field of science criteria for both government and higher education, 1981-2013. Socioeconomic objective criteria for government, 1981-93; for government and higher education, 1995, 1997, 1999–2013.

For Spain, we follow our usual practice and base our estimates for 1981–2013 on the OECD field of science data. For years from 1995 onward, in which field of science and socioeconomic objective data are both available, the field of science estimates tend to be *lower* than the socioeconomic objective estimates. Also, from 1997 onward, field of science data for agricultural sciences are also available from the National Institute of Statistics (INE); they are essentially the same data reported to OECD. For the years 1981–93, however, when socioeconomic objective data are reported only for government-performed research, it is interesting to note that field of science estimates for government-performed research are *higher* than the socioeconomic objective estimates.

With the exception of the years 1991-93, when the Pardey et al. (1999) estimates begin to increase more rapidly than the OECD estimates, reported estimates from OECD, Pardey et al. (1999), and Pardey and Roseboom are very similar when they overlap. As a result, we simply use the Pardey and Roseboom/Pardey et al. (1999) estimates to extend the series back to 1960.

We are also able to obtain Pardey et al.'s (2016) estimates for Spain in given years. In 1980 and 1990, Pardey et al.'s (2016) estimates are lower than both our estimates and the estimates by Pardey et al. (1999). In 2000, 2005, 2010, and 2011, the Pardey et al. (2016) estimates are higher than ours. The latter result may be because Pardey et al. (2016) are using socioeconomic objective criteria rather than field of science. It is unclear why the difference is in the opposite direction in earlier years.

Europe, Central (general)

In general, the six countries in our study from this region—the Czech Republic/Slovakia, Estonia, Hungary, Poland, and Slovenia—have less, and less reliable, data than the other countries in the study. OECD data for these countries tend to start about 1990 or even later. There are no data in either Pardey and Roseboom and Pardey et al. (1999). Judd et al. (1983), building on earlier work by Boyce and Evenson (1975), estimate public agricultural research expenditures for earlier years for four countries: the Czech Republic/Slovakia, until January 1, 1993, joined as Czechoslovakia; Hungary; and Poland. There are no earlier estimates for the smaller countries, Slovenia and Estonia, that were until mid-1991 smaller jurisdictions within much larger countries, Yugoslavia and the Soviet Union, respectively. Estimates in current local currency units are not available from Judd et al.; they are made in 1980 U.S. dollars. Furthermore, Judd et al. convert to U.S. dollars first by using the official exchange rate and then to 1980 dollars by using the U.S. wholesale price index. Thus, their 1980 U.S. dollar estimates are not the same as they would be had they applied a "first deflate, then convert" procedure (using GDP deflators and PPP exchange rates) as recommended by Craig et al. (1991) and done elsewhere in this study. Nonetheless, we use their data to estimate earlier public agricultural R&D expenditures in the countries where they are available. The data from these countries should be treated with particular caution. In the case of the Czech Republic, and by extension, Slovakia, we are able to improve the estimates considerably by following Ratinger and Kristkova (2015). Further details, country by country, follow.

Czech Republic/Slovakia, former Czechoslovakia (Europe, Central)

Judd et al.: 1959, 1962, 1965, 1968, 1971, 1974, 1977–80 average.

OECD current database—Czech Republic: Field of science criteria for both government and higher education, 1995–2013; socioeconomic objective criteria for both government and higher education, 1998–2006.

OECD current database—Slovakia: Field of science criteria for both government and higher education, 1996–2014; socioeconomic objective criteria for both government and higher education, 1997–2014.

We use the OECD field of science data for estimated public-sector agricultural research in both the Czech Republic and Slovakia. We note that in the Czech Republic, total public agricultural research estimated using field of science criteria is always larger than the socioeconomic objective estimates for all overlapping years. In Slovakia, the field of science estimates are lower through 2002 but larger every year thereafter.

To create a longer time series for the Czech Republic/Slovakia, or the former Czechoslovakia, we wish to link the Judd et al. data to the more recent data from OECD. This case illustrates that this must be done with caution. Judd et al.'s estimates show public-sector agricultural research in Czechoslovakia as larger than in any other country in the former centrally planned economies outside of the former Soviet Union.[52] This is despite the fact that during those years, the agricultural GDP of Poland may have been five times the agricultural GDP of Czechoslovakia and the agricultural GDP of Hungary over twice as large as Czechoslovakia's. Fortunately, Ratinger and Kristkova (2015) have estimated agricultural research expenditures for the Czech Republic from 1975 to 2012, and these estimates provide further insight. Ratinger and Kristkova argue that in the years of the centrally planned economy, large numbers of nonscientific workers were employed in "agricultural research." Following the "abandonment" of the centrally planned economy in 1989, these workers were "rapidly expelled" from agricultural research to other parts of the economy. As a result, Ratinger and Kristkova make sharp reductions to the estimates from statistical yearbooks to make their own estimates of agricultural research expenditures for 1992 and earlier years. We use their estimates to help us create longer time series for both the Czech Republic and Slovakia.

For the Czech Republic, we note that the Ratinger and Kristkova estimates from 1995 onward correspond with OECD estimates of all agricultural research, including the business sector. Therefore, for 1993 and 1994, our estimate of public agricultural research is the Ratinger and Kristkova estimate reduced by 29 percent (based on the ratios for succeeding years) to account for presumed business-sector research in those years. For 1975–92, we make the assumption that prior to the dissolution of Czechoslovakia, all reported agricultural research was in the public sector and simply use the Ratinger and Kristkova estimate. For years prior to 1975, we assume the rates of growth are as given in the Judd et al. estimates, but the levels are only about one-quarter of the Judd et al. estimates to make them consistent with the later data.

For Slovakia, we use the OECD estimates for field of science from 1996 onward. For 1990–95, we apply percentages to total government and total higher education research, as reported by OECD,

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[52] In addition to Czechoslovakia, Hungary, and Poland, which are in this present study, Judd et al. estimate public agricultural research expenditures for Bulgaria, Romania, and the former Yugoslavia.

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based on the percentages for a few years following the dissolution of Czechoslovakia. For 1989 and earlier years when Czechoslovakia was a single state, we assume public agricultural research in Slovakia was half that in the Czech Republic, and, therefore, our estimates are also related to the Ratinger-Kristkova and Judd et al. estimates. This proportion was determined by the fact that in recent years, agricultural GDP, arable land, and total population estimates from the Czech Republic and Slovakia have a roughly 2:1 ratio.

Estonia (Europe, Central)

OECD current database: Field of science, 2005–14; socioeconomic objective, 2005–14. Earlier field of science estimates, 1993–2004, consistent with the OECD data, are available from Eurostat. Earlier socioeconomic objective estimates for 1996–2004, consistent with the OECD data, are available from Eurostat. Some of the earlier Eurostat data are in krooni rather than euros and need to be converted to euros to make the longer series consistent.

Estonia's formal independence from the former Soviet Union took place on August 20, 1991. We do not construct a series of estimated public agricultural research before 1990. For 1993-2014, we use the OECD/Eurostat field of science estimates, which, in most years, are lower than the socioeconomic objective estimates. For 1992, we estimate public agricultural research for the government and higher education sectors as a percentage of total government and higher education research. Estimates for 1990–91 are backward projections of the 1992–95 trends.

Hungary (Europe, Central)

Judd et al.: 1959, 1962, 1965, 1968, 1971, 1974, 1977–80 average.

OECD current database: Field of science, 1987–2013; socioeconomic objective, 1999–2013.

We use the OECD field of science estimates for 1987-2013. For most but not all years, where they overlap, these are lower than the socioeconomic objective estimates.

Even though the Judd et al. estimates are not PPP estimates, we assume they are and convert them from 1980 to 2011 PPP dollars. We then interpolate between the various years for which these estimates are available and interpolate between the Judd et al. estimate for 1980 and the average of the OECD estimates for 1987–89, with the latter also converted to real 2011 international dollars. We use the average of the 1987–89 OECD estimates rather than the 1987 estimate alone because this creates a slightly smoother series for the implicit estimates of nominal public agricultural research expenditures in the 1980s. Although the use of the Judd et al. estimates is not ideal, their estimates in this case appear more consistent with the more recent data from OECD. A sharp drop in real public spending in Hungary occurred between 1990 and 1997, but this is during a period estimated only using OECD data. In other words, it is not the result of our use of disparate sources of data.

Poland (Europe, Central)

Judd et al.: 1959, 1962, 1965, 1968, 1971, 1974, 1977–80 average.

OECD current database: Field of science estimates for government from 1994 to 2010; for higher education from 1995 to 2013. Socioeconomic objective estimates for government only from 2009–13.

For recent years, our estimates are the OECD field of science estimates, except for 2011-13, when only socioeconomic objective estimates are available for government. For those years, we use the estimates of government research based on socioeconomic objective criteria.

For the years 1990-94 in the case of government and 1990–95 in the case of higher education, we began with estimates of total government research and total higher education research from OECD, which go back to 1992, and supplemented them with total research estimates from Eurostat, which are consistent with the OECD estimates but go back earlier in time. We then calculated government agricultural research and higher education agricultural research for those years in the early 1990s by applying percentages derived from mid-1990s observations.

For earlier years, we relied on the Judd et al. estimates. We interpolated between their 1980 estimate converted to 2011 U.S. dollars and our 1990 estimate, also in terms of 2011 U.S. dollars, to obtain estimates for the years 1981–89. Again, this procedure is not ideal. However, a more serious impediment to accurate estimates for the late 1980s and early 1990s may be the extremely high rate of inflation during those years.

Slovenia (Europe, Central)

OECD current database: Field of science estimates, 1995-2013; socioeconomic objective estimates, 1994–2013. Eurostat has field of science estimates that are consistent with the OECD estimates but also include 1993 and 1994.

Slovenia's formal independence from the former Yugoslavia took place on June 25, 1991. We do not estimate public agricultural research for Slovenia before 1990. For 1993–2013, we use the field of science data from OECD and Eurostat. In the years of overlap, field of science estimates are generally but not always larger than socioeconomic objective estimates.

For 1990–92, we simply assume real public agricultural research was constant at the 1993–95 average. This procedure was followed because there are no observations on total public research by sector for 1990–92 that would allow us to apply a reasonable percentage, and estimates of total public research in those years would be compromised by high inflation rates.

Estimates of Total Public R&D for All Countries

For most countries in this study, OECD tends to have more data on total R&D by the government, higher education, and private nonprofit research sectors than it does for either "agricultural science" (field of science) or "agriculture" (socioeconomic objective) by sector. For most countries outside of Central Europe, these data begin in 1981 or shortly thereafter. For the countries in Central Europe, these data begin around 1990 or shortly thereafter. Although these data are also incomplete, they are usually sufficient for relatively consistent time series to be constructed using interpolation or extrapolation when necessary. However, our procedures for four countries are noted in greater detail.

Japan (Asia-Oceania)

As with the agricultural research data described in the previous subsection, total higher education research data for Japan from 1995 and earlier is overestimated compared to later years because it is estimated on a faculty count rather than a full-time equivalent basis. As with the agricultural

research data, we reduce the total higher education data from 1981 to 1995 by dividing by 1.4 to make it consistent with the more recent estimates.

Korea (Asia-Oceania)

Total public-sector research estimates for Korea are available in the OECD database for 1995–2014. However, estimates for all research, private as well as public, are available for 1991–94, not broken down by sector (government, higher education, private nonprofit, and business). Furthermore Chung (2011) estimates all research, private as well as public, for 1981. To complete estimates of public-sector research for 1981–94, we first assume all research, public and private, grew at the same annual rate between 1981 and 1991. We then estimate the rate of decline in the public proportion of the total for 1995–2014 with a semi-log regression and use this rate to project the public proportion back to 1981. This may approximate all public research fairly well back to about 1985, although an unpublished earlier version of Chung's paper suggests our estimates of total public research in the early 1980s are underestimates.

Luxembourg (Europe, NW)

Data for total public-sector research (and for all research, including the private sector) are only available for 2000–14. As described in the section on agricultural research in Luxembourg, publicly performed research in general only began with the creation of two public research institutes in 1987. We assume total public research in Luxembourg was zero in 1986 and then grew at an equal annual rate between 1987 and 2000.

Israel (Mediterranean)

Data on all research performed by the public sector are available for 1991–2014. From 1991 to 1997, growth in nominal public research is fairly smooth, so we use the estimated average annual growth rate from this period to project total public research back to 1981.

Estimates of Agricultural GDP and total GDP

Most of our estimates of agricultural GDP and GDP are taken from the World Bank, World Development Indicators dataset. However, the extent of the coverage varies in the current dataset. In a few cases, earlier downloads from the World Development Indicators included earlier observations. If not, we relied on print publications of World Tables, also by the World Bank. These publications are available for 1976, 1980, 1989–90, 1991, 1992, 1993, 1994, and 1995. We followed the practice of recording observations for given years from the most recently published source. Although the long time series generated in this fashion are not completely consistent, they provide reasonable estimates of underlying trends in agricultural GDP and total GDP. When estimating the proportions of total GDP accounted for by agriculture, we attempted to use the same source for both measures, agricultural and total, in a given year. For most but not all countries outside of Central Europe, some data are available from 1960 onward. Data begin around 1980 for Czechoslovakia (now the Czech Republic and Slovakia), Hungary, and Poland, and around 1990 for Estonia and Slovenia.

In a few cases, we used other information. Although composite series for the United States from the World Bank are fairly close to information from the U.S. sources noted here, we can construct

a complete, single source series for GDP from the Bureau of Economic Analysis at the U.S. Department of Commerce and a complete series for agricultural GDP from the ERS Farm Income and Wealth statistics, so we used this information. Other sources consulted included Statistics Canada, Petmezas (2009) for Greece, and Wolf (2009) for Poland.

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Appendix C. Developing Estimates for the Cost of Scientific Labor for Seven Countries

In this appendix, we describe the sources used to develop estimates for indexes of the costs of scientific labor. We also indicate the information we used to construct R&D-based purchasing power parity (PPP) exchange rates for different countries.

Data on the costs of scientific labor were used in constructing Griliches-Jaffe indexes, the basis for alternative international comparisons of public agricultural R&D in seven countries: Canada, the United States, Japan, Australia, France, Germany, and the United Kingdom (UK). The Griliches-Jaffe deflators are based on rates of change in general price levels as well as rates of change in the compensation of scientific labor. We use academic salary and related information as a proxy for the cost of scientific labor. We choose the time period ending in 2012 rather than in 2013 as we do for much of our other data because a substantial number of our data sources ended before 2013. The year 1992 was chosen as a starting year because additional data from an earlier cross-country survey (Altbach, 1996) are sometimes available for that year. In four countries—Canada, the United States, Japan, and Australia—we have some data on actual academic salaries. For France, Germany, and the UK, we have relatively limited information on salaries but somewhat more information on general budgets for academic staff and academic staff numbers, or budgets for all higher education and all higher education employees. For the UK, relatively disaggregated academic budget and academic staff data are available, so that dividing one by the other appears to come closer to actual salary levels available from other sources. For Germany and France, there is less detailed information on higher education expenditures and on either academic or all higher education staffing. Enough information exists to estimate rates of change in academic compensation, but it is somewhat less reliable than the data from the other countries. In some countries, particularly in Europe, dual-track systems including both universities and other institutions of higher technical learning can also make it difficult to estimate a general academic salary level.

For all countries, some estimate of an actual salary level, in addition to the rates of change, is necessary to calculate the R&D PPP exchange rate. The French data do not include such information, so we have to use another approach to anchor the annual rates of change to a presumed "salary level." So in this case, our results are somewhat less strong than those for the other countries. Nonetheless, we can compare our estimates of implied "academic salary levels" for 2010 with estimated real academic salary levels for 2010 in a large cross-country study (Altbach, et al., 2012). The actual estimates are not the same, but the ranking of real salary levels for 2010 from our estimates is very close to the ranking in Altbach et al. (table C.2). In the Altbach et al. study, the average real academic salaries for France and Japan are almost indistinguishable; our calculations show Japanese salaries about 6 percent higher. Also, the Altbach et al. salary estimates for the UK and Australia are fairly close to the U.S. estimates. In our calculations, the gap is somewhat wider.

Table C.1
Ranking of 2010 academic salary levels

Rank (1=highest, 7=lowest)	Altbach et al. (2012)	This study
1	Canada	Canada
2	United States	United States
3	United Kingdom	United Kingdom
4	Australia	Australia
5	Germany	Germany
6	France	Japan
7	Japan	France

Source: USDA, Economic Research Service using sources detailed in this appendix and Altbach et al. (2012).

Canada (North America)

Canadian university salaries for the years 1980–83 are available from von Zur-Muehlen (1983). From 2000 to 2010, we obtained average salary levels from the Canadian Association of University Teachers (CAUT). These data had been provided by Statistics Canada. Statistics Canada cancelled this particular survey, but we were able to obtain some information from Ontario for 2011 and 2012. We updated our series to 2012 by assuming the Canada-wide average increased at the same rate as the Ontario average for the 2 remaining years.[53] For years between 1983 and 2000, we assumed equal rates of growth each year. We used our estimates for 1992–2012 as the basis of our analysis.

United States (North America)

Average faculty salaries for the United States were obtained from the American Association of University Professors annual reports on the economic status of the profession. This is the same source used for one of the three components in the ERS research deflator for the United States.

Japan (Asia-Oceania)

Salaries by rank (going back to 1962) are available for private universities in Japan from the Research Institute for Higher Education (RIHE), Hiroshima University. Counts by rank, including counts by rank for private universities (going back to 1970), are also available from RIHE. To get average salaries, we weighted salaries by rank using the counts by rank.

Australia (Asia-Oceania)

We obtained academic salaries by rank from four sources. For even-numbered years between 1992 and 2002 (data from this source go back further than 1992), we used data from Horsley and Woodburne (2003). These data were reported in 1977 Australian dollars, which we converted to current Australian dollars using the consumer price index from the Australian Bureau of Statistics. For 2003-08, we used data on academic salaries by rank from Coates et al. (2009). Data for 2010

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[53] Since we collected the data we used, CAUT has reported academic salaries for 2013–14. These were obtained by the National Faculty Data Pool at Western University (London, Ontario), using the same instrument as Statistics Canada. However, coverage of this voluntary survey is probably less than the coverage of the earlier Statistics Canada survey, particularly for smaller institutions.

were obtained from Welch (2012), and data for 2012 were obtained from Deloitte (2012). The data for 2012 covered only eight major universities.

Data on employment numbers by rank and full-time equivalents are available from the Australian Bureau of Statistics from 1989 to 2015. We used these data from 1992 to 2012 along with the salary level by rank data to create a weighted-average annual academic salary.

France (Europe, NW)

Data for France were obtained from the Ministry for National Education, Higher Education and Research. These data are less ideal than for some of the other countries. The total higher education budget was available for 1980, 2000, and 2005–12. The percentage of the budget devoted to staffing was available for 2006–12. We interpolated to create time series for the total higher education budget from 1992 to 2012, and assumed the proportions devoted to staffing for the years 1992–2005 changed at the same rate they did in the United Kingdom over those years (the UK data were from the UK Higher Education Statistical Agency, described below). Thus, we were able to construct a series for 1992–2012 of the total higher education budget devoted to staffing.

Data were also available on "numbers of public researchers" for 1992, 1997–2004, and 2006–10, and for "higher education researchers" from 1997 to 2013. We used these to create a series of researcher counts from 1992 to 2012. We combined the estimates calculated from the higher education budgetary data with the researcher counts to get estimates of "higher education budget per researcher" for 1992–2012. This figure in each year was considerably higher than likely actual faculty salaries in France, perhaps in part because the budgetary data spanned a broader group of institutions than the researcher data and covered more costs than salaries alone. Nonetheless, we used these data to approximate annual rates of change in actual faculty salaries, necessary for calculating the cost of scientific labor component of the Griliches-Jaffe approximation of a research deflator. These estimates show apparent stagnation in expenditures per researcher over the first half of the period covered.

To create the R&D PPP exchange rate, we needed to combine the rate of change data with some observation on actual salary levels. We did this by using the implied salary level for business sector scientific researchers in France in 1997 reported by Dougherty et al. (2007) and assume this is equal to the salary for academic scientific personnel in that year, even though it is likely to be an overestimate. Although the resulting estimates of "academic salaries" for France are far from ideal, they are consistent with anecdotal and other evidence (e.g., Angermuller, 2017) that academic salaries in France are lower than in many other high-income countries and have sometimes stagnated.

Germany (Europe, NW)

Faculty compensation data for Germany are also less than ideal. Faculty count data are available from the German Federal Statistical Service, but no corresponding budgetary estimates are available. However, the Federal Statistical Service provides other useful information, total university personnel costs and total numbers of employees for 2001–14. We use this to calculate cost per employee for these years and use the rates of change in this figure as a proxy for the rates of change in academic salaries for these years. We can also calculate an average salary for 2007 from data presented by Teichler and Höhle (2013) and use this to fix levels for the years 2001–14. Finally, we

can calculate an average salary for 1992, in this case for West Germany only, from data in Altbach (1996). We interpolate between 1992 and 2001 to complete the series.

We also obtained research deflators (for 1992–2012) for business in Germany from Christian Rammer (personal communication) of the Centre for European Economic Research (ZEW). ZEW uses salary-based R&D deflators for both services and manufacturing and another R&D deflator for capital expenditures. Our faculty salary index rises more slowly than the ZEW indices for services and manufacturing but more rapidly than the deflator for capital expenditures. Rammer did not know of specific faculty information but indicated that, in general, faculty salaries in Germany rise more slowly than private-sector salaries. This is consistent with the comparison between our faculty salary index and the ZEW salary-based deflators.

United Kingdom (Europe, NW)

Academic salary data per se for the UK are only readily available for a few years. However, from 1995 to 2012, fairly detailed data are available from the Higher Education Statistical Agency. We took the data series for "total academic staff costs, academic departments" and divided each annual observation by the observation on "FTE's, academic staff, academic departments" and used the resulting figure as an "average academic salary" for that particular year. We extrapolated this series backward from 1995 to 1992 to create our final series.

There are single-year salary estimates for the UK from the same sources and for the same years as in the example of Germany. Altbach (1996) provide data that can be used to calculate an average academic salary for the UK in 1992, and Teichler and Höhle (2013) do the same for the UK in 2007. Our estimates for those years are actually 15–20 percent lower than the estimates from these sources. This may be because of broader coverage in the HESA data. However, the implied average annual rate of growth between 1992 and 2007 is about the same—4.3 percent calculated from our data, and 4.1 percent when comparing the Teichler and Höhle and Altbach et al. estimates.

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