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The Evolving Institutional Structure of Public and Private Agricultural Research

Keith O. Fuglie and Andrew A. Toole

Over the past several decades, the private sector has assumed a larger role in developing improved technology for food and agriculture. Private companies fund nearly all food processing research and development (R&D) and perform a growing share of production-oriented R&D for agriculture. In addition, institutional partnerships for public–private research collaboration are growing in the United States and other countries. This article outlines the major forces driving these changes and offers an interpretive framework to explore some of the implications for the volume and nature of research performed by the public and private sectors. One of the critical issues is whether public agricultural research complements and thereby stimulates additional private agricultural R&D investments. Another important issue concerns the role and contribution of alternative public–private partnership arrangements. To date, changes in the institutional structure of public and private agricultural research have outpaced systematic investigation, and new theoretical and empirical research is needed to help guide policy and address key societal challenges, such as climate change, clean energy, water scarcity, food safety, and health.

Key words: Agricultural Biotechnology, Agricultural Input Industries, Complementarity, CRADA, Institutional Change, Pasteur's Quadrant, Patent Licensing, Public-private Technology Transfer, Research Consortia.

JEL codes: O3, Q16, O3.

Most economists and policy makers identify the growth in agricultural productivity as a leading reason why global food production has continued to meet growing food demand. In turn, evidence suggests that research and development (R&D) investments in food and agricultural research systems produce new knowledge and technologies that fuel improvements in agricultural productivity. However, over the past several decades, major changes have taken place in these research systems, both in terms of their structure and financing. In particular, some traditional areas of the public sector in financing and performing research are being supplanted by the private sector. In the United States, three major developments in the system that generates most of the new technology for food and agriculture are (*a*) support for public agricultural research has stagnated, (*b*) private agricultural research spending has grown, and (*c*) new institution models have emerged for public and private research and technology development. This article reviews these changes and how they have redefined public and private agricultural R&D.

We first describe the changing volume, composition, and structure of private sector agricultural research with a focus on the United States. Next, we describe major changes to federal science policy regarding the nature of public–private research collaboration, including institutional arrangements such as cooperative research agreements, patent licensing, and research consortia. We use the Stokes–Ruttan "quadrant" model of scientific and technology development as a conceptual framework to explore implications for the kinds of research performed by the public and private sectors. We then review empirical evidence on the economic implications of these developments. Several recent studies have examined whether public agricultural research "crowds out" or

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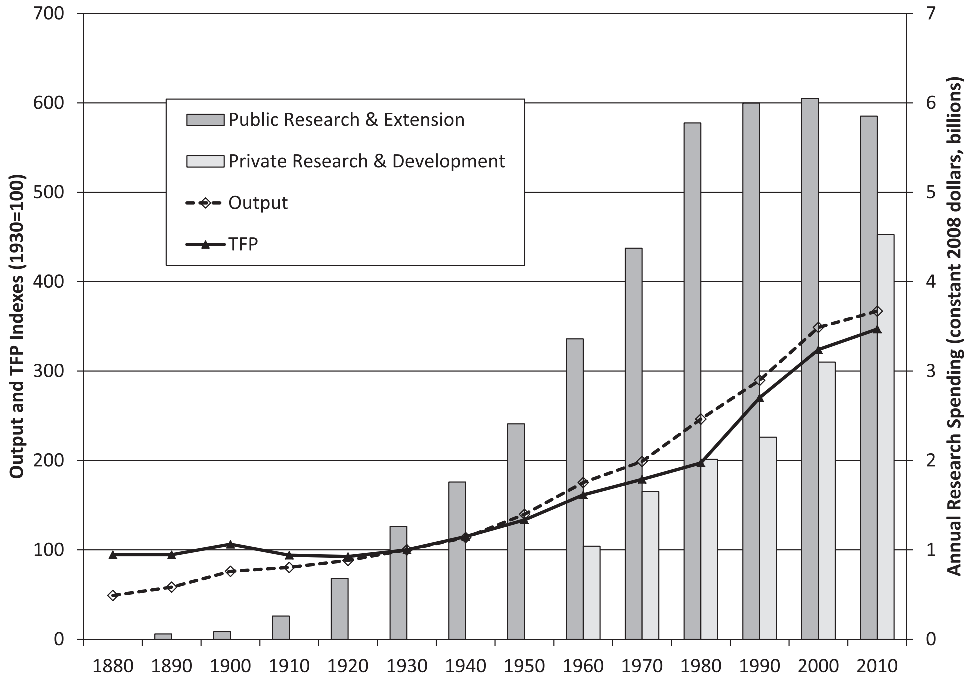

Figure 1. Agricultural research investment and productivity in the United States

Sources: The output and total factor productivity indexes for 1880–1950 are from Hayami and Ruttan, and those for 1950–2009 are from the Economic Research Service. Public research and extension spending information is from Alston et al. (2010) and private agricultural research and development spending is from Fuglie et al. (2011).
Note: Private research spending only includes research oriented toward farm productivity and excludes research in food processing.

stimulates private research (i.e., whether they are substitutes or complements). Few studies, however, have examined economic implications of direct public–private collaboration in agricultural research. We selectively review evidence from other sectors to draw some lessons for agriculture.

Biotechnology and the Rise of Private-Sector Agricultural Research

Long-term productivity growth in agriculture is strongly determined by investments in R&D. In the United States, before 1930 there was little or no measurable change in agricultural total factor productivity (TFP), and growth in output came mainly from bringing new resources into production (figure 1). Since then, nearly all growth in output has come from raising TFP, with aggregate resources used remaining largely unchanged. The rise in productivity came after several decades of public investment in research that began with the 1887 Hatch Act, but which rose substantially in the first two decades of the twentieth century. Growth in public agricultural research spending further accelerated after World War II until the 1980s, after which farm production–oriented research stagnated (Alston et al. 2010). The leveling off of public R&D investment since 1980 would seem to imply that agricultural TFP growth must eventually slow.[1] But the agricultural TFP series maintained by U.S. Department of Agriculture (USDA), Economic Research Service (ERS), showed few signs of significant slowdown, at least through 2011 (the latest year of available data).[2]

[1] Models linking R&D investment to TFP growth treat R&D like an investment in capital but with a long lag between when the investment is made and when that investment begins to affect productivity. But like physical capital, knowledge capital eventually depreciates. Eventually, constant R&D spending just replaces depreciating R&D stock and further growth in TFP ceases (Alston et al. 2010).

[2] An alternative productivity series constructed by International Science & Technology Practice & Policy (INSTEPP) and described in Alston et al. (2010) for 1950–2002 does seem to show a slowing of U.S. agricultural TFP growth after approximately 1980, but that series also shows more rapid TFP growth before 1980 than the ERS series. Both the ERS and INSTEPP productivity accounts show TFP accounting for virtually all U.S. agricultural output growth since the mid-twentieth century. They also show almost identical cumulative output and TFP growth between 1950 and 2002.

One possible reason why flat public R&D spending may not (yet) have resulted in flat TFP is that other sources of knowledge and technology, such as private industry, have substituted for public R&D. Farm machinery innovations from the private sector have been important for U.S. agriculture for a long time, dating back to the cotton gin (1793), the mechanical reaper (1831), and the first steel moldboard plow (1837). By 1900, the farm machinery industry was the single largest manufacturing industry in the United States. Other important areas that emerged later were food processing, agricultural chemicals, and crop breeding and biotechnology. Private-sector research expenditures for food and agriculture research rose relative to public sector expenditures throughout the 1960s and, by the late 1970s, surpassed public research expenditures. They have remained higher than public R&D for the most part ever since.

For much of the post-1950 period, research in food manufacturing has constituted roughly half of the U.S. private food and agricultural research total. Food manufacturing R&D concentrates on post-harvest activities that in general do not increase farm-level productivity.[3] More relevant for agriculture is research conducted by manufacturers of agricultural inputs, such as the agricultural business segments of machinery, chemical, pharmaceutical, and biotechnology companies.

Figure 1 shows that private-sector R&D spending on agriculture (that is, by firms providing production inputs to farms) more than tripled in real terms between 1960 and 2010. Not only has private agricultural R&D increased, but its composition has changed markedly. Private agricultural research in the decades immediately after World War II focused primarily on farm machinery and agricultural chemicals. As late as 1980, these two sectors accounted for more than three-fourths of the total. In the 1980s and 1990s, however, private investment in crop-related research began to grow rapidly, and by the late 1990s, private crop seed/biotechnology research had surpassed research in all other agricultural input sectors. By 2010 (the last year for which detailed data on private agricultural research are available), crop seed/biotechnology made up more than 45 percent of the total (figure 2). This, in turn, drove an increase in private crops research in general, whereas private animal research has not grown much in real terms. Some of the increase in seed/biotechnology research represented a substitution from agricultural chemical research (especially with the development of genetically engineered crops for insect resistance and herbicide tolerance), but the total of seed/biotechnology and agricultural chemical research also increased in real terms. This rise in private agricultural research could provide an explanation for why agricultural TFP growth did not stagnate after the leveling off of public agricultural R&D after 1980. Of course, the rise in private R&D spending itself could be incentivized by advances in public science and technology, in which case stagnation in public R&D spending may eventually lead to stagnation in private R&D investment as the pipeline of opportunities for commercial development dries up. This is an issue we revisit later in the article.

A number of factors drove the increase in private crop-related research. Advances in molecular genetics opened up new technological opportunities in agricultural biotechnology. These included many steps over a long period of time, but one of the notable developments was the production and replication of DNA recombined from multiple organisms. The fundamental scientific advances in recombinant DNA were made at open science research institutions, especially Stanford University. At the same time, strengthened intellectual property protection over biological inventions helped incentivize private, for-profit research in breeding and genetics. The United States enacted the Plant Varietal Protection Act in 1970, and expanded its scope in 1994. More important, however, was the extension of utility patent protection for microorganisms in 1980 through a U.S. Supreme Court decision (*Diamond v. Chakrabarty*) and to higher plants and animals in 1985 and 1987, respectively, through internal U.S. Patent Office decisions. Finally, growth in global agricultural input markets, resulting from increased global demand for agricultural products, privatization of agricultural input markets, and falling barriers to trade, expanded market

[3] There are some exceptions. Some food processing firms also develop inputs for production agriculture. The great majority of food industry R&D, however, appears to be oriented toward the development of new food products. Moreover, the data reported here assigns farm-oriented research by food processing firms to the private agricultural R&D series, such as research by feed processors to animal nutrition. See Fuglie et al. (2011).

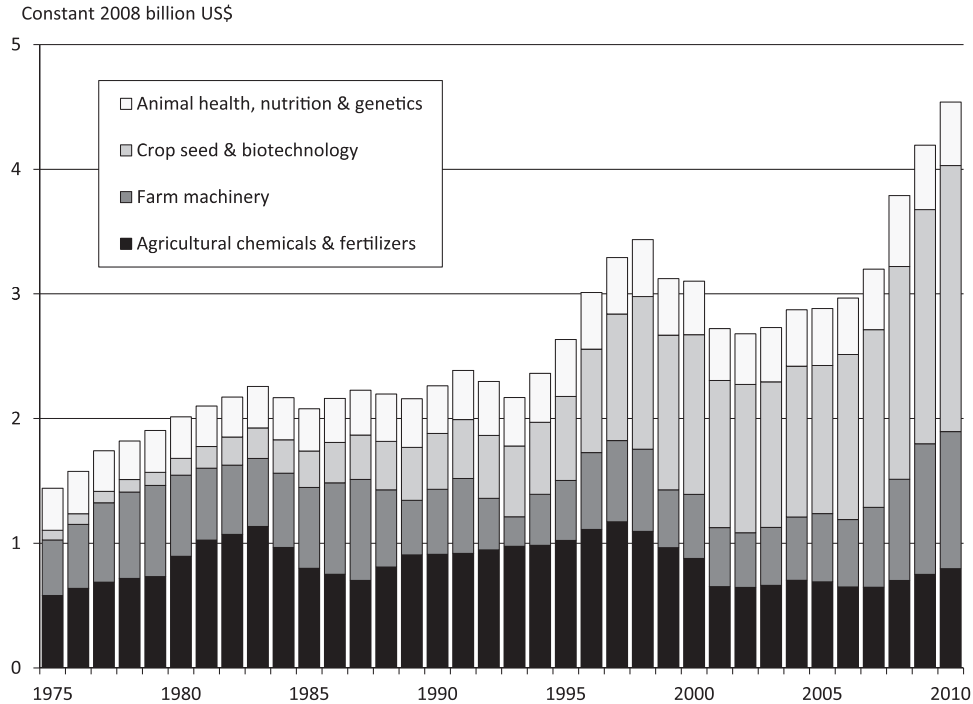

Figure 2. Changing composition of private agricultural research by U.S. companies

Source: Fuglie et al. (2011).

opportunities for private research both in the United States and worldwide (Fuglie et al. 2012; Pray and Fuglie 2002; Shoemaker et al. 2001).

The growing role of the private sector as a major source of food and agricultural innovation is not limited to the United States. Globally, the private sector accounted for approximately 36% of the $54 billion spent on food and agricultural research in 2008 (figure 3), and its share has risen over time (Bientema et al. 2012). A bit less than half of the private-sector R&D spending was oriented toward farm production and the rest toward food manufacturing. Although more than 90% of private research done globally was by companies based in high-income countries, developing countries represented an important market for the machinery, chemical, pharmaceutical, and biological products these firms sold to farmers for use as inputs into agricultural production (Fuglie et al. 2011). Public food and agricultural research was mostly oriented toward agriculture rather than food, although a precise breakdown is not available. In high-income countries like the United States, a declining share of public food and agricultural research is devoted to production agriculture. In 2008, only about 57% of U.S. public agricultural research was allocated to crop and animal production, and the remainder was allocated to other topics, such as broader environmental issues or to food and human nutrition. Also by 2008, the private sector accounted for more than half of total U.S. production agriculture research and more than three-quarters of total U.S. food research.

Concurrent with the rise of private sector research on agricultural inputs was significant structural changes in these industries. Mergers and acquisition activity led to fewer and larger firms accounting for a larger share of R&D, ownership of proprietary technology, and market sales. By 2009, the four-firm concentration ratio in global markets for commercial crop seed, agricultural chemicals, animal health products, farm machinery, and animal genetics had all risen to more than 50% (table 1). Although several, often industry-specific, reasons explain the rising concentration in these industries, in the crop and animal genetics industries, economies of size in biotechnology R&D seem to have

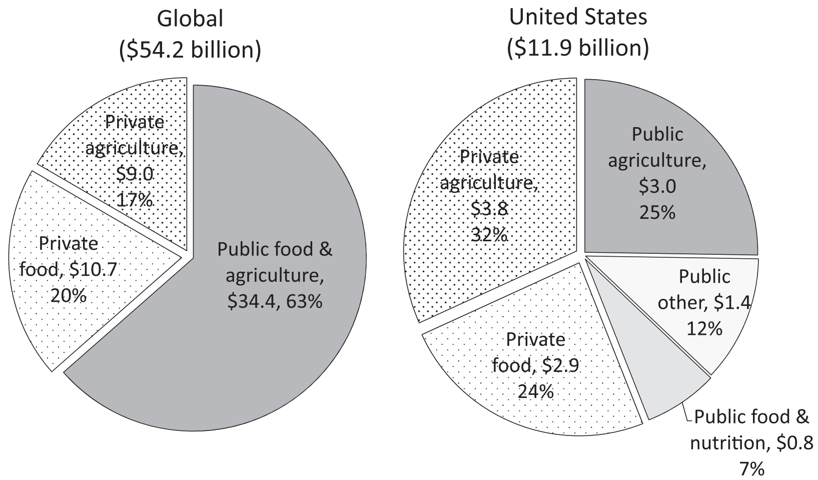

Figure 3. Public and private spending on food and agricultural research in 2008

Source: Global figures are from Bientema et al. 2012. For the United States, private figures are from Fuglie et al. (2011), and public figures from the National Institute of Food and Agriculture.
Notes: Figures are in billions of 2008 purchasing power parity dollars. Figures may not add up due to rounding.

played a significant part. Companies investing in agricultural biotechnology sought to acquire complementary technology and marketing assets and serve larger markets to spread the large fixed costs associated with research and meeting regulatory approval for new innovations (Fuglie et al. 2011). Integration of biological and chemical technologies for crop protection also drove mergers across the seed and agricultural chemical industries. Between 1994 and 2009, the increase in concentration was particularly acute in the global seed market, with the four-firm concentration ratio rising from 21% in 1994 to 54% in 2009. Although high levels of industry concentration raises concerns about excessive market power, if it increases incentives for private R&D, it could be welfare enhancing. By stimulating more rapid economic growth, it could offset short-run welfare losses from the exercise of monopoly power. In essence, monopoly rents form a new pool of resources to fund agricultural R&D. The evidence from table 1, however, suggests that despite the rise in concentration, R&D intensity (R&D spending as a percentage of industry sales) hardly changed in these industries. It would seem that most merger activity occurred among firms with similar R&D intensities. One implication may be that potential short-run social welfare losses from greater monopoly power have not been offset by potential long-run social welfare gains from more rapid technical change.

The Evolving Institutional Relationships for Public–Private Collaborative R&D and Technology Transfer

Stronger incentives and greater capacity for research in the private sector changes the portfolio allocation of publicly funded research and creates new opportunities for public–private research collaboration and technology transfer. Public research may focus more on upstream, fundamental science, leaving more applied research and market development to the private sector.[4] However, to efficiently transform advances in fundamental sciences into commercial opportunities may require closer collaboration between public and private institutions.

In the United States, new laws and regulations were put in place in the 1980s and 1990s to encourage the transfer of technology between public research laboratories and the private sector. These laws affected ownership rights to new technologies developed with government funds and established mechanisms for direct research collaboration between public- and private-sector scientists.

[4] The way in which the public and private sectors delineate their areas of responsibility will vary by technology field and depending on who the end-users of new technology are. Huffman and Evenson (2006) (p. 51) and Ruttan (p. 220–21) present a detailed description of the linkages among scientific and technology disciplines and between public and private sectors in the U.S. agricultural research system.

Table 1. Market Concentration and R&D Intensity in Global Agricultural Input Industries

Year	Herfindahl Index	Four-Firm Concentration Ratio	Eight-Firm Concentration Ratio	Industry R&D Intensity
		Share of Market (%)		R&D/Sales (%)
Crop protection chemicals				
1994	398	28.5%	50.1%	7.0%
2000	645	41.0%	62.6%	6.8%
2009	937	53.0%	74.8%	6.4%
Crop seed/biotechnology				
1994	171	21.1%	29.0%	11.0%
2000	349	32.5%	43.1%	15.0%
2009	991	53.9%	63.4%	10.5%
Animal health				
1994	510	32.4%	57.4%	8.6%
2000	657	41.8%	67.4%	8.5%
2009	827	50.6%	72.0%	8.6%
Farm machinery				
1994	264	28.1%	40.9%	1.9%
2000	353	32.8%	44.7%	2.3%
2009	791	50.1%	61.4%	2.7%
Animal genetics				
1994	NA	NA	NA	NA
2000	NA	NA	NA	NA
2006/07	1,025	55.9%	72.8%	7.3%

Source: Fuglie et al. (2011).
Note: NA = not available.

The primary goal was to increase the economic impacts of public R&D by moving public research findings that have commercial potential rapidly into the marketplace (Day-Rubenstein and Fuglie 2000).

The USDA and state agricultural universities responded to this new framework by strengthening ties with the private sector. The traditional model of technology transfer was for public institutions to provide technologies and knowledge directly to users (farmers, processing companies, agricultural input suppliers) through the agricultural extension service or indirectly through publication and media channels. The atomistic structure of the agricultural sector, which includes many small, competitive farms, meant that these farms had few incentives to conduct their own agricultural research. However, the expansion of private-sector agricultural R&D did not take place on farms, but instead was largely driven by firms in the manufacturing and service sectors seeking to spin off applications to agriculture. The growing agricultural R&D capacity in these machinery, chemical, pharmaceutical, and especially biotechnology firms created new opportunities for public–private partnerships in agricultural technology development (Fuglie et al. 1996).

The Changing Environment for Technology Transfer

The development of technology transfer policy in the United States has been incremental. Congress has enacted successive pieces of legislation aimed at creating new institutions for technology transfer between the public and private sectors and periodically has introduced modifications to improve or strengthen them. Some of the major technology transfer legislation that has affected the food and agricultural sector are listed in table 2.

One of the first major changes dealt with patent policy. Although universities and public institutions had for some time possessed the right to seek patents, the federal government assumed ownership of any invention resulting from federally funded research. Discoveries described in patents are often far from commercial viability, however, and without exclusive licenses, companies may be

Table 2. Major U.S. Legislation Encouraging Public–Private Research Collaboration 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 technology transfer to private companies.
1980	Bayh–Dole Act	Authorized 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	Tax credit for R&D grants to universities for basic research
1982	Small Business Innovation Development Act	Established the SBIR Program. The program requires a minimum percentage of each federal agency's extramural R&D budget to be allocated to small businesses.
1984	National Cooperative Research Act	Encouraged companies to conduct joint research by providing exemptions to antitrust (competitiveness) laws for technologies developed in research consortia
1986	Federal Technology Transfer Act	Authorized government research laboratories to enter into CRADA with private companies
1988	Omnibus Trade and Competitiveness Act	Created the Manufacturing Extension Partnership to assist small companies in accessing knowledge and technologies developed in government laboratories. It also created the ATP to provide seed funding, matched by private-sector investment, to companies or consortia of universities, industries, and government laboratories to accelerate development of generic technologies that have broad applications across industries. The ATP was terminated in 2007.
1993	National Cooperative Production Amendments Act	Extended antitrust exemptions to include joint manufacturing (not just joint R&D)

Source: Schacht (2012).

unwilling to make the investments necessary to commercialize them. Responding to this constraint, the Bayh–Dole Act (the Patent and Trademark Act Amendments of 1980)[5] gave institutions "certainty of title" for inventions resulting from research funded by the federal government. The legislation allowed universities, nonprofit organizations, and other institutions receiving government funding for research to obtain, own, and license the patents on any invention they discovered. It also expanded the right of federal laboratories to issue licenses for patents of their inventions. Previously, federal laboratories had been able to grant only nonexclusive or open licenses, but the Bayh–Dole Act allowed them to grant exclusive licenses as well. These changes to patent policy were designed to encourage scientists at universities and other public institutions to seek more patents and to provide private companies with incentives to work with these patents.

Other legislation sought to promote greater research collaboration between government laboratories and private companies. The 1980 Stevenson–Wydler Technology Innovation Act mandated that each federal agency develop specific mechanisms for disseminating government innovations. Before this act, technology transfer activities by

[5] U.S. laws are often referenced by the names of their principal sponsors as well as by their official title. In addition, they are designated a specific number (Public Law 96-517 in the case of the Bayh–Dole Act).

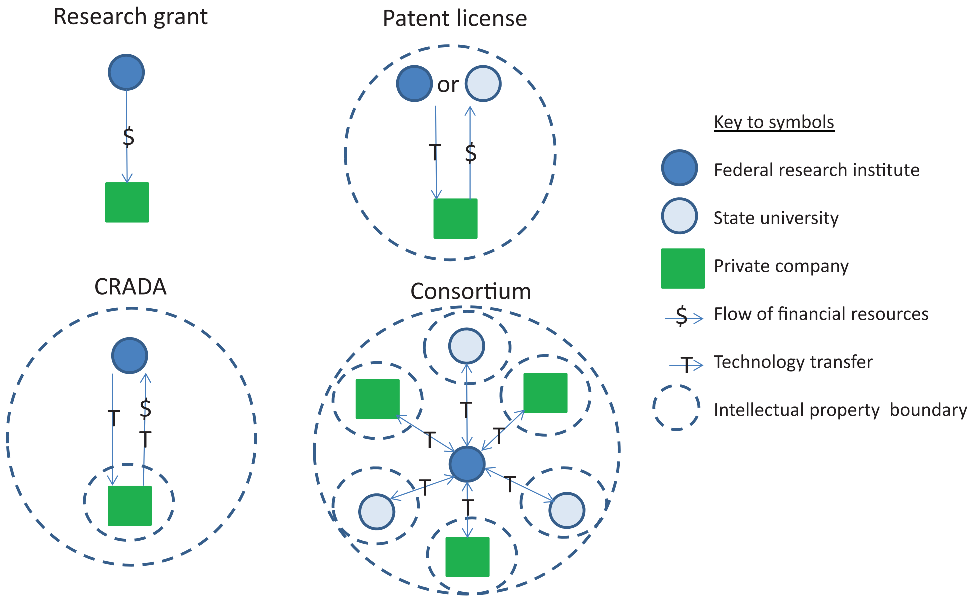

Figure 4. Models of public–private research collaboration and technology transfer

Source: Day-Rubenstein and Fuglie (2000).

federal agencies had been voluntary, and each agency had used its own method of disseminating information on new research discoveries and technology. Further incentives were provided in the 1986 Technology Transfer Act. This act spelled out conditions under which federal laboratories could work directly with researchers employed by private companies. This involves developing a written agreement between the public and private research partner that specifies the responsibilities and resource commitments of each. These agreements are referred to as Cooperative Research and Development Agreements (CRADAs). Before the 1986 act, government researchers were not permitted to collaborate directly with private firms. Further legislation in 1991 (the National Defense Reauthorization Act) and 1995 (the National Technology Transfer and Advancement Act) clarified the rules regarding patent licensing and royalty sharing for inventions developed in CRADAs.

Other initiatives encouraged government agencies to provide direct research grants to the private sector. The Small Business Innovation Act of 1982 required federal agencies to earmark a portion of extramural research funds to small companies (i.e., companies with 500 or fewer employees) through the Small Business Innovation Research (SBIR) program. The 1981 Economic Recovery Tax Act provided tax credits for research grants given by companies to universities. Other legislation sought to encourage research cooperation among firms within industries. The 1984 Cooperative Research Act provided incentives for private research consortia by providing some antitrust exemptions and liability limits on companies collaborating on precommercial R&D. In 1988, Congress created incentives for public–private research consortia through the Advanced Technologies Program (ATP). The ATP provided seed funding (with matching private R&D investment) to consortia of companies, universities, and government laboratories for the development of generic technologies with broad application across industries. The ATP was replaced by the Technology Innovation Program in 2007, which excluded large companies from receiving government research grants, but the Technology Innovation Program was terminated in 2012.

Models of Technology Transfer

The legislation described previously governs the exchange of information and resources between public and private collaborating institutions and, in general terms, states how rights to new inventions are to be owned and benefits shared. Figure 4 presents a stylized model of the various mechanisms available to government research agencies for cooperating with the private sector and other nongovernment institutions.

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 nongovernment partner, and the grant recipient has sole ownership over any patentable technology. This type of arrangement characterizes the SBIR program and the former Advanced Technology Program. Often, government R&D grants are targeted toward projects of high government priority. In 2000, the USDA and Department of Energy combined a portion of their SBIR resources to form the Biofuel Research and Development Initiative. The Biofuel Research and Development Initiative 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).

The patent licensing model. Under the patent licensing model, a public research institution develops and patents a technology and then assigns the rights to use the patented technology to nongovernment 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 commercialization—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 CRADA joint-venture model. 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 nongovernment 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 nongovernment partner. Patents resulting from a CRADA may be jointly owned, although the nongovernment partner has first right to negotiate an exclusive license. 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 after the passage of the 1986 Technology Transfer Act was between the USDA and Embrex, Inc., which led to the commercialization of a method for vaccinating poultry against disease before they hatch.

The research consortium. The research consortium is a somewhat more complex model. 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 precommercial, 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.

Public–Private Research Collaboration on the Basic Applied Research Spectrum

Underlying these changes in federal science policy was the emergence of a new paradigm of the relationship between scientific research and technology development. Previously, the principal paradigm for U.S. science policy was a linear or assembly line model in which advances in basic scientific knowledge lead to new technological applications. This paradigm was persuasively expressed by Franklin Roosevelt's science advisor Vannevar Bush in *Science: The Endless Frontier*. Bush argued for a strong government commitment to support curiosity-driven basic science, which would subsequently feed into private sector–led technological and

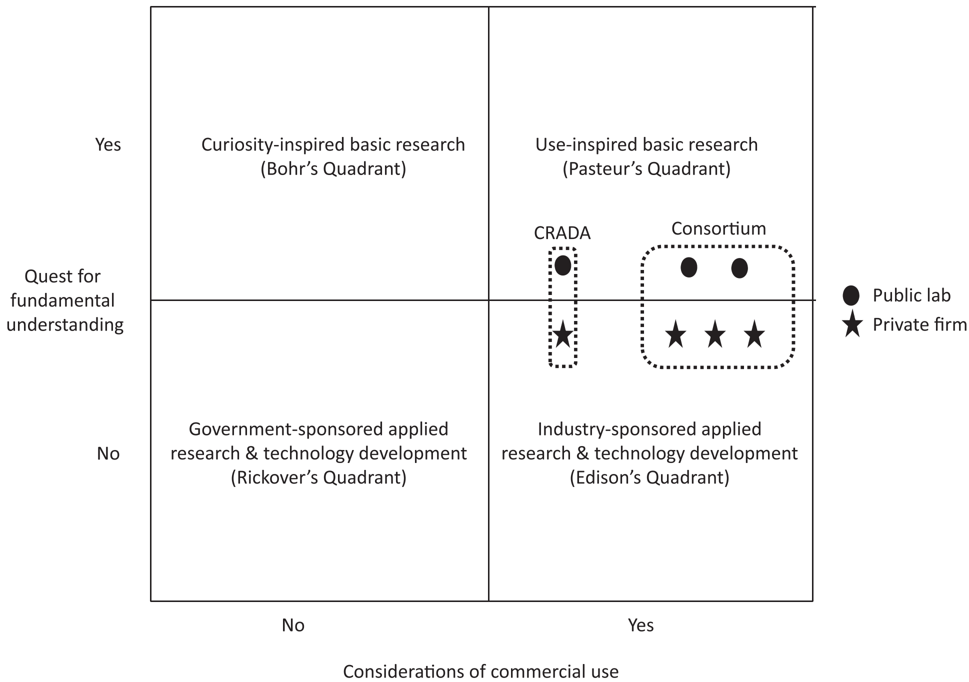

Figure 5. Technology transfer mechanisms along the basic applied research spectrum

Source: Adapted from Stokes and Ruttan.
Notes: On the y-axis, research endeavors are divided among those that seek fundamental scientific understanding and those aimed at technology development. On the x-axis, research endeavors are characterized by those that are inspired by potential commercial use and those that are aimed at other societal needs.

commercial applications. Over time, a more complex interpretation emerged regarding the relationship between scientific research and technology development. "It is no longer believed that a heavy investment in pure, curiosity-driven basic science will itself guarantee the technology required to compete in the world and meet a full spectrum of other societal needs" (Stokes 1997, p. 58). Critics of the linear model emphasized that advances in science and technology are often closely inter-related, with the distinction between who "does science" and who "does technology" becoming increasingly blurred (Ruttan 2001, p. 536). In 1997, Princeton political scientist Donald Stokes, drawing on the example of nineteenth-century French chemist Louis Pasteur, proposed a new science policy paradigm. Stokes made a distinction between basic scientific research that is motivated solely by the quest for understanding without thought of practical use and research that seeks to extend frontiers of understanding but is also inspired by considerations of use. He labeled pure science endeavors as "Bohr's Quadrant," after the Danish physicist Niels Bohr's search for a model of atomic structure, and use-inspired science as "Pasteur's Quadrant," whose research to improve fermentation led to fundamental advances in microbiology. Stokes relegated research that is guided solely by applied goals without seeking more general scientific understanding to "Edison's Quadrant" (figure 5). Later, Ruttan modified Stoke's paradigm by making a further distinction between applied R&D for commercial use and applied R&D that addresses other society goals. In addition to economic growth, public science may be expected to contribute more broadly to societal welfare, including security, human and environmental health, equity, and other quality-of-life issues. Ruttan labeled this type of research as falling into "Rickover's Quadrant," in reference to the effort by Admiral Hyman Rickover to develop the first power plants for nuclear submarines. Ruttan placed much of federal and state investment in agricultural research in Rickover's Quadrant, noting that it focused on developing technologies that significantly affected U.S. agricultural productivity, but in areas where commercial returns were low because of the difficulty for private innovators to appropriate returns. Besides defense and agriculture, much of the applied research in social sciences and policy, environment, and health, and research that supports government regulatory functions and program performance, also fall into Rickover's Quadrant.

Although the research paradigm described in figure 5 suggests distinct areas of responsibility for public and private research, it does not imply that research institutes or scientists working in these institutes are homogeneous or monolithic. Scientists working on agricultural biotechnology may have different value orientations, which affect their willingness to engage in research with proprietary or commercial applications (Glenna et al. 2011). In the Stokes–Ruttan framework, individual scientists could place themselves exclusively or primarily in the Bohr, Rickover, or Pasteur Quadrants, depending on their value orientation. Similarly, entire research institutes or departments could carve out a specialized role in one of these domains. Figure 5 also does not imply that all applied applications of agricultural biotechnology fall into Edison's Quadrant. The development of crop and livestock genetic traits with positive environmental attributes (e.g., water conservation and reduced greenhouse gas emissions), that enhance the nutritional content of food, or that are targeted toward specialty or "orphan" commodities are examples of applied agricultural biotechnology where gaps between social and private returns are likely to be large (National Research Council).

In figure 5, we show the new institutional arrangements such as CRADAs and research consortia as potential bridging mechanisms across these scientific and technology quadrants. Although CRADAs typically involve single public and private partners and focus on one narrowly defined project, a consortium may involve multiple partners from both sectors and include exploration of a wider array of R&D opportunities. Joint public–private research endeavors include both precommercial research (performed by the public partner, but possibly with funding from the private partner) and applied research and technology development aimed at commercialization of new products and processes (performed mainly by the private partner).

Dynamic Response of Public and Private Agricultural Research

To this point, our analysis highlights both the growth in private agricultural R&D investments and the emergence of new institutional mechanisms for public–private research collaboration as major forces shaping the structure of the agricultural research system. In this section, we examine the extent to which these changes have altered the respective roles of the public and private sectors in the agricultural research and development process.

The growth of private R&D investment is likely to have a lasting influence on both the volume and mix of projects undertaken by the public and private sectors. For the private sector, the overall volume of projects has increased in response to better technological opportunities, stronger appropriability conditions, and larger markets. Improvements in technological opportunities moved (at least some) previously unprofitable projects into profitability and also introduced new projects that were not previously foreseen. Stronger appropriability conditions increased the private returns to existing projects by allowing companies to capture more of the overall stream of project benefits. That is, private companies now capture a greater share of the social return from a project. Larger markets made it profitable to undertake new R&D projects aimed at inventing novel products and services or adapting existing products and services to new customer needs.

Better technological opportunities and stronger appropriability conditions suggest a reorientation of private sector research and a new mix of active research projects. Some projects that were only attractive to public-sector funders, because of higher social returns than private returns, are now attractive to private-sector performers. In terms of figure 5, some previously unprofitable projects in Rickover's Quadrant become profitable and shift to Edison's Quadrant. An early illustration of how changes in intellectual property rights over agricultural innovations may affect private incentives for agricultural research is the case of soybean breeding in the United States. Before the 1970 Plant Varietal Protection Act, there was little soybean breeding taking place in the private sector, and almost all farmer varieties were from university breeding programs.

With breeder's rights, private investment in soybean breeding grew rapidly. By the 1990s, private proprietary varieties accounted for more than 80% of new soybean variety releases (Huffman and Evenson 2006). Advances in biotechnology and other sciences that create entirely new technological opportunities, on the other hand, expand the size of these quadrants, including new endeavors that require scientific and technology competencies that span across the Edison and Pasteur Quadrants. Private firms may have an incentive to extend some of their own research into Pasteur's Quadrant and/or seek public partners who can fill this role. Such scientific advances may be accompanied by changes to intellectual property regimes, such as the U.S. Supreme Court rulings that established the patentability of biological inventions.

For the public-sector research institutions, the growth in private-sector R&D is likely to influence the mix of projects more than the volume (because of budget constraints). As the private sector reorients its portfolio toward research areas that were traditionally and predominantly public, the project selection criteria for allocating public support become critically important for maintaining the proper balance within the research system. As Jaffe points out, public-sector decision makers need to support those projects with scientific/commercial potential that have large "spillover gaps," defined as how much social returns exceed private returns. It is clear that the spillover gap is reduced when stronger appropriability conditions allow private companies to capture a greater share of the social return. In these cases, public decision makers need to reassess the spillover gaps expected from their research programs and reallocate resources to new projects as necessary.

The new institutional mechanisms for public–private collaboration, which is the second major structural change to the agricultural research system, represent an opportunity to restructure research relationships and transition the public and private portfolios. In the current environment, both public and private sector organizations have stronger incentives to collaborate. For the public sector, some established and ongoing research areas have experienced a reduction in the spillover gap and increased potential for privatization. In these areas, private returns have increased relative to social returns because of stronger appropriability and new technological opportunities stemming from public research. For public-sector decision makers, their collection of research materials, equipment, and personnel should be attractive to the private-sector partners because these are the research areas where the private sector wants to transition its portfolio to take advantage of increased returns. As these collaborative relationships evolve, public-sector decision makers can transition to new program areas, topics, or research areas in Pasteur's Quadrant where the spillover gaps remain large. At the same time, public institutions may have incentives to partner with private firms to access new technical knowledge in Edison's Quadrant that complements and informs more basic Pasteur-style research.

Evidence on the Nature and Interactions between Public and Private R&D

There are a handful of recent empirical studies that attempt to characterize the nature and interactions between public and private agricultural R&D. Most of this work draws its conceptual framework from a broader literature that asks whether public R&D "complements" or "substitutes" for private R&D (David, Hall, and Toole 2000; Toole 2007). Complementarity takes place when public R&D investments stimulate additional private R&D investments. This could happen because of differences in the nature of the research conducted in public and private organizations. For instance, if public-sector researchers conduct curiosity-driven or use-inspired basic research (Bohr's or Pasteur's Quadrant), the results may improve technological opportunities for privately conducted applied research (Edison's Quadrant). Substitution (or "crowding out") takes place when public funds support R&D activities that would otherwise have been completed by the private sector. Substitution is more likely when public and private researchers work in the same topical areas (e.g., crop research) and conduct research that falls in the same quadrant of the modified Stokes framework (i.e., the same nature and objectives). When substitution takes place, private firms have reduced their own investment relative to a situation without public funding. In regression analyses, finding a positive and significant effect of public R&D on private R&D is taken as evidence

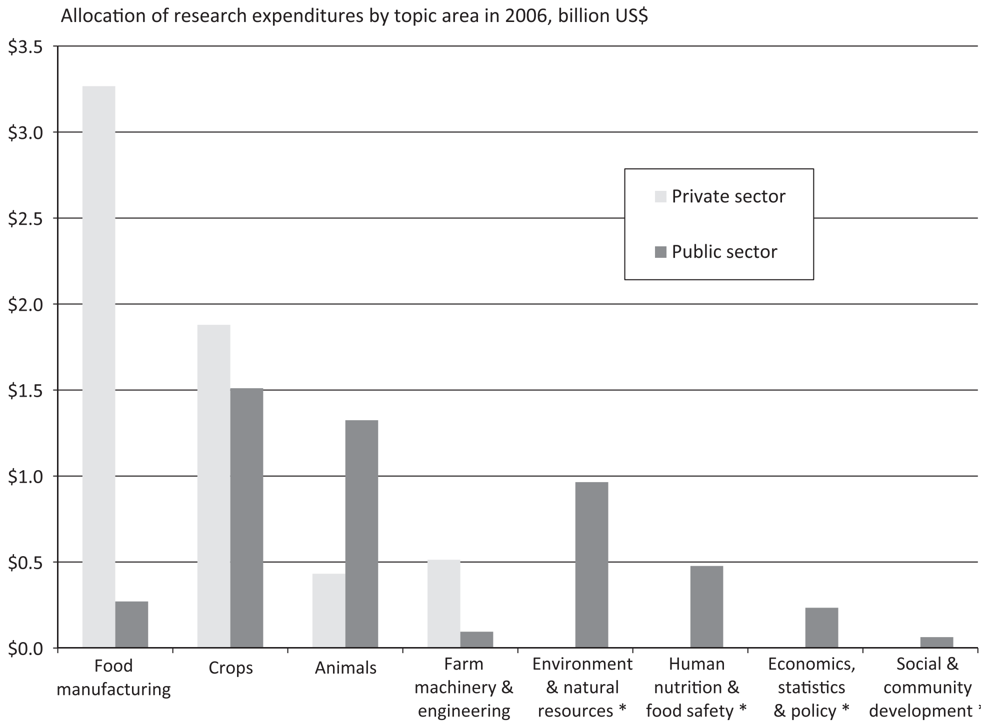

Figure 6. The allocation of public and private sectors in agricultural research in the United States

Source: King, Toole, and Fuglie (2012).
Note: *Private sector investment is likely to be greater than zero, but reliable figures could not be obtained.

of a complementary relationship, whereas a negative and significant coefficient indicates substitution.

Comparisons of public and private agricultural R&D resource allocations across topic areas reveal a fairly distinct division of research effort that seems consistent with prior beliefs about the size of spillover gaps. Narrod and Fuglie used various indicators to create a ranking of spillover gaps (lowest to highest) across livestock breeding in poultry, swine, and beef/dairy. Based on their ranking, the private sector should allocate more R&D to poultry and the least to beef/dairy, with the public sector having the opposite ranking. Their data for 1996 are consistent with this ranking. They also find that the public sector allocated more of its research to Pasteur science (microbiology), whereas private industry allocated more to Edison applied R&D (breeding). For more recent data covering a broader array of topic areas, King, Toole, and Fuglie (2012) showed the public–private division of research across major fields of food and agricultural research (figure 6). Private R&D dominated food manufacturing and farm machinery, whereas public R&D addressed a broad set of socially important issues such as environment and natural resources, food nutrition and safety, economics and statistics, and community development, for which private R&D incentives are especially weak. The public sector also dominated animal R&D, except for animal health product development. The important exception appears to be crop research, where each sector spent roughly equal amounts on R&D (private crop-related R&D included work on crop breeding and biotechnology as well as chemical pesticides).

Although crop research shows significant R&D activity by both the public and private sectors, differences in the nature of the research conducted suggests complementarity rather than substitution. Frey, who conducted a near-census survey in 1994 of U.S. public and private crop breeding institutions and companies, found that even though the private sector employed nearly twice as many plant breeders (1,499) as the public

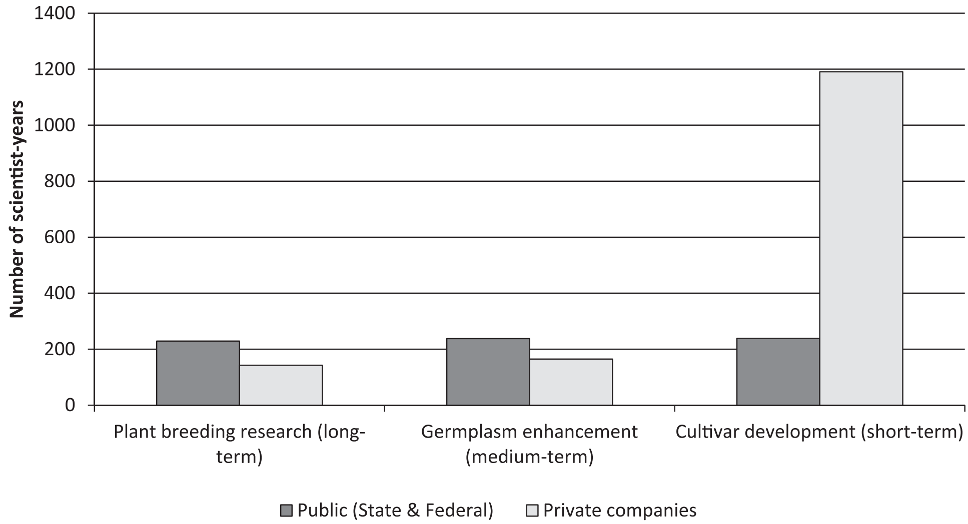

Figure 7. Public and private research allocation in U.S. plant breeding

Source: Frey (2000).

sector (706), 80% of private-sector breeders were concentrated on downstream "cultivar development" (figure 7). The more upstream "germplasm enhancement" and "basic plant breeding research" were primarily in the public sector. Because scientific advances from upstream research are hard to appropriate, private returns to research in these areas are likely to be significantly lower than their social returns (i.e., a large spillover gap). Frey's descriptive findings were extended by Fuglie and Walker, who performed regression analysis of public and private research on eighty-four commodities based on the Frey database. They found that commodities with higher levels of public basic research (basic breeding and germplasm enhancement), after controlling for market size and other factors, were associated with higher private applied R&D (cultivar development), whereas higher public applied research (cultivar development) was associated with less private applied R&D. This evidence suggests that within broad topic areas such as crop research, it is necessary to look at the nature of research conducted to assess complementarity.

Several recent studies have used regression analyses to test complementary versus substitution in public and private agricultural research. Most of these studies focus on the United States and generally find evidence of complementarity. Toole and King (2011) analyzed agricultural patenting by companies in the chemical and allied products industry and found that public agricultural research performed in universities stimulated (and thereby complemented) private invention at the firm level. Using the Standard and Poor's Compustat database for the period 1991–2003, Wang, Xia, and Buccola (2009) estimated an elasticity of private agricultural R&D with respect to public life sciences research of 0.65 (i.e., a 1% increase in public research leads to a 0.65% increase in private R&D). Tokgoz, using national aggregate R&D expenditure data, found that public basic life sciences research had a positive and significant elasticity of 0.69 on private agricultural R&D but found no significant relationship between public applied life sciences research and private agricultural R&D. Using agricultural R&D data extended to more recent years and disaggregated into components, Tokgoz and Fuglie found that public agricultural R&D stimulated private "land-saving" R&D but not private "labor-saving" R&D. Their elasticity estimates for private land-saving R&D ranged from 0.61 to 0.97. Wang et al. (2013) separated private R&D into crop and livestock components. Using a vector autoregression model and data covering 1970–2009, they found that a shock (exogenous spending increase) to public crop research caused private crop research to rise, but no significant interactions were found between public and private livestock research. Wang et al. (2013) also found that a shock to private applied crop research caused public applied crop research to fall and that a negative shock to public applied crop research led to public research in other agricultural areas to rise. These results suggest the public sector responded to the changing market and institutional environment by reallocating its research portfolio in a way that avoided direct competition with the private sector. However, evidence of short-run substitution between public and private funding of bioscience at U.S. universities was found by Buccola, Ervin, and Yang (2009). Based on a national survey of U.S. academic bioscience researchers in 2003–04, they found that individual scientists tended to specialize in their sources of research funding and that an increase in private funding led to a decrease in public funding (and vice-versa) for that scientist. This could cause crowding out in funding sources in the short run but would not likely affect the system level in the longer run given entry and exit possibilities of new scientists. International evidence is relatively sparse, and findings are mixed. In a study of agricultural R&D investment in China, Hu et al. (2011) found private agricultural R&D spending increased with public investment in basic research but decreased with public investment in development research. However, Alfranca and Huffman (2001), using data from seven European Union countries in the period 1984–1995, found significant crowding out (substitution) between public and private agricultural research spending.

Evidence on the Success of the New Institutional Mechanisms

Despite the considerable importance given to public–private technology transfer in federal science policy, there is surprisingly little evidence on whether these measures are actually effective at stimulating more rapid economic growth. Most studies have either described impact in terms of "success stories" of technologies that were commercialized or conducted assessments of how processes and procedures used in public–private R&D arrangements might be improved. A recent, comprehensive review of technology transfer across federal laboratories found that in measuring success agencies rely primarily on activity metrics (Hughes et al. 2011), which are now reported systematically by federal agencies on an annual basis (see National Institute of Standards and Technology 2012). In this section, we provide a selective review of empirical studies on the economic implications of the new technology transfer mechanisms, focusing on the SBIR, CRADA, and consortia models and referencing evidence involving agricultural and life sciences research where possible.[6]

SBIR grants The academic literature on the impact of the SBIR program on business performance is mixed. Studies using survey data collected from SBIR participants, either at the project or firm level, consistently find positive program effects across a variety of indicators such as sales, employment, and patenting (Archibald and Finifter 2003; Audretsch 2003; Audretsch, Link, and Scott 2002; National Institutes of Health 2003). But survey-based evidence frequently lacks a credible counterfactual: How would these firms have fared in the absence of an SBIR grant? In contrast, regression-based evaluations using data from both participant and nonparticipant firms, such as those of Lerner and Wallsten, do not find significant sales or employment effects from participation in the SBIR program. However, Lerner did find that SBIR participant firms located in regions with substantial venture capital activity had better employment and sales growth than nonparticipant firms. Toole and Czarnitzki note that the SBIR program serves an important "bridging" function that can increase incentives for private-sector sources of finance to support new technologies. Using data that included agricultural and nonagricultural companies, Toole and Turvey showed that participation in the SBIR program allowed firms to reduce technical and market uncertainties and increased the probability of obtaining follow-on funding from venture capital investors. Their theoretical results suggest that banks and other sources of private financing would respond similarly.

CRADAs Federal agencies enter into about 3,000 new CRADAs with private firms

[6] Our focus is primarily on research collaboration involving federal research agencies. There are also myriad arrangements for research collaboration between private companies and universities, but these are outside the scope of this article. In particular, we do not cover economic implications of the patenting provisions of the Bayh–Dole Act. See Mowery et al. (2001) and Kenney and Patton (2009) for critical perspectives of the implications of Bayh–Dole for commercialization of university inventions.

each year (National Institute of Standards and Technology). Probably the most well-known and controversial CRADA was a 1991 agreement between the National Institutes of Health (NIH) and the pharmaceutical company Bristol-Myers Squibb (BMS) to commercialize the naturally occurring taxol compound into an anticancer drug. The CRADA was successful in mobilizing significant private sector resources to bring the drug to market and develop alternative sources of supply to the Pacific Yew tree (from which the compound was first isolated). The drug was also very profitable for the private-sector partner, becoming by 2001 the best-selling anticancer drug in the world. A 2003 study by the Government Accounting Office questioned the terms of the CRADA, noting that royalties received by NIH amounted to only a fraction of NIH's own substantial investment in taxol and that the agreement did not restrict what Bristol-Myers Squibb could charge for the drug (Government Accounting Office).

Whether public–private research partnerships draw public resources away from the provision of public goods to the subsidy of private goods is a recurring theme in debates on collaboration mechanisms, but evidence on this question is mostly anecdotal. In fact, largely because of a lack of data, the academic literature contains very few studies evaluating CRADA performance (Cohen and Noll 2005; Stiglitz and Wallsten 2000). One exception is Day-Rubenstein and Fuglie (2000), who examined how public research resources were allocated among the USDA's CRADA agreements, SBIR grants, and intramural research between 1986 and 1995. They found that CRADA and SBIR, compared with USDA intramural research, placed greater emphasis on postharvest utilization, similar levels of emphasis on production agriculture, and relatively less emphasis on natural resources and human nutrition. This corresponds to what we might expect about the relative size of the spillover gap between social and private returns, being largest in the case of environmental and nutritional goods and services and smallest in the case of postharvest products. However, the authors did not find evidence that private collaboration influenced USDA research priorities toward private preferences. In fact, over this period, overall USDA intramural research resource allocation shifted slightly toward more environmental and human nutrition research, areas with the smallest share of CRADA and SBIR activity.

Research consortia. The academic literature on industry consortia is quite large, even when restricting attention to government-supported industry consortia. Although it is not feasible to summarize this literature here, the studies are generally of two varieties: (*a*) case studies or comparative case studies (Grindley, Mowery, and Silverman 1994; Katz and Ordover 1990; Roos, Field, and Neely 1998; Sperling 2001; Thornberry 2002) and (*b*) quantitative studies based on survey results (Aldrich and Sasaki 1995; Link, Teece, and Finan 1996; Sakakibara 1997). Although existing studies do not consider agricultural consortia, some lessons can be learned from the experience of other industries.

Perhaps the most well-known government-supported research consortia in the United States is SEMATECH, a partnership formed in 1987 between the U.S. government and fourteen U.S.-based semiconductor manufacturers to enhance U.S. competitiveness in the global semiconductor business. Each member company contributed financial and human resources, with government matching support, to a central research facility owned and managed by the member companies. The research facility was located in space rented from the University of Texas, although no public research institution was directly involved in the consortium. Government matching funds were discontinued after 1996, and SEMATECH has continued to operate solely through member support since then.

Grindley, Mowery, and Silverman (1994) provide a detailed discussion of SEMATECH's evolution and a comparative analysis with other high-technology consortia in Japan and Europe. They highlight three complex design and management challenges that all consortia face: (*a*) how to define the research agenda and projects to undertake; (*b*) how to transfer research results to participants; and (*c*) how to allow sufficient flexibility to permit change as industry needs and circumstances evolve. In contrast with most European consortia, SEMATECH's centralized management structure and strong industry control allowed it to address these problems more efficiently. Moreover, they point out that the feasibility and eventual success of consortia-style collaboration in

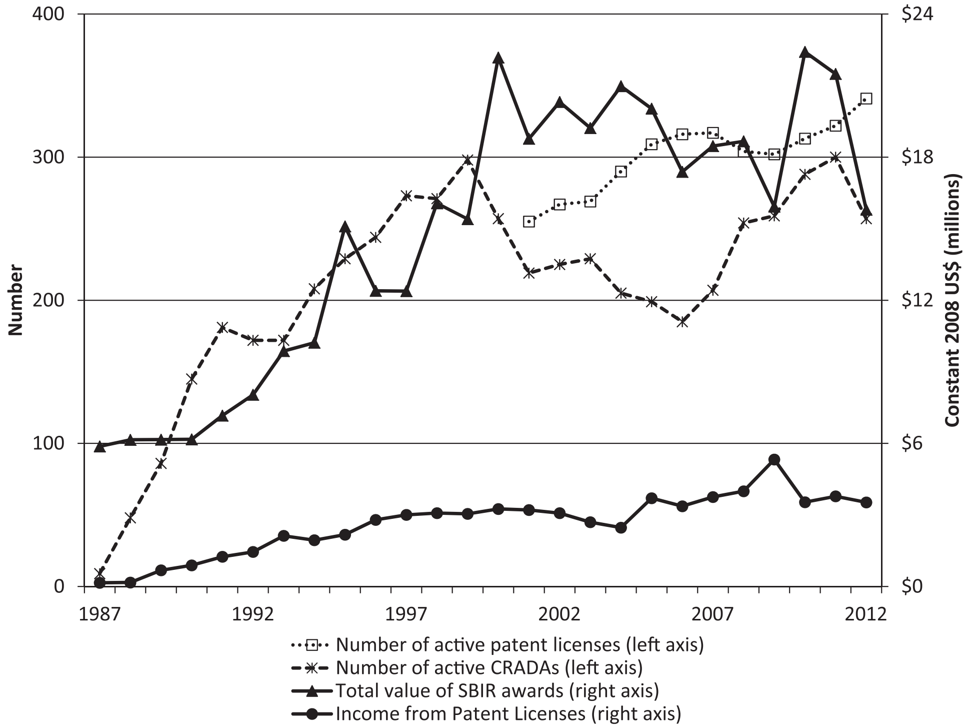

Figure 8. USDA collaborative research and technology transfer with private industry

Source: Number of active CRADAs, active patent licenses, and income from patent licenses are from King, Toole, and Fuglie (2012), updated with data from the U.S. Department of Agriculture (2013). SBIR awards are the SBIR/STTR official website, http://www.sbir.gov/.

other industries will depend on the structure of the consortium, the political and economic expectations of the sponsors, and the alignment between the research activities of the consortium and the competitive problems in the industry.

One of the few examples of a research consortium in agriculture is the Genetic Enhancement of Maize project. This consortium was formed in 1994 to increase genetic diversity in commercial maize hybrids, and by 2010 had more than sixty members, including the USDA, several state agricultural experiment stations, U.S. and foreign seed companies, and foreign public research institutions. The U.S. government has provided approximately $500,000 annually for the consortium, whereas member companies have contributed in-house resources of roughly matching value (Pollock 2003). The public institutions develop exotic germplasm with valued production or postharvest characteristics and share these with the private companies. The private companies then cross this material with their own elite in-bred lines and share the crosses with other members of the consortium. This provides adapted material for use in commercial breeding while at the same time protecting the intellectual property of the companies' in-bred elite lines (because it is virtually impossible to back out the in-bred parent from a cross). This arrangement has helped overcome the lack of incentives faced by individual companies to do high-risk and long-term research on germplasm enhancement (Knudson 2000), which would likely fall in Pasteur's Quadrant. Using the crosses with elite in-bred lines assures that the materials released by the consortium can move quickly into commercial varieties (Pollock 2003).

Collaborative Public–Private Research and Technology Transfer at the USDA

The USDA has had a long and unique history of collaboration with private agricultural industries, in part because public agricultural research is often more applied in nature than research conducted by other federal agencies (Fuglie et al. 1996). The USDA has transferred many technologies to the private sector and maintains close ties to farmers and suppliers of agricultural technologies. Yet the new mechanisms for public–private collaboration in research have had a significant impact at the agency. The USDA has significantly increased collaborative research and technology transfer with private industry since the 1980s.

In 2012, the Agricultural Research Service (ARS), the USDA's primary in-house research agency, was participating in 257 active CRADAs and had 384 active patents licensed to private firms (figure 8). The private sector has played a substantial role in the technology transfer process. Financial data from 366 CRADAs entered into by the ARS between 1986 and 1995 show that 64% of CRADA resources come from collaborators and 36% come from the USDA (Day-Rubenstein and Fuglie 2000). Patent licenses have brought in relatively small revenues from royalties (approximately \$3 million annually in the late 2000s compared with ARS's total annual research budget of approximately \$1.1 billion). Rather than being used for raising revenue, ARS uses patenting and licensing primarily as a means of technology transfer for cases in which a technology requires additional development by a private-sector partner to produce a commercial product. The license may provide exclusive rights to market products developed from the patented technology as a way of reducing commercial risk to the company (Heisey et al. 2006).

The size of the USDA's SBIR program is tied to congressional appropriations for extramural research, which is managed by the agency's National Institute for Food and Agriculture (NIFA). In 2012, NIFA awarded eighty-eight SBIR grants totaling \$16.8 million, approximately 2.5% of the USDA's total extramural research expenditure.

Federal regulatory guidelines governing the new technology transfer mechanisms leave government agencies considerable discretion to formulate policies for collaborating with the private sector. As technology transfer activities have increased, the USDA has instituted a number of administrative procedures to try to ensure that CRADAs, patent licensing, and other collaborative efforts achieve USDA policy objectives. These guidelines, which govern the selection of private-sector collaborators and sharing of research costs and benefits, aim to assure that all parties fulfill their commitments.

Conclusions

The private sector has played an important role in the U.S. agricultural research and innovation system since its inception, but the volume and impact of private research has accelerated in the past three decades with the application of biotechnology to crops. Until 1980, most private, agriculturally oriented research focused on providing improved machinery and chemical inputs to farmers, but by the first decade of the twenty-first century, private crop seed/biotechnology R&D formed the largest component of private agricultural research. At the same time, changes in federal science policy enabled new institutional relationships between public and private research performers, such as patent licensing, cooperative R&D agreements, small business innovation grants, and public–private research consortia. Increased incentives for and capacity in private research changed the allocation of public-sector research and created new opportunities for public-private research collaboration.

Conceptually, these changes in incentives and structures for research closed gaps between social and private returns to some research endeavors, making some research more suitable for the private sector to fund and perform. It also created opportunities to more closely link science-oriented basic research in the public sector with applied research and technology development in the private sector. Synergies between science and technology created incentives for both sectors to engage in closer collaboration. But without dynamic response from public and private research institutions and clear delineation of the appropriate division of research effort between sectors, these changes could lead to crowding out of private research by the public sector or unrealized social benefits from public R&D investments because of insufficient commercialization efforts.

Several studies have examined the crowding-out hypothesis in public–private agricultural R&D. One approach has been to compare the basic applied or commodity area R&D allocations between the public and private sectors to see whether these are consistent with a priori beliefs about where the largest spillover gaps exist. Even though the distributions analyzed are broadly consistent with prior expectations and can be interpreted as facilitating complementarity, this research approach does not rule out other possibilities that may explain observed R&D allocations. A second approach applies econometric methods to time series and/or cross-sectional data at various levels of aggregation. Seven studies using U.S. and Chinese data found evidence supporting complementarity between public and private agricultural research, particularly for public investments in basic agricultural sciences. Two other published studies found evidence of crowding out between public and private agricultural R&D. One of these used country-level data on European Union members and the other used researcher-level data for U.S. academic bioscientists.

Although seven of nine regression studies find that public agricultural research complements private agricultural R&D, achieving a deeper understanding of these inter-relationships is critical going forward. The current body of work is too small and varied to reach credible conclusions. Outside of agriculture, a number of sophisticated microeconomic studies have emerged in the broader economics and business literatures that use quasi-experimental methods to address problems of endogeneity of public R&D. Empirical approaches such as nonparametric matching, difference-in-difference, instrumental variables, and selection models offer potential for improving the agricultural literature (see, e.g., Czarnitzki, Ebersberger, and Fier 2007). There are also opportunities for theoretical work using structural models to clarify the mechanisms that lead to complementarity (Takalo, Tanayama, and Toivanen 2013).

Direct public–private partnerships that involve active research collaboration, such as CRADAs and research consortia, are a growing component of the technology transfer portfolios of the USDA and other federal agencies. Such arrangements are expected to fuel innovation by fostering greater interaction among participants, limiting the duplication of research efforts, and selecting the most important research topics. At this time, very little is known about these potential impacts, particularly for agriculture. Future empirical work could apply a "treatment–control" empirical approach using the same methodological approaches mentioned herein as long as data on participant and nonparticipant firms can be collected.

In December 2012, the President's Council of Advisors on Science and Technology identified seven grand challenges facing the nation's agricultural research enterprise. Meeting these challenges, which include wide-ranging objectives related to food production, the environment, energy, and health, will require new policies and strategies that depend on interactions and interdependencies between public and private R&D funders and performers. In an era of stagnant public funding for agricultural research, USDA and other public agencies may be able to increase the return to public investments by leveraging knowledge and resources through private-sector collaboration.

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