Chapter 7

THE US AGRICULTURAL INNOVATION SYSTEM

This chapter describes the US Agricultural Innovation System in relation with the general innovation system, outlining how it adjusted to changes in the global science landscape. It presents main actors and their roles in the system, and provides an overview of governance mechanisms. It also describes main trends in public and private investments in R&D, and discusses complementarities and changes in funding mechanisms. It provides an overview of policy incentives for fostering innovation, outlining the role of farm extension, Intellectual property rights, tax incentives and public-private partnerships, and reports evidence on R&D outputs and impacts, as well as examples of adoption of innovation. Finally, the role of US agricultural science in international co-operation is discussed.

The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

Foundations of the US agricultural innovation system

By the middle of the 20th Century, the United States had emerged as the global leader in agricultural science and technology. Through a federal-state partnership, it had developed an integrated research-extension-education system (Box 7.1). Not only did this contribute to produce an internationally competitive farm sector, but agricultural science and technology itself became an export industry. Agribusiness suppliers of improved farm inputs — crop seeds, animal breeds, agricultural chemicals, and farm machinery — developed export markets for their products, and agricultural universities attracted numerous foreign students for advanced study.

Over the ensuing decades the US agricultural innovation system has adjusted to a changing global landscape for science and technology. This chapter focuses on three major developments to this landscape and how US agricultural science policy, particularly at the federal level, has responded. First, major scientific advances in biological and computation sciences have led to the emergence of a "*New Biology*".[1] In response, the agricultural research system has sought to forge stronger linkages with these sciences and develop applications for food and agriculture. Second, there has been major growth in the agricultural research and development (R&D) capacities of the private sector. Whole classes of farm technologies that were once the purview of the public sector are now developed and disseminated by commercial firms. The public system has needed to redefine its role and forge stronger linkages with commercial R&D capacities. Third, as science and technology capacities of other countries have grown, the relatively dominance of the US system has declined. This has opened up new possibilities for international scientific partnerships to work on common challenges. At the same time, the United States has continued to help build agricultural innovation capacity in low income countries as part of its historical commitment to achieving global food security.

Box 7.1. Foundations of the public agricultural innovation system in the United States

US public agricultural research began with federal efforts in the late 18th Century to collect seeds and plants from around the world and distribute them to American farmers to test for their suitability for US agricultural conditions. Starting in 1819, seed collection was organised by the Patent Office. In 1862, the US Department of Agriculture (USDA) was established as an agency within the executive branch of the Federal government and took over this function from the Patent Office. The USDA greatly expanded seed collection and distribution, as well as the gathering of agricultural statistics. While broadly conceived, USDA's initial focus was to procure, test and distribute new plants and seeds; to diffuse useful information on subjects connected with agriculture; and to raise the productivity of US agriculture.

In the same year, the Morrill Act of 1862 created the Land Grant Colleges (so named because they were funded using sales of public land). Congress saw the need to establish educational institutions in each state, focused on practical studies in agriculture and the domestic and mechanical arts. While initial funding came from the federal government, the Land Grant Colleges are governed and supported by the states.

Some states began to establish research programmes to facilitate the sharing of scientific knowledge among academics, and to disseminate their findings to agricultural producers. However, the need for a concerted, coordinated national approach was seen. The Hatch Act of 1887 provided federal funding to establish a State Agricultural Experiment Station (SAES) in each state, for the purpose of agricultural research, including problems of regional importance. Most SAES are part of or connected to the Land Grant Colleges. The USDA was raised to a cabinet-level department in 1889, and began reporting directly President. Intramural research by the USDA was significantly expanded in the late 19th and early 20th Centuries and provided scientific leadership for the federal-state agricultural research system. In 1953, agricultural research in the various USDA bureaus was consolidated into the newly formed Agricultural Research Service (ARS). ARS now employs more than 2 000 scientists in 90+ laboratories throughout the country.

Despite the steady gains in higher education and research programmes at the Land Grant Colleges and SAES, disseminating technical innovation to farmers remained an obstacle. The Smith-Lever Act (1914) created cooperative state extension services as a federal-state-local partnership. Based in land grant institutions, extension services specifically were designed to share the results of agricultural research with farmers, household managers and young people. Together, the Morrill Act, the Hatch Act and the Smith-Lever Act established the three legs of the US agricultural innovation system — education, research and extension.

Further federal legislation strengthened and expanded the system. The Bankhead-Jones Act (1935) provided increased federal funding to Land Grant Colleges, based on formulas based on states' populations. The Act also required that such federal funds must be matched by state governments. The matching requirement encouraged farmers to get more involved in their state Land Grant programs and lobby their state legislators to support them. The economic rationale for matched funding is that benefits of agricultural research often spillover across state boundaries. Left to themselves, states face an incentive to under-invest or "free ride" on other states' investments in agricultural research.

Other changes expanded the system to address needs of under-served populations and communities. A second Morrill Act of 1890 created separate Land Grant Colleges that did not discriminate on the basis of race in states that at that point did not admit African Americans to their land grant universities. The Equity in Educational Land-Grant Status Act of 1994 conferred land grant status to Tribal Colleges and Universities, which primarily serve Native Americans in remote and underserved communities, boosting federal funding for these institutions.

Source: This summary draws heavily upon Ruttan (1982) and Huffman and Evenson (1993).

Agriculture in the US research system

Agriculture has a unique history in US science and technology policy. Prior to the Second World War (WW II), agriculture was the only economic sector receiving significant federal government support for R&D. Legislation passed in the late 19th and early 20th Centuries — especially the Morrill Act (1862), the Hatch Act (1887) and the Smith-Lever Act (1914) — established a federal-state partnership to support agricultural education, research and extension (Box 7.1). As late as 1940, nearly 40% of total federal government R&D spending was for agriculture, with most of the remainder focused on national defence (Mowery and Rosenberg, 1989).

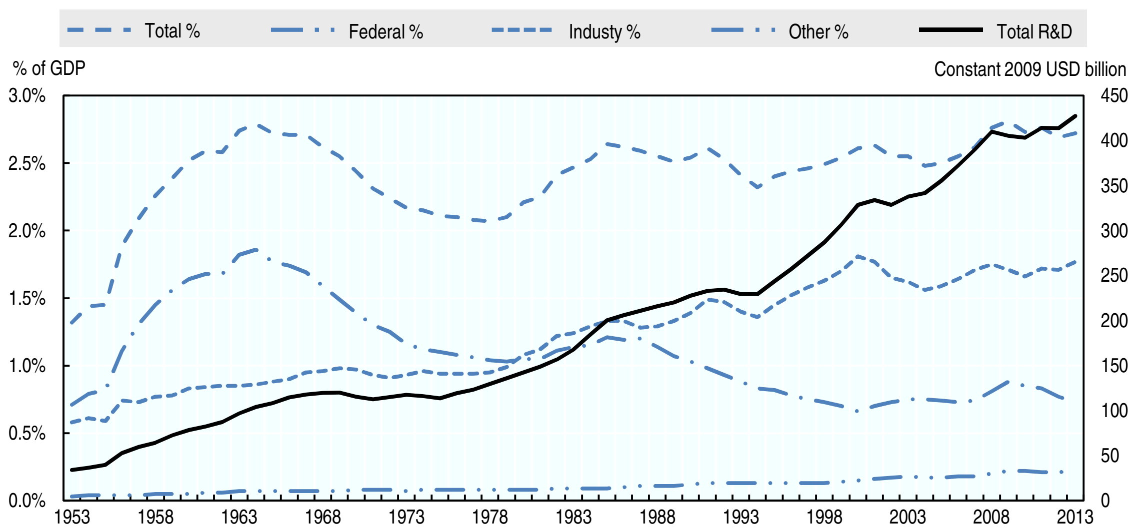
WW II transformed the US R&D system. During the war, the nation's university science and engineering communities were mobilised to support the development of new military technologies. As the war ended, the President's science advisor, Vannevar Bush, proposed a much larger role for the federal government in support of post-war scientific research. His report, *Science: The Endless Frontier* (Bush, 1945), established the new charter of US research policy. Government investment in research would contribute not only to national security but also to the development of new products, new industries and job creation. Subsequently, government funding for R&D rose quickly, and the United States became the pre-eminent world leader in scientific and technological discoveries.

The economic justification for the expanded government role in R&D was that the social returns to R&D exceeded the private returns by a wide margin (Nelson, 1959; Arrow, 1962). Much of the benefits of R&D would "spill over" to other firms and consumers. In other words, the creation of knowledge has the properties of a "public good" – it is non-rival (several individuals can consume it without diminishing its value) and non-excludable (once in the public domain, an individual cannot be prevented from making use of it). Since a firm could only capture a fraction of the total benefits of R&D, industry would significantly under-fund it. The market failure argument was originally formulated to justify public support for basic research. But economic studies have also found large gaps in the social and private rates of return to applied research for a wide range of industries (Hall, Mairesse and Mohnen, 2010), including agriculture (Pardey, Alston, and Ruttan, 2010). Thus, the private sector responding to market incentives is likely to significantly under-fund applied research as well (Ruttan, 2001).

US investment in research and development

Total government and private R&D spending as a percentage of GDP doubled from 1.4% in 1953 to 2.7% in 2013 (Figure 7.1). R&D spending rose quickly, peaking in 1964 on the back of rapidly rising federal R&D spending in support of the Apollo space project. Federal R&D spending as a share of GDP rose to 1.9% by 1964, but then was gradually scaled back as the Apollo project came to an end. Another surge in federal R&D spending occurred in the 1980s led by increased spending on energy R&D following the oil price shocks of the 1970s. This also tapered and federal R&D spending fell to 0.7-0.8% of GDP by 1995. It has remained at about this level since, with health research receiving a growing share of the total. R&D spending from industry, however, steadily rose from a low of 0.6% in 1953 to 1.8% by 2013, accounting for almost two-third of the total, while federal spending is slightly over one-fourth. Industry spending overtook federal spending in 1980 and has remained the dominant source of US R&D funding since. The category "other" includes spending by non-federal governments, universities and colleges, and other non-profits. It rose from negligible amounts to 0.22% of GDP.

Figure 7.1. Total R&D spending as a share of GPD, 1953-2013



Source: National Science Foundation (2016), Science and Engineering Indicators Report, Appendix Tables. www.nsf.gov/statistics/2016/nsb20161/#/downloads/report.

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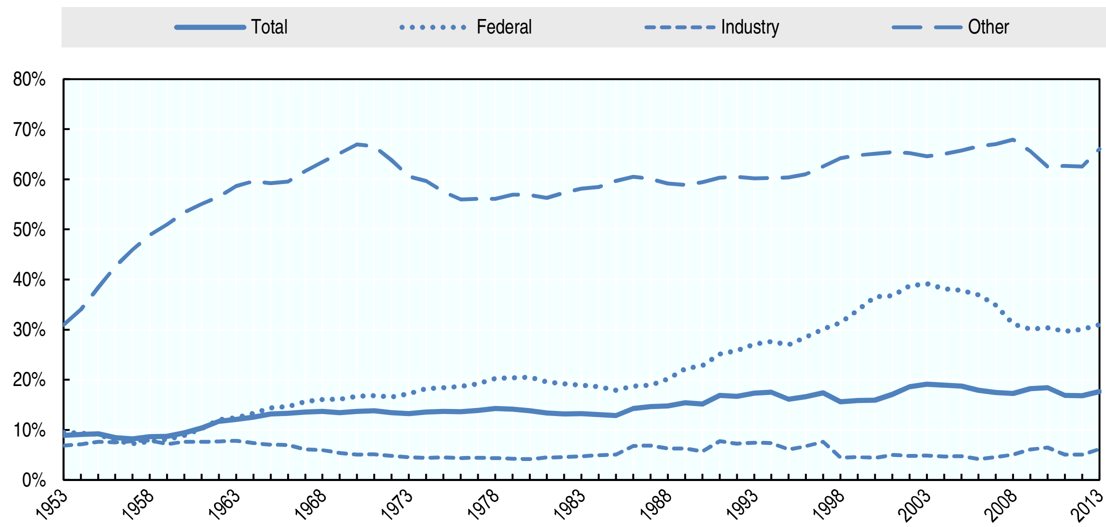
R&D is typically divided into three categories: basic research, applied research, and development (see the footnote to Table 7.2 for definitions of these terms). Basic research constitutes the work of fundamental discovery, with the purpose of enhancing our knowledge about the world. The share of basic research in total R&D spending has risen from 8.9% in 1953 to 17.6% in 2013 (Figure 7.2). Of the remaining R&D spending, in 2013 most went to development (62.4%), rather than applied research (20.0%). The rise in basic research as a share of R&D has been driven largely by the increasing specialisation of the Federal Government in basic research, and by the growth of the "other" category in total spending. While the Federal Government has long allocated more of its R&D to basic research than industry, the two were quite close through the 1950s. Since then the share of basic research in federal funding has risen to a peak of 39.2% in 2003, before falling to 31.0% in 2013. In contrast, the share of basic research in industry R&D has kept in the 4-8% interval over the period 1953-2013. The "other" category, which includes universities and colleges, has consistently devoted between 55-70% of R&D spending to basic research since 1961. As total funding in this category grew, it also contributed to the overall tilt towards basic research.

Figure 7.2. Basic research share of R&D expenditures, 1953-2013

Share of R&D that is basic research (%)



Source: National Science Foundation (2016), Science and Engineering Indicators Report, Appendix Tables. www.nsf.gov/statistics/2016/nsb20161/#/downloads/report.

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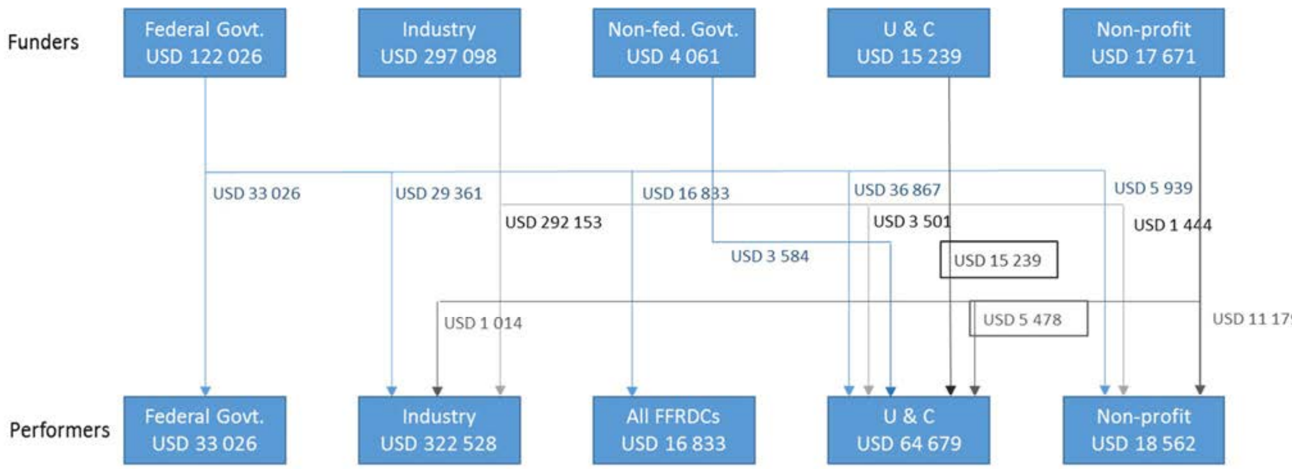
Figure 7.3 provides more detail on how R&D in the United States is currently funded and performed. Industry provides the largest share of funding for R&D. It also is the chief performer of R&D. Only a very small share of industry R&D funding is contracted to universities and colleges, or other non-profits, but the Federal Government allocates nearly a quarter of its own funds to industry performers. The Federal Government is also the largest source of funds for research performed by universities and colleges. Taken together, industry supplies 65% of R&D funds, but performs 71% of all R&D activities. Industry is also heavily skewed towards development, rather than basic or applied research. Development accounts for 78% of industry's R&D performance.

The Federal Government has a more balanced R&D profile, channelling approximately one third of its expenditures to basic research, one fourth to applied research, and the remainder to development. Because the Federal Government is one of the biggest funders of R&D, the USD 37.9 billion it spends on basic research accounts for 47.1% of all funding of basic research. As a performer of R&D, however, the Federal Government is more similar to industry, with development accounting for about half of federal R&D performance, and basic research accounting for 19%.

Universities and colleges supply just 3.3% of R&D funds, but are significant performers of research (14%). Universities and colleges also take the lead in basic research, performing half of all basic research. Other non-profit agencies contribute more to overall R&D spending, but have a much smaller footprint in terms of performing R&D. Universities and colleges, and other non-profits, are heavily tilted towards funding basic research.

Figure 7.3. R&D expenditures by sources of funds and performing sector in 2013



Figures in millions of current USD.

U&C: Universities and Colleges.

FFRDC: Federally-Funded Research and Development Center. FFRDCs are operated by industry, U&C, or non-profits.

Non-federal governments also performed USD 467 million of R&D (not shown in figure) with their own funds.

Source: National Science Foundation (2016), Science and Engineering Indicators Report, Appendix Tables. www.nsf.gov/statistics/2016/nsb20161/#/downloads/report.

Composition of federal R&D expenditures

For most of the post WWII period, defence has dominated R&D expenditures by the US government (Table 7.1). As late as 1990, at the end of the Cold War, defence R&D made up nearly two-thirds of total federal R&D spending. Since then, the share of non-defence R&D has risen, with most of the increase going to health research. Agriculture's share of total federal R&D declined in recent decades from 1.9% in 1980 to 1.4% in 2014.

Table 7.1. Federal R&D expenditures by function, 1960-2014

	Total spending	Defence	General science (NSF)	Atomic energy general science	Space	Energy	Trans-porta-tion	Health	Agri-culture	Natural res. and environ.	All other	Total non-defence
	Billion USD	% of total										
1960	42 056	81.1	0.8	2.5	4.5	2.2	1.1	3.8	1.5	0.9	1.7	18.9
1970	67 920	52.9	1.9	2.6	23.2	3.0	2.7	7.1	1.6	2.0	3.0	47.1
1980	69 506	48.4	2.8	1.1	14.1	10.9	2.8	12.2	1.9	3.1	2.6	51.6
1990	96 276	64.4	2.4	1.2	8.8	3.7	1.5	12.9	1.5	1.9	1.7	35.6
2000	90 766	55.5	3.3	3.0	7.3	1.7	1.9	21.5	1.7	2.3	1.7	44.5
2010	139 711	57.5	3.4	2.4	5.6	1.4	0.9	24.5	1.3	1.3	1.6	42.5
2014	121 490	53.7	4.0	3.1	8.2	1.8	1.0	23.4	1.4	1.5	1.9	46.3

Total spending given in constant 2009 USD where annual spending is deflated by the US GDP price deflator.

Source: Office of Management and Budget (2015) Historical Tables Table 9.8. www.whitehouse.gov/omb/budget/Historicals.

Table 7.2 breaks down the Federal Government's R&D expenditures by agency, character of work, and field of science for 2013. The Department of Defense (DOD) and the Department of Health and Human Services (DHHS) account for three-quarters of all federal R&D. DOD, which is heavily specialised in development, accounted for 50.0% of R&D expenditures on its own. In contrast, the DHHS (which includes the National Institutes of Health) is heavily specialised in basic and applied research in life sciences, and accounts for another 23.2% of federal R&D funding. In 2013, the USDA accounted for 1.6% of federal R&D obligations and primarily specialised in basic and applied research in the life sciences.

Table 7.2. Federal Government R&D obligations by selected agency, character of work and field of science, 2013

Million USD

	DOD	DHHS	DOE	NASA	NSF	USDA	Other	Total
Development	57 602	68	2 508	4 946	0	151	913	66 188
R&D plant	97	130	556	126	373	17	611	1 910
Applied	4 093	14 026	3 482	2 598	594	1 025	3 602	29 420
Basic	1 863	15 288	3 851	2 824	4 362	844	747	29 779
Total R&D	63 655	29 513	10 397	10 494	5 329	2 037	5 873	127 297
Basic and applied research by field of science								
Environmental science	301	362	320	1 202	922	33	901	4 041
Life science	713	24 599	390	321	666	1 462	1 179	29 330
Math and Computer Science	986	159	988	99	988	12	195	3 427
Physical science	739	154	2 696	1 365	872	97	359	6 282
Psychology	49	1 725	0	22	31	0	108	1 935
Social science	63	154	3	1	173	186	657	1 237
Other science	281	813	145	245	434	0	81	1 999
Engineering	2 823	1 348	2 793	2 167	870	79	868	10 948
Total basic and applied research	5 955	29 314	7 335	5 422	4 956	1 869	4 348	59 199

Definitions:

Research: the systematic study directed toward fuller scientific knowledge or understanding of the subject studied. Research is classified as either basic or applied research according to the objectives of the sponsoring agency.

Basic research: the objective of the sponsoring agency is to gain more complete knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific applications toward processes or products in mind.

Applied research: the objective of the sponsoring agency is to gain knowledge or understanding necessary for determining the means by which a recognised need may be met.

Development: the systematic use of the knowledge or understanding gained from research directed toward the production of useful materials devices systems or methods including design and development of prototypes and processes.

R&D Plant: investment in long-lived R&D physical assets such as facilities fixed equipment and land.

DOD = Department of Defense; DHHS = Department of Health & Human Services; DOE = Department of Energy; NASA = National Aeronautics & Space Administration; NSF = National Science Foundation; USDA = US Department of Agriculture.

Source: National Science Foundation (2016), *Science and Engineering Indicators Report*, Appendix Tables. www.nsf.gov/statistics/2016/nsb20161/#/downloads/report.

The US food and agricultural R&D system: Actors and funding

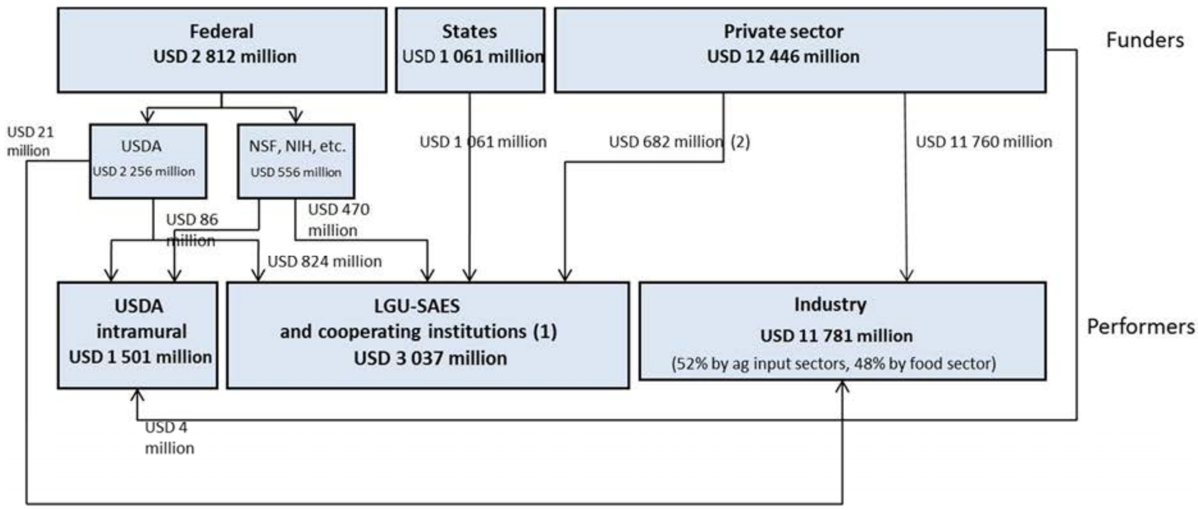
Over the past 150 years the original federal-state cooperative enterprise providing agricultural research, extension and education services evolved to accommodate changes in the broader innovation systems affecting agriculture. One important development is the increasing research capacities in the private business sector to provide innovations for farms. While formal research by farms remains negligible, manufacturing firms, seed companies and other private R&D service providers invest significant resources in research to develop new technologies for use in agriculture. Another significant development is the emergence of stronger linkages between agricultural sciences and other fields, especially biological sciences and information technologies. This has expanded the set of institutions funding and preforming research relevant to agriculture. How these developments have affected the organisation and function of the US food and agricultural R&D system are discussed below.

Funders and performers of food and agricultural research

In 2013 (the latest year for which comprehensive estimates are available), federal, state, and private institutions funded and performed approximately USD 16.3 billion worth of R&D for food and agriculture (Figure 7.4). Of this total, the majority was funded and performed by the private sector. The Federal Government, through the USDA and other federal agencies, funded approximately USD 2.8 billion of R&D (or 17% of R&D for food and agriculture). Of this total, about USD 1.5 billion worth of federally-funded research was performed by USDA intramural research agencies. Land Grant Universities (LGUs), State Agricultural Experiment Stations (SAES), and other cooperating institutions received USD 3.1 billion from all sources, including USD 1.3 billion in federal monies, for agricultural R&D. About two-thirds of the federal support for LGUs was channelled through the USDA and the rest from other federal agencies. These state institutions received another USD 1.1 billion from State governments and USD 0.7 billion from non-government sources for research. Non-government sources include contributions from commodity groups (check-off funds), private companies, non-profit foundations, and earnings from licensing fees and product sales. Research performed at USDA, LGU-SAES, and cooperating institutions is mostly oriented toward agriculture, but also includes research on forestry, natural resources, food and nutrition, economics and statistics, and rural development.

Food and agricultural research performed by private industry is financed almost entirely by for-profit companies, and include firms from several industrial sectors. Of the estimated USD 11.8 billion in R&D performed by these firms in 2013, just under half was by the food manufacturing sector (companies that process raw agricultural commodities into food products). Research by these firms was heavily oriented to new product development or manufacturing process improvements. Relatively little of the R&D performed by the food manufacturing sector was for agricultural technology. The other part of private R&D was to develop improved inputs for use on farms and was performed by crop seed and livestock genetic companies as well as a range of manufacturing industries (chemical, machinery, biotechnology, and pharmaceutical). In addition to the for-profit sector, some agricultural research is conducted by private, non-profit institutes funded primarily through charitable or government grants (these form a very small part of the system in terms of funds involved and are not shown in Figure 7.4).

Figure 7.4. Funders and performers of food and agricultural research in 2013



1. LGU-SAES and cooperating institutions: The 1862 and 1890 Land Grant Universities and State Agricultural Experiment Stations. Cooperating Institutions include Veterinary Schools, Forestry Schools, and other US colleges and universities receiving agricultural research funding from the USDA.

2. Private sector contributions to LGU-SAES (USD 682 million) consist of (i) research grants and contracts from private companies (ii) research grants from farm commodity groups, philanthropic foundations, individuals and other organisations, and (iii) revenue and fees from the sale of products, services, and technology licenses.

Source: USDA Economic Research Service.

Long-term trends in food and agricultural R&D spending

In recent decades, food and agricultural R&D performed by the private sector has grown faster and has become significantly larger than food and agricultural R&D spending by public institutions (Figure 7.5). Private food and agriculture R&D nearly doubled between 2003 and 2013, from around USD 6 billion per year USD 11.8 billion in 2013 (in constant 2013 USD). Private R&D spending by food manufacturing firms and agricultural input industries increased in tandem.

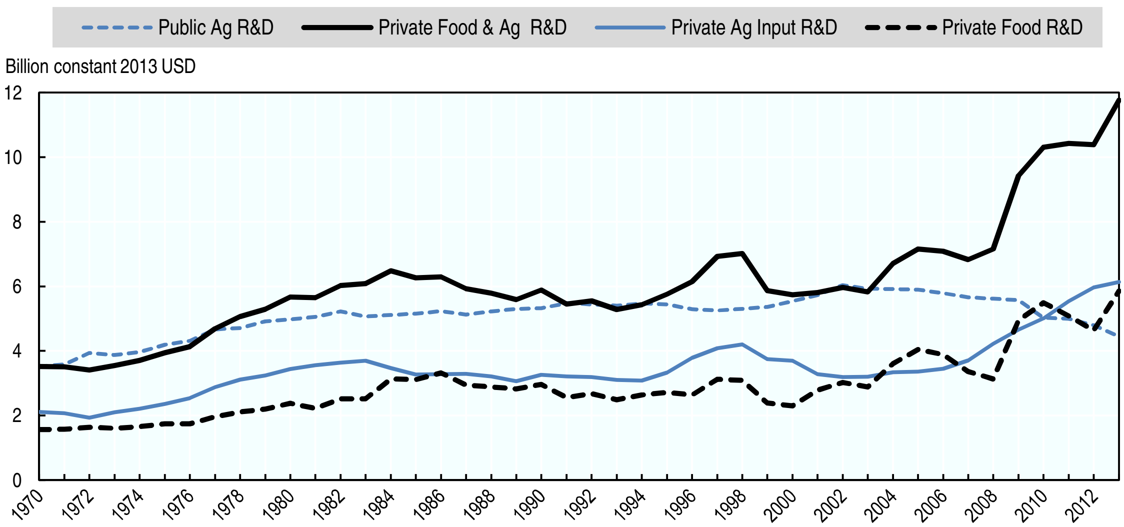
Public agricultural R&D, meanwhile, declined in real terms. For agricultural-related research alone, which historically the public sector has dominated, by 2011 the private had overtaken the public sector. Some of the key drivers of the growth of private investment in food and agricultural research have been: 1) advances in science that have opened up new opportunities for commercial technology development, 2) stronger intellectual property rights over biological innovations, 3) expansion of national and global markets for new food products and agricultural inputs, and 4) new regulatory requirements over new product introductions (Fuglie et al., 2011).

Trends in public sector research have been driven particularly by expenditures by state institutions, where two thirds of the public sector research was performed in 2013. State-level public agricultural research expenditures rose in real terms until about 1990, with funding increases coming from many sources, including appropriations from state legislatures. Since 1991, however, total agricultural research appropriations by all State governments combined has fallen in real terms. Decline in state funding was initially offset with increases in funding from other sources, including non-USDA federal agencies and industry (Schimmelpfennig and Heisey, 2009). However, total agricultural research expenditures by state institutions began to fall in 2002. USDA intramural research expenditures have fluctuated over time and also drifted downwards in real terms after 2002.

As a result of lower public sector expenditure on agricultural R&D in the United States combined with higher capacity in emerging economies in particular, the US share of global spending on public agricultural research fell from 21% to 13% between 1960 and 2009 (Pardey et al., 2013).

In purchasing-power-parity dollars, US spending on public agricultural research has fallen substantially below spending by China and Western Europe (Figure 7.6).

Figure 7.5. Public and private spending on food and agricultural R&D, 1970-2013



Annual spending on research is adjusted for inflation by a research price index constructed by ERS.

Source: USDA (2015a), Economic Research Service. www.ers.usda.gov/data-products/agricultural-research-funding-in-the-public-and-private-sectors.aspx.

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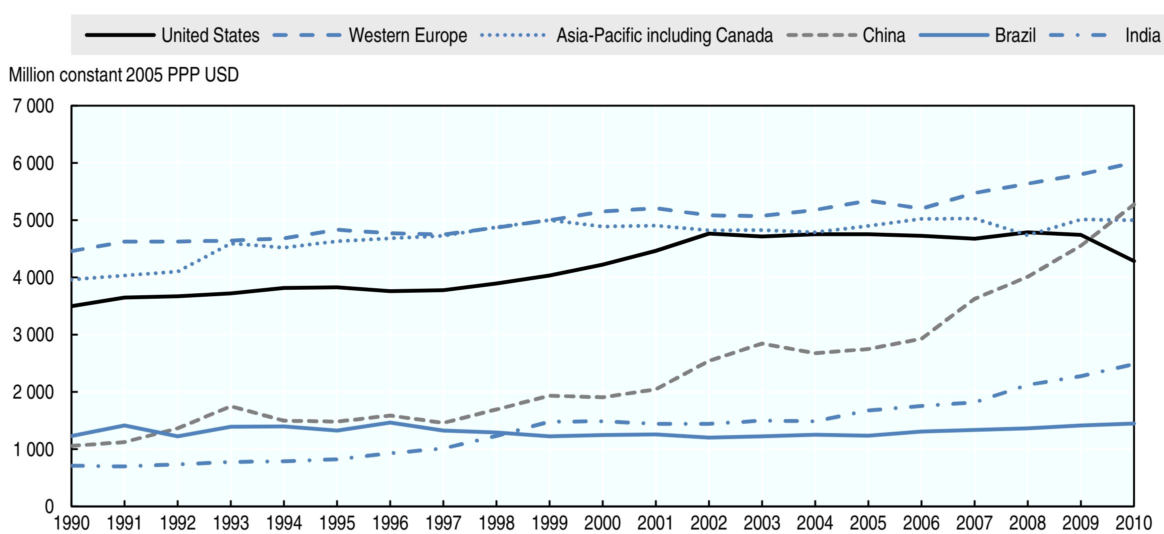
Figure 7.6. Expenditures for public agricultural research by the United States and other major countries and regions, 1990-2010

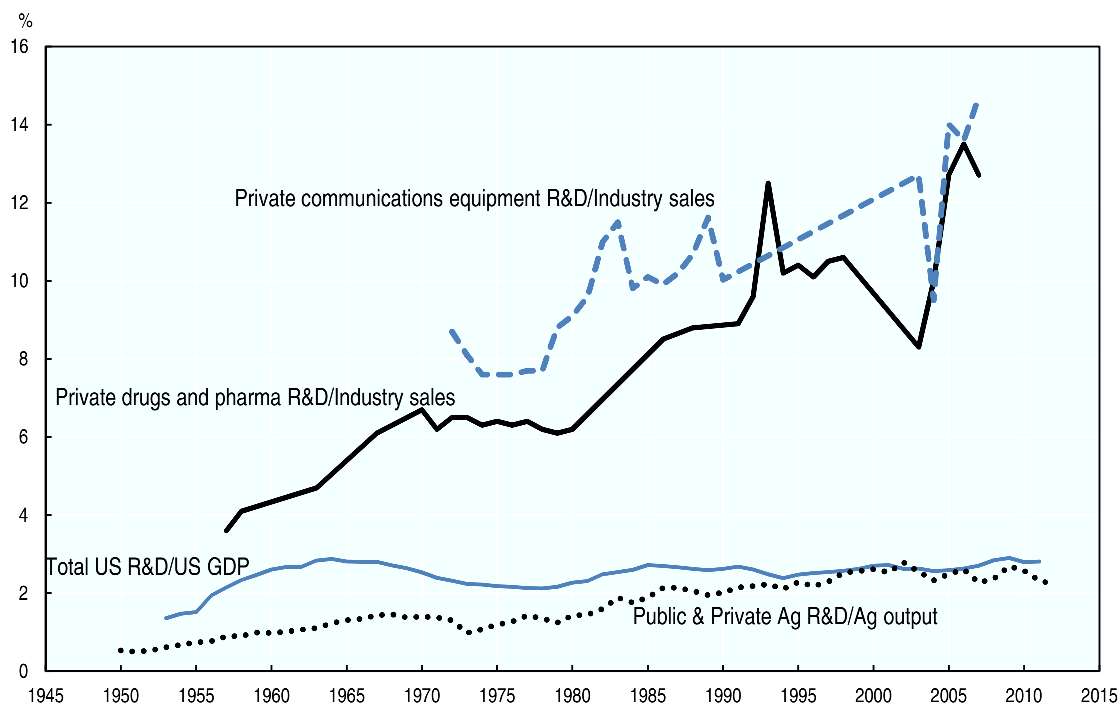


Source: Agricultural Science and Technology Indicators (2015) (ASTI) www.asti.cgiar.org/data and USDA (2015a), Economic Research Service. www.ers.usda.gov/data-products/agricultural-research-funding-in-the-public-and-private-sectors.aspx.

StatLink http://dx.doi.org/10.1787/888933408958

Despite the recent growth in private R&D, total funding for agricultural R&D in the United States is not exceptional when compared with the size of the sector. As a share of the gross value of output (the research intensity), total public and private R&D spending for agriculture was equivalent to 2.32% the value of farm sales in 2011, compared with 2.57% for the US economy as a whole (Figure 7.7), This is far below private R&D levels in high-technology sectors like information technology and pharmaceuticals, where research intensity exceed 15%. The food manufacturing sector is even lower, with business R&D is less than 1% of gross sales (not shown in the figure). Although data are not strictly comparable in their coverage of activities, it seems that the share of public expenditure on agriculture R&D in agricultural value-added in the United States was close to that in Brazil and Australia, but lower than in Canada and the Netherlands (OECD, 2015b). It would be useful to improve data comparability at the international level to be able to better evaluate respective efforts.

Figure 7.7. Research intensities for agriculture and selected sectors of the US economy, 1940-2013



Source: National Science Foundation (2014), www.nsf.gov/statistics/seind14/index.cfm/etc/sitemap.htm, except for agriculture, which is from USDA (2015b), Economic Research Service, www.nsf.gov/statistics/seind14/index.cfm/etc/sitemap.htm.

StatLink http://dx.doi.org/10.1787/888933408963

Public and private agricultural R&D: Crowding out or complementary?

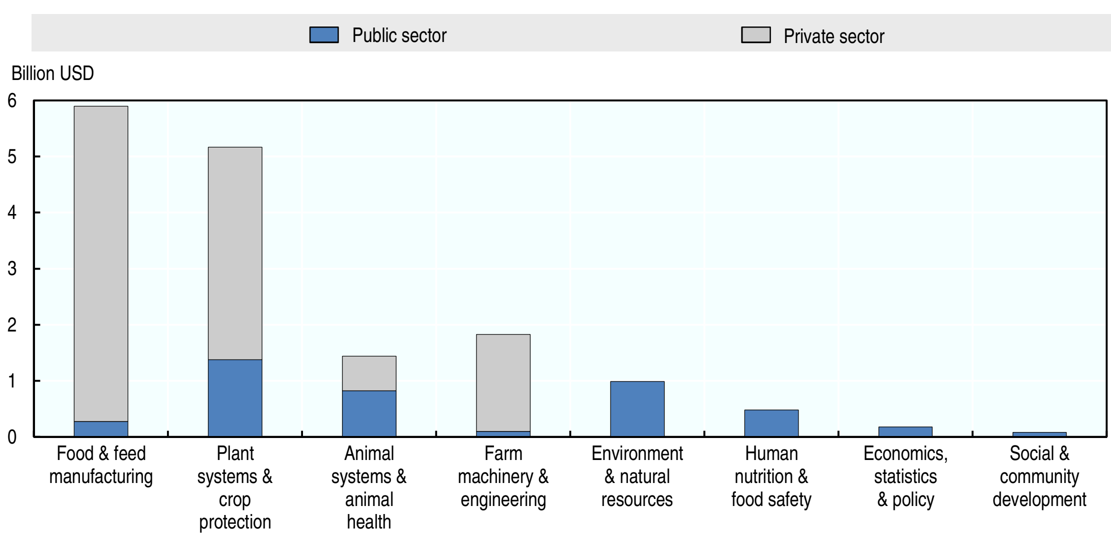
The market failure argument provides an economic rationale for the public sector to fund basic and applied R&D. However, if the public sector competes directly with private innovators in the provision of new technologies for businesses or consumers, it could crowd out private R&D. On the other hand, by focusing on areas where there is thought to be a large gap between social and private returns to research — in other words, on areas that have a large public-good component — public R&D could complement private R&D.

Economic studies have tested the crowding-out hypothesis for agricultural research and have generally found that US public and private agricultural research are complementary. These studies find evidence that public R&D stimulates greater private R&D by creating opportunities for businesses to develop and commercialise new products and processes for economic growth. Each dollar spent on public food and agricultural research appears to stimulate about USD 0.70 in additional private R&D spending (Fuglie and Toole, 2014). One implication of the complementarity between public and private research is that continued robust public investments in science may be necessary to prevent private agricultural R&D spending from eventually tapering off.

Comparisons of public and private agricultural R&D resource allocations across topic areas help to illustrate this complementarity (Figure 7.8). Private R&D dominates food manufacturing and farm machinery and makes major investments in plant systems, while public R&D addresses a broad set of socially important issues like environment and natural resources, food nutrition and safety, economics and statistics, and community development, where private R&D is low due to the significant public goods dimension of these kinds of research. It is difficult for private companies to justify research investments such as those exploring human nutrient requirements, soil and water resources conservation, and other important public goods because of the difficulty of capturing a return on investment in these activities.

Both the public and private sectors make significant investments in plant and animal systems. A closer inspection of the specific kinds of research and fields of science emphasised by each sector reveals further evidence of complementarity. Much of the private R&D for plant and animal systems is oriented toward the discovery and commercialisation of new agricultural pesticides, veterinary pharmaceuticals, and introducing genetically-engineered (GE) traits into crop cultivars, areas with little public-sector counterpart. Even in crop and livestock breeding, public and private R&D appears to be concentrated on different fields of science, with public scientists concentrated in more basic biological disciplines and private sector scientists in more applied fields (Figure 7.9) Public plant breeders, for example, focus more on upstream research like developing new general-purpose plant breeding tools and enhancing germplasm (parent lines used to breed commercial cultivars), whereas private plant breeders are heavily concentrated on cultivar development.

Figure 7.8. Composition of public and private food and agricultural R&D by sub-sector in 2013

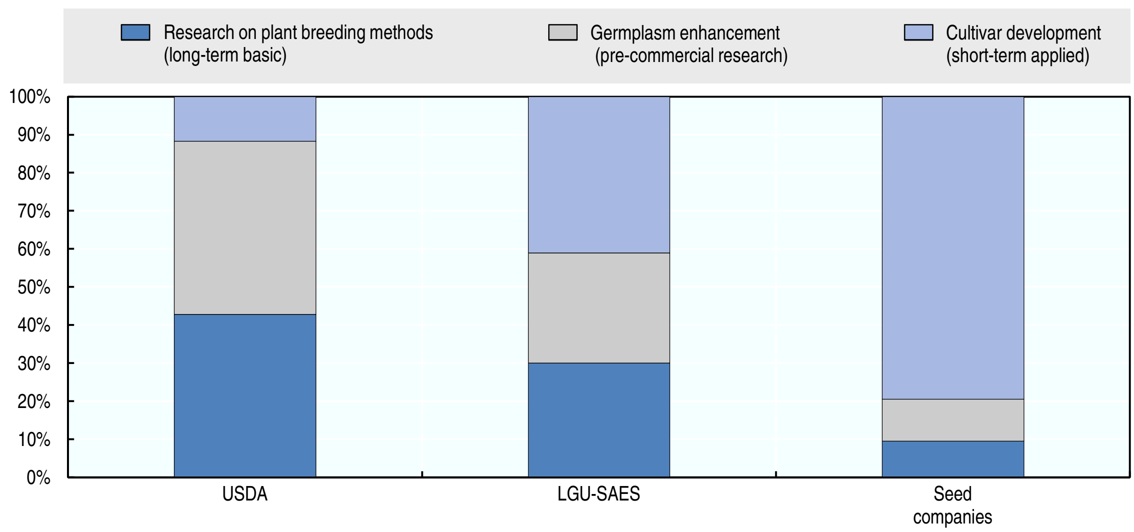


Sources: Public R&D spending from USDA (2015c), National Institute for Food and Agriculture https://nifa.usda.gov/data; private R&D spending is from Fuglie (2016, forthcoming).

StatLink http://dx.doi.org/10.1787/888933408978

Figure 7.9. Allocation of public and private plant breeding among basic, pre-commercial and applied research activities, 1994

Share of breeders' time devoted to activity



Source: Frey (1996), *National Plant Breeding Study*, Special Report 98. http://nifa.usda.gov/sites/default/files/resource/National%20Plant%20Breeding%20Study-1.pdf.

StatLink http://dx.doi.org/10.1787/888933408983

Governance of the R&D System

In the US Federal Government, there is no single science agency that sets research priorities. Rather, there is a highly decentralised process by which priorities and budgets for R&D are established in the several departments and agencies responsible for research (Ruttan, 2001). It involves these departments and agencies, the authorisation and appropriation committees of Congress, and at the level of the Executive Office of the President, the Office of Budget and Management, the Office of Science and Technology Policy (OSTP), and the National Science and Technology Council (NSTC).

The NSTC is responsible for coordinating science and technology policy across the diverse entities that make up the federal R&D enterprise. Chaired by the US President, the NSTC membership includes the Director of OSTP, cabinet secretaries, heads of agencies with significant science and technology responsibilities, and other officials. The work of the NSTC is currently organised around five committees, each with sub committees and interagency working groups that coordination work on specific areas of research. The USDA is represented on several of the coordination bodies.

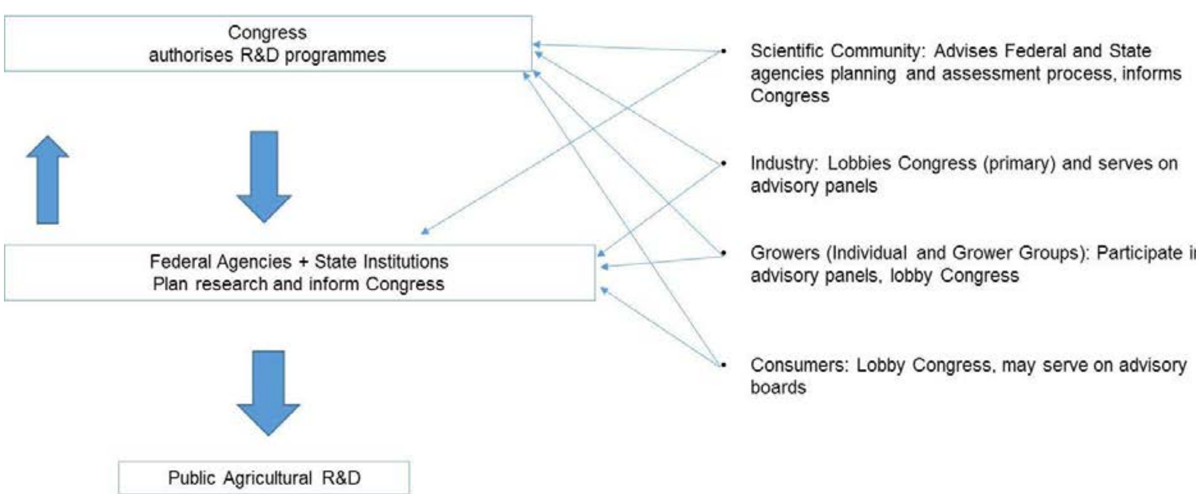
The Congress is responsible for the legislation that enables federal programmes and agencies, and determines their funding levels. In 1993, the Congress passed the Government Performance and Results Act (GPRA), which established performance guidelines for all federal agencies. Under GPRA, departments and agencies are required to develop five-year strategic plans with measurable, result-oriented goals and annual performance reports that review the agency's success or failure in meeting its targeted goals.

USDA research planning and stakeholder input

Within the USDA, agricultural research is conducted among various mission areas and by multiple agencies. The Agricultural Research Service (ARS) is the USDA's primary intramural research performer. The National Institute for Food and Agriculture (NIFA) is responsible for USDA's extramural programmes that fund research, extension and education activities at universities and in the private sector. The National Agricultural Statistic Services (NASS) and the Economic Research Service (ERS) are responsible for collecting agricultural statistics and providing analysis for food, agricultural and natural resource policy. These four agencies make up the USDA's Research, Education and Extension (REE) mission area. Additional research is conducted outside REE. Among that, research related to forests and grasslands conducted by the US Forest Service is of particular importance. (The Forest Service operates within the USDA's Natural Resource and Environment mission area.)

The Office of Chief Scientist (OCS) is responsible for coordinating agricultural research within the USDA-REE agencies and with other federal research agencies. Research priorities are established with significant stakeholder inputs (Figure 7.10). Stakeholders inform and influence these priorities not only through lobbying activities, but also through formal mechanisms such as advice and recommendations from the National Agricultural Research, Extension, Education, and Economics Advisory Board (NAREEEAB). The twenty-five NAREEEAB members each represent a specific stakeholder category, such as a national nutritional science society, national farm organisations, commodity groups, agricultural universities, and industry associations.

Figure 7.10. Stakeholders and governance structure for setting agricultural research policy



In addition, each major programme area within REE research agencies engages stakeholders when planning their programme activities. For example, the ARS currently organises its research into 17 National Programmes. To establish their research agendas, each National Program consults stakeholder groups to help identify key research needs and opportunities. The National Programmes provide an important mechanism for coordinating research within the broader US agricultural innovation system. University partners with similar interests are closely engaged in order to coordinate research between federal and state institutions. The private sector (commercial firms and non-profit organisations) is also represented in these planning discussions.

Another important source of stakeholder inputs is external scientific advice from the National Academies of Sciences, Engineering and Medicine. The National Academies are self-governing, private, non-profit organisations charged by Congress to provide independent advice to the Federal Government. They draw upon pre-eminent scientific expertise from colleges and universities to author their reports. In 2009, the National Academy of Science released a study, *A New Biology for the 21st Century*, which called for stronger integration of new advances in fundamental biological sciences into federal science agencies to address pressing societal needs, especially for food, environment, energy and health. The National Research Council Board on Agriculture and Natural Resources (an operational arm of the National Academies) also periodically releases studies on aspects of the federal agricultural research enterprise. In 2014, for example, it published a critique of the USDA's principal competitive research grants programme, the Agriculture and Food Research Initiative.

To assist in coordination and planning, the USDA maintains a detailed database of all agricultural research projects funded and carried out by federal and state partners in the US agricultural research system. The *Current Research Information System* (CRIS) has been in place since 1966 to track research resources by subject matter, performer, source and amount of funding, and outcomes. It was activated in 1969. USDA-funded projects dealing with human nutrition are also reported in the *Human Nutrition and Information Management* (HNRIM) database maintained by the National Institutes of Health (part of DHHS). The USDA, DHHS, and other federal agencies funding nutrition research all report to this database. These searchable on-line databases and their annual reporting summaries are valuable tools for federal and state science managers and scientists. In addition, CRIS has been a critical resource for retrospective assessments of the economic impacts of agricultural research. Using data that measure research resource flows to specific subject areas and specific geographic areas, and linking them to subsequent changes in farm productivity, economists have been able to conduct cost-benefit analysis of public investments in agricultural research. A summary of the findings from these studies is given in Chapter 7.

The USDA Research, Education and Extension Action Plan

The current USDA strategic plan for agricultural research (the Research, Education, and Economics Action Plan) identifies seven priority goals:

- Sustainable intensification of agricultural production
- Responding to climate and energy needs
- Sustainable use of natural resources
- Nutrition and childhood obesity
- Food safety
- Education and science literacy
- Rural prosperity and rural-urban interdependence.

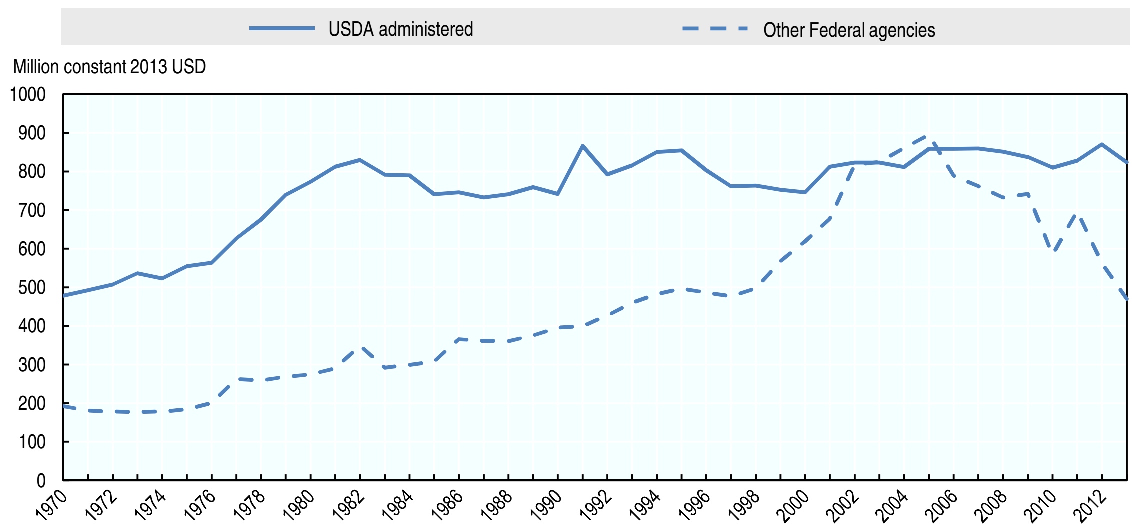
Each of these seven goals has strategies and planned actions that designate the specific USDA agencies responsible for implementing the actions (For an update of the REE Action Plan, see USDA, 2014b).

Co-ordination among USDA and other federal agencies in food and agricultural R&D

Increased opportunities to exploit advances in fundamental biological sciences for food and agriculture, expanded uses of agricultural commodities for new industries like biofuel, implications of food and agricultural systems for human nutrition, food safety, and the environment, issues of biosafety and national and homeland security, all serve to draw several federal science agencies into food and agricultural research. Funding of agricultural research by non-USDA federal agencies grew rapidly in the 1980s and 1990s, and briefly surpassed extramural research funding by the USDA, before dropping sharply after 2007 (Figure 7.11). The DHHS (primarily through the National

Institutes of Health), the National Science Foundation, the Department of Energy, the Department of Defense, and USAID were all important sources of this funding.

Figure 7.11. Extramural funding for agricultural research by the USDA and other federal agencies, 1970-2013



Annual spending is adjusted for inflation using a "cost of research" price index from ERS.

Source: USDA (2014a), Economic Research Service. www.ers.usda.gov/data-products/agricultural-research-funding-in-the-public-and-private-sectors.aspx.

StatLink http://dx.doi.org/10.1787/888933408991

NSTC sub-committees and interagency working groups, as well as federal science project databases like HNRIM for human nutrition research, are important mechanisms for coordinating among these diverse players. Research coordinating bodies are often established around key federal research priorities, such as the special initiatives presented in Box 7.2.

Box 7.2. Coordinating research across federal agencies: Examples involving agriculture

Plant Genomics. To develop and exploit fundamental advances in biological sciences for plant genomics, in 1997 the NSTC formed an Inter-Agency Working Group on Plant Genomics (IWGPG). With representatives from the USDA, NSF, DHHS, DOE, USAID, other federal offices, and inputs from stakeholder groups, the IWGPG has developed a series of five-year plans and reported on the achievements of the National Plant Genome Initiative. The plan outlines the priority areas for investing federal resources and describes the commitments of each agency toward these priorities. The USDA has major responsibilities for the conservation and characterisation of crop genetic resources and broadening biodiversity in advanced breeding material for use in commercial breeding programmes.

Climate Change. The United States Global Change Research Program (USGCRP) began as a presidential initiative in 1989 and was mandated by the Congress in 1990. The USGCRP coordinates climate change research across thirteen federal agencies and is steered by NSTC Subcommittee on Global Change Research. Under the current USGCRP ten-year strategic plan (2012-21), USDA contributions include assessing the impacts of climate change on agriculture, developing greenhouse gas inventories, developing new production technologies and practices that are drought tolerant and resilient, and developing and deploying decision-support tools for agricultural producers and policy-makers.

Human Nutrition. Improving nutrition could be one of the most cost-effective ways to address morbidity, mortality and socioeconomic burdens associated with chronic diseases and disorders. In the 1970s, mounting evidence of hunger and malnutrition in the United States led to increased funding for human nutrition research by the Federal Government. Since 1983, human nutrition research has been coordinated by the Interagency Committee on Human Nutrition Research (ICHNR). The ICHNR is co-chaired by the USDA and the DHHS and includes representatives from eight other federal departments and agencies as well as the White House Office of Science and Technology Policy. The ICHRN has been instrumental in strengthening procedures for the monitoring of the nutritional status of the US population and improving the Dietary Guidelines for Americans. The Guidelines, issued by the Federal

Government every five years, provide recommendations for a nutritionally balanced diet developed from a review of relevant scientific evidence. The Guidelines are widely used by government agencies, for all federal dietary guidance, and food assistance programmes (Toole and Kuchler, 2015), as well as by consumers and diet-related industries (USDA, 2015). The ICHRN also put in place the HNRIM system to record and track all nutrition research projects performed or funded by the Federal Government. ICHRN is presently developing a new five-year strategic plan for federal nutrition research (ICHRN, 2016).

Bioenergy. Advancing bioenergy technologies has been an important objective for both the USDA and the DOE. Coordination of bioenergy-related R&D activities across federal agencies is achieved through Biomass Research and Development Board (BRDB), rather than the NSTC. The BRDB was mandated by Congress in the Biomass Research and Development Act of 2000 and subsequent legislation. Board members include representatives from the USDA, DOE, Department of Transportation, the OSTP, and other federal agencies. Stakeholder input is provided by the BRDB Technical Advisory Committee, which draws its members from industry, academia, non-profit organisations, and local governments. The USDA and DOE collaborate on the Biomass Research and Developing Initiative, a competitive research grant programme to promote feedstock development, biofuel and bio-based product development, and analysis on energy and environmental impacts.

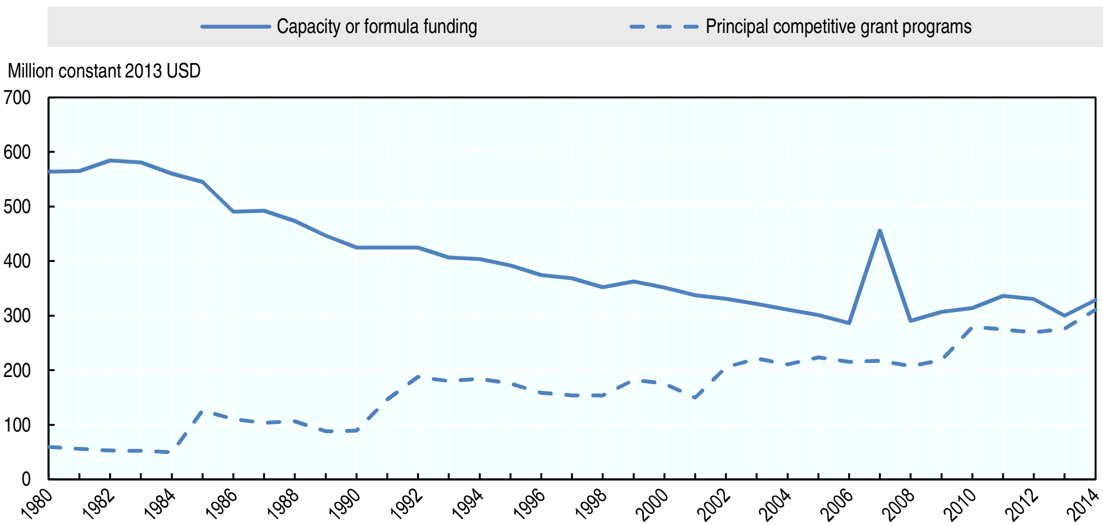
USDA funding mechanisms for extramural research

In the early years of the federal-state agricultural R&D system, the USDA supported Land Grant University-State Agricultural Experiment Stations (LGU-SAES) through a formula funding system (also called capacity research grants) where states received a fixed share of available federal funds. State governments were required to match the federal contribution. The matching requirement helped to mobilise farmer support for and involvement in their state agricultural research system (Huffman and Evenson, 1993). The federal contribution also serves as partial compensation for the fact that research performed by state institutions produces significant 'spillover' benefits to other states (Ruttan, 1982). Decisions regarding resource allocation of capacity research grants to LGU-SAES are largely left to the states, and much of this effort focused on problems and needs of the individual state or region.

In recent decades, the USDA has given greater emphasis to competitive funding mechanisms for research support at LGU-SAES. Competitive project funding programmes shift decision-making on resource allocation from state institutions to the federal funding agency. Centralised, competitive funding can direct funding to research that has greater national scope and to scientists and institutions thought to be best able to carry it out. Competitive funding programmes are also open to universities and other institutions outside the LGU-SAES system. However, competitive funding programmes also entail significantly higher transactions costs (scientist and research administration resources devoted to obtaining funding and managing projects) compared with capacity funding (Huffman and Evenson, 2006a; Prager et al., 2014). Congress may determine funding priorities for some competitive programmes, though scientists generally determine the institution performing the research.

The US Congress authorised the USDA's first competitive grants programme for agricultural research in 1977, and expanded it in 1990 when it established the National Research Initiative (NRI) Competitive Grants Program. In 2009, the NRI was replaced by the Agriculture and Food Research Initiative (AFRI). Meanwhile, funds allocated to capacity grants declined. By 2010, USDA extramural support for agricultural research was almost evenly split between capacity and competitive grants (Figure 7.12). However, empirical studies have not been able to find clear superiority of one funding mechanism over another. Huffman and Evenson (2006a) found that states receiving a higher proportion of agricultural research funds through institutional support (capacity grants and state appropriations) achieved higher productivity growth than states that relied more heavily on project support (competitive grants, contracts and other forms of research support). Prager et al. (2014) found that despite individual scientist's devoting significantly more time to research project administration and management, their per capita research output remained about the same.

Figure 7.12. Budgets for USDA capacity and competitive extramural research, 1980-2014



Principal competitive grant programmes include the National Research Initiative (1991-2007) and the Agriculture and Food Research Initiative (2008-present).

Capacity or formula funding include Hatch Act funds allocated to the State Agricultural Experiment Stations (SAES); Evans-Allen funds allocated to 1890 (historically black) agricultural universities; McIntire-Stennis funds for forestry research; and Animal Health funds.

Not included in the figure are Congressionally-earmarked and other grant programmes targeting specific areas such as sustainability, organic agriculture, bioenergy, and specialty crops. Earmarked funds are non-competitive. Some, but not all, area-targeted research programmes are also allocated competitively. The spike in capacity funding in 2007 reflects a one-time transfer of funds from a non-competitive programme to the Hatch programme.

Source: USDA (2015d), Office of Budget and Program Analysis. www.obpa.usda.gov/budsum/budget_summary.html.

StatLink http://dx.doi.org/10.1787/888933409000

Evaluation procedures of research in government agencies

Governance also ensures that policy outcomes and impacts are evaluated against government priorities. Solid and transparent evaluation procedures are needed to improve the performance of the research and innovation system. The main tool for evaluating all federal agencies, including research agencies, is the Government Performance and Results Act. USDA is also a partner in the STAR METRICS consortium (Science and Technology for America's Reinvestment: Measuring the EffecT of Research on Innovation, Competitiveness and Science) between US federal science agencies and research institutions to document the return on investment, research impact, and social outcomes of federally funded research and development.

ARS programme performance against targets is monitored annually. Each National Program Team (NPT) prepares an annual report featuring the National Program major accomplishments. Data for annual monitoring are provided by the research projects.

At the end of each national programme's five-year cycle, the NPT prepares an accomplishment report, which is discussed with an external review panel, who in turn prepare the National Program evaluation report. Criteria used to select stakeholders in external review panel are not known (Jolly et al., 2016).

The purpose of impact evaluation is to demonstrate accountability to partners and the Federal Government regarding the benefits of ARS-funded research systems programmes, through monitoring and evaluation. Annual monitoring and end of funding review provide information for the new funding cycle and accomplishments at the level of ARS. Evaluation results are posted on the agency's website.

There are no public guidelines for evaluation design, methods and methodology, but some harmonisation in the format of National Program accomplishment reports. An Action Plan Scorecard measures outputs and outcomes, using narratives from the reports to provide evidence for impact. Methodologies include mixed review panels (academics, stakeholders and government). Measurement of achievement includes programme-based quantitative targets; science quality, client satisfaction, and diffusion of scientific output beyond academia.

In addition to this formal evaluation, researchers in government agencies (e.g. ERS) and universities have produced numerous studies evaluating the impact of R&D and innovation on the economic and environmental performance of the sector. Using the long time series available in the United States, studies report high rates of return to agricultural research (see section 7.6 for some examples).

Fostering innovation

Special features of agriculture mean that the extent and nature of the market failures to invest in technology development and dissemination differ from elsewhere in the economy. Because of the atomistic structure of production (comprised of relatively small firms producing multiple homogeneous products), few farms are willing or able to investment in formal R&D for their farms. Furthermore, because of the biological nature of agriculture, improved crop seed and animal breeds are self-replicating. This complicates the ability of innovators to protect intellectual property. In addition, many agricultural technologies tend to be geographically specific, meaning that they do not transfer directly to other locations with different soil types, weather patterns, or topography. These features imply that unique policies to foster innovation in agriculture are required.

While farms themselves do little formal R&D, specialised firms do invest in R&D for the agricultural sector. Manufacturing firms in the machinery, chemical and pharmaceutical sectors, crop and animal breeding companies, and biotechnology companies conduct R&D to develop improved inputs for sale to farmers. The growing R&D capacity of the private sector for agriculture implies that public agricultural R&D is increasingly focused on more fundamental science and pre-commercial research activities. But transfer of scientific advances to commercial application is also confronted with market failure. This section describes policies designed to strengthen incentives for businesses to invest in agricultural research and new institution structures that have developed to strengthen linkages between public science and private R&D.

While manufacturers of agricultural inputs (seeds, chemicals, machinery, veterinary pharmaceuticals, etc.) market their innovations to farmers, the public sector has long maintained an agricultural extension system to extend new knowledge and management practices to farms and rural households. The US public agricultural extension system is a unique federal-state-local government partnership with a broad mandate not only to foster agricultural innovations but which also includes rural youth and community development

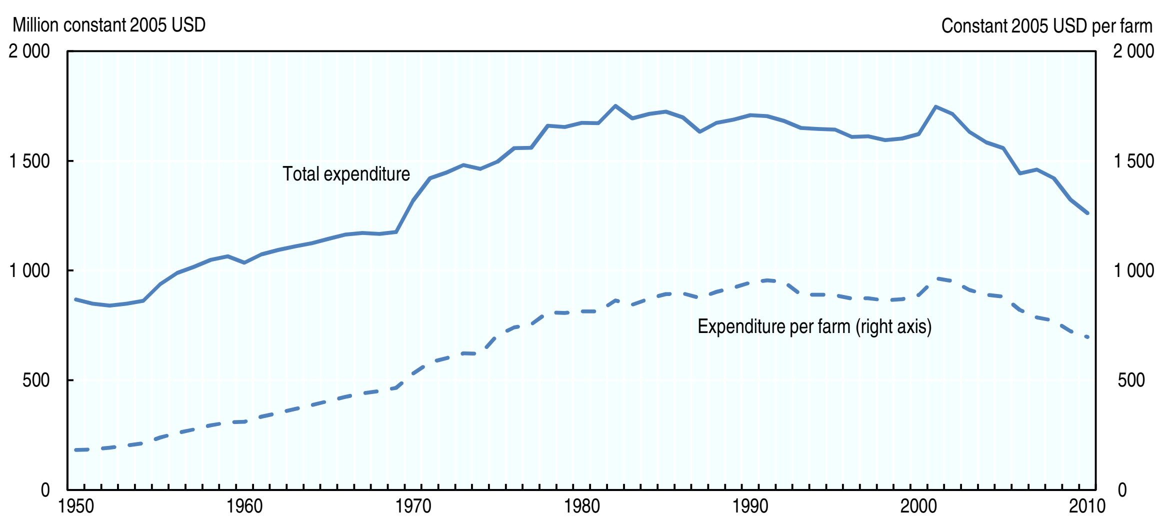
Agricultural extension

Throughout its history cooperative extension has been a unique partnership between federal, state and local governments to promote agriculture, conservation, youth education, rural development, health and nutrition. In its early decades, the Federal Government, through the USDA, provided 40-50% of the total funding for cooperative extension, with state and local governments providing the rest. The federal share of funding for cooperative extension has gradually declined over time, and presently makes up 20-25% of total extension funding. In constant 2005 dollars, total public expenditures for cooperative extension peaked in 1982 at just over USD 2 billion and by 2010 had declined to under USD 1.5 billion (Figure 7.13).

While the USDA establishes broad programme priorities for the funds it provides and state matching funds, state and local partners play a major role in defining priorities for cooperative extension. States report how cooperative extension funds are allocated across Knowledge Areas to the USDA. While priorities across individual states and associated territories differ, at the national level there is a significant degree of cohesion in budget allocation across major programme areas, regardless of funding source. While originally cooperative extension had a strong agricultural technology transfer focus, in its present form it addresses a wide range of rural and non-rural community needs. Only about one-fourth of extension expenditures are to support crop and animal farming ("plant systems" and "animal systems" in Figure 7.14). Education activities for families, youth and communities, most notably the youth-oriented 4-H program, accounts for 30% of extension resources. Human nutrition and health education made up another 17% of extension funding (Figure 7.14).

By 2010 there were just over 12 000 full-time staff employed in the US cooperative extension system, down from over 16 000 at the peak funding period of the early 1980s (Figure 7.15). A large part of the reduction came about by consolidating programmes in rural counties and reducing the number of county agents (generalists responsible for administering extension programmes within counties). The number of extension staff with specialised expertise serving regional or state-wide programmes has remained at approximately 4 000 nation-wide since the 1980s.

Figure 7.13. Public agricultural extension expenditures, 1950-2010



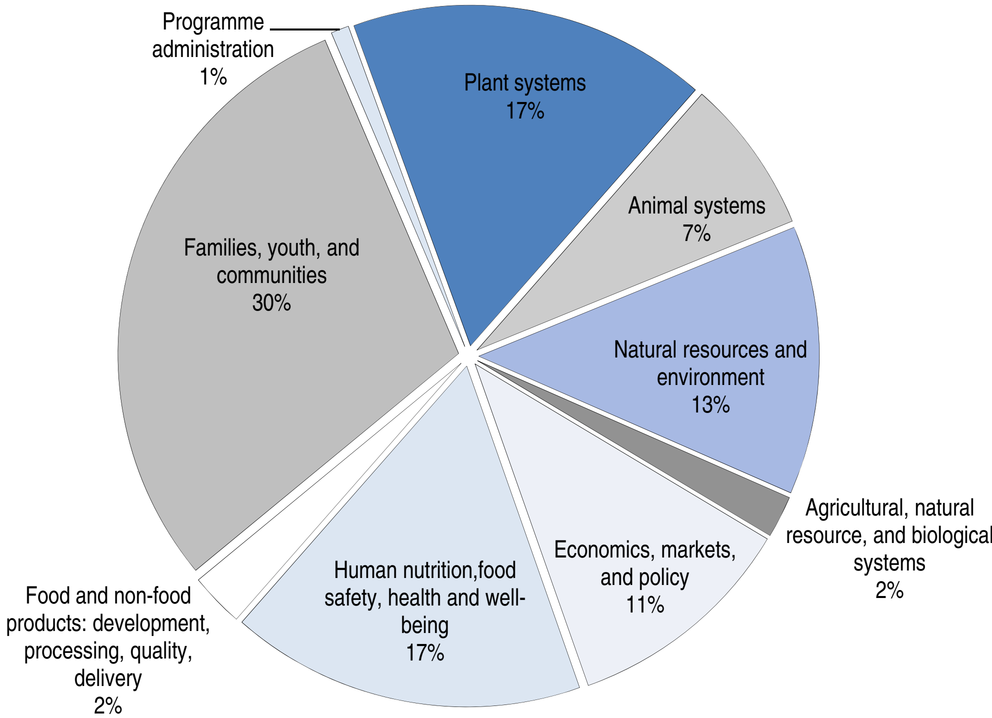
Nominal expenditures adjusted for inflation by a cost of research price index.

Figures include contributions from federal, state and local governments.

Source: Extension expenditures from Alston et al. (2010) with updates from USDA-National Institute for Food and Agriculture (b); Number of farms from USDA (2015e), National Agricultural Statistical Service. https://nifa.usda.gov/data; Cost-of-research price index from USDA-Economic Research Service.

StatLink http://dx.doi.org/10.1787/888933409012

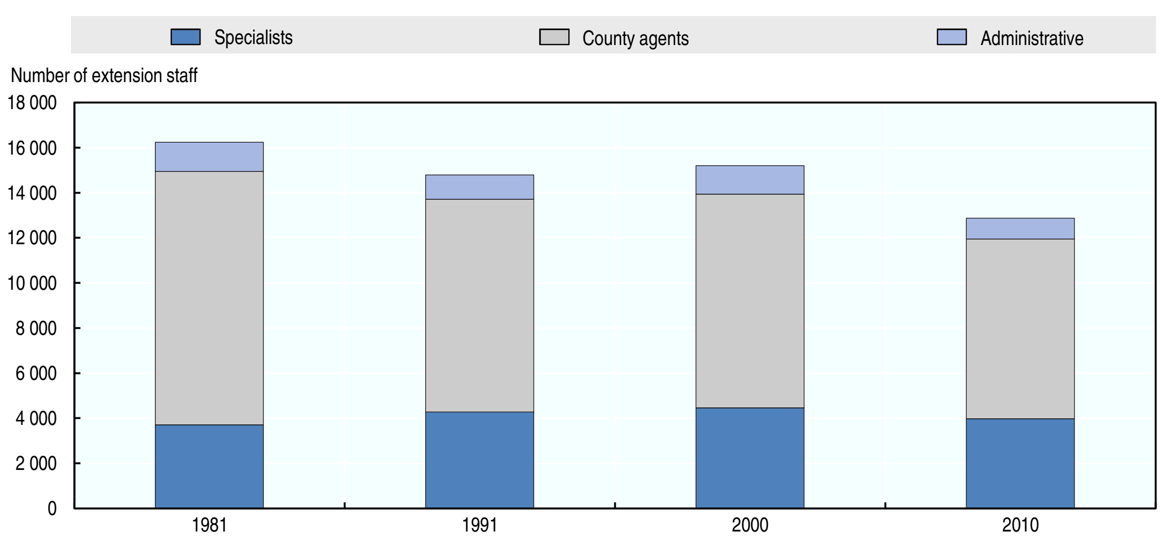
Figure 7.14. Allocation of agricultural extension spending by programme area in 2012



Source: USDA (2016a),National Institute for Food and Agriculture, Research, Education, and Economics Information System, US Department of Agriculture, Washington, DC. https://nifa.usda.gov/data.

StatLink http://dx.doi.org/10.1787/888933409023

Figure 7.15. Composition of agricultural extension staff in 1981, 1991, 2000 and 2010



Source: USDA (2016b), National Institute for Food and Agriculture, Salary Analysis of Cooperative Extension Service Positions, US Department of Agriculture, Washington, DC. https://nifa.usda.gov/data.

StatLink http://dx.doi.org/10.1787/888933409036

Intellectual property rights for biological innovations

Whereas public R&D can justify the cost of research by pointing to society-wide benefits, the costs of private R&D must be outweighed by the benefit to the performing firm alone. Private firms deploy a number of approaches to maintain exclusive control over their discoveries. The menu of options available, especially for plants and animals, has expanded considerably over time, concurrent with the rise in private agricultural R&D as a share of all agricultural R&D (Table 7.3). This section is based on Janis and Kesan (2002); Moschini (2001) and Lemley (2008).

The use of **Trade Secrets** has played an important role in protecting intellectual property in agriculture. So long as firms make a reasonable effort to maintain the secrecy of an economically valuable discovery, the law forbids rivals to discover the product by certain prohibited means (for example, corporate espionage). Notably, independent invention and reverse engineering do not fall under these prohibited means, which has tended to make trade secrets applicable only in some technological domains. In agriculture, hybrid seeds are particularly amenable to trade secrecy protection, because replicating the performance of the seed in future generations is nearly impossible without the parent lines, which are held privately by the firm. However, commercial production of hybrid seed is only viable for a few commodities (maize, sorghum, some vegetable species, and in animal breeding, to poultry and pigs), and private R&D in breeding historically focused on these commodities. Trade secrecy protection is based on state-level, rather than federal legislation. Although 48 states have adopted a version of the Uniform Trade Secrets Act, state-level modifications to the act, as well as state-level differences in interpretation of the act by courts means there is some variation in trade secrecy protection across the country.

Table 7.3. Intellectual Property Rights for agricultural innovations in the United States

Type	Year available	Length of protection	Eligibility criteria	Limitations
Trade Secrecy	Grew out of common law beginning in 1837	Indefinite	- Economically valuable information not generally known - Firms make reasonable efforts to maintain secrecy	- Reverse engineering is not protected - Independent invention is not protected - State-level enabling legislation is not uniform across country
Plant Patents	1930	20 years	- Asexual plants - At least one distinguishing characteristic - Nonobvious - Not sold or released in US more than one year prior to application	- Tubers are not eligible
Plant Variety Certificates	1970 (with 1994 amendments)	25 years for trees and vines 20 years otherwise	- Sexually reproducing plants and tubers - New - Distinct - Uniform - Stable	-Farmers may save seeds that result from growing for reuse (but not resale) - Researchers may use for breeding and other bona-fide research
Utility Patents	1790 (extended to plants and animals in 1980)	20 years	- "Anything made by man under the sun" - Novel - Useful - Nonobvious	- Must disclose invention so that someone skilled in the relevant arts can replicate

Newly discovered asexually reproducing plants (excluding food tuber crops like potatoes) have been eligible for **Plant Patents** since the Plant Patent Act of 1930. To be eligible for a plant patent, a plant must differ from known related plants by at least one distinguishing characteristic, must not have been sold or released in the United States more than one year prior to the date of the application, and must be nonobvious to one skilled in the art at the time of invention. A plant patent gives the assignee the right to exclude others from asexually reproducing, selling, or using the patented plant for a period of 20 years. At that point, the plant becomes part of the public domain.

Protection for newly discovered varieties of sexually reproducing plants, and tubers, was extended by the Plant Variety Protection Act of 1970 and its 1994 amendments, which established a system of **Plant Variety Protection Certificates (PVPC)**. Plants must be new, distinct, uniform, and stable in order to receive a certificate, and must provide seeds to a public seed bank. Upon being granted the certificate, the plant has protection from resale and commercial use for 20 years (25 years for trees and vines). There are a number of exceptions to the protections provided by plant variety certificates though. Most important are the saved seed exemption, which allows farmers to retain and use (but not sell) the seed that results from growing the protected plant, and the research exemption, which allows use of the protected plant for breeding and other bona fide research. These exemptions mean PVPCs provide a more limited form of intellectual property rights than standard utility patents. While PVPC's facilitate wider use of new seeds to stimulate further innovation, patents have generally held higher economic value for innovating firms (Fuglie et al., 2016).[2] The United States is a member of the 1991 UPOV convention, which established harmonised plant breeder rights among members.

Utility patents (hereafter patents) have a much longer heritage, being established in the United States in 1790. Originally, five categories of subject matter were patentable; machines, compositions of matter, articles of manufacture, processes, and improvements in each of the preceding. Discoveries that are novel, non-obvious, and useful are eligible for patent protection which entails a 20 year right to exclude others from commercial exploitation of the innovation. In exchange, the patent holder must disclose the invention, providing enough information for someone skilled in the relevant arts to replicate it.

The understanding of what subject matter is eligible for patent protection has changed over time. Until 1980, plants and animals were viewed as products of nature and therefore *not* eligible for patent protection. Nonetheless, patents remained an important incentive for agricultural innovation in other agricultural input sectors, such as farm machinery. Patent rights were extended to plants via the Supreme Court case Diamond vs. Chakrabarty (1980) which established multicellular living plants and animals are not excluded from patent protection, a decision that was reaffirmed by *ex parte* Hibberd (1985) for plans and ex parte Allen (1987) for animals. Now, the same new crop variety may obtain a Plant Variety Certificate and a utility patent. Plants protected by utility patents do not have saved seed or research exemptions, and so they offer a more stringent form of intellectual property rights. This stimulates private investment in plant breeding, but imposes higher costs for farmers and other researchers. There is widespread use of patents for transgenic crops.

Tax incentives for R&D

Because intellectual property rights are imperfect, private sector R&D may be underprovided, relative to society's best interests. To encourage private firms to engage in R&D, the government offers a number of tax incentives. At the federal level there are three such provisions. These include the deduction from taxable income for research expenses, a tax credit for increasing research activities, and an exemption for donations to charitable agricultural research organisations. As of 2015, each of the incentives is permanent.

The deduction for research expenses allows businesses to elect to deduct from taxable income the entire amount of eligible R&D expenditures in the year in which they were incurred. Without this provision, expenses associated with the development or creation of an asset having a useful life extending beyond the current year must be capitalised and depreciated over its useful life. Eligible R&D costs generally include all costs incurred in the experimental or laboratory sense related to the development or improvement of a product. Examples of qualifying costs include salaries for those engaged in research or experimentation efforts, amounts incurred to operate and maintain research facilities (e.g. utilities, depreciation, rent), and expenditures for materials and supplies used and consumed in the course of research or experimentation.

The federal R&D credit is an incremental credit designed to encourage businesses to increase R&D spending. Under the credit, businesses are allowed to reduce their federal income tax by an amount equal to 20% of their qualified R&D expenditures in excess of a base amount. The base amount is determined by multiplying a fixed-base percentage and the average sales over the preceding four years. For most businesses, the fixed base percentage is the average ratio of R&D expenses to sales over the five-year period 1984-88. A special rule allows new businesses without sales during the period to utilise a specified base percentage of 3% of gross receipts for their first five years.

The base credit is extremely complex and businesses may elect an alternative simplified credit. The simplified credit allows a credit equal to 14% of research expenses in excess of 50% over the average qualified research expenditures for the three prior years.

Qualified research expenses must be experimental, for the purpose of discovering information that is technological in nature and used in the development of a new or improved product, process, formula or invention. Eligible expenditures are limited to direct wage and salary, supplies, costs for equipment and from 65% to 100% of contract research expenses. The credit is not refundable. However, it can be carried forward for 20 years to reduce future tax liability.

A variety of farming and food manufacturing and processing activities are potentially eligible for the credit. Examples include developing new or improved strains of crops or livestock, developing new or improved processes for maintaining food quality and safety, new or improved feeding or breeding techniques for livestock and new or improved production processes for efficiency and waste reduction.

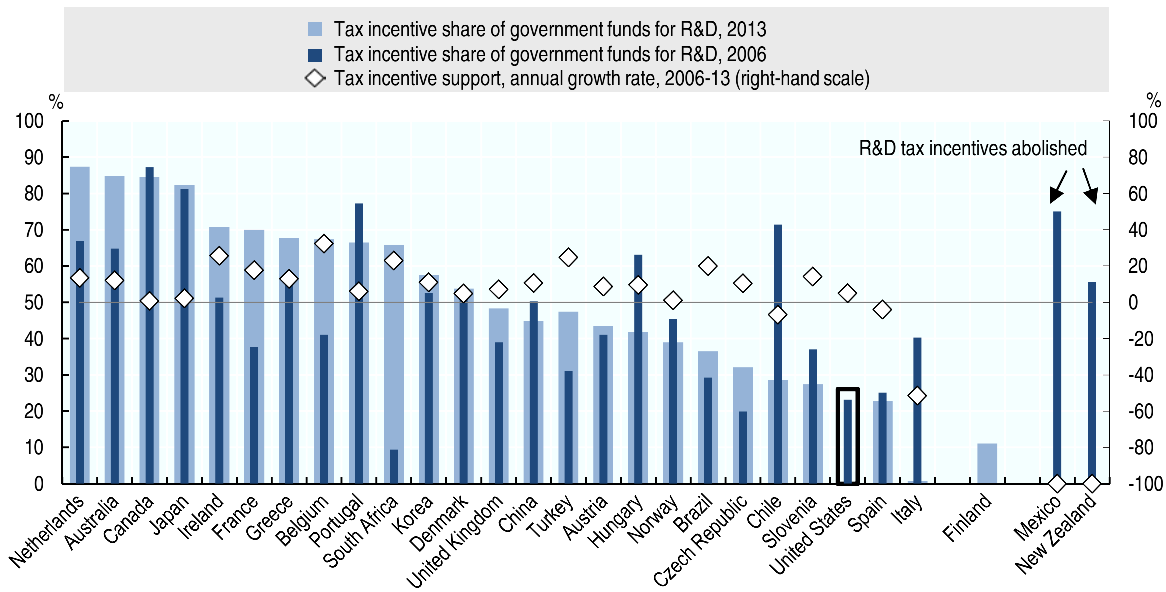
The federal R&D credit primarily benefits manufacturing and professional, scientific and technical service firms with over 75% of the total credit going to such firms in 2008. This would include many firms involved in food processing and suppliers of inputs to agricultural producers. However, only about 0.1% of the credit was received by firms involved in agricultural production. The credit primarily benefits large corporations with about 87% of the credit going to firms with over USD 50 million in assets in 2008.

Since the enactment of the federal credit for R&D expenses in 1981, both the number of states offering such a credit and the level of the credit have increased steadily. Currently, as many as 39 states have adopted a credit for R&D expenses and as of 2005 the average effective rate of the various state level credits had reached 6% of qualified R&D expenditures (Wilson, 2005). In many instances, these credits generally follow the federal guidelines with regard to eligible expenses and the incremental nature of the credit. However, there is some variability in the types of eligible expenditures and the base for determining the incremental expenditures to which the credit rate is applied.

Charitable donations to agricultural research organisations (AROs) are also eligible for exemptions. In 2015, new legislation on the treatment of AROs was passed, modelled on the treatment of medical research organisations. AROs are now considered public charities, regardless of their source of funding and donations are eligible for the higher individual limits, if the organisation commits to use the funds for agricultural research within five years.

Over the period 2006-13, tax incentives as a share of government support for business R&D has increased slightly but remains lower than in most OECD countries (Figure 7.16).

Figure 7.16. Change in government support for business R&D through direct funding and tax incentives, 2006-13



For the United States, 2013 data is replaced by 2012 data.

Source: OECD (2015), OECD Science, Technology and Industry Scoreboard 2015: Innovation for growth and society. http://dx.doi.org/10.1787/sti_scoreboard-2015-en.

Public-private research collaboration

The growing capability of the private sector in many areas of agricultural research has created new opportunities and challenges in transferring knowledge and technology across sectors. Federal legislation enacted since the 1980s created new mechanisms to encourage public-private collaboration in R&D (Table 7.4). These collaborations can take several different forms (Box 7.3).

Public sector grants to the private sector. In 2014, 30.5% of the Federal Government's R&D spending was conducted by private industry. In the research grant model, the Federal Government funds private in-house research, and has no claims over any patentable discoveries that emerge as a result of research. One example of a private research grant model is the Small Business Innovation Research (SBIR) programme. The **Small Business Innovation Development Act of 1982** requires federal agencies to earmark a portion of their extramural R&D budgets to the funding of research at small businesses, defined as businesses with 500 or fewer employees.

In 2000, the Department of Energy (DOE) and the USDA pooled a portion of their SBIR funds to create the Biofuel Research and Development Initiative (BRDI). Between 2002 and 2006, the agencies contributed about USD 160 million (USD 130 million from the DOE, USD 30 million from the USDA) which was used to fund public and private research for R&D on biofuels, with the majority of funds going to biofuel producers. In general, however, the USDA devotes only a small portion of its R&D funds to research grants to private industry. Total funds allocated to the SBIR programme have grown in real terms, as indicated in Figure 7.18. Nonetheless, in fiscal year (FY) 2011, just USD 18.3 million from a budget of USD 2.6 billion was allocated to industry performers.

Table 7.4. Major US legislation encouraging public-private collaboration in research and technology transfer

Year	Legislation	Action
1980	Stevenson-Wydler Technology Innovation Act	Encouraged government laboratories to increase cooperation with the private sector. Each major government laboratory was directed to create an Office of Research and Technology Applications to facilitate transfer to private companies.
1980	Bayh-Dole Act	Authorised government agencies to grant exclusive licenses to government-owned patents and allowed universities to own patents on research developed with government funds
1981	Economic Recovery Tax Act	Established tax credits for R&D grants to universities for basic research
1982	Small Business Innovation Development Act	Established the SBIR Programme. The programme requires a minimum percentage of each federal agency's extramural R&D budget to be allocated to small businesses.
1986	Federal Technology Transfer Act	Authorised government research laboratories to enter into CRADA with private companies
2014	Agricultural Act of 2014 (Farm Bill)	Established the Foundation for Food and Agricultural Research (FFAR), a non-profit, non-government organisation. FFAR supports joint public-private funding of food and agricultural research
2015	Consolidated Appropriations Act, 2016 (Omnibus Spending Bill for FY16)	Created tax exemptions for charitable agricultural research organisations (ARO). AROs are modelled after medical research organisations established in the 1950s to encourage charitable contributions for medical research.

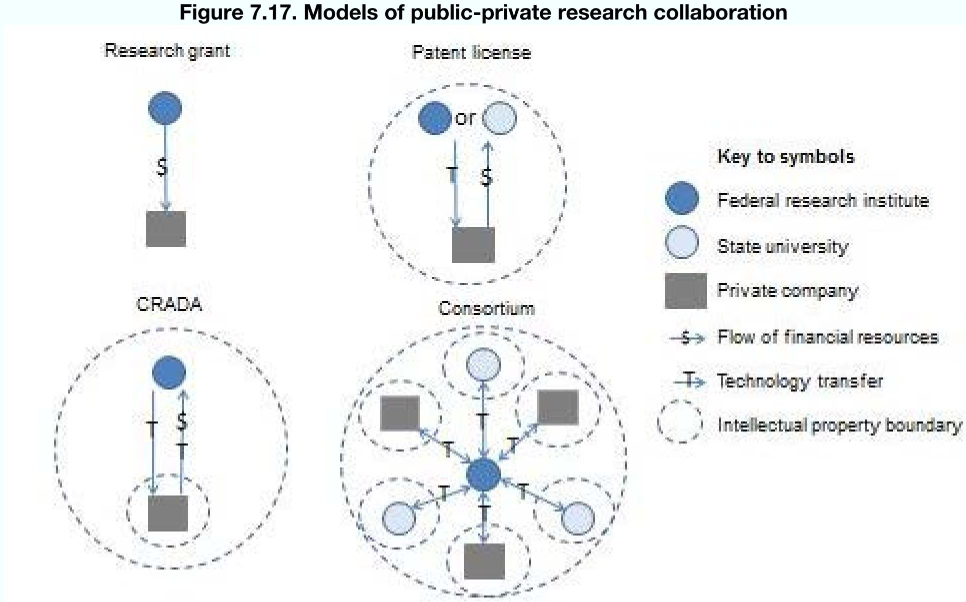
Sources: Schacht (2012), www.nist.gov/mep/data/upload/Industrial_competitiveness_-Technical_advancement.pdf; USDA (2014b), www.usda.gov/wps/portal/usda/usdahome?contentidonly=true&contentid=2014/07/0156.xml; and United States Congress (2016) www.congress.gov/bill/114th-congress/house-bill/2029/text.

Box 7.3. Mechanisms for public-private R&D collaboration

US government legislation provides federal science agencies with a number of mechanisms for working with the private sector (Table 7.4). These mechanisms differ in how they finance research and assign rights over intellectual property (Figure 7.17). The appropriate form of collaboration for a specific project depends on several factors, including the characteristics of the research undertaken (e.g. pre-commercial or developmental), the market for the product or service being developed, and the research capabilities of each partner in the collaboration.

The research grant model. The simplest mechanism for collaborative research is for the government to fund private in-house research. In this model there is no formal research collaboration between a government lab and the non-government partner and the grant recipient has sole ownership over any patentable technology. This type of arrangement characterises the SBIR programme and the former Advanced Technology Program. Often, government R&D grants are targeted toward projects of high government priority. In 2000, the USDA and DoE combined a portion of their SBIR resources to form the Biofuel Research and Development Initiative (BRDI). The BRDI provided research grants to companies for biofuel-related "plant science research" and "biorefinery demonstration and deployment" projects, as well as feasibility studies on next generation biofuels (Fuglie et al., 2011).

Figure 7.17. Models of public-private research collaboration



Source: Fuglie and Toole (2014).

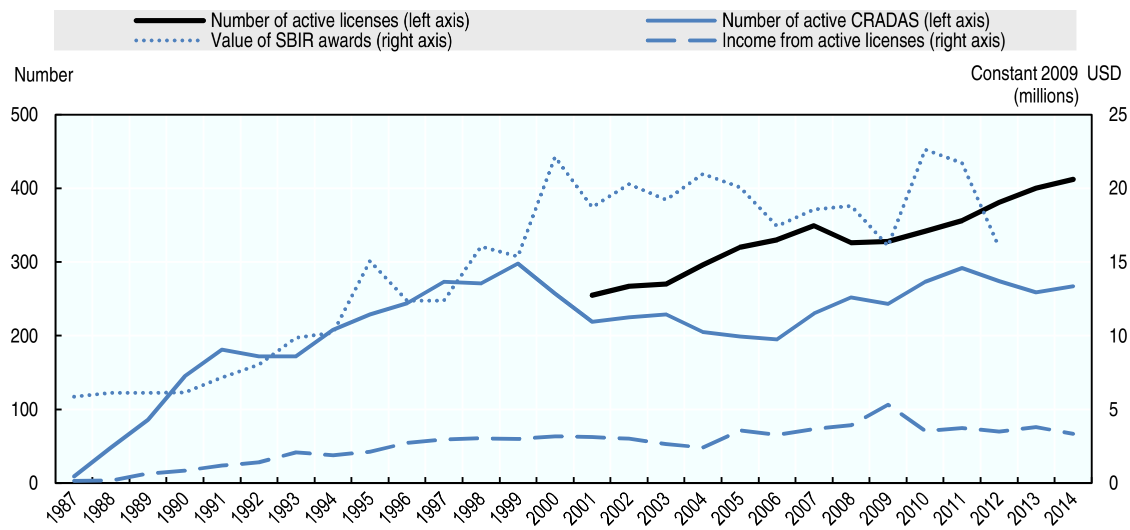
The patent licensing model. Here, a public research institution develops and patents a technology and then assigns the rights to use the patented technology to non-government institutions or private companies. The rights may be exclusive, partially exclusive, or nonexclusive (Heisey et al., 2006). Exclusive patent licenses are awarded when they are deemed necessary to promote private commercialisation — for example, when a company must make significant investments in product and market development, or when substantial commercial risk is involved. Patent licenses usually include a royalty payment that returns either a fixed fee or a percentage of revenues to the public institution that owns the patent.

The joint-venture model: Cooperative Research and Development Agreements (CRADA). A CRADA typically involves a government laboratory collaborating with one company to develop a technology for a specific commercial application. Both parties commit in-house resources to R&D, and the non-government collaborator may provide the government laboratory with some research funds. Government laboratories may provide personnel, equipment, and laboratory privileges, but not financial resources, to a non-government partner. Patents resulting from a CRADA may be jointly owned. The non-government partner has first right to negotiate an exclusive license for those patents resulting from a CRADA that are solely owned by the government. Some data also may not be publicly disclosed for a certain period of time (Day-Rubenstein and Fuglie, 2000). The first CRADA that was established by a federal agency following the passage of the 1986 Technology Transfer Act was between the USDA and Embrex, Inc., which led to the commercialisation of a method for vaccinating poultry against disease before they hatch.

The research consortium. Unlike a CRADA, which involves only one private and one public partner, a consortium brings together several private companies to undertake joint research, with or without a public sector partner. Consortium members contribute resources for the research, which is usually pre-commercial, and have first rights to technologies developed by the consortium. Companies can protect spinoff technologies through trade secrets or new exclusive patents. Research consortia have proven useful for increasing support for research that is considered to be long term and high risk, and for research to develop common standards in an industry. Additional applied and adaptive research is often required, however, to develop and diffuse technology to farmers or other users. Thus, a consortium often relies on the in-house research capacity of its members to develop specific applications from the more generic results of consortium-sponsored research. The Germplasm

Enhancement of Maize (GEM) project is an example of a public-private research consortium in agriculture. GEM was established in 1994 to increase biodiversity in maize cultivars developed by the private sector. GEM's membership includes the USDA, several Land Grant universities, more than 20 seed domestic and international companies, and some foreign public institutions.

Figure 7.18. Public-Private Research Collaboration by the USDA, 1987-2014



Implicit GDP price deflator used to adjust dollar values for inflation (Economic Report of the President, Table B-3).

Sources: CRADA and licensing data from USDA (2014b), Agricultural Research Service Office of Technology Transfer. www.ars.usda.gov/business/Docs.htm?docid=24718; SBIR data from Small Business Innovation Research (SBIR) and Small Technology Transfer Research (STTR) (2014), Small Business Administration. www.sbir.gov/awards/annual-reports.

StatLink http://dx.doi.org/10.1787/888933409044

The 2014 Farm Bill established the Foundation for Food and Agricultural Research, a non-profit corporation that seeks private donations in order to fund agricultural research. The Foundation was initially endowed with USD 200 million from Congress, with the condition that it be matched by non-federal funds. As of 2016, it was operating a Rapid Response Program, designed to rapidly fund research that responds to sudden and unanticipated challenges to the food and agriculture system, and New Innovator programme that sponsored young researchers in food and agriculture sciences.

Patenting and licensing by public institutions to foster private innovation. The cost of public R&D is justified by the benefits to society provided by new discoveries. To benefit from public R&D, discoveries made with federal R&D funds need to be used by society. Traditionally, the fruits of agricultural R&D have been distributed to end consumers via extension services, or more indirectly through academic and government publishing. Patented discoveries made with federal R&D funds were required to issue nonexclusive licenses to help distribute government funded discoveries as widely as possible. Moreover, any revenues associated with patents based on federal R&D were shared with the government, a practice justified by the government's role in funding the R&D.

However, bringing an innovation to market requires a different set of capabilities than those that led to initial discovery (and typically requires additional expense). Because universities and federal agencies usually do not have these capabilities, they often license their innovations to private firms that do. However, if universities must share their license revenue with the government, they may have a reduced incentive to search for these firms. Furthermore, firms make a costly and risky investment by bringing new innovations to market, and a nonexclusive license reduces the profit they can earn. The **Bayh-Dole Act** of 1980 was intended to facilitate the transfer of knowledge between federally funded sources and society by permitting organisations to retain all patent revenues and issue exclusive licenses of patented discoveries made with federal funds. It was complemented by the **Stevenson-Wydler Technology Innovation Act** of 1980, which mandated federal agencies develop specific mechanisms for disseminating government funded innovations. Prior to the passage of the act, technology transfer activities were voluntary.

The USDA has a long history of licensing to the private sector and has made use of the expanded licensing rules that followed the Bayh-Dole Act. The USDA ARS has more than 400 active patent licenses as of 2014, including some exclusive licenses (Figure 7.18). While licensing revenue has been on the rise in real terms, it remains a relatively small as a share of the ARS budget. Through the 2000s, annual licensing revenues were around USD 3 million annually, compared to an annual ARS research budget of USD 1.1 billion. Instead of being used to augment ARS R&D resources, licensing is primarily used as a vehicle for facilitating technology transfer.

Public-Private Cooperative R&D Agreements (CRADAs). As private agricultural R&D rises, so does the research capacity of the private sector. Given the relative specialisations of the public and private sectors, there are new opportunities for direct research collaboration. Collaboration was facilitated by a set of legislation passed in the 1980s and 1990s.

The **1986 Technology Transfer Act** provided conditions under which federal laboratories could work directly with the private sector. Previously, direct collaboration between government researchers and industry was not permitted. Under the rules laid out by the act, public and private research partners could develop a Cooperative Research and Development Agreement (CRADA). A CRADA is a written agreement specifying the resource commitments and responsibilities of each partner. The National Defense Reauthorization Act of 1991 and the National Technology Transfer and Advancement Act of 1995 clarified rules for revenue sharing arrangements in CRADAs.

Typically, a CRADA involves a government laboratory and one company, both of whom contribute in house resources. While the company may contribute in kind resources (e.g. personnel, laboratory space, and research equipment) and financial resources, the government can only contribute in kind resources. Resulting inventions (patents) from the collaboration can be jointly owned. The nongovernment partner has the first right to negotiate an exclusive license for those inventions (patents) made under the CRADA that are solely owned by the government. CRADAs may also specify that some data not be publicly disclosed for a period of time.

Federal agencies enter into approximately 3 000 new CRADAs per year. Figure 7.18 depicts the number of active CRADAs at the USDA's primary in-house research agency, ARS. After rising sharply in the years following the passage of the 1986 Technology Transfer Act, the number of active CRADAs has mostly stayed between 200 and 300 since 1994. As of 2014, ARS had 267 active CRADAs. Day-Rubenstein and Fuglie (2000) found the USDA typically contributed 36% of CRADA resources for the set of CRADAs entered into between 1986 and 1995.

To facilitate the commercialisation of public research, the USDA founded the Agricultural Research Partnerships (ARP) network, a loose coalition of more than 30 groups, ranging from private companies to state-sponsored economic development non-profits. To firms who have acquired ARS research outcomes via CRADAs or patent licenses, the network can provide complementary business development assistance, for example mentoring, identification of funding sources (venture capital and angel investors are part of the network), marketing assessments, and so forth. In many cases, ARS research is commercialised by a start-up, who can then draw on ARP network support to develop necessary commercial capabilities. At the same time, the ARP network also works to connect existing firms with relevant ARS resources (e.g. patents, researchers, facilities, equipment).

R&D outputs and impacts

Trends in agricultural science and technology outputs

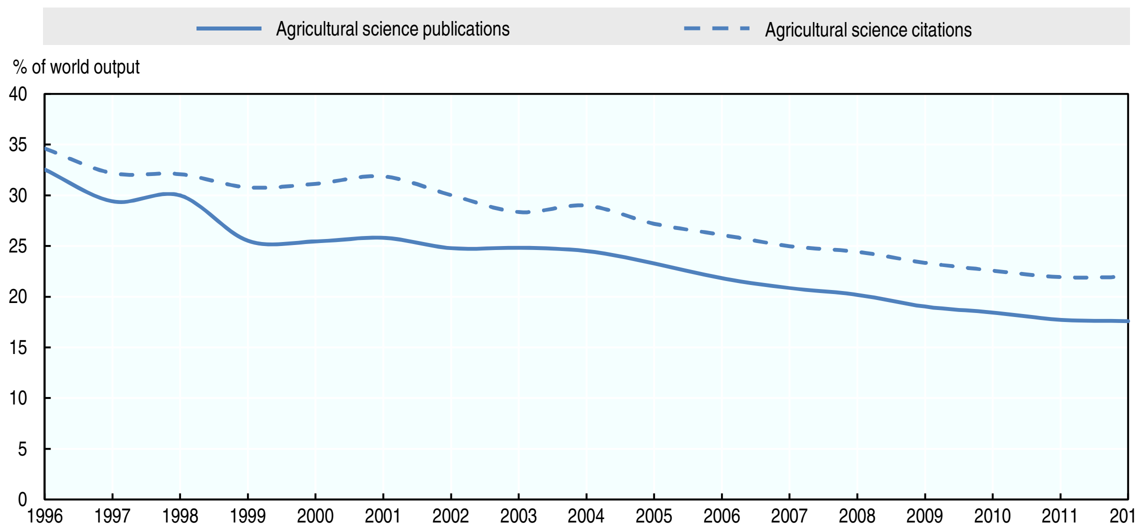
Scientific publications provide one indication of the large role the United States plays in global agricultural science. Like many other countries with substantial scientific research output, agricultural science publications in the United States constitute a relatively small role (less than 6%) of total scientific output. Nonetheless, in 2012 the US share of global agricultural science publications (about 18%) was more than twice as great as that of China, the next highest country. The US share of the world total has declined from nearly a third in 1996, the result of increased agricultural science publication in other countries rather than a decline in US scientific output. Similarly, the United States accounts for over a fifth of all citations to agricultural science publications, the largest share of any country. Again, the US citation share has declined over time for similar reasons to the decline in the publication share. The citation share has been consistently higher than the publication share, suggesting US publications in agricultural science are cited at higher than the average rate (Figure 7.19). Citation analysis has also underlined the importance of public agricultural science for private firms. Private firms' science publications have increasingly cited US public agricultural science publications (Figure 7.20).

Agricultural patents provide another indicator of US agricultural R&D output. Over the period 2006-11, US inventors were granted over 4 500 patents in agricultural science under the Patent Co-operation Treaty (PCT), more than three times the numbers granted to inventors from Germany and Japan, the next largest grantees of agricultural science patents (Figure 7.21). The same pattern holds for general agriculture patents, where the United States total of over 18 000 over 2006-11 was nearly three times the total from Japan, the next highest country (not shown). General agriculture patents may possibly indicate research somewhat downstream from the research reflected in agricultural science patents, just as patents may indicate research somewhat downstream from the research represented by agricultural science publications.

GE crops have been a major emphasis of increased private sector agricultural R&D investment in the United States. Companies wishing to test GE crops in open fields must first obtain approval from the USDA's Animal and Plant Health Inspection Service (APHIS). After collecting the necessary health, safety, and performance data a company must submit a deregulation petition to APHIS before GE crops can be produced and sold commercially. The number of field permit applications and deregulation petitions received by APHIS are often used as measures of R&D activities in agricultural biotechnology (Fernandez-Cornejo et al., 2014). Such approvals rose very rapidly until the early 2000s but have declined since (Figure 7.22). Since real investments in seed and biotechnology research by private companies have continued to rise, the somewhat lower number of field trial approvals may indicate a maturing industry which is now bringing somewhat greater focus to its GE crop research efforts. Over time, companies and other institutions petition USDA for deregulation of a much smaller number of GE crop innovations they wish to market to farmers. Deregulation petitions also show a pattern of a great deal of activity in the late 1990s, followed by a fluctuating and lower level since. Petition approvals naturally lag petition requests (Figure 7.23).

The use of intellectual property protection for new plant technologies and new crop cultivars is sometimes taken as another measure of R&D output in the area of seed and biotechnology. However the use of instruments such as utility patents, PVPCs, and plant patents may also indicate a response to changes in the strength of protection and changes in the scientific environment. There has been a rapid increase in utility patents for both plant cultivars and lines and for general plant modification technologies (including but not restricted to cultivar patents). Although many of these patents have been granted for GE cultivars or technologies, not all of them relate to GE technology. At the same time, the use of PVPCs and plant patents has also increased (Figure 7.24). Companies often apply for both a utility patent *and* a PVPC for the same cultivar, particularly for maize and soybean cultivars, the two most widely patented crops.

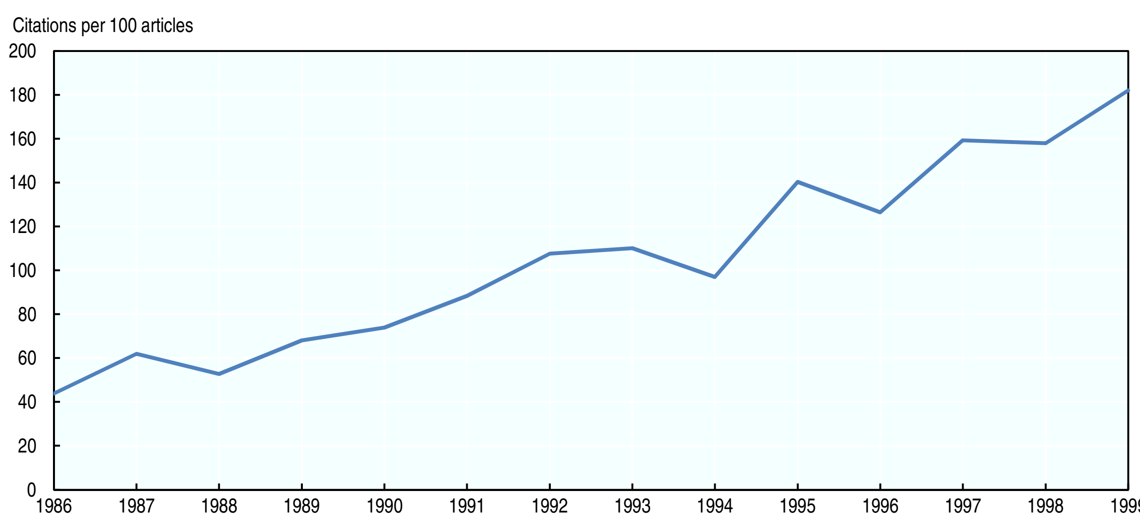
Figure 7.19. US share of global agricultural science publications and citations, 1996-2012



Source: SCImago (2014), *SJR—SCImago Journal & Country Ran*, www.scimagojr.com.

StatLink http://dx.doi.org/10.1787/888933409056

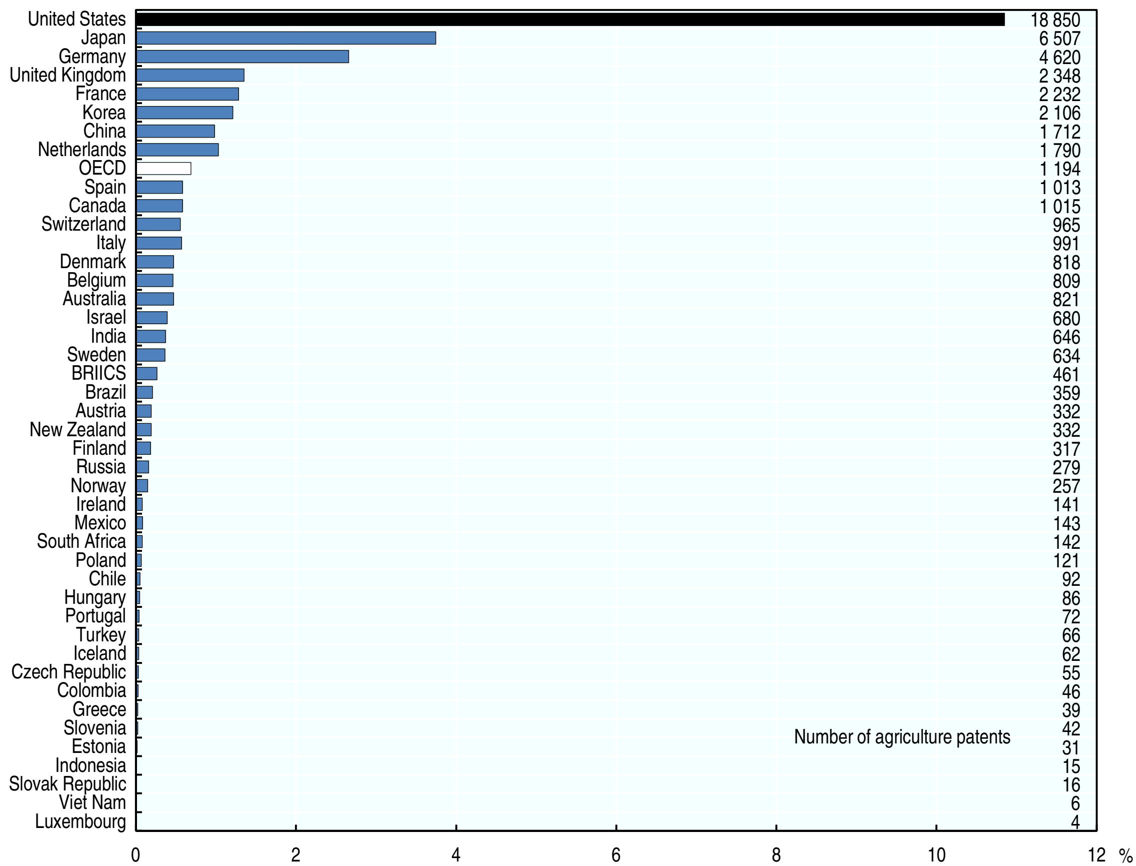
Figure 7.20. Private firms' citation intensity of public agricultural science publications, 1986-99



Source: Toole and King (2011), http://ftp.zew.de/pub/zew-docs/dp/dp11064.pdf.

StatLink http://dx.doi.org/10.1787/888933409060

Figure 7.21. Number of agricultural science patents issued by country, 2006-11



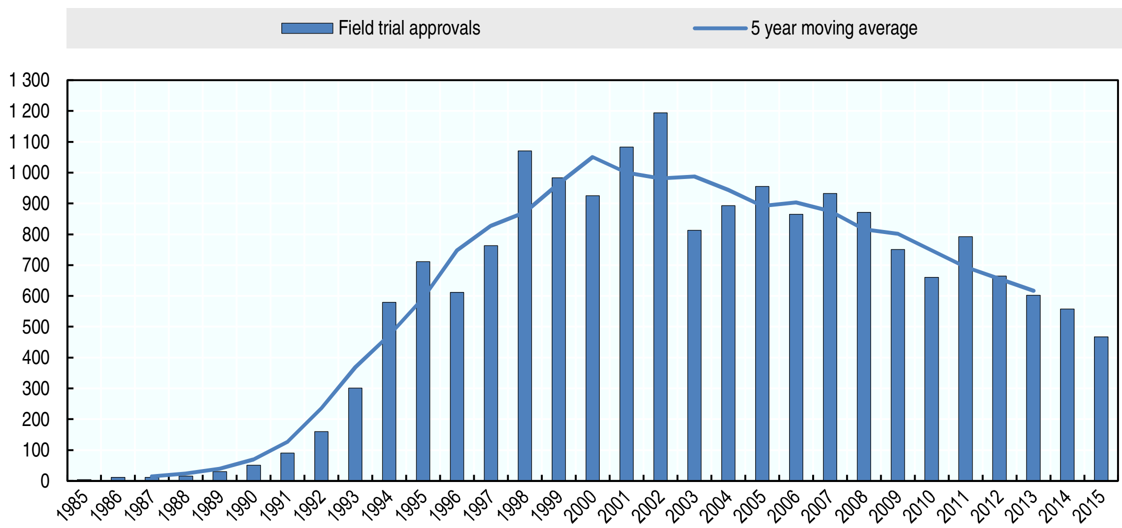
Agriculture includes patents from IPC classes A01, A21, A22, A23, A24, B21H 7/00, B21K 19/00, B62C, B65B 25/02, B66C 23/44, C08b, C11, C12, C13, C09K 101/00, E02B 11/00, E04H 5/08, E04H 7/22, G06Q 50/02.

Patent counts are based on the priority date (first filing of the patent worldwide), the inventors country of residence, using fractional counts.

Source: OECD (2014), Patent Database. www.oecd.org/sti/inno/oecdpatentdatabases.htm.

StatLink http://dx.doi.org/10.1787/888933409075

Figure 7.22. Number of Genetically Engineered (GE) crop variety events approved for field testing by APHIS, 1985-2015[1]

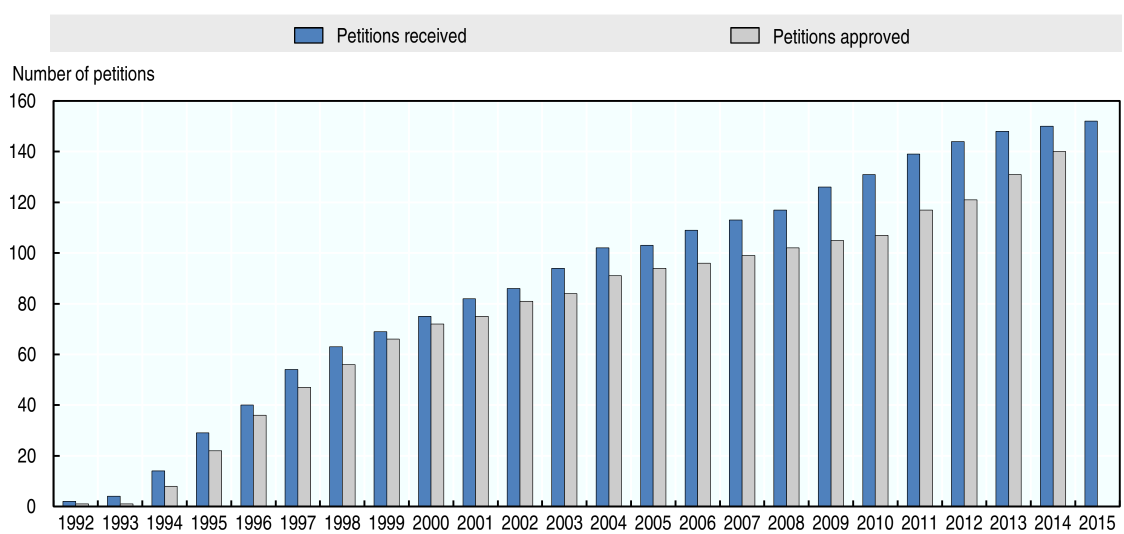


1. Includes permits and notifications.

Source: Information Systems for Biotechnology (2016). www.isb.vt.edu.

StatLink http://dx.doi.org/10.1787/888933409088

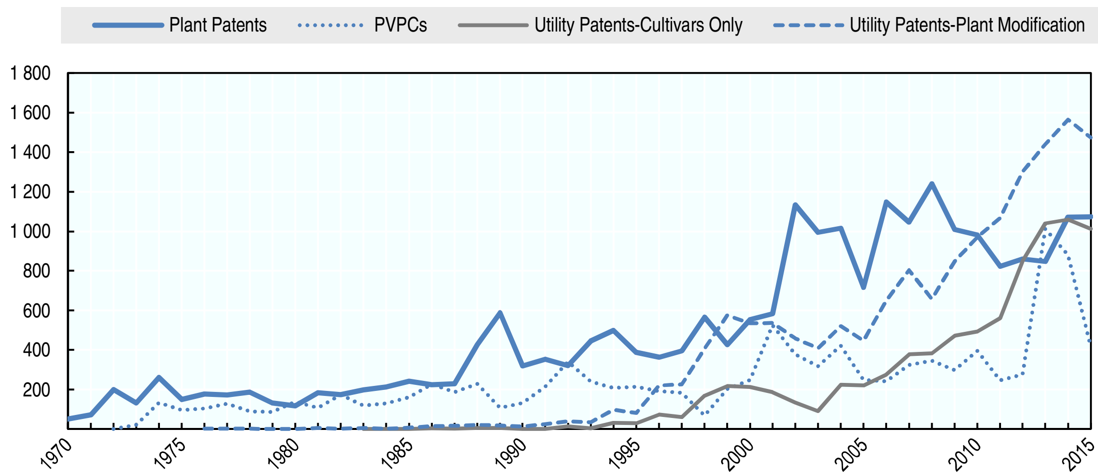
Figure 7.23. Cumulative number of petitions to USDA for deregulation of Genetically Engineered (GE) crops, 1992-2015



Source: Information Systems for Biotechnology (2016), www.isb.vt.edu.

StatLink http://dx.doi.org/10.1787/888933409092

Figure 7.24. Intellectual Property protection for plant varieties and plant modification technology in the United States, 1970-2015



Source: USDA, Economic Research Service, based on US Patent and Trademark Office (USPTO) (2015), US Plant Variety Protection Office (PVPO) databases. www.uspto.gov/patents-getting-started/patent-basics/types-patent-applications/general-information-about-35-usc-161.

StatLink http://dx.doi.org/10.1787/888933409102

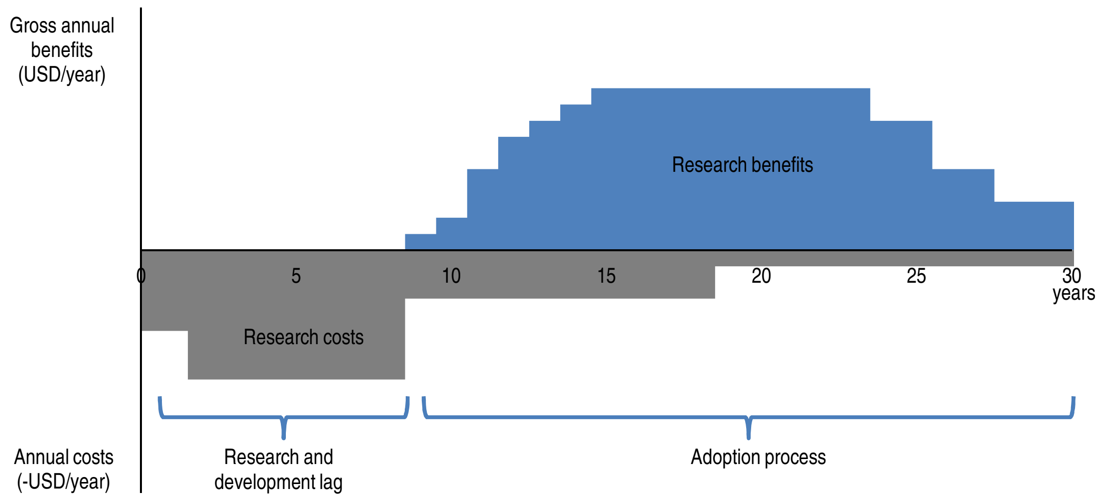
Research impact: Returns to public investment in agricultural R&D

Several studies have evaluated the returns to investment in the US agricultural research system. At the sector level, economic evaluations of agricultural research are typically based on comparisons between 1) public and private investments in agricultural knowledge creation and dissemination, and 2) long-term changes in agricultural productivity. The way this process is conceptualised is:

- Expenditures on agricultural research generate new knowledge that eventually leads to improved technology that is adopted by farmers;
- adoption increases average productivity (the output of crop and livestock commodities per unit of land, labour, capital and intermediate inputs employed in production);
- higher productivity of agricultural resources leads to lower costs, higher production and/or exit of some resources (such as labour) from the agricultural sector;
- given physiological limits to per capita demand for food, higher agricultural production leads to lower commodity prices, passing some of the technology-induced cost reductions on to the food industry and consumers. Thus, benefits of productivity-enhancing agricultural research are shared between the farm and non-farm sectors of the economy.

Figure 7.25 illustrates a typical time pattern of development, adoption and eventual obsolescence of agricultural technology. In the diagramme, a public (or private) institution invests in the development of a new technology (such as a new crop variety with disease resistance) and spends several years working on that effort ("research costs" in the diagramme). In this stylised representation, after about seven years the technology is successfully developed and farmers begin to adopt it. Costs are still incurred in extension efforts, and benefits grow as more farmers adopt the technology and reap higher yield or lower production costs. In the diagram, it takes about eight years (from year 7 until year 15) for the technology to be fully adopted and benefits maximised thereafter. But after some time the technology eventually goes out of use, either because something better replaces it or because it loses its effectiveness (due to build-up of resistance in the pathogen, for example). An economic evaluation of the research endeavour weighs the size of the research and extension costs against the economic benefits from technology adoption, discounting the benefit and cost streams to measure them in terms of their "present value."

Figure 7.25. Flows of research costs and benefits over time



Source: Alston, Norton and Pardey (1995).

There are two main approaches used to estimate economic returns to agricultural research. One approach is the use of ***Statistical analysis*** to relate past expenditures on research to current changes in productivity. These models try to establish a statistical correlation between when, where, and on what research was done and productivity gains in agriculture. It is usually done at a fairly aggregate level and covers a long period of time. These studies also examine effects of other factors that may contribute to productivity growth, like investments in rural education, extension and infrastructure. If regression analysis finds positive and significant correlations between research expenditures (appropriately lagged) and productivity changes, then this is taken as evidence of a causal relationship. An estimate of the rate of return to research is derived from the regression coefficients. A second approach uses ***Project evaluation methods*** to trace the development, dissemination and impact of specific innovations. A good and early example of this approach was a study by Zvi Griliches (Department of Economics, University of Chicago) in the 1950s on the returns to research on hybrid maize. He estimated the benefits of hybrid maize by measuring the economic value of higher maize yield made possible from this innovation. On the cost side, he estimated the cost of research and extension (by both the public and private sectors) beginning with the work of George Schull of the Carnegie Institution and Donald Jones of the Connecticut Agricultural Experiment Station who developed the theory of hybrid vigour and invented the double-cross method of hybrid seed production.

The project evaluation or case study approach provides a clearer cause-and-effect relationship between agricultural research and productivity growth. But the method has largely been limited to analysis of research "success stories". Regression methods, on the other hand, assess the system at a more aggregate level and take into account expenditures on research that may or may not lead to successes, and therefore tend to give a more balanced measure of average returns to a research system. Both approaches involve estimating relationships between the size of investment in research and the economic value of increased productivity, taking into account the appropriate time dimension between when research is done and when economic benefits are realised such as the case depicted in Figure 7.25. Estimates of social returns to research may be overstated if undesirable outputs (e.g. environmental degradation) are not taken into account. Similarly, social returns may be understated if new technology reduces undesirable outputs.

Some of the most challenging aspects of these models are

- ***Lags***: identifying the appropriate lag relationship between when research is done and when productivity growth occurs.
- ***Spillovers***: accounting for knowledge or research "spillovers" across geographic space. "Spillovers" occur when research done in one state, region, or country contributes to new knowledge or technology that is used in another geographic area.
- ***Attribution***: Many elements come together to contribute to the development and application of new technology to agriculture. In addition to publicly-funded agricultural research, there are contributions made by basic sciences, innovations from the private sector, farmer education, the training role of extension services, improvements to rural infrastructure, and so on. These institutional sources often act in complementary ways and failure to account for the contribution of one source may over-attribute observed gains in productivity to another source. Including all these sources in a model may give an indication of the relative importance of each source (and the relative rate of return to each). Some studies for the United States go even further to try to distinguish returns to agricultural research done by federal or state institutions, or even by different federal funding instruments (e.g. formula versus competitive grants). But putting finer and finer distinctions among sources of innovation and types of research expenditure places a very heavy burden on the data.

Table 7.5 summarises findings from 22 studies, which evaluated the impact of public agricultural research on the productivity of the entire farm sector using the methods described above. Estimates vary due to the methodology employed and time period covered, but all show significant and high returns to research, and the median estimate from these studies is 40%. This means that USD 1 of initial spending on agricultural research generated a stream of economic benefits averaging USD 0.4 per year, with these benefits lasting for several decades. Adding up these benefits and casting them in present values is consistent with a benefit-cost ratio of at least 20:1 (Alston et al., 2011). These studies also found benefits of public agricultural research were widely shared, not only among farmers but also with consumers in the form of more abundant and lower cost food.

Table 7.5. Estimates of the internal rate of return to public investments in agricultural research

Study	Authors	Pub. year	Publication	Period of study	Rate of return to research
1	Jin and Huffman	2016	Agricultural Economics	1970-2004	67
2	Andersen and Song	2013	Agricultural Economics	1949-2002	21
3	Wang, Ball, Fulginiti and Plastina	2012	CABI volume chapter	1980-2004	45
4	Plastina and Fulginiti	2012	Journal of Productivity Analysis	1949-1991	29
5	Alston, Andersen, James and Pardey	2011	American Journal of Agricultural Economics (Ag Econ)	1949-2002	23
6	Huffman and Evenson	2006b	American Journal of Ag Econ	1970-1999	56
7	Gopinath and Roe	2000	Econ, Innov. and New Technology	1960-1991	37
8	Makki, Thraen and Tweeten	1999	Journal of Policy Modeling	1930-1990	27
9	White	1995	Journal of Ag and Applied Econ	1950-1991	40
10	Chavas and Cox	1992	American Journal of Ag Econ	1950-1982	28
11	Norton and Ortiz	1992	Journal of Production Agric.	1987	58
12	Yee	1992	Journal of Ag Econ Research	1931-1985	54
13	Braha and Tweeten	1986	Tech. Bull., Oklahoma State U	1959-1982	47

Table 7.5. Estimates of the internal rate of return to public investments in agricultural research (*cont.*)

Study	Authors	Pub. year	Publication	Period of study	Rate of return to research
14	Lyu, White, Liu	1984	Southern Journal of Ag Econ	1949-1981	66
15	White and Havlicek	1982	American Journal of Ag Econ	1943-1977	22
16	Davis	1979	PhD thesis, U Minnesota	1949-1974	60
17	Knutson and Tweeten	1979	American Journal of Ag Econ	1949-1972	38
18	Lu, Cline and Quance	1979	Ag Econ Report, USDA	1939-1972	27
19	Bredahl and Peterson	1976	American Journal of Ag Econ	1937-1972	48
20	Cline	1975	Oklahoma State U, PhD thesis	1939-1948	46
21	Evenson	1968	U Chicago, PhD thesis	1949-1959	47
22	Griliches	1964	American Economic Review	1949-1959	33
	Median estimate				40
	Low - to - high estimate				21 - 67

Source: See references.

Adoption of innovations

Agricultural innovations occur when farms adopt new technologies and farm practices, develop new enterprises, or achieve economies of scale. The aggregate changes in agricultural productivity described in previous chapters are the cumulative effect of the adoption of such innovations. Adoption is largely driven by the desire of producers to increase the profitability of their farm operations. Market forces and price signals serve as powerful instruments to spur rapid adoption of productivity-enhancing technologies and practices. Extension and education activities, provision of financial and risk management services, and access to commodity and input markets improve the flow of information and uptake of innovations by farmers. But in cases where externalities are present (i.e. when what one farmer does affects other people), market incentives alone may be insufficient to incentivise adoption. Achieving effective control of plant and animal pests and diseases, mitigating environmental impacts of agricultural production practices, and assuring the quality and safety of food products, are cases where technological and informational externalities may require collective or government action to achieve widespread adoption. This section illustrates these dimensions of the innovation process by drawing on examples from US agriculture.

Technological change in maize production

Maize, the single most import crop in US agriculture, provides a good illustration of the cumulative and multifaceted nature of technical change in agriculture. Over the past century, land and labour productivity in maize production have risen dramatically. Between 1900 and 1974, the hours of labour required to produce 100 bushels of maize fell from 179 to 4 (Sundquist et al., 1982). Average maize yield, which remained static at around 1.6 metric tonnes (MT) per hectare (ha) (26 bushels per acre) between 1866 and 1940, rose to 10.7 MT per ha (170 bushels per acre) in 2014. Since the 1930s, maize production rose from 50 million MT of grain to an annual average of more than 350 million MT (in 2013-15). At the same time, the total area harvested for grain remained constant at about 34 million ha. Yield of maize silage (grown on an additional 2.5 million ha) also increased, from about 2.4 MT per ha in the 1930s to over 7 MT per ha today.

One of the first major technological changes to affect US maize production was the conversion from animal and human power to mechanised power for farm operations. By the 1960s, tractors, combines and trucks had largely replaced draft animals in field cultivation, harvesting and farm transport.

Not only did mechanisation reduce labour requirements, it freed up large amounts of cropland that had previously been used to produce forage and feed grain for draft animals. Farms could now devote more land to commercial crop and livestock production. Olmstead and Rhode (2001) estimate that roughly 22% of the output all cropland harvested over the 1880 to 1920 period was consumed by farm draft animals. By 1960, when the replacement of draft animals by tractors and other farm machines was largely complete, this land had been converted to other uses, including commercial crop production and cropland retirement for environmental and recreational purposes.

Breaking the link between crop production and feed requirements for draft animals facilitated the regional specialisation of commodity production. Regions where maize could not be grown efficiently could now convert that land to other uses; and regions where maize was best suited could now grow maize on lands previously needed for pasture and forage crops. Beddow and Pardey (2015) estimate that regional specialisation in maize production accounted for as much as 21% of the increase in average national maize yield between 1909 and 2007. The regional specialisation in maize production closely mirrored where pigs were raised, since farmers historically have converted their surplus maize production into pigmeat as a means of adding value to farm production.

After 1940, there was a revolution in maize yield. The intensification of maize production can be attributed to the development and adoption of a series of innovations involving varietal improvement, fertilisation, pest and disease management, advancement of irrigation, and changes in soil tillage practices (Figure 7.26). Between the 1930s and the 1950s, hybrid seed varieties gradually replaced open-pollinated varieties in all major maize-growing states. One characteristic of improved maize hybrids is that their erect structure has allowed farmers to steadily increase planting density. Between 1930 and 2000, seeding rates rose from about 30 000 to over 80 000 plants per ha (Duvick, 2005).

Another major innovation in seed technology began in the 1990s, when the first GE crop varieties became available. GE crops have had genes inserted into them that provide specific traits. The principal traits introduced to-date are insect resistance and herbicide tolerance. The most recent GE hybrids have "stacked" traits involving multiple inserted genes. Additional GE traits in the development "pipeline" include drought tolerance, improved nitrogen utilisation, and enhanced quality characteristics for animal feed (Parisi et al., 2016). The first commercial GE maize variety was adopted in the United States in 1996. By 2013 GE maize varieties had spread to 90% of total maize acreage in the country (Fernandez-Cornego et al., 2014).

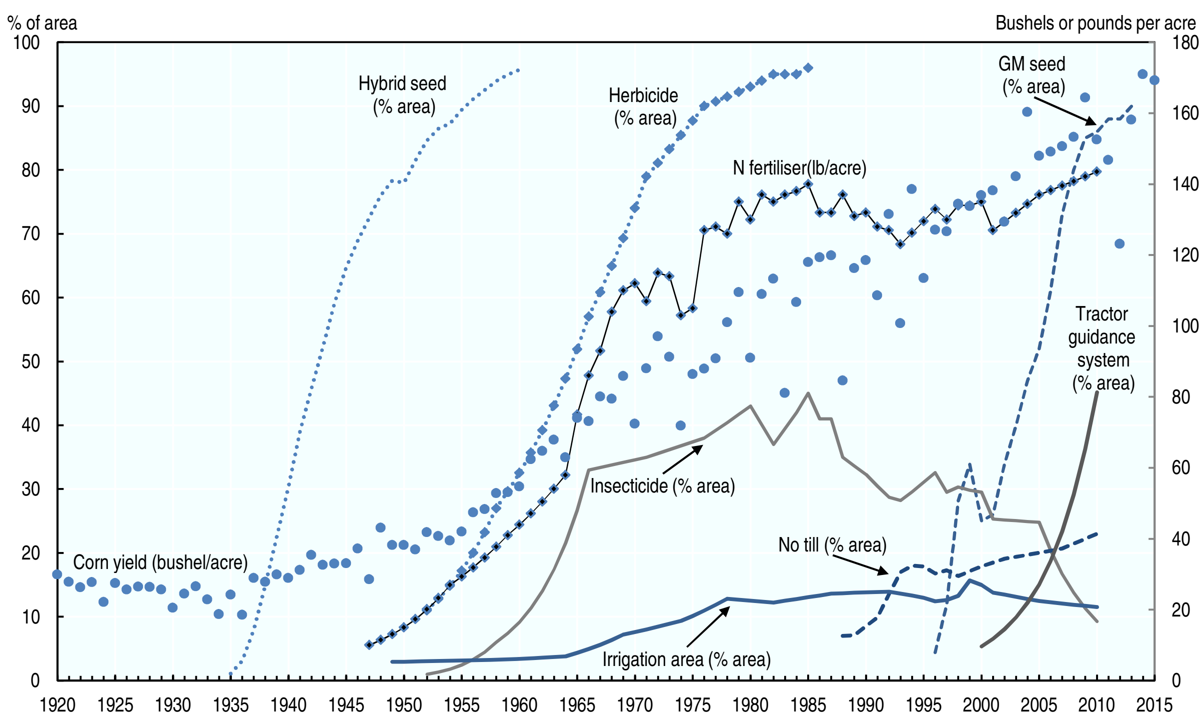
In addition to new varieties, several other technologies and cropping practices have been adopted by maize growers to raise productivity. After WW II, farm applications of inorganic fertilisers and chemical pesticides rose significantly. The increase in fertiliser and pesticides was necessary to realise the higher yield potential in the new hybrid varieties that were adopted during this period. Nitrogen fertiliser use rose very rapidly from under 22 kg per ha (20 pound per acre) in 1950 to nearly 157 kg per ha (140 pounds per acre) by the mid-1980s. Between 1960 and 1982, the share of maize acreage treated by herbicides rose from less than 10% to more than 95%, and has remained at about that level since. Insecticide use never reached more than 45% of maize area, and subsequently fell to only about 25% of acreage in the mid-2000s. The advent of GE maize varieties resistant to major maize pests reduced the need for insecticides (however, seeds are commonly coated with insecticides and fungicides to improve their viability, but at much lower rates than field spraying).

Two important cropping practices that affecting maize productivity are the use of irrigation and no-till cultivation. The share of maize under irrigation expanded slowly since the 1950s to reach 12-15% of total acreage by the 1990s, and has remained at about that level since. No-till maize took off rapidly in the early 1990s and reached 23% of total area by 2010 (Wade et al., 2015). Adoption of these new technologies and cropping practices are often complementary: no-till maize is often used together with herbicide-tolerant GE varieties and herbicides, with the seed-chemical combination acting as a substitute for the use of mechanical tillage for weed control. Some important advantages of no-till include significantly reduced soil erosion and lower machinery, fuel and labour costs, which have to be compared with the impact of higher herbicide application.

Recently, new information technologies have been developed and applied in maize production under the general heading of precision agriculture. Precision agriculture encompasses an evolving suite of practices that include the use of yield monitors; variable rate applicators for fertilisers, chemicals and irrigation water; autosteer tractor guidance systems: and sensors to detect emerging biotic and abiotic yield stresses during the growing season. The use of autosteer tractor guidance systems has expanded rapidly in maize production, rising from less than 5% of planted acres in 2000 to 45% by 2010 (the last year for which comprehensive statistics are available). By enabling more precise and less demanding field operations (such as planting), autosteer tractor guidance systems have saved labour, fuel, seed, and extended the work-day during the critical planting season. This has enabled farmers to maintain sown area even in years where untimely rainfall or late winter thaw shorten the period available for planting.

The sets of new technologies described above served to increase maize productivity by saving resources, namely the amount of land, labour, chemicals, energy and machinery, needed to produce a given quantity of output. Saving these resources reduced the unit cost (cost per bushel) of producing maize. These costs savings increased the profitability of farming and made US maize producers more competitive in international markets. Some of the gains from productivity were also passed on to the food industry and consumers in the form of lower prices for commodities, which results from the increased supply of maize to markets.

Figure 7.26. Crop yield and technological change in maize production, 1920-2015



Some series are only available periodically. For these series, adoption rates for intervening years have been interpolated.

Sources: Maize yield and hybrid seed area are from the USDA (2015f), *Agricultural Statistics*. Maize irrigated area is from USDA (2015g), *Census of Agriculture*. Adoption rates for herbicides, insecticides, no till, tractor guidance systems, and N application rates for fertiliser are from the USDA (2015h), Economic Research Service. GM seed adoption rates are from Fernandez-Cornejo et al. (2014).

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Innovation and structural change in the pig industry

The US pig industry provides a striking example of how innovation and structural change combine to produce productivity growth (McBride and Key, 2013). In 1992, about 190 000 farms had swine onsite. Most were "farrow-to-finish" farms that combined all life stages of pig production, along with the production of crops for feed. Pigs were sold through cash markets to local packers.

All that changed rapidly in the next few years. Production shifted to fewer but larger farms. By 2012, the number of farms with swine had fallen by two-thirds to 63 000 farms, even as total production increased. The new system featured farms that specialised in single stages of pig production, such as farrow-to-wean, wean-to-feeder, or feeder-to-finish, and which were linked together through production contracts (Table 7.6). Most still produced crops, using pig manure as an input, but feed was purchased and some farms specialised only in pigs.

Under production contracts, firms called integrators provide contract growers with feeder pigs, age-specific feeds, veterinary services, and technical advice. Contract growers are paid fees per animal or per pig space, which may also be tied to target values for feed conversion and mortality. Integrators that are also processors manage placements of pigs on farms, and flows to packing plants to meet demand and minimise processing costs. Integrators that are not processors typically sell market pigs to processors under marketing contracts specifying weekly and daily flows of animals to plants, and that tie pig prices to pig attributes.

The new system facilitated a set of interrelated innovations. Genetic adjustments could be introduced rapidly, on a large scale. On-farm technologies — such as all-in/all-out production (where, to control the spread of diseases only pigs of similar age are housed together and facilities are cleaned and disinfected between generations), feed formulations tied to the phase of production, artificial insemination, and improved ventilation and sanitation in houses — were widely adopted and allowed integrators to provide uniform animals to processors at lower costs while also maintaining or improving animal health. With integrators and processors assuming price risks and marketing functions, farmers could be induced to invest in larger facilities to realise scale economies. With steady supplies of pigs, processors also invested in larger production facilities to realise scale economies.

Structural change was associated with striking changes in productivity. Feeder-to-finish farms showed large improvements in feed conversion and labour productivity between 1992 and 2004, and real average production costs fell by over 40% (Table 7.6). Those measures also improved among farms in the traditional farrow-to-finish system, because only the most productive and adaptable of those farms survived.

The gains came through three channels: improvements available to and used by all farms; efficiencies introduced by integrators via the contract system: and new scale economies captured by expanding operations. Scale is an important part of the story, and the impacts are summarised for feeder-to-finish farms in Table 7.7. Farms are sorted into five size classes, and an estimated scale elasticity is reported for each class. The estimate — the percentage change in output attendant upon a 1% increase in all inputs — is based on production functions reported in McBride and Key (2013) and other sources cited therein. In 1998, the estimates exceeded one for each of the four smaller size classes, indicating that farms in those classes could reduce unit costs by expanding output.[3]

Farms responded rapidly to available scale economies. In 1992, only 9.3% of pigmeat output was in the two largest classes, close to constant returns. But by 1998, 65% of production was in the largest two classes, and by 2009, 91% was. That adjustment was an important driver of improved productivity and reduced real production costs during 1992-2009. In turn, those developments limited increases in retail pigmeat prices in the face of sharp increases in feed costs, and led to improved international competitiveness. Annual pork exports increased from 0.5 billion pounds in 1992-94 to 4.0 billion pounds in 2007-09 as the United States became a net exporter.

Table 7.6. Structural change and efficiency in pig production, 1992-2009

Item	1992	1998	2004	2009
Share (%) of all pigmeat production:				
Under contract	5	40	67	71
On farrow-to-finish farms	65	38	18	20
Feeder-to-finish farms				
Average size (head sold per farm)	804	2 756	4 730	7 222
Feed conversion (pounds per cwt gain)	383	282	214	207
Labour rate (hours per cwt gain)	0.89	0.24	0.15	0.12
Production costs (per cwt, 2009 USD)	69.22	51.35	39.69	37.62
Farrow-to-finish farms				
Average size (head sold per farm)	886	1 239	1 472	3 980
Feed conversion (pounds per cwt gain)	416	374	354	300
Labour rate (hours per cwt gain)	1.13	0.72	0.54	0.48
Production costs (per cwt, 2009 USD)	85.89	71.59	62.36	43.86

cwt is hundredweight equivalent to around 45 kg. The production cost estimates are adjusted to 2009 dollars using an input price index derived from a USDA/NASS national feed price index and a USDA/NASS national agricultural production items index, with expenditure weights for each derived from a national survey.

Source: McBride and Key (2013), www.ers.usda.gov/publications/err-economic-research-report/err158.aspx.

Table 7.7. Scale economies and adjustment in feeder to finish operations, 1992-2009

Size class (cwt gain)	1998 scale elasticity	1992	1998	2004	2009
		Share of total output (%)			
<1 000	1.23	14.7	1.9	0.5	0.1
1 000-2 499	1.14	35.0	6.7	3.0	1.0
2 500-9 999	1.08	41.0	26.5	16.7	8.0
10 000-24 999	1.04	9.3	29.2	36.3	46.1
>24 999	0.97		35.7	43.4	44.8

Source: McBride and Key (2013), www.ers.usda.gov/publications/err-economic-research-report/err158.aspx.

Improved feed conversion reduced the environmental risks associated with feed production and manure generation. However, structural change that consolidates pigs on much larger operations also consolidates manure, raising the risks associated with manure storage failures and with excess nutrient applications. US regulatory policy aims to control those risks associated with large operations, while conservation programmes aim to provide incentives to adopt improved control structure and technologies.

Adoption of innovations when externalities are present

There is a class of worthwhile agricultural technologies for which market mechanisms may be insufficient to ensure widespread adoption. Many technologies involving pest and disease control in crops and livestock, for example, may not work effectively at the individual farm-level due to the mobility of these pests. This is a case where technology involves a significant externality, i.e. where the private and the social costs and benefits of technology adoption sharply diverge. US agricultural policy has devised special institutions and policies to incentivise adoption in these cases.

Externalities are often present in pest and disease control. Since pests and diseases can be highly mobile, actions taken (or not taken) on one farm or field may impact neighbouring farms. In some cases it may be possible to completely eradicate an agricultural pest or disease, but only if carried out on a large scale with all affected areas participating. Often, pest control and eradication programmes may be ineffective if confined to a community or state, and need to be coordinated at the federal or even international level.

Animal disease control. US legislation dating back to the late 19th century established the means by which the USDA and other federal government agencies could undertake and require collective action to protect agriculture from major biological threats. In 1884, Congress created the Bureau of Animal Industry (BAI) and authorised it to carry out the necessary scientific research and regulatory controls to address major livestock pest and disease problems. The BAI was able to eradicate a number of highly contagious pests and diseases from the United States, include bovine pleuropneumonia, tick-born Texas fever, Foot and Mouth Disease (FMD), bovine tuberculosis and pig cholera, many of which also infected humans (Olmstead and Rhode, 2015). Achieving these outcomes required scientific advances to understand the nature of the disease, its means of transmission, and to determine options for control. In addition, institutional innovations were necessary to coordinate an inter-state campaign to monitor for disease outbreaks, quarantine affected areas, and treat or destroy affected livestock. One innovation was developing an effective indemnification policy. As farmer cooperation in these efforts was essential, the BAI was authorised to indemnify (compensate) farmers for their losses. But to avoid moral hazard (where the promise of indemnification may discourage farmers to take proper precautions in protecting their livestock) compensation was calibrated according to the severity and ease of transmission of the disease. Full compensation was limited to highly infectious diseases like FMD. In other cases, farmers were offered only partial indemnification for losses. Olmstead and Rhode (2015) document that the economic benefits of these efforts far outweighed their costs.

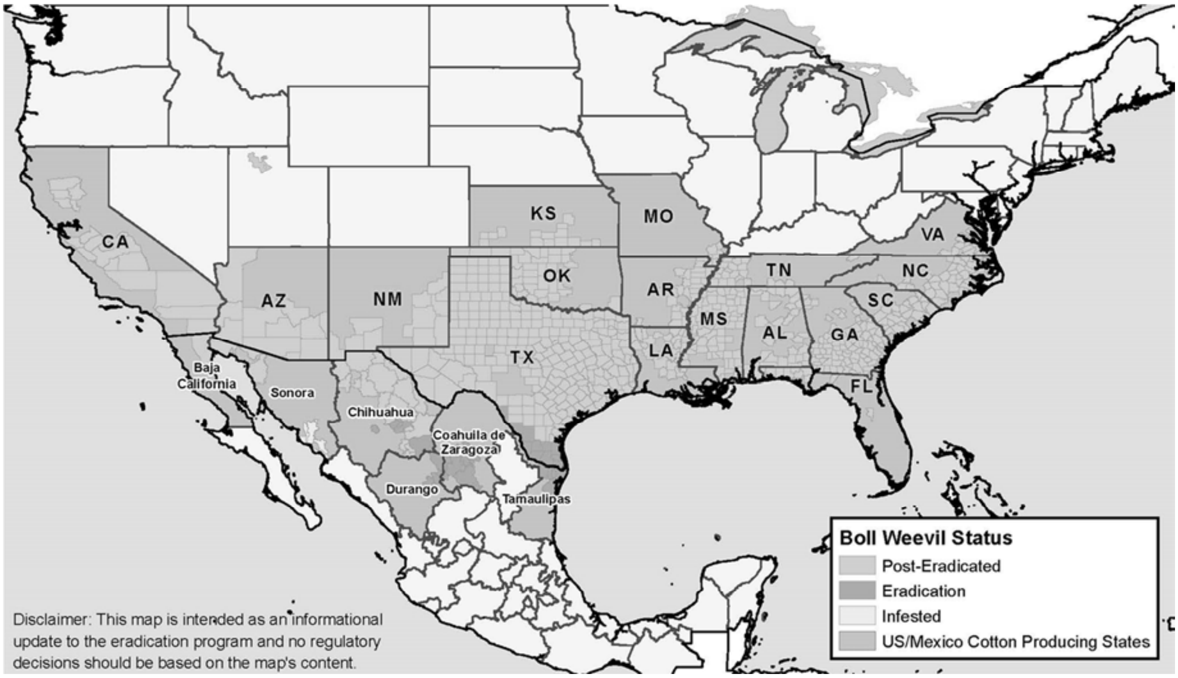
Boll weevil eradication. One of the most devastating pests affecting US crops has been the cotton boll weevil (*Anthonomus grandis*). The boll weevil crossed the border between Mexico and Texas 1892 and by 1924 had spread to all cotton-growing states in the country. Farmers adopted a number of practices to limit damage, such as adoption of early-maturing varieties, destruction of crop residues that might provide over-wintering insect refuges, and, especially after WWII, chemical pesticides. While farmers were eventually able to limit yield losses from the boll weevil, these control practices added considerably to the cost of production. By the 1960s, more than half of all insecticides used in US agriculture were applied to cotton (Ridgway et al., 1978). The widespread use of chemical pesticides also created environmental and health hazards. During the 1960s, scientific advances — especially the discovery of the diapause behaviour of weevil and the synthesis and use of pheromones to trap and monitor insect populations — suggested that it might be possible to eradicate the boll weevil from the United States. However, eradication could only be effective if carried out collectively, as weevils from one untreated field could rapidly re-infect surrounding areas. The 1973 Agricultural Act authorised the USDA to carry out a boll weevil eradication programme if it was considered feasible to do so. In 1978, large-scale field trials demonstrated the efficacy of eradication, and the USDA embarked upon a nation-wide programme. Under the terms of the programme, and to ensure farmer support, the programme was initiated in states where at least 70% of cotton farmers in a state voted in favour of the programme. Participation by all farmers then became mandatory, with about 30% of the costs borne by producers and 70% by the government

(Haney et al., 2009). Eventually farmers in all cotton-produced states voted to participate. International cooperation in boll weevil eradication was also extended to cotton-producing states in northern Mexico. By 2014, the boll weevil had been eradicated from all cotton-growing areas of the United States except for southern Texas, as well as many parts of Mexico (Figure 7.27). Boll weevil eradication led to a significant reduction in pesticide use on cotton fields and greatly improved the profitability of cotton growing. Some states, like Georgia, saw a resurgence of their cotton industry following eradication (Figure 7.28), subsequent to the long period of decline following the first appearance of the pest (Haney et al., 2009).

Screwworm eradication. In some cases, new technologies to control agricultural pests and diseases can be carried out by government authorities without direct participation or actions by farmers. For crops not native to the United States, classic biological control, in which exotic predators of insect pests are identified, multiplied and released, has often been an effective strategy. An example of where scientific advances led to new opportunities for government-led pest control is the case of the New World Screwworm (*Cochliomyia hominivorax*). The screwworm is a maggot that feeds off living flesh, and for decades the screwworm was the cause of suffering, death and expensive treatment measures for livestock. In the 1950s, researchers from the USDA and Texas A&M State University discovered it might be possible to eradicate the screwworm using the Sterile Insect Technique (SIT), in which mass numbers of sterile males would be bred and released to interfere with insect reproduction. After successful local trials the programme was carried out nationwide, and by 1966, one of the greatest scourges of vertebrate animals had been eradicated from the United States (Wyss, 2000). Through a cooperative international effort, screwworm eradication was extended to Central America, and by 2006 the screwworm had been eliminated as far south as the Darien Gap on the Isthmus of Panama. The biological control of screwworm represents a case where government agencies led the application of the technology; farmers were largely passive observers to the dissemination process.

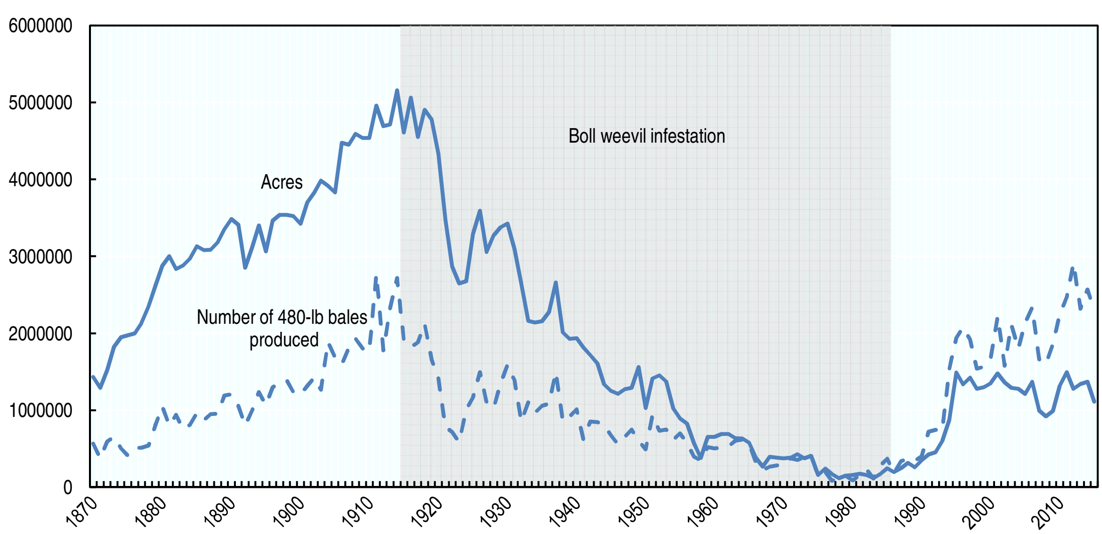
New pests and evolving diseases remain a constant threat to agriculture, whether they have been introduced from external sources, or have evolved to overcoming existing control measures. Recent examples of new threats to US agriculture include HLB disease (citrus greening) first detected in Florida orange groves in 2005, the Porcine Epidemic Diarrhea Virus (PEDv) detected in swine herds in 2013, and the emergence of a new highly infectious strain of avian influence in US poultry flocks in 2015. Each of these diseases has resulted in millions of dollars in economic losses to farm producers and consumers, and effective measures of control are still under development.

Figure 7.27. Cotton boll weevil eradication in North America



Source: USDA (2015i), Animal and Plant Health Inspection Service (APHIS). www.aphis.usda.gov/plant_health/plant_pest_info/cotton_pests/downloads/bwe-map.pdf.

Figure 7.28. The boll weevil and cotton production in Georgia



Source: Cotton statistics from USDA. See Haney et al. (2009) for a detailed assessment of the boll weevil's impact on the Georgia cotton industry. http://extension.uga.edu/publications/files/pdf/RB%20428_2.PDF.

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International cooperation

The benefits of international cooperation for national innovation systems stem from the specialisation it allows and from international spillovers of agricultural science and technology. International cooperation in agricultural R&D is particularly important where global challenges (as in the case of responding to climate change) or trans-boundary issues (related to water use or pest and disease control) are confronted, and when initial R&D investments needed to address a common problem are exceptionally high.

With growing capacities in agricultural science and technology elsewhere in the world, US public research institutions have placed greater emphasis on international collaboration to address shared challenges. In addition, the United States continues to give priority to investing in agricultural innovation systems to promote food security in low income countries. Moreover, US agricultural universities attract significant numbers of foreign students, and US foreign agricultural assistance programmes emphasise building national capacities in agricultural sciences in developing countries. This section describes US government engagement in international agricultural R&D cooperation and technical assistance.

International cooperation in agricultural research

The USDA's ARS engages in international collaboration through multilateral and bilateral partnerships. Multilateral partnerships have been particularly effective for controlling agricultural pests and diseases that threaten whole regions of the world. ARS currently participates in the STAR-IDAZ Global Network for Animal Disease Research (which includes specific groups of collaborators working on Foot and Mouth Disease in cattle, African Swine Fever, and avian influenza) and the Borlaug Global Rust Initiative (to combat wheat rust, a fungal disease of global importance). Global and regional partnerships have also been established to address specific resource challenges, such as the Global Research Alliance on Agricultural Greenhouse Gases, the Global Genetic Resources Information Network, and the Middle East Water and Livelihood Initiative.

ARS has formal agreements with nearly 60 countries for research collaboration, and maintains long-term bilateral research agreements with key research partners, including China, Brazil, Israel and Korea. ARS maintains overseas laboratories in France, Australia, and China to study the biological control of exotic pests in order to protect US agriculture against potential invasive species. A major component of ARS international research engagement is direct scientist-to-scientist collaborations, which includes informal scientific and information exchange, hosting visiting scientists, or co-authoring publications.

Measure of R&D collaboration

About 14% of US agriculture patents have a foreign co-inventor, which is more than the OECD average but less than in many countries (Table 7.8). However, the United States is by far the first producer of agriculture-related patents with foreign co-inventor in the world, contributing to more than 10% of the world's total, well above the second largest contributors which are Germany, France and the United Kingdom (Figure 7.29). This can be explained by the large size of the US agricultural research system the importance of research activities by US agri-food enterprises, including plant breeding multinational companies.

The share of publications with foreign co-authors in US agriculture-related publications is lower than the OECD and EU15 averages, but also lower than in Australia and Canada (Table 7.8). Again, reflecting the large size of research activity on food and agriculture within the United States, US publications with foreign co-authors make the largest contribution to all publications on agricultural and food sciences, followed by the United Kingdom, Germany and France (Figure 7.30).

Table 7.8. Agri-food R&D co-operation, 2006-11

Agri-food outputs with co-authors as a share of total agri-food outputs (%)

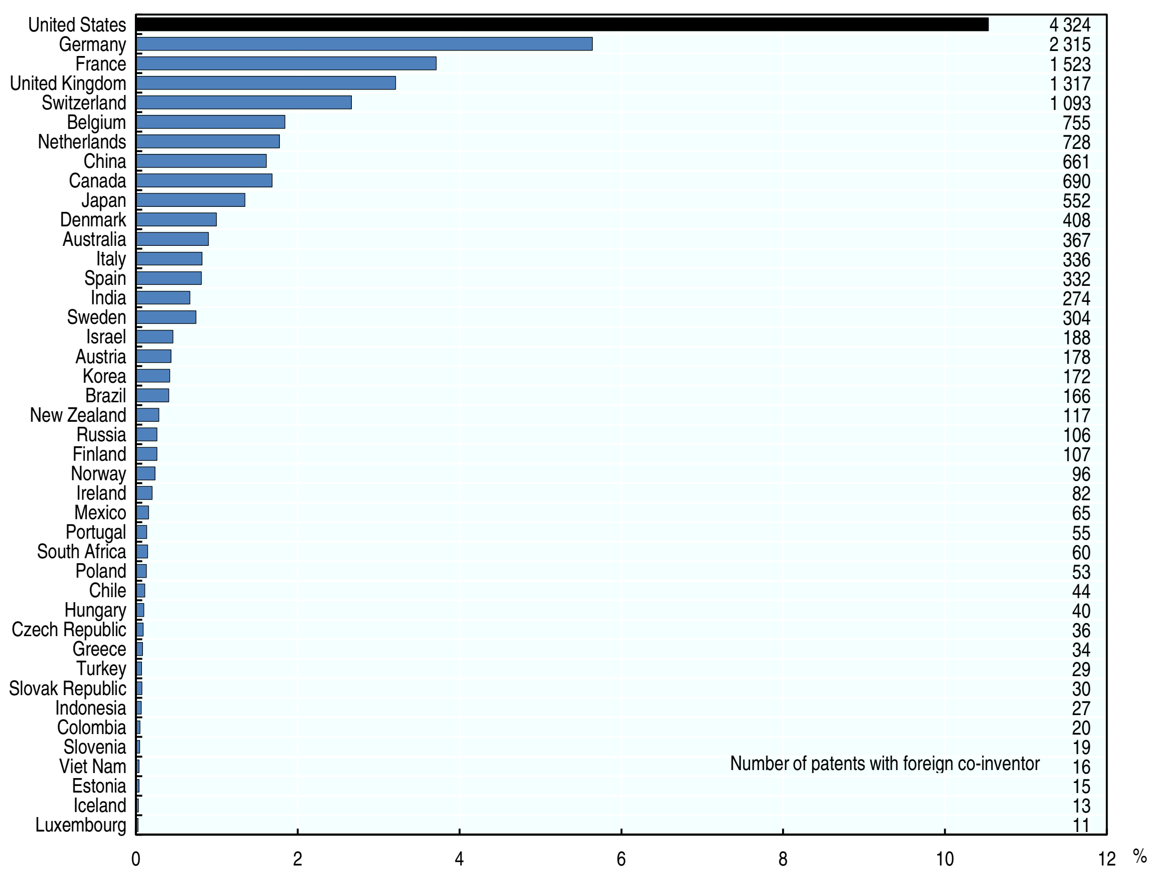
	United States	Australia	Brazil	Canada	Netherlands	EU15 average	OECD average
Patents	14.3	23.1	29.7	29.7	27.1	36.2	11.8
Publications[1]	36.4	47.3	22.3	48.9	65.1	5.7	50.8

1. 2007-12.

Source: OECD Patent Database, January 2014; SCImago. (2007), www.scimagojr.com.

Figure 7.29. Agriculture patents with a foreign co-inventor filed under the Patent Co-operation Treaty (PCT), 2006-11

Country share of agriculture patents with foreign co-inventor as a % of world total



Agriculture includes patents from IPC classes A01, A21, A22, A23, A24, B21H 7/00, B21K 19/00, B62C, B65B 25/02, B66C 23/44, C08b, C11, C12, C13, C09K 101/00, E02B 11/00, E04H 5/08, E04H 7/22, G06Q 50/02.

Patent counts are based on the priority date (first filing of the patent worldwide), the inventors country of residence, using fractional counts. EU28 and BRIICS totals exclude intra-zone co-operations.

Source: OECD Patent Database, January 2014. www.oecd.org/sti/inno/oecdpatentdatabases.htm.

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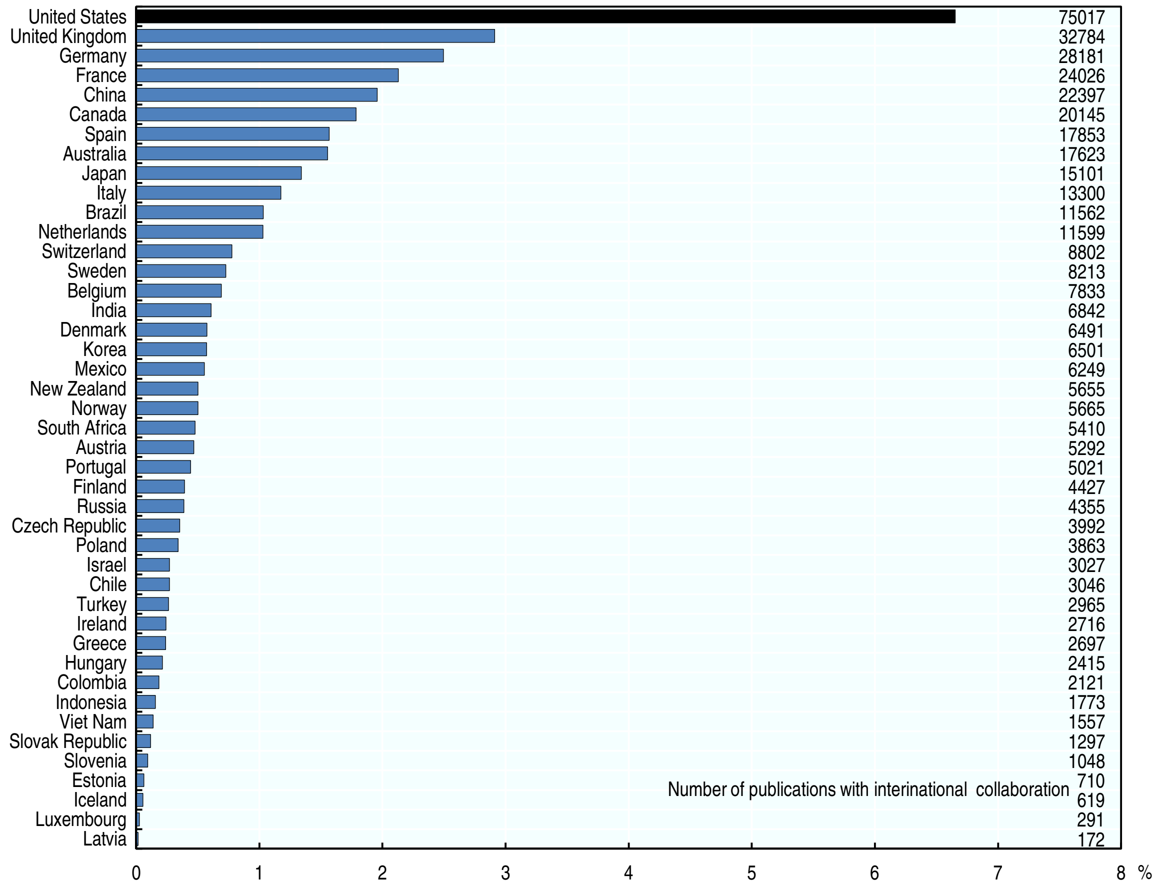
Figure 7.30. Agriculture publications in collaboration, 2007-12

Country share of agriculture publications with foreign co-authors as a % of world total agriculture publications



Agriculture publications include agricultural sciences and food sciences.

Agricultural sciences include Scopus journal classifications: agronomy and crop science, animal science and zoology, aquatic science, ecology/evolution/behaviour systematics, forestry, horticulture, insect science, plant science and soil science, and miscellaneous agriculture/biological sciences.

Source: SCImago (2007), *SJR — SCImago Journal & Country Rank*, Retrieved March 2014, from www.scimagojr.com.

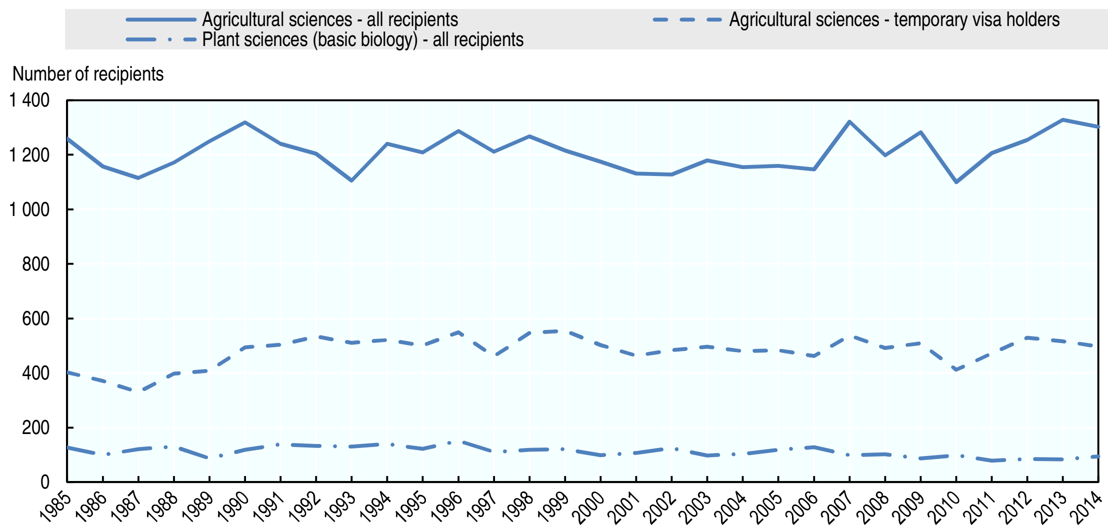
StatLink http://dx.doi.org/10.1787/888933409147

Agricultural universities and training of foreign agricultural scientists

Each year, US universities award about 1 200 doctoral degrees in agricultural sciences (Figure 7.31). About 40% of these are to non-resident foreign students, most of whom return to their home countries following graduation. Over the last 30 years there has been a gradual shift in the composition of Ph.D. degrees awarded in the agricultural sciences. In the 1990s about half of all agricultural science Ph.D.'s were in plant or animal sciences; that proportion has fallen to about one-third. A growing share of agricultural science degrees are being awarded in natural resources (including forestry, fisheries and wildlife).

While the number of doctoral degrees awarded in agricultural sciences has remained fairly constant over the past three decades, the number of Ph.D. degrees awarded in life science disciplines has soared. Between 1984 and 2014, the number of doctoral recipients in life science disciplines increased from 5 800 to 12 500 (National Science Foundation, 2014). Much of this growth was driven by a substantial increase in US Government funding for human health research over this period (see below). Included in life science disciplines (but not classified as agricultural sciences) is a growing number of Ph.D.'s awarded to US and foreign nationals in basic biological and biotechnology sciences, including the fields of plant genetics, plant pathology, and plant physiology (Figure 7.31). Some of the Ph.D. graduates in biological sciences can be expected to pursue careers in agriculture and agricultural biotechnology.

Figure 7.31. Number of doctoral degrees awarded in agricultural sciences by US universities, 1985-2014



Source: National Science Foundation (2016). www.nsf.gov/statistics/2016/nsf16300/digest/.

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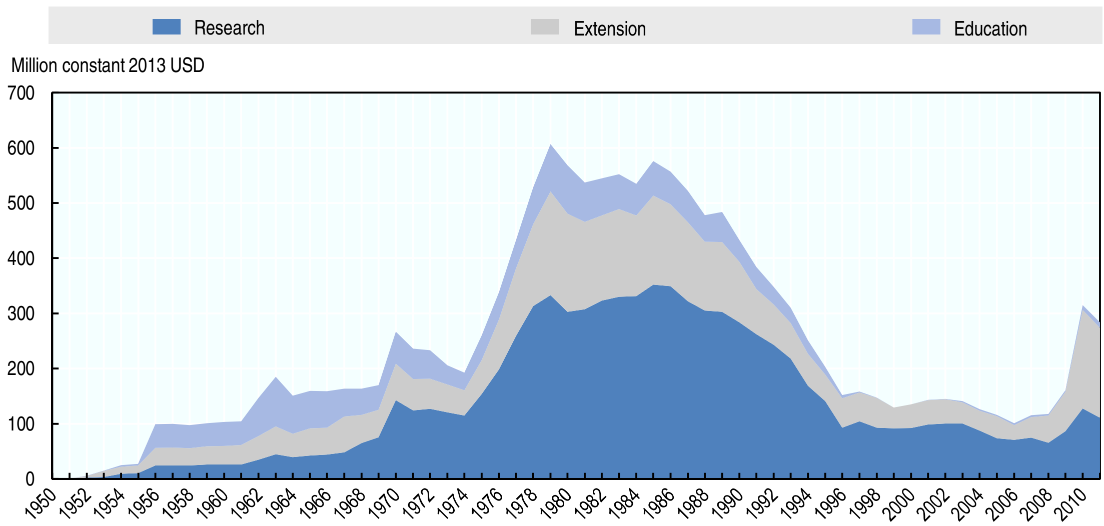
Foreign development assistance for agricultural science and technology

Ever since President Truman' *Point Four Program*, the US Government has offered significant scientific and technical assistance to developing countries. Agriculture has been a major part of this assistance. Funding to support Agricultural Innovation Systems, which includes agricultural research, extension and education, rose rapidly in the 1960s and 1970s, peaking in 1979 at around USD 600 million in 2013 USD (Figure 7.32). Agriculture's role in US foreign assistance diminished in the 1990s, but was reinvigorated through the *Feed the Future Initiative* of the Obama Administration. The *Feed the Future Initiative* is a whole-of-government approach that coordinates activities of several federal government agencies. Since the launching of *Feed the Future Initiative* in 2010, funding for agricultural innovation increased from around USD 100 million to about USD 300 million per year. The US Agency for International Development (USAID) channels funding for agricultural research projects through US universities, national agricultural programmes in developing countries, the CGIAR Consortium of international agricultural research centres, USDA research agencies, and other partners. In 2016, the US Congress passed the Global Food Security Act to establish the *Feed the Future Initiative* as a permanent part of US foreign assistance.

The United States has historically been the largest single donor to the CGIAR since its inception in 1972. In 2014, US contributions to the CGIAR totalled USD 130 million, or 12% of total CGIAR funding (CGIAR, 2014). The CGIAR Consortium includes 15 independent research centres dedicated to improving agriculture, nutrition, and natural resource management in developing countries. In its early years, most CGIAR efforts on crop improvement were focused on Asia and Latin America. Major impacts were achieved through the development and diffusion of high-yielding "Green Revolution" varieties of rice, wheat and maize. Increasingly, the CGIAR has turned its attention to Sub-Saharan Africa, where about half of its research activities are currently oriented

(CGIAR, 2014). By 2010, improved crop varieties had been adopted on 35% of the total area planted to 20 major food crops in Sub-Saharan Africa, with CGIAR Centres contributing about two-thirds of these improvements (Walker et al., 2015).

Figure 7.32. US foreign assistance for agricultural research, extension and education, 1950-2011



Source: Gary Alex, USAID, personal communication (Alex, 2016).

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New initiatives in international cooperation: The G20 MACs and the Global Alliance for Climate-Smart Agriculture

Heightened concerns about the state of global food supply-and-demand balances and the potential effects of climate change on agriculture have led the US Government to strengthen international scientific cooperation in agriculture. In 2012, the Agricultural Ministers of the world's 20 largest economies (the G20) endorsed intensified collaboration in agricultural research amongst their respective countries in order to raise productivity in agriculture. Since 2012, the agricultural chief scientists of G20 nations have meet annually to discuss and explore exploring new mechanisms for undertaking collaborative research on priority topics of mutual interest.

At the United Nations Climate Summit 2014, the United States joined 46 other countries and organisations in forming the Global Alliance for Climate Smart Agriculture. The goal of the Alliance is to develop and promote agricultural production systems that sustainably increase productivity and resilience. A major focus of the Alliance is to increase research and development of new farm technologies and practices that will help farmers deal with the heightened risks associated with climate change.

Information sharing

The US government is committed to the sharing of information from publically-funded research, and promotes the sharing of agricultural research-related information at the international level. Box 7.4 presents the example of the US National Plant Germplasm System, which collects and distributes crop genetic resources from and to different sources, including non-US ones.

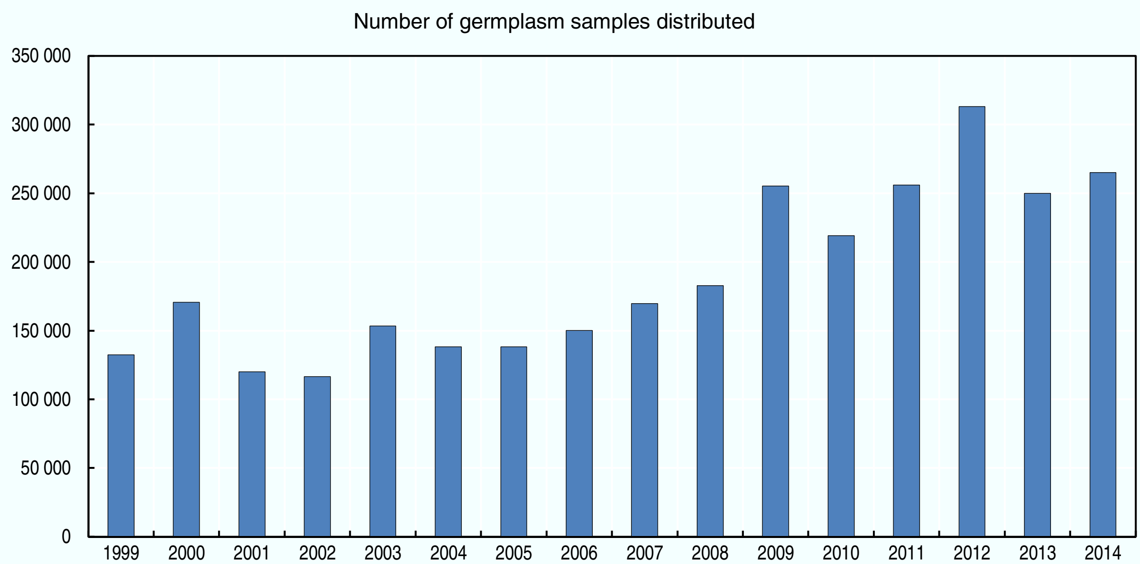
As a G8 member and as part of the New Alliance for Food Security and Nutrition, the United States committed to "share relevant agricultural data available from G8 countries with African partners and convene an international conference on Open Data for Agriculture, to develop options for the establishment of a global platform to make reliable agricultural and related information available to African farmers, researchers and policymakers, taking into account existing agricultural data systems." This led to the creation of the Global Open Data for Agriculture and Nutrition (GODAN) initiative in 2013. GODAN seeks to support global efforts to make agricultural and nutritionally relevant data available, accessible, and usable for unrestricted use worldwide. The initiative focuses on building high-level policy and public and private institutional support for open data.

Box 7.4. Conserving and sharing crop genetic resources

Crop breeders need to have access to a wide diversity of genetic resources to make steady improvements to cultivars, including building their tolerances to biotic and abiotic stresses. The US National Plant Germplasm System (NPGS) is a collaborative effort managed by the USDA's Agricultural Research Service to safeguard the genetic diversity of agriculturally important plants. The NPGS mission is to acquire, conserve, evaluate and characterise, and distribute crop genetic resources. The NPGS has extensive holdings of crop genetic resources, called accessions, which it maintains in gene banks. Many NPGS gene banks are located at state land-grant universities, which contribute field, greenhouse, and laboratory space for operations. The NPGS freely distributes crop germplasm accessions and information about them to researchers, breeders, and educators. It serves a large international scientific community. Requests for materials from the NPGS system has been rising, with over 300 000 crop accessions distributed in 2014 alone (Figure 7.33).

Like all countries, the United States depends on genetic material that is not incorporated into its own gene banks or found within its borders, and thus the NPGS regularly exchanges materials with other institutions. National working groups of specialists familiar with a given crop, called Crop Germplasm Committees, identify gaps in NPGS collections and develop proposals for filling those gaps. For a number of reasons, which may include both the greater codification of rules for germplasm exchange and for intellectual property protection (as well as the fact that many large genetic resource collections have already been transferred from gene bank to gene bank), the number of accessions transferred to the NPGS from non-US sources in a recent five-year period was only about 8% of what it was in a similar period 30 years earlier. In contrast, in the mid-2000s, the NPGS estimated that it distributed approximately six accessions to other countries for every accession it received.

Figure 7.33. Distributions of crop germplasm by the USDA National Plant Germplasm System, 1999-2014



Source: Bretting (2013). http://escop.ncsu.edu/docs/2013%20NPGCC%20Briefing%20Bretting.pdf.

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Summary

- The US agricultural research and innovation system is the leader in terms of its share of global investment and results. Public and private actors play complementary roles, with public efforts focusing on public good provision such as research with long term effects, natural resources and policy issues. A federal-state partnership supports education, research and extension, which are integrated through the unique Land Grant system. Among government agencies, the Agricultural Research Service (ARS) of the USDA is the main performer of agriculturally-related research.

- The office of the USDA chief scientist coordinates agriculturally-related research across the USDA and other federal government agencies, through participation in science and innovation coordination bodies. Government also receives advice from national academies. Stakeholders inform and influence priorities through formal mechanisms such as membership to a national advisory board, and *ad hoc* consultations when planning major programme activities.

- With the emergence of stronger linkages between agricultural sciences and other fields, especially biological sciences and information technologies, the set of institutions funding and preforming research relevant to agriculture has broadened.

- Government research programmes are evaluated annually and at the end of five-year cycles, providing useful information for the next cycle. Evidence of widespread adoption of some innovation is well-documented and analysed.

- Private expenditure on food and agriculture R&D nearly doubled in real terms between 2003 and 2013, while public expenditure declined. Federal expenditure now accounts for 17% of the total and the combined share of federal and state expenditures does not reach 25% of total.

- Agriculturally-related research alone was traditionally dominated by the public sector but private expenditures have overtaken public expenditures since 2011.

- Mechanisms to fund research have evolved. Main funding for University-State Agricultural Experiment Stations (LGU-SAES) traditionally came from capacity research grants, with federal-state co-funding. In recent decades, the USDA has given greater emphasis to competitive funding mechanisms, which accounted for half of resources by 2010.

- Federal-state partnerships support education, research and extension, which are integrated through the unique Land Grant system. In addition to advice from input suppliers, public extension services provide a widening range of advice on agriculture, conservation, rural development, health and nutrition through partnerships between federal, state and local governments. As for research, the USDA establishes broad priorities for programmes it co-funds, and state and local partners define priorities for cooperative extension. Over time, the share of federal funding has decreased.

- Intellectual Property is well-protected using a diversity of mechanisms, and thus have encouraged private investment in R&D and adoption of innovation. There is widespread use of patents for transgenic crops, although companies often apply for both patents and Plant Variety Protection Certificates for the same cultivar.

- The Federal Government offers three tax provisions to encourage private firms to engage in R&D: a deduction from taxable income for research expenses, a tax credit for increasing research activities, and an exemption for donations to charitable agricultural research

organisations. In 2015, tax exemptions for charitable agricultural research organisations were created to encourage charitable contributions to agricultural research.

- Direct support to innovation includes grants to private firms engaged in R&D activities, public-private R&D collaboration agreements, and patenting and licensing by public institutions to foster private innovation. In the early 1980s, new legislation encouraged government laboratories to increase cooperation with the private sector; authorised the patenting of publically funded research; and established the SBIR programme, where a minimum percentage of government agency R&D funding is required to be allocated to small businesses. More recently, the Foundation for Food and Agricultural Research was established as a non-profit, non-government organisation to support joint public-private funding of food and agricultural research.

- Scientific publications and patents illustrate the leading role the United States plays in global agricultural science. The number of petition approvals of GE crops submitted to government agencies also illustrates the growing activity of US research in this area.

- Numerous studies of the impact of public agricultural research on the productivity of the entire farm sector show significant and high returns to research (estimates range from 20% to 60% with a median of 40%), with these benefits lasting for several decades. These studies also found benefits of public agricultural research were widely shared, not only among farmers but also to consumers in the form of more abundant and lower cost food.

- With growing capacities in agricultural science and technology elsewhere in the world, US public research institutions have placed greater emphasis on international collaboration to address shared global challenges. In addition, the United States continues to give priority to investing in agricultural innovation systems to promote food security in low income countries.

Notes

1. The National Academy of Sciences (2009) characterised New Biology as the integration of life sciences with physics, engineering, computational sciences, mathematics and other disciplines. It affords new opportunities for biological research to address pressing societal problems regarding food, the environmental, energy, and health. Adapting crops to changing environments, developing sustainable alternatives to fossil fuels, improving human nutrition, and developing new biomaterials for industry are some of the areas where the New Biology can be applied to agriculture.
2. Box 7.4 in OECD (2015b) discusses the roles of IPR in plant breeding, including in the WTO and developing country context. It suggests ways to amend the patent system to broaden innovation in plant breeding.
3. Only estimates for 1998 are reported to save space; there were not enough operations in the largest class to generate an estimate for 1992, and estimates in 2004 and 2009 changed little.

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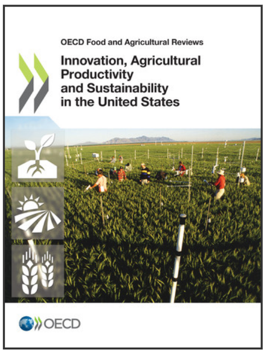

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